Roadside Revegetation

An Integrated Approach to Establishing Native Plants and Pollinator Habitat

Version 1.2 — September 2017

U.S. Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Roadside Revegetation: An Integrated Approach to Establishing Native Plants and Pollinator Habitat

5. Report Date
September 2017

6. Performing Organization Code

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8. Performing Organization Report No.

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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Federal Highway Administration, 1200 New Jersey Avenue, SE
Washington, DC 20590

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes
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16. Abstract
Native plants are a foundation of ecological function, affecting soil conservation, wildlife habitat, plant communities, invasive species, and water quality. Establishing locally-adapted, self-sustaining plant communities can also support transportation goals for safety and efficiency. Past obstacles to establishing native plant communities on roadsides have been technical, informational, and organizational. Effective strategies and practical techniques for revegetating the disturbed conditions with limited resources must be made available to practitioners. Multiple disciplines including engineering, landscape architecture, soil science, ecology, botany, and wildlife science must work cooperatively and not in isolation.

Roadsides play an important role in the conservation of declining wild pollinators and in supporting the health of managed pollinators. Throughout the revegetation process, practitioners and designers can enhance roadsides to benefit pollinators. This report offers an integrated approach to facilitate the successful establishment of native plants and pollinator habitats along roadsides and other areas of disturbance associated with road modifications. It guides readers through a comprehensive process of: 1) initiating, 2) planning, 3) implementing, and 4) monitoring and managing a roadside revegetation project with native plants and pollinator habitat.

17. Key Words
pollinators, integrated roadside vegetation management, butterflies, bees, moths, nectar plants, host plants, roadside habitat, reduced mowing, native plants, roadside landscape design, roadside maintenance

18. Distribution Statement
No restriction. This document is available to the public from the sponsoring agency website.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	xx	$0.00

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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U.S. Department of Transportation
Federal Highway Administration

FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The FLH has an interest in using new technology to assist in designing and constructing roads more efficiently. One emerging three-dimensional mapping technology is terrestrial or ground-based LiDAR. LiDAR (Light Detection and Ranging), also often referred to as "3D laser scanning", employs a laser and a rotating mirror or housing to rapidly scan and image volumes and surficial areas such as rock slopes and outcrops, buildings, bridges and other natural and man-made objects. Ground-based or terrestrial LiDAR refers to tripod-based measurements, as opposed to airborne LiDAR measurements made from airplanes or helicopters.

This project shows how the new technology of ground-based LiDAR could assist FHWA with highway rock slope stability. Site characterization for rock slope stability involves the collection of geotechnical data, and in the current practice, much of this data is collected by hand directly at exposed highway slopes and rock outcrops. There are many issues with the collection of this data in the field, including issues of safety, slope access, and human bias. It is shown in this report that some of the most important types of geotechnical information for rock slope stability can be acquired using LiDAR at a safe distance from the slope. In many cases, this information can also be automatically extracted from LiDAR point clouds using currently available point cloud processing software, reducing human bias issues. This report concludes that indeed there are benefits available when round-based LiDAR is employed.

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ACRONYMS AND ABBREVIATIONS

AASHTO — American Association of State Highway and Transportation Officials

AMF — Arbuscular mycorrhizal fungi, formerly called endomycorrhizae

AOSA — Association of Official Seed Analysts

AWHC — Available Water-holding Capacity

BAMONA — Butterflies and Moths of North America

BFM — Bonded Fiber Matrix

BLM — Bureau of Land Management

BPA — Bonneville Power Administration

CCE — Calcium Carbonate Equivalent

CEC — Cation Exchange Capacity

COTR — Contracting Officer's Technical Representative

CRF — Control-release Fertilizers

DFC — Desired Future Condition

DOT — Department of Transportation

EPA — U.S. Environmental Protection Agency

ET — Evapotranspiration Rate

EWPPS — Ecoregional Workhorse and Pollinator Plant Selector

FHWA — Federal Highway Administration

GIS — Geographic Information System

HWY — Highway

IBDU — Isobutylidene Diurea

IRVM — Integrated Roadside Vegetation Management

MTDC — Missoula Technology & Development Center

NAPT — North American Proficiency Testing

NOAA — National Oceanic and Atmospheric Administration

NRCS — Natural Resources Conservation Services

OM — Organic Matter

PAM — Polyacrylamides

PLS — Pure Live Seed

PMS — Plant Moisture Stress

PNW — Pacific Northwest

PVC — Polyvinyl Chloride

RGP — Root Growth Potential

RQD — Rock Quality Design Index

SMP — Shoemaker-McLean-Pratt buffer

STA — Seal of Testing Assurance

TAWHC — Total Available Water-holding Capacity

TMECC — Test Methods of the Examination of Compost and Composting

TZ — Tetrazolium

USDA — U.S. Department of Agriculture

USFS — U.S. Forest Service

WFLHD — Western Federal Lands Highways Division

PREFACE

In 1998, the Western Federal Lands Highway Division (WFLHD) partnered with the USDA Forest Service Pacific Northwest Region (USFS-PNW) to revegetate highway rights-of-way in the western United States with native plants. This partnership culminated in the release of the 2007 Technology Deployment Report "Roadside Revegetation: An Integrated Approach to Establishing Native Plants" (FHWA-WFL/TD 07-005) funded under the Federal Lands Highway Technology Deployment Initiatives and Partnership Program and the Coordinated Technology Implementation Plan. While the original report was being written, the authors had the opportunity to test and evaluate many of the techniques that it described.

In the decade since this report was published, the importance of pollinator species and their decline has become a significant public concern. Though little is known about the status of most of North America's native pollinators, the data that exists suggests that numerous species are experiencing declines similar to or more severe than the decline seen in honey bees, which since 2006, has accounted for annual hive losses of 29 percent or more. One-quarter of North America's native bumble bees have experienced similarly steep declines, including species that were formerly common. Because of a variety of factors, the iconic monarch butterfly in North America is now vulnerable to extinction, having suffered significant population declines since the late 1990s.

What does this have to do with roadsides? In June 2014, the White House released the Presidential Memorandum – Creating a Federal Strategy to Promote the Health of Honey Bees and Other Pollinators. The memorandum identified how each Federal department, office, and agency was expected to contribute to the strategy to protect, restore, and increase the health, habitat and population of pollinators in the United States. The U.S. Department of Transportation was charged to identify opportunities to increase pollinator habitat along roadways and to implement improvements, as appropriate. Noted opportunities included "…planting pollinator-friendly vegetation, increasing flower diversity in plantings, limiting mowing practices, and avoiding the use of pesticides in sensitive pollinator habitats through integrated vegetation and pest management practices." (FR Doc. 2014).

A subsequent report contracted by the U.S. Department of Transportation Federal Highway Administration to ICF International and Xerces Society for Invertebrate Conservation reported the findings of a literature review that focused on pollinators and roadsides (Hopwood and others 2015) with follow-up reports (Hopwood and others 2016a; Hopwood and others 2016b) that applied these findings to developing best management practices for roadsides in relation to creating and maintaining favorable pollinator habitat. One of the major opportunities addressed in these documents is the potential that roadsides could play in benefiting pollinators by providing habitat for foraging, breeding, and nesting, while linking fragmented habitats to aid in the dispersal of pollinators. The key to providing these services is in the establishment and maintenance of healthy native plant communities along roadsides.

To address some of these issues and opportunities, Associate Administrator of Federal Lands Timothy Hess, in late 2015, issued a memorandum stating that "*…the Office of Federal Lands implements the use of the revegetation procedures provided in the manual…*" and that "*…the Office of Federal Lands Highway will lead the update of the Roadside Revegetation manual to include guidelines specific to the use of pollinator friendly plant species in the revegetation of roadsides.*" In meeting these objectives, the Federal Highway Administration (FHWA) brought together an interdisciplinary team of scientists to review the 2007 report in light of the current understanding of pollinators and roadsides. This updated report is a product of their effort.

The Intended Audience

This publication was written specifically for the "designer," those individuals or members of a road design team who will be directly involved in planning, implementing, monitoring, or maintaining a revegetation project. Chapter 2 and Chapter 3 are directed toward those who will be developing a revegetation plan. These are typically members of a road design team who have some experience in revegetation planning and design. It is also for landscape contractors who specialize in the installation of revegetation plans. Chapter 4 is an example of a revegetation plan.

Chapter 5 provides detailed information intended for those who may be developing contract documents and implementing portions of a revegetation plan. These include project engineers, road building contractors, landscape or revegetation contractors, or other specialist subcontractors on the road construction team. This chapter gives the background (the "why" and "how") for contract specifications that are specific to a revegetation treatment. Chapter 6 is written for those monitoring the outcome of a revegetation project. It focuses on strategies for monitoring the revegetation installation and the pollinators it will support. It is recommended that the individuals who conduct monitoring tasks will have had some previous experience in developing and implementing a monitoring plan, including experience assessing specific plant and pollinator attributes in a statistical format. Chapter 7 is written for specifically for maintenance personnel; the staff who will be maintaining the revegetation project and adjacent roadsides after the project is completed. Chapter 8 provides case studies of revegetation projects that include development of pollinator habitat. For managers and others who just want an overview of the revegetation process and contents of the Roadside Revegetation report, a companion Primer has been provided.

1— Introduction

INTRODUCTION

The Roadside Revegetation report was written to provide current best practices for planning, designing, and implementing a revegetation project that will also create habitat for pollinators. The report identifies steps and considerations in developing a revegetation project from a variety of perspectives, and presents them in a typical design project order from planning through implementation and maintenance. A diverse writing team of experienced civil engineers, transportation engineers, landscape architects, botanists, geneticists, pollinator conservation specialists, soil science specialists, restoration specialists and environmental protection specialists applied their specific experience and knowledge to this report. Technical aspects of the writing was reviewed by Department of Transportation (DOT) civil engineers and landscape architects and revegetation specialists from several state and federal agencies, who also applied their regional perspective on the planning, design, installation, and maintenance processes.

Users of this report may find it beneficial to review Table 1-1 and the Primer for a quick overview of a revegetation process and an outline of the report chapter contents in order to gain an understanding of the full scope of the report and how it is organized. The Primer also provides an introduction to the online Ecoregional Revegetation Application (ERA) tool and the Native Revegetation Resource Library. The ERA is an extensive ecoregional plant database that also includes pollinator value information for each plant. The ERA provides a list of all native plants within an ecoregion as well as a list of "workhorse" plant species, the primary beneficial native plants for pollinators and roadside revegetation in a specific ecoregion, and then allows designers to download either form of information in a digital spreadsheet for evaluation and manipulation for their project. The Native Revegetation Resource Library is an online depository that contains copies of applicable revegetation and pollinator educational resource material, referenced from other online sources, compiled in this one location for designer convenience.

This report was written by technical experts for the technical experts involved in the revegetation planning, design, and implementation process. Many report topics include regional and optional considerations and techniques that designers can evaluate for applicability to their project conditions. The writers of this report envision the following ways to use this report:

- **Primary Revegetation Reference—**Designers, revegetation specialists, and contractors can reference the document as they work through revegetation project planning, design, implementation, and monitoring and maintenance.
- **Education Tool—**The report may be used in the classroom and field demonstration setting to educate the next generation of designers, installers, and maintenance professionals.
- **Supplemental Information—**Using the information to revise and supplement existing agency standards and best practices.
- **Planning Resource—**The Table of Contents (TOC) can be used to identify applicable revegetation tasks for specific projects.
- **Scope of Work Development—**For creating a revegetation project scope of work for a Request for Qualifications or a Request for Proposal.
- **Scope, Schedule, and Budget Resource—**The TOC can be used as a template for creating a list of revegetation tasks for an estimate of labor hours, project budget, and project schedule.
- **Project Team Evaluation—**For evaluating the project team strengths and identifying additional sub-consultant expertise that may be needed for the revegetation project.
- **Revegetation Project Agenda Outline—**Using the TOC as a project kick-off meeting agenda to discuss revegetation topics and to start team coordination.

- **Operations and Maintenance Report—**Portions of the information can be used as an outline of the revegetation project operations and maintenance tasks.
- **Project Management Resource—**The client, managers, and team members can identify the revegetation project tasks and then track progress of each task throughout the project duration.

1.1 AN INTEGRATED APPROACH

Integrating societal goals for safe, efficient transportation with goals for ecological health is a crucial issue that is receiving increased attention from transportation agencies (Forman and others 2003; NRC 2005). Today, most road projects involve modifications to existing roads rather than new construction (NRC 2005). As roads are modified or updated section by section, a tremendous opportunity presents itself to remedy the oversights of the past, mitigate environmental impacts, and improve conditions for healthy ecosystems (Figure 1-1).

Figure 1-1 | **Pollinator habitat on roadside**

Roadsides offer an opportunity for improving ecosystems by establishing and maintaining native plant communities.

Photo credit: Kirk Henderson

Native plants are a foundation of ecological function, affecting soil conservation, wildlife and pollinator habitat, plant communities, invasive species, and water quality. Although all of these ecological functions are important, recent emphasis has been placed on supporting pollinators and this facet is highlighted throughout this updated report. Establishing locally adapted, self-sustaining plant communities can also support transportation goals for safety and efficiency. Protecting existing native vegetation during construction and establishing native plants on roadsides following disturbance is key to integrating road systems into natural systems.

Past obstacles to establishing native plant communities on roadsides have been technical, informational, and organizational. Designer and project technical success can be achieved when effective strategies and practical techniques for revegetating the disturbed conditions with limited resources are made available to designers. Project success and efficiency can increase when multiple disciplines, ranging from landscape architecture to engineering, soil science, ecology, botany, genetics, entomology, and wildlife conservation are able to communicate and coordinate as a team early in the project planning, working cooperatively, not in isolation. Finally, improved interagency cooperation and planning processes that consider ecological effects at every step can enhance the success of a revegetation project.

This report offers an integrated approach to facilitate the successful establishment of native plants and pollinator habitat along roadsides and other areas of disturbance associated with road modifications. It guides readers through a comprehensive process of initiating, planning, implementing, maintaining and monitoring a roadside revegetation project with native plants and pollinator habitat.

1.2 THE ECOLOGICAL CONTEXT OF ROADS

Our road system infrastructure is large, covering over 17 million acres (Ament, Begley, Powel, Stoy 2014), widespread, and affects all but our most protected lands (NRC 2005). The total road corridor (paved road plus roadside or right-of-way) covers over 1 percent of the nation's land surface, an area equal to the size of South Carolina (Forman and Alexander 1998). If unpaved roads are also included, the percentages increase (FHWA 2008). The ecological effects of roads extend into a zone far beyond the edge of the pavement, with effects including habitat fragmentation, wildlife mortality, noise and chemical pollution, disruption of hydrologic cycles and water quality, increased erosion, and the potential creation of transportation corridors for noxious and invasive weeds that can invade adjacent lands. With these considerations, an estimated 15 to 20 percent of the United States is ecologically affected by roads (Forman and Alexander 1998). The enormous challenge of understanding and mitigating the ecological effects of roads deserves attention and dedication on local, regional, and national scales.

1.2.1 PAST OVERSIGHTS

Much of the existing road network in the United States was designed and constructed prior to the 1970s, in an era before ecological health became a widespread concern among American citizens and before ecological science had evolved to address large-scale issues (Forman and others 2003). Safety and efficiency were the primary goals of transportation programs in the past, and the ecological context of roadways were largely overlooked in planning, construction, and maintenance efforts. The effects of roads on natural systems (habitat fragmentation; interruption of natural flows of water; and disturbances to animals, plants and their pollinators, soils, and other resources) were not well understood or considered. Lack of awareness about these factors led to a largely antagonistic perception of the relationships between natural systems and road systems.

For example, without effective revegetation of the road disturbance with desirable plants, undesirable vegetation can encroach on the roadway. Undesirable vegetation can disrupt safety and visibility, leading to expensive and potentially hazardous maintenance measures. Undesirable vegetation can invade and wipe out areas of desirable native plants that pollinators need for food and cover to survive. Conflicts with neighboring land uses could result if corridors for invasive weeds are established or if vegetation control measures are viewed as a health or safety concern by the community. These are all issues that arise when ecology and revegetation science are not considered during road design, construction, or modification. Eventually, poorly integrated or addressed natural processes can threaten the function and structural integrity of the road itself, leading to premature deterioration of the road's infrastructure (Berger 2005).

1.2.2 PRESENT AWARENESS

For over 20 years, the ecological effects of roads have been increasingly recognized by the Federal Highway Administration and by state and county transportation agencies (NRC 2005). Today, road effects on ecological processes are major concerns among private citizens, land management agencies, and the transportation community. Consequently, an emphasis has been placed on the integration of ecological considerations into all phases of road design and construction processes. For example, legislation in some areas now requires road modification and construction projects to restore aquatic connectivity; fish passages have been built to reconnect natural water flows under roads. Other projects have modified roads that were deemed particularly dangerous to endangered species. These roads are being made more permeable to wildlife, greatly reducing losses by improving habitat connectivity, ensuring better visibility for drivers and animals, and creating safer underpasses or overpasses for wildlife (Forman and others 2003). Given the recent decline of pollinator species, there is now a greater emphasis on supporting pollinators by creating habitat on roadsides. A National Pollinator strategy (FR 2014) has recently been released, tasking federal agencies to do more with their land-holdings, development practices, and maintenance operations to support pollinators in order to reverse pollinator declines (Section 1.5.4). Efforts to limit inappropriate road expansion and to obliterate unnecessary roads remain important. Where modification and increased capacity are needed, ecological health, safety, and efficient transport should not be seen as mutually exclusive goals. Understanding roadside environments, how they interface with adjoining lands, and how to minimize environmental impacts has become a key focus of the Federal Highway Administration. Given political will and proper levels of attention, integration of environmental concerns with transportation can result in significant gains.

1.2.3 TRENDS IN ROAD CONSTRUCTION

For the purposes of this report, the primary focus is on Federal, State, and County road corridors, that include highways, interchanges, rural routes, farm to market routes, river roads, and most roads through our National, State, and County parks and preserves. Roads are widespread, fairly permanent fixtures on the landscape and in the culture of the United States. Given current trends, road networks are expected to persist and expand over time. Current modifications predominantly involve updating infrastructure to increase capacity and to improve safety, including widening roads, replacing bridges, and reducing or altering curves and grades to make the road safer for motorists (NRC 2005). The opportunity to integrate ecological goals with transportation was largely overlooked when the road networks were originally constructed. However, as the nation's roads are being updated and modified, the opportunity cannot be ignored. While attempts to integrate ecological factors are positive, much of the potential for improved integration is still largely unrealized. This has been due, in part, to a shortage of practical information and the absence of an integrated approach to the challenge. The question is, what can be done to balance societal desires for safe, efficient transport with requirements for a healthy environment? In other words, what can be done to help road systems function better with natural systems?

1.2.4 CHALLENGES AND OPPORTUNITIES

The fact that the nation's road networks are in varying states of updates, repairs, and maintenance presents an opportunity to improve road systems so that they integrate better with natural systems. Planners and designers strive to understand detrimental effects associated with roads and how to mitigate them by minimizing the ecological footprint of roads and maximizing potential ecological benefits. Many groundbreaking resources have emerged to support these efforts. Road Ecology: Science and Solutions (Forman and others 2003) places the challenges into comprehensive frameworks, illuminating goals and principles for an ecological approach to transportation issues. Multiple intervention points are identified to help road systems function better with natural systems, integrating transportation goals for safety and efficiency with approaches to protect water, soil, vegetation, wildlife, and aquatic life. The Federal Highway Administration published a landmark book called Roadside Use of Native Plants (Harper-Lore and Wilson 2000) that brought the issue of native plant communities on roadsides to the forefront in the transportation community, highlighting the importance of native plants and their broad utility. The National Research Council of the National Academies of Science expanded on the frameworks identified in Forman and others (2003) in its publication, Assessing and Managing the Ecological Impacts of Paved Roads (2005). Processes within the Federal Highway Administration, state departments of transportation, and other agencies are being improved for better integration.

In addition to these advances directly related to roads, many advances in the field of restoration ecology have distilled essential principles applicable to severely degraded sites (e.g., Munshower 1994; SER 2004; Clewell and others 2005; Claassen 2006). In addition, vegetation specialists from a variety of organizations have come to consensus about what truly defines a "native" plant and have developed seed collection, transfer, and propagation guidelines to ensure that locally adapted materials are used for optimum results (Withrow-Robinson and Johnson 2006, Johnson and others 2010, Basey and others 2015). In both the public and private sectors, seed and plant producers and installers have been developing innovative methods to meet unique site conditions.

Figure 1-2 | **Recently planted trees on an obliterated section of highway in Oregon**

Most road projects today do not involve building new roads, but rather modifying or obliterating existing roads. This photograph shows an abandoned road where the soils were restored and seedlings planted.

Photo credit: Lynda Moore, USFS

Recently, the opportunity to support declining pollinator species through habitat creation on roadsides has been addressed with great success (Hopwood and others 2015, Hopwood and others 2016a, and case studies in this report). Designers have created "pollinator-friendly" roadside habitat, and agency maintenance departments have altered procedures to better maintain these habitats with a focus on the needs of pollinators.

While the publications above assess the best available conceptual and theoretical information, each also recognizes extensive needs for further work, particularly in developing practical approaches to integrating ecological needs with transportation goals. Central to ecosystem function is native vegetation (SER 2004). However, much of the pertinent information related to protecting and establishing native plants on roadsides has been scarce, scattered, unexamined, or not translated into practice. This report is intended to bridge some of the informational, technical, and organizational gaps to facilitate successful roadside revegetation with native plants. An integrated approach is offered to support both designers and field-based practitioners in successfully revegetating roadsides and obliterated roads with native plant communities (Figure 1-2).

1.2.5 WHY REVEGETATE ROADSIDES WITH NATIVE PLANTS?

Long-term economic and ecological advantages can be gained by establishing desirable native plant communities on roadsides (Berger 2005). Roadside vegetation can support safety goals by reducing headlight glare, reinforcing the road alignment, serving as crash barriers, protecting view planes and visibility, controlling snow drifts, and reducing wind speeds (Forman and others 2003). Pollinator-friendly plants species, many of which are showy flowering plants, can improve the experience of the road user by creating natural beauty via plant form and color diversity along the roadside, in addition to improving driver performance by reducing monotony and stress. Importantly, creating pollinator habitat along roadsides can directly support imperiled pollinators such as the iconic monarch butterfly (*Danaus plexippus*), economically important managed species such as the European honey bee (*Apis mellifera*), as well as a wide variety of native pollinators including wild bees, butterflies, moths, flies, beetles, and wasps. A self-sustaining native plant community on a roadside stabilizes slopes, protecting water and soil quality. In addition, the establishment of healthy native plant communities is often the best long-term defense against invasive and noxious weeds. Maintenance costs for managing problematic vegetation are reduced, as is the pollution and controversy that sometimes results from roadside herbicide use (Berger 2005). Establishing healthy roadside vegetation can also help sequester carbon dioxide, one of the factors responsible for global climate change (Palumbo and others 2004, Ament and others 2013).

Using native vegetation supports every aspect of the goals identified as best management practices by the transportation community for road design. These include goals to:

- Produce a safe, cost effective, environmentally friendly, and practical road design that is supported by and meets the needs of the users
- Protect water quality and reduce sediment loading into water bodies
- Protect sensitive areas and reduce ecosystem impacts
- Maintain natural channels, natural stream flow, and passage for aquatic organisms
- Minimize ground and drainage channel disturbance
- Control surface water runoff and stabilize the roadbed driving surface
- Control erosion and protect soil
- Implement slope stabilization measures and reduce mass wasting
- Stormproof and extend the useful life of the road (Keller and Sherar 2003)
- Create and maintain pollinator-friendly habitats (Hopwood and others 2015)

Clearly, the goals of safe and efficient transportation and the goals of establishing and protecting native vegetation overlap; when properly integrated, native vegetation supports road objectives. At the same time, considering vegetation as part of road planning processes aids in minimizing and mitigating the ecological footprint of roads during and after construction. Native plants can provide wildlife habitat and improved connectivity for the length of the road (Forman and others 2003). Understanding vegetation and forage preferences, and careful design that accounts for visibility and safety, can guide animals to safe passageways for travel while minimizing dangerous interactions with vehicles. The presence of birds and small animals can be enhanced when appropriate plant species are established. Processes that work for roadside revegetation are also applicable to the process of obliterating roads where roads are no longer needed.

Figure 1-3 | **Unsuccessful roadside revegetation on steep slopes**

Steep slopes are often difficult to revegetate and many past attempts at roadside revegetation did not succeed.

Photo credit: Lynda Moore, USFS

Despite the potential benefits, many past attempts at roadside revegetation have not succeeded. Although revegetation was considered important, some efforts emphasized seeding of exotic plants; these species were perceived as inexpensive, readily available, and easy to establish on disturbed sites, however, this practice has not been effective or self-sustaining on many projects; either the exotic plants spread to become problematic, or failed to persist because they were not locally appropriate species. Once established, exotics may preclude reintroduction of desirable natives. In other cases, little consideration was given to establishing roadside vegetation during or after construction; if vegetation was considered, it was often as an afterthought. A short-term approach to revegetating roadside disturbances often predominated past efforts, while efforts toward long-term development of native plant communities did not receive adequate consideration. The ineffectiveness of revegetation efforts in the past has resulted in such problems as soil erosion and landslides that affected water quality (Figure 1-3). Visually, unvegetated road disturbances diminish the experience of the road user and economically translate into high costs associated with ongoing maintenance.

Past shortcomings may be attributed to past approaches that were often piecemeal and lacking the cooperation and coordination of disciplines necessary to fully integrate native vegetation into the road planning and construction processes. Revegetation specialists typically worked in isolation from engineers, and sometimes even the biological specialists (soil scientists, botanists, wildlife biologists) failed to coordinate their knowledge and efforts. Success will require both practical and technical information and a systematic, comprehensive approach.

1.3 OBJECTIVES OF THIS REPORT

This report brings theoretical and practical information to bear on the challenge of revegetating roadsides with native plants. Written by and for project designers and field-based practitioners, it synthesizes a comprehensive, holistic approach that can be used to effectively revegetate roadsides and other similarly disturbed areas. Given the unique ecological factors at play on each project, the report is not prescriptive, but rather provides principles and a step-by-step process for designers to use in the field to generate and implement their own locally appropriate, context-sensitive revegetation plan. Examples and proven strategies are offered to serve these goals. Topics covered include how to:

- Improve interagency cooperation in order to think ecologically about road modifications and make revegetation an integral part of road design
- Coordinate information and efforts to bring multiple disciplines such as soil science, genetics, botany, ecology, wildlife science, landscape architecture and engineering together for a holistic approach to revegetation
- Integrate goals for native vegetation establishment with transportation goals for safety, function, and efficiency
- Mitigate harsh, drastically disturbed conditions of road disturbance areas to enable native plants to establish through natural colonization and/or active replanting
- Apply a step-by-step planning, implementation, and monitoring process, including mid-course corrections, to overcome potential pitfalls, resulting in cost-effective, successful establishment of native plants
- Share knowledge, including new revegetation tools and techniques

For the Designer
This report is not prescriptive but instead provides principles and a step-by-step process of revegetation.

1.4 SCOPE

The complexity of ecologically sensitive road design, implementation, and maintenance will require increasing cooperation from multiple sectors of society and multiple fields of practice and expertise. This report should be of interest not only to field-level practitioners and project designers in both public and private sectors, but also to transportation and planning professionals; land managers; policy-makers; owners and operators of roads on county, state, and federal scales; and concerned citizens. Any agency or organization involved in altering, developing, operating, maintaining, or decommissioning roads will find this publication useful. This report is especially intended to serve field-based practitioners and planners of diverse backgrounds whose goal is to establish locally appropriate, low-maintenance native plant communities on roadsides.

Because integration of multiple sources of expertise is necessary for effective long-term revegetation, this report does not assume that the designer has a particular specialized background but more, a broad level understanding of such disciplines as botany, plant propagation, soil science, genetics, entomology, landscape architecture, and engineering. The designer may be one of these specialists and may involve one or more of these other specialists during the planning process, depending on the project's complexity. The report states where specific expertise may be required. Key information specifically for designers or contractors and key milestones for communication and integration between engineers and non-engineers are highlighted.

The approach in this report is applicable to any type of road-related project that involves disturbances to soil and vegetation. Revegetation of roadsides adjacent to dirt, gravel, and paved roads would involve similar processes, although differences in scale and intensity of efforts would be required. This report applies to new construction or reconstruction and modifications of existing roadways. The principles and practices are also applicable in revegetating other drastically disturbed sites with similar limiting factors to roadsides, such as utility gas, oil, or powerline rights-of-way and mine reclamation projects.

This report focuses on opportunities for integration during road construction or modification. Long-term maintenance and management of established roadsides is discussed briefly, with references to related management practices and guidelines such as Integrated Roadside Vegetation Management (IRVM) (Berger 2005). Roads must be made more permeable to natural flows of water, animals, and plants to help mitigate the ecological effects of the road. Efforts to improve habitat connectivity and road permeability, as well as storm-water drainage and created wetlands, can be supported by the revegetation practices described in this report. However, specific mitigations for these important topics are beyond the scope of this publication. Also beyond the scope are the myriad other potential ecological and social issues that affect, and are affected by, the engineering and transportation planning processes. Issues of social justice and community planning are not addressed. Larger policy-making and planning procedures are also beyond the scope of this report.

Figure 1-4 | **Roadside native plant community**

The establishment of native plant communities is the cornerstone of ecological restoration.

Photo credit: Lynda Moore, USFS

1.5 APPROACH

The establishment of native plant communities, in order to re-initiate natural processes of succession is a cornerstone of most ecological restoration work (Dorner 2002) (Figure 1-4). Effective revegetation on highly disturbed roadsides aims to initiate or accelerate processes of natural succession following disturbances. Three aspects are generally considered: (1) health (the functional processes of the ecosystem); (2) integrity (species composition and community structure); and (3) sustainability (resistance to disturbance and resilience) (Clewell and others 2005). While restoring plant communities to a pre-disturbance state is not typically a goal on highly disturbed roadsides, each of the above three ecosystem aspects can be improved with appropriate roadside revegetation practices. The establishment of reference sites, or natural models for the desired recovery process, is key to identifying and overcoming limiting factors and accelerating succession by establishing native plants.

Native species play an important role in ecosystem development. If native species can become established on a disturbed site, the processes of succession, including soil recovery and nutrient cycling, are initiated (Brown and Amacher 1999). In most cases, native plants are established on roadsides through seeding or planting, although sometimes passive revegetation (natural colonization) is possible where native seed banks are nearby and limiting factors are mitigated.

1.5.1 SUSTAINABLE REVEGETATION ON ROADSIDES

Sustainable revegetation projects attempt to integrate disturbed sites with the surrounding, non-disturbed landscape. An ideal integration is both visual and functional in nature, and the blending of the two is often considered an art.

Revegetation efforts are most likely to be sustainable if they are process-based in approach, rather than form-based. Process-based projects aim to create healthy and resilient ecosystems with the necessary components to develop multiple natural processes. Many desired natural processes take hundreds of years to fully develop, so it is unreasonable to think a designer can anticipate, replicate, and accelerate their development over the course of a project that might span three, five, or ten years. The objective, rather, is to install as many components of as many processes as possible, to facilitate their development. In this sense the designer is often most interested in the trajectory of the developing processes, rather than their presence in complete form.

The purpose of this section is not to discuss every possible contributor to resiliency or process building. Rather, it is to provide the designer with information that might assist in the recognition of actions they can take to potentially increase resiliency and accelerate the development of natural processes.

Encouraging Resiliency

Resiliency is a system's ability to recover quickly, and hopefully entirely, from disturbance. The use of genetically appropriate plants, collected from throughout the project and surrounding area within the provisional seed zone(s), can encourage genetic health and resilience of the restoration plant population as well as those populations surrounding the project area. Restoration plants, installed at sufficient spacing, can increase competition and facilitate the site's resistance to invasion by non-native or weedy plant species, thereby making it more resilient to plant compositional changes when they do occur. Plant species and form diversity creates redundancies in life form, functional grouping, and services; all of which increase resiliency.

Consideration of Natural Processes

Multiple natural processes have components for which the designer can assist when re-integrating a disturbed site into the surrounding landscape. The designer may want to identify and initiate the enhancement or construction of those processes that already naturally occur, or would be expected to occur, on the surrounding landscape. There would be little point in allocating resources to try to develop a wetland in a sage steppe of a high desert upon which no wetlands occur, for example.

Soil forming processes can be considered during a number of project activities such as decommissioning roads, constructing cut and fill slopes, or when shaping the final grade of spoils areas. Knowing that wind and water erosional forces shape and sculpt land formations, attention to the contours of the surrounding landscape can inform designers and equipment operators of how best to blend the target area with its environment. By doing so the newly formed contours not only visually re-integrate the project site into the surrounding setting, but also prevents out-of-proportion, angular, or inappropriate landforms from interrupting wind and water patterns. In addition, the accumulation of plant detritus is a basic component of soil formation. It is often useful to de-compact the soil and leave the site in a roughened, irregular, and undulating condition. The resulting hummocks and low spots can seem small and inconsequential, but they provide pockets for soil to accumulate and will eventually support plant life. Avoiding compaction of the soils frequently provides for better water infiltration and drainage, reduced erosion, and overall stability of soil particles.

The use of annual and perennial plants in revegetation projects contributes plant litter to the system throughout a prolonged period of time compared to a site that only uses one or the other. This litter then becomes reduced and incorporated into disturbed sites, facilitating the nutrient cycling. Including various plant life forms in a revegetation plan, including shrubs and trees where appropriate, provides refuge, breeding-, feeding-, rearing-grounds, as well as domicile habitat for insects, birds, and various small and large animals. The abundance and diversity of organisms supported on the revegetation site contribute greatly to the development of a functioning nutrient cycle. In addition to facilitating nutrient cycling, the abundance and diversity of organisms supported also play critical roles in the dispersal of seeds and spores.

Consider Maintenance Operations and Costs

Sustainability from the maintenance stand point is a component that is easy to overlook, when focused on the biology of a project. Roadside maintenance programs are designed to insure the safety of travelers and to protect the integrity of the road. If the life forms planted are inappropriate for the roadside, if setbacks or roadside zones are ignored, if the structural integrity of the selected plants is not sound, or if the restoration plantings create visibility and safety issues, then the revegetation project will not be sustainable. Maintenance operations and costs are components to be considered in all phases of a revegetation project as its success and sustainability is partially dependent on understanding the needs of roadside maintenance programs.

1.5.2 WHAT IS THE "ROADSIDE"?

In this report, the term "roadside" refers to any area of disturbance associated with road construction, reconstruction, waste areas, source pits, and maintenance, (Figure 1-5). The roadside includes the sides of the road corridor beyond the paved road (shoulders and verges), including impacted or maintained roadside areas within the right-of- way. The roadside area is sometimes narrow, but sometimes extends several hundred feet or more beyond the edge of the road surface, depending on the project. In some situations, revegetation efforts may encompass areas beyond the right-of-way that are affected by or affect the road. The area where the revegetation specialists will focus their efforts is usually dependent on two factors: ownership of the right-of-way and surrounding lands, and areas of disturbance (construction footprint). Most roadsides are drastically disturbed environments, where soil may be severely compacted and consist of a mixture of subsoil and parent material (Figure 1-6). Beneficial microorganisms, nutrients, and organic matter necessary to sustain plant growth may be absent or severely depleted. Often, slopes can be very steep and inaccessible, exposed to the erosive effects of wind and water. These environments represent a revegetation challenge of high intensity and magnitude.

1.5.3 WHAT ARE NATIVE PLANTS?

"Native plants," as defined in this report, are locally adapted, genetically appropriate native plant materials (Withrow-Robinson and Johnson 2006). These plants are best suited evolutionarily to the local conditions, and generally require less maintenance and persist longer than non-local species. When properly established, they form plant communities with the potential to be self-sustaining and self-perpetuating over time, requiring little or no input from humans to persist. Native plants also support more robust communities of pollinators, birds, and other small wildlife.

Figure 1-5 | **Roadsides are disturbed areas**

"Roadside" refers to disturbed areas resulting from road construction, modification, or improper maintenance.

Photo credit: Lynda Moore, USFS

Figure 1-6 | **Roadsides can be highly disturbed**

Roadsides are often drastically disturbed and infertile environments with no topsoil, severe compaction, and a lack of beneficial microorganisms.

Photo credit: Matt Horning, USFS

Inset 1-1 | **Recent Policies Mandating Native Plants for Revegetation**

Many land management agencies have policies mandating the use of native plants as the first choice in revegetation efforts. For example, the USDA Forest Service has the following policies in placer applicable to road projects on Forest Service lands:

- **National Native Plant Materials Policy:** "Native plant materials are the first choice in revegetation…" (USFS 2005)
- **BAER Manual (FSM 2523):** "…when practical, use genetically local sources of native species…" (USFS 2003)
- **National Fire Plan Strategy:** "…promote the establishment of local sources of native seed and other plant material…" (USFS/USDI 2001)
- **R6 Revegetation Policy:** "…use local native plants to the extent practicable…" (USFS 2004)
- **NW Forest Plan; Interior Columbia Basin Ecosystem Management Project:** "…maintain and restore native species and ecosystems…" (USFS/USDI 1994; USFS 2006)
- **Federal Register Notices:** "… promote the use of native plant materials in revegetation for restoration and rehabilitation…native plant materials are the first choice in revegetation for restoration and rehabilitation efforts." (FRN 2006)
- **National Strategy to Promote the Health of Honey Bees and Other Pollinators:** "…establish a reserve of native seed mixes, including pollinator-friendly plants…" (Pollinator Health Taskforce 2015)
- **National Seed Strategy for Rehabilitation and Restoration:** "…ensure the availability of genetically appropriate seed…" (BLM/WO/GI 2015)

Challenges to establishing native plants on roadsides are significant, partially due to difficulties in obtaining appropriate materials. However, the technological capacity of native plant propagation and outplanting efforts in both private and public sectors has increased significantly in the past two decades. Innovative stocktypes and application methods have made roadside revegetation more effective. Recent policy mandates from many federal agencies that manage roads now require the use of native plant materials as the first choice in revegetation efforts, thereby making roadside revegetation an important and expanding frontier for native plant suppliers.

1.5.4 WHY THE EMPHASIS ON POLLINATORS?

An estimated 85 percent of the world's flowering plants depend on animals for pollination (Ollerton and others 2011). Animal pollinators visit flowering plants seeking floral resources and, in the process, incidentally transfer pollen from anthers (male reproductive structures of the flower) to stigmas (female reproductive structures), vectoring fertilization and allowing these flowering plants to reproduce. Pollinators rely on flowering plants for food, requiring nectar (a sugar-rich liquid) and sometimes pollen itself (a source of protein) as sources of energy and nutrition. Most animal pollinators are insects, such as honey bees, bumble bees, flies, and butterflies. However, vertebrates such as birds (e.g., hummingbirds), mammals (e.g., bats, rodents) and some reptiles pollinate certain plant species. The pollination services provided by pollinators are essential to the health and persistence of the plant species that depend on them, and for the wildlife and pollinators that in turn depends upon the plants for food, nesting, and shelter.

Pollinators are also important to human health and the global economy. More than 75 percent of the world's 115 principal cultivated crops are reliant on animal pollinators or benefit from animal pollination. Roughly 35 percent of global crop production is dependent on pollination by animals (Klein and others 2007). Insect-pollinated forage plants such as alfalfa and clover also provide feed for livestock. Pollinator-dependent food crops, namely fruits, vegetables, and nuts, make up a critical component of our diet (McGregor 1976). The majority of minerals, vitamins, and nutrients needed to maintain human health (such as vitamin C, lycopene, calcium, and folic acid) come from crop plants that depend partially or fully on animal pollinators (Eilers and others 2011). Consequently, pollinators provide essential agricultural services with a high economic value. A recent worldwide estimate suggests pollinators in general contribute 9.5 percent ($216 billion per year) to crop value (Gallai and others 2009). In the United States it is estimated that pollinators (both managed and wild) contribute $29 million in farm income annually (Calderone 2012). Importantly, native pollinators specifically have been shown to contribute approximately $1 billion to the California crop economy (Chaplin-Kramer and others 2011).

Globally, pollinators are in decline (National Research Council 2007; Potts et al. 2010). In the United States, wild pollinators such as monarch butterflies and many bumble bee species, as well as colonies of managed honey bees, are experiencing declines due to a loss of habitat, the spread of disease, overuse of pesticides, and various other factors (National Research Council 2007; Hatfield and others 2015; Jepsen and others 2015). Pollinator declines threaten the viability of agricultural productivity and the health of natural ecosystems.

With at least 17 million acres of roadsides in the United States, roadside vegetation can serve as much needed habitat for pollinators, offering food, breeding, or nesting opportunities and connectivity that can aid pollinator dispersal (Hopwood and others 2015). Roadsides can support a diversity of generalist pollinators, including bumble bees, honey bees, butterflies, and hummingbirds as well as rare or federally listed species. Roadsides sustain plants that are sources of pollen and nectar for adult pollinators as well as host plants for the caterpillars of butterflies and moths. The availability of floral resources influences the abundance and diversity of butterflies and bees found on roadsides (Saarinen and others 2005; Hopwood 2008). Pollinators on roadsides benefit in particular from native plants (Ries and others 2001; Hopwood 2008). Roadsides planted with native plants also can provide pollinators with shelter, sites for nesting or egg-laying, and overwintering habitat. Pollinators have complex life cycles, with different needs at different stages of their lives. Roadsides can provide resources for a portion of the life cycle of some species, while providing resources needed for the entire life cycle of other species.

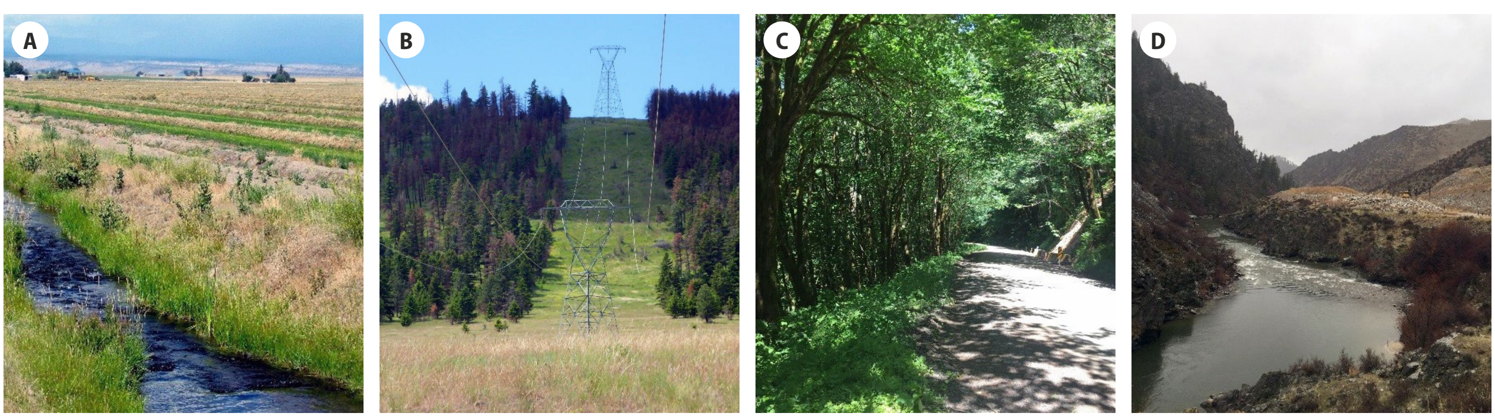
Evidence also suggests that the linear shape and connectivity of roadsides may help pollinators to move through landscapes in search of food or in pursuit of new habitat (Ries and others 2001; Dirid and Cryan 1991). Roadsides extend through all landscapes and can be particularly important sources of habitat for pollinators in highly altered landscapes such as intensely managed agricultural lands (Figure 1-7).

Not all roadsides are equally beneficial to pollinators. Roadsides that are intensively mown, blanket-sprayed with herbicides, or planted with introduced grasses support far fewer species

Figure 1-7 | **Vegetated linear corridors as habitat for pollinators and other wildlife**

Linear corridors such as irrigation canals (A), utility rights-of-way (B), roadways (C), and river ways and riparian areas (D), present opportunities to reconnect fragmented pollinator habitats.

Photo credits: (A) Chris Jensen, USFS; (B) Justin Moffett, BPA ; (C) Lynda Moore, USFS; (D) Lynda Moore, USFS



of pollinators and smaller population densities than roadsides managed for native plants (Smallidge and Leopold 1997; Johst and others 2006; Reis and others 2001). Roadside vegetation management influences how pollinators use roadsides, and even influences the number of pollinators killed by vehicles. For example, butterfly vehicle mortality rates increase with more frequent mowing and decrease with high plant diversity in roadside vegetation (Skorka and others 2013) (Figure 1-8).

Figure 1-8 | **Roadside mowing**

Although mowing a clear zone directly adjacent to the pavement poses little harm to pollinators, frequent roadside mowing of the entire roadside can decrease the densities of pollinators.

Photo credit: Idaho Transportation Department

Roadsides play an important role in the conservation of declining wild pollinators and in supporting the health of managed pollinators. Throughout the revegetation process, practitioners and designers can enhance roadsides to benefit pollinators.

1.5.5 GOAL-ORIENTED, CONTEXT-SENSITIVE, AND INTEGRATED

The overall approach in every aspect of this report is goal-oriented, context-sensitive, and integrated (Clark and others 2001). The goals of establishing and protecting native plant communities are considered along with transportation goals, including safety, efficiency, and cost-effectiveness for the life of the road. This is not an idealistic approach; while recognizing that resources are limited and conditions are degraded, the approach is technically and economically feasible while still enabling the integration of roads with ecological processes.

Sensitivity and appropriateness to the local context are essential parts of successful revegetation. This report is intended to facilitate the process of developing locally appropriate, context-sensitive prescriptions on a project-by-project basis, integrating top-down and ground-up information to meet the specific challenges at hand. For this reason, the report does not provide cookbook-type "recipes" or specific prescriptions. For example, no "one-size-fits-all" seed mix exists for roadside revegetation. The process and tools needed to arrive at context-sensitive solutions are not difficult to apply; by following the steps outlined in this report, practitioners will be able to generate the information they need.

1.6 HOW TO NAVIGATE THROUGH THIS REPORT

Navigating through this report can be done in several ways:

- **Search Field**—The easiest way to find a topic in this report is to use the "Search" field. If the topic is very specific, this may be the quickest method. However, if it is a broad topic, discussed throughout the report, this method may not easily narrow down the location in the report. When this is the case, referring to the table of contents and/or using search tools (for digital formats) may be the better approach.
- **Table of Contents**—The table of content is a quick way of getting to the main sections of the report through hyperlinks.
- **Revegetation in 15 Steps**—For those who wish to see the revegetation process in a step by step approach may want to use Table 1-1 to navigate through the report. Case studies of completed revegetation projects that create habitat for pollinators are provided in Chapter 8.

Table 1-1 | **Revegetation in 15 steps**

		Revegetation Process Steps	Further defined here
Initiation Phase	**1**	Due diligence, plan development	Chapter 2
Planning Phase	**2**	Objectives and desired future condition	Section 3.2, Section 3.7
	3	Pre-field information	Section 3.3
	4	Revegetation units and reference sites	Section 3.4, Section 3.5
	5	Field information	Section 3.6
	6	Limiting factors to plant establishment and pollinator habitat	Section 3.8, Section 3.9
	7	Site resources	Section 3.10
	8	Maintenance strategy	Section 3.11
	9	Site improvement treatments	Section 3.12
	10	Plant species	Section 3.13
	11	Plant establishment methods	Section 3.14
	12	Revegetation plan	Section 3.15, Chapter 4
Implementation Phase	**13**	Implementation	Chapter 5
Monitoring and Maintenance Phase	**14**	Monitoring	Chapter 6
	15	Operations and maintenance	Chapter 7

2— Initiation

2.1 INTRODUCTION

Incorporating ecological concepts into all aspects of road design, construction, modification and maintenance is a goal of the transportation community (NRC 2005; Forman and others 2003). The Federal Highway Administration, state departments of transportation, and other federal, state, and county agencies that are responsible for road infrastructure all strive to achieve this goal. One successful approach for meeting this goal is to integrate issues of native plant revegetation (including protection of existing vegetation) into the larger design and construction processes of road projects. Revegetation planning is now an integral part of road planning and is an important aspect of road projects that can achieve a higher level of success and project benefits when incorporated early in project design. Experts recommend (as illustrated on the timeline Figure 2-1) that the implementation phase of revegetation begins while the overall project development process is still underway. Waiting until construction begins reduces the likelihood that locally-adapted native plant materials in the quantities needed, will be able to be propagated in advance.

To increase the opportunity for successful integration of revegetation issues within the overall road project, the designer of a revegetation plan can identify the cooperators and agencies involved, discover how their processes and timelines work, and coordinate at the appropriate times and with the appropriate people. The revegetation plan designer can add greater project value if involved in planning and construction processes whenever soil and vegetation disturbances are planned. Agency schedules, milestones, and budgetary issues are commonly defined in the planning process to effectively synchronize the revegetation efforts with road development and construction.

For the Designer
It is beyond the scope of this manual to cover all the specific procedures and processes for every agency involved in road projects. However, this chapter provides a general overview.

Road projects may be administered from local, state, or federal levels, or sometimes from a combination of all three levels. In terms of timing, road projects can be complex and span many years, whereas other projects are streamlined and on a compressed timeline. It is beyond the scope of this manual to cover all the specific procedures and processes for every agency involved in road projects. This chapter, however, provides an overview to successfully navigate the various processes for a project. Designer involvement and input is important from the inception of a project through completion. The earlier one can get involved, the more input provided. The preliminary steps for initial involvement include:

For the Designer
Incorporation of revegetation planning very early on in road project development can benefit project coordination, schedule, and budget.

- Defining cooperators, processes, timelines, and milestones.
- Defining objectives: What is the project trying to accomplish?

This chapter provides an overview of each of these steps, followed by a discussion of typical road development processes which include key points of involvement. This chapter also discusses the technical content, interpretation and use of road project plans and views.

2.2 PRELIMINARY TASKS OF INITIATION

Roadside revegetation is a complex process, frequently involving numerous agencies and individuals. Appointing a single designer to coordinate the planning, implementing, and monitoring/adaptive management of the revegetation aspects of the road project can help streamline revegetation coordination. Typically, the designer will be the responsible professional landscape architect or civil engineer in charge of sealing the revegetation documents and is required to be directly involved with the design and supervision of others who are assisting in the preparation of the design documents. Depending on the training and expertise of the designer, the project scale, level of environmental impacts of the project, and level of political and public scrutiny, the designer and owner of the project are often best served by enlisting experts from other natural resource disciplines to help with the revegetation planning so that expertise in botany, plant genetics, horticultural practices, landscape architecture, soil science, engineering, hydrology, wildlife biology (including pollinator specialists), geology, and ecology is available for the project as necessary. Project quality and efficiency is enhanced when the designer is the coordinator of the technical and organizational aspects of the revegetation project, as well as the contact between revegetation efforts and the other aspects of road planning and construction.

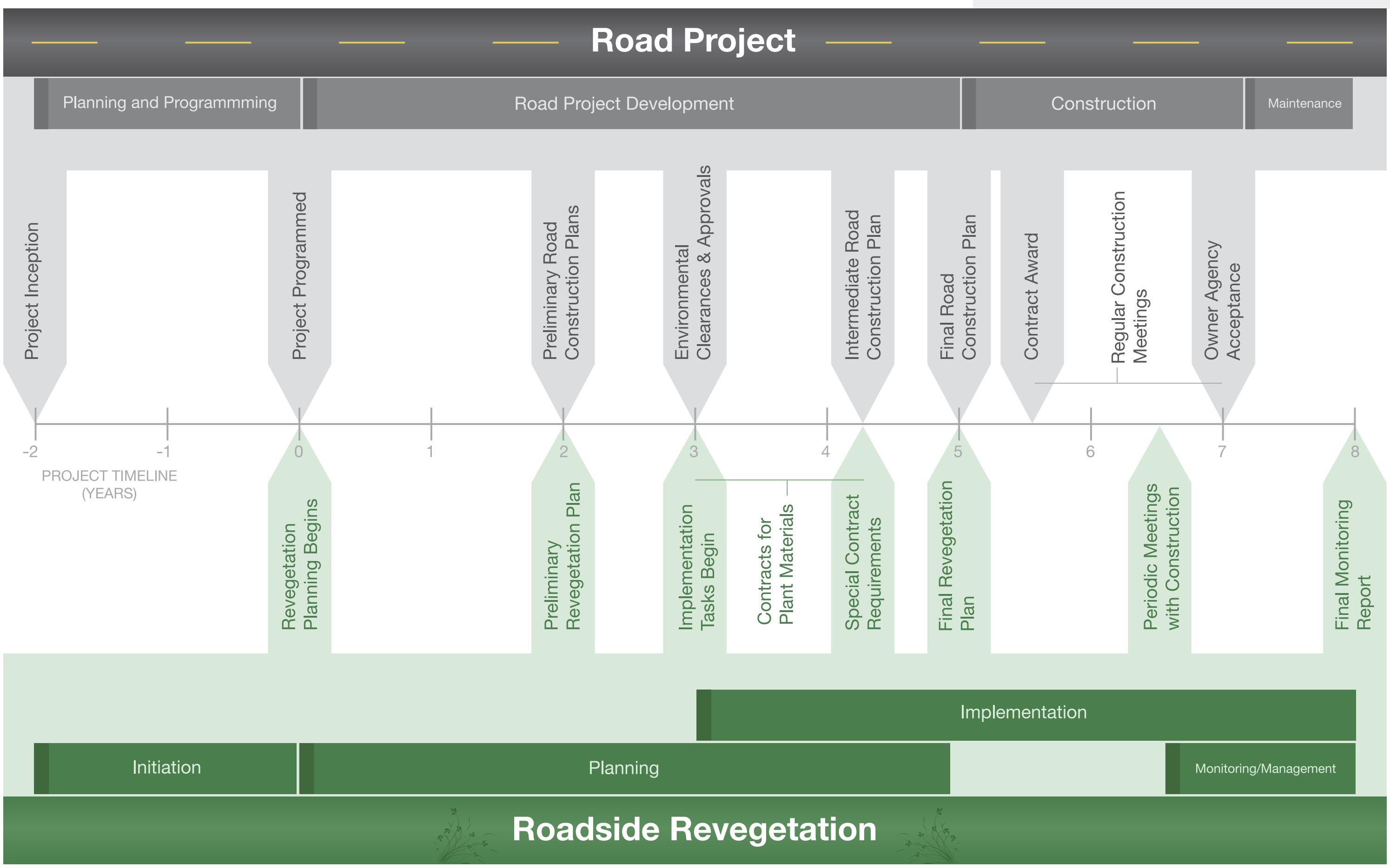
2.2.1 DEFINING COOPERATORS PROCESSES, TIMELINES, AND MILESTONES

Designer due diligence early in the project planning process includes identification of the reviewing agencies and individuals involved in the road construction project, along with their respective roles and responsibilities. It is especially important to understand: (1) who are the actual decision-makers, (2) who is the land owning agency, (3) who maintains the road and roadsides, (4) who will be carrying out the road construction project, and (5) who is funding the project. Sometimes, the actual decision-makers are not the same people who are attending the design meetings. It can be important for the designer and design team to confirm the agency organizational dynamics and to get key design direction approvals in writing at the appropriate times in the planning and design process.

An understanding that the timing, responsibilities, and, most important, the plan review and approval processes associated with each agency will vary, will allow the designer to plan, communicate, and interact more effectively with the right people at the right time. While this may seem complicated, many agencies have a procedural manual that describes how a project is carried out from conception to completion, defining the timelines, milestones, roles and responsibilities, terminology, and how funding works. Most current documents are online, however, some may only be available in hardcopy upon request. The designer may want to confirm the location of current documents with the reviewing agencies. Location and use of these documents and agency manuals to help create a project schedule can be

Figure 2-1 | **Project coordination timeline example**

Coordinating revegetation with the larger processes of road construction is essential. While the timelines and agencies involved will vary, this figure illustrates some of the key opportunities for communication and integration.



a key due diligence item for the designer. Initial meetings with owners, maintainers, and agency plan reviewers are also beneficial for the designer, as they can create relationships that strengthen the lines of communication during the project, and are an ideal time to clarify project requirements, expectations, and various cooperator processes.

Each agency has certain approvals and procedural activities, including some that involve fulfilling environmental regulations. Early designer due diligence may include defining these activities and determining how revegetation work fits within them. The steps in the approval process are often important milestones for the agency, and they expect the designer to have that understanding and to provide input at appropriate times. Defining appropriate roles can help the designer to coordinate with the proper people, follow protocols, and avoid duplicating efforts.

Many variables affect the overall timelines from inception to construction. Timelines vary depending on the complexity of the project, the amount of controversy involved, and the availability of funds. Some projects take less than two years, while some can take over ten years. Reviewing Figure 2-1 with the assigned road project engineer and discussing milestones, timelines, procedures, budgets, and roles can be an effective approach to getting oriented to the complex process of road development.

2.2.2 DEFINING OBJECTIVES: WHAT IS THE PROJECT TRYING TO ACCOMPLISH?

Once the agencies and processes for each phase of the project are clarified, the designer can begin to understand how their work relates to the overall objectives of the project. Objectives can be found in the programming documents that originally identified the need for the project. These objectives often center on improving safety or updating the road infrastructure. Phase One of the planning process (Chapter 3) describes how to identify the objectives of the road project and translate them into specific goals for revegetation.

Environmental protection, pollinator habitat creation, and maximizing the ability of the roadside to regenerate native vegetation are primary revegetation goals. When a revegetation designer is involved early in a project, when disturbances to soil and vegetation are planned, the designer can be a key link to understanding the potential disturbances that might be caused and how to best minimize or mitigate them. The designer, with specialist input, can help the roadway engineer understand what types of disturbances can be feasibly revegetated with native plants. If a disturbance to soil and vegetation will not allow for revegetation, alternatives to that type of disturbance can be considered. Specialist input can be crucial for determining potential strategies and alternatives. The project objectives also help determine the types of native vegetation that are most appropriate for the work. Revegetation design solutions can vary widely depending if the project crosses a wildlife corridor, is a scenic drive, is in an ecologically sensitive area with more intensive recovery needed, travels through open farm land, or contains steep slopes.

Safety, efficiency, protecting and enhancing environmental health, and creating habitat for pollinators are all important priorities in road projects. While safety concerns may at times limit what is appropriate in roadside revegetation (e.g., tall trees along a roadside may be a desirable choice from an environmental and aesthetic standpoint, but may not from a safety or visibility standpoint), experienced design professionals recommend that these concerns not be viewed as an impediment to successfully revegetating roadsides. Experts do recommend that the designer coordinate early with the roadway engineer to gain a full understanding of safety issues, particularly regarding visibility and the ability of drivers to recover if they drive off the road and into the roadside area (see discussion of how to define roadside revegetation zones in Chapter 3).

2.3 THE PROCESS OF ROAD DEVELOPMENT

While each cooperating agency will divide up and define tasks differently, the process of road development generally has four stages: (1) planning and programming, (2) project development, (3) construction, and (4) maintenance. There are many opportunities for integration during each of these phases. For revegetation work, the implementation phase often begins well before road construction is initiated (with the collection of plant materials for propagation). Revegetation efforts also continue after road construction is completed. Figure 2-1 compares the revegetation process with the overall road development process, showing process steps where interface is crucial.

During road project development, a number of meetings will take place involving representatives from the agencies and interests involved with the project. Experts recommend setting revegetation and wildlife objectives, such as developing pollinator habitat, accommodating wildlife corridor crossings, and planning stormwater features as habitat enhancement, early in the planning and programming phase, as they each have project safety, schedule, and budget implications. During the planning phase, meetings usually take place at the preliminary, intermediate, and final stages of the road plan. It is recommended that the designer attend all of these meetings. This ensures that good information gets into the project budget and schedule, that good communication takes place, and that trust is built during the road planning process.

Meetings also offer the opportunity for reminders and confirmation that regulations and requirements are being met by all designers and that proper channels are utilized to get the job done. Regular communication between designers and quality control plan review at similar preliminary, pre-final, and final milestones can lead to developing a complete set of construction documents that can be easily interpreted and tightly bid. During the construction phase, the construction manager, design engineer, and other key players carrying out the project typically meet on a weekly basis. Attending some of these meetings can be valuable both for learning and contributing input as the project progresses, and for interacting with contractors, inspectors, and other stakeholders who may also be at the meetings or field site. Key contacts (such as the construction manager or design engineer) can help clarify the most appropriate meetings to attend, as well as the channels for communicating with other individuals who are involved with the project.

For the Designer
Providing wildlife crossings under roadways can increase driver safety. Planning and budgeting of wildlife under-crossings is often overlooked.

2.3.1 ROAD PLANNING AND PROGRAMMING

The process of deciding when to modify or build a section of road is often lengthy. Transportation planners identify and prioritize functional, structural, and safety issues regarding roads. If an issue is becoming problematic, alternatives to address it will be considered (FHWA 2005). The negative effects of transportation infrastructure and rights-of-way on communities and the environment are well documented. New road alignments or major road widenings are often controversial and often require extensive study of functional, cultural, environmental, and aesthetic issues.

Context Sensitive Solutions (CSS) are design solutions, often developed through a public engagement process, that identify and address site specific effects in an attempt to physically and visually connect transportation facilities into communities and their surrounding context. Depending on the project scope and context, solutions often prescribe bridge and wall structure aesthetic design, lighting and signage styles, bicycle, pedestrian and wildlife crossing accommodations, development of stormwater facilities as wildlife habitat, and providing appropriate types and amounts of vegetation. Each solution has function, safety, schedule, and cost implications for a project and are typically most successful when addressed early in the planning and programming of a road project. The revegetation design professional is often well-versed in Context Sensitive Solutions and can benefit the road project if their input is included in the early planning and programming phase.

The Federal Highway Administration (FHWA), several Departments of Transportation (DOT), and several States have adopted policies to provide sustainable highway design, Context Sensitive Solution studies, and incorporation of CSS solutions into their transportation projects. As examples, the policy framework to provide Sustainable and Context Sensitive Solutions is found in the governing policies and design procedures for both the Illinois Department of Transportation and the Indiana Department of Transportation. In the State of Illinois Statute 605 ILCS 5/4-219 Context Sensitivity, the Illinois General Assembly intends to ensure that highway projects "meet the State's transportation needs, exist in harmony with their surroundings and add lasting value to the communities they serve." The design process is to include "early and on-going collaboration with affected citizens, elected officials, interest groups, and other stakeholders to ensure that the values and needs of the affected communities are identified and carefully considered in the development of transportation projects." Further, the CSS process and design "shall promote the exploration of innovative solutions, commensurate with the scope of each project that can effectively balance safety, mobility, community and environmental objectives in a manner that will enhance the relationship of the transportation facility with its setting" (State of Illinois General Assembly-a, 2013).

Similarly, the Indiana Department of Transportation has a written policy "to incorporate Context Sensitive Solutions (CSS) into the planning, development, construction and maintenance process for improvement to the state jurisdictional transportation system." The Indiana Procedural Manual for Preparing Environmental Documents 2008, (Indiana, 2008), includes section II.B.3.f Context Sensitive Solutions (CSS), that highlights that CSS seeks to benefit the community by:

- incorporating feedback from the locals affected by the proposed project,
- encouraging collaboration between neighborhoods and local, state and federal officials,
- enhancing roadway and transit communities,
- considering bicycle and pedestrian access needs,
- assisting the development of strategies for smart growth and
- encouraging assessments and design of alternatives consistent with local needs.

While the CSS process works to identify both broad and detailed impacts of a project and proposes appropriate mitigation and enhancements, the process must also accomplish the prime goal of the project and be sustainable over the long term.

Sustainable design in the design-build environment seeks to balance environmental, functional and financial needs and impacts. All can be accomplished through thoughtful and efficient design that seeks to do no harm, minimize its footprint, and strives to incorporate dynamic functional solutions. Ideal sustainable design solutions often accomplish their intended function, are aesthetically pleasing, endure and improve over time, and reduce future costs and impacts.

Many Departments of Transportation have committed to utilize the Federal Highway Administration's (FHWA) Infrastructure Voluntary Evaluation Sustainability Tool (INVEST). This tool facilitates the development and tracking of sustainability measures throughout a project's life, including overall planning, project development, and operations and maintenance. A project is measured for "triple bottom line" Social, Environmental, and Economic accomplishments with the INVEST scorecard; for example, the Rural Extended Project Development module lists 25 weighted items on which the project can score. A "Platinum" rating is achieved when 60 percent or more of the possible sustainability rating points are achieved. More information on FHWA's INVEST tool is available at the website www.sustainablehighways.org. (Parsons Brinckerhoff, 2014)

Design studies and tools such as CSS and INVEST attempt to create projects and budgets that address the "triple bottom line" for the benefit of the public and the environment. With or without these tools, wildlife corridor crossings and bicycle/pedestrian connections are two issue areas that are often overlooked when roadway budgets are initially set. The accommodations for wildlife corridors and bicycle/pedestrian connections through transportation routes are detailed functional, structural, and safety issue items, with significant project cost implications. Wildlife crossings can require taller bridge heights, longer spans, and may be needed at multiple bridges to accommodate safe movement of large animals across the right-of-way. Bicycle/ pedestrian connections can require wider bridges for bicycle lanes and sidewalks, protective medians or barriers, and may be needed over or under multiple roadway bridge structures. Ignoring these accommodations can have long-lasting functional, safety, and financial impact on communities, motorists, and wildlife.

Once it has been determined that a road will be built, modified, or updated, how it will be built or modified, and an alignment selected, a budget and schedule are created. At this point, the project has been "programmed" for a specific delivery year. This process usually identifies the following:

- Project purpose and need
- Roles and responsibilities of partnering agencies
- List of project alternatives established
- Primary contacts for project
- Preliminary project delivery schedule with milestones
- Collection and analysis of traffic data (accident history, average daily traffic volumes, etc.)
- Preliminary construction cost estimate

Environmental concerns for the project (cultural and natural resource) and estimation of the affected environment (WFLHD 2005 p. 8)

Experts recommend that a revegetation designer be involved throughout the early planning and programming of a roadway project in order to identify issues and solutions, refine the budget, and help assess the feasibility of various alternatives.

2.3.2 ROAD PROJECT DEVELOPMENT

The road project construction (contract) document development process begins after the project is programmed and ends with the beginning of construction. Depending on environmental concerns and right-of-way issues, the project development process may take between one and five years. Contract documents are typically defined in the Owner-Contractor Agreement within the specifications Division 00. Contract documents typically consist of drawings, specifications, addendums to 100 percent documents distributed to bidders, and supplemental drawings provided by the designer to the contractor.

The road project development phase usually has three document review and approval sub-phases. These involve developing, analyzing, and considering approaches and alternatives to various design details within the project until a strategy and specifications of how to best proceed are shared in the final documents. The process usually involves:

- **Preliminary**—review of road construction documents that are approximately 30 percent complete
- **Intermediate**—review of road construction documents that are approximately 50 to 70 percent complete
- **Final**—review of road construction documents 70 to 100 percent complete. Final reviews often have a 95 percent or 100 percent pre-final review and the designer is able to make final corrections before plans are distributed for bidding or construction. Ideally, only the approved 100 percent plans will be advertised for bids and then given to the awarded contractor for construction or in a design-build process, the 100 percent plans will be reviewed and approved by the contractor and project owner team and construction will begin.

Inset 2-1 | **Roadside vegetation and driver safety**

Greater safety for the traveling public is the primary objective of many road projects. The designer can support road safety when they do not propose vegetation strategies that might make the roadway less safe. Integrating revegetation goals with safety goals requires an awareness of visibility issues, wildlife interactions, and other factors. Highway roadside design and revegetation efforts are subject to clear zone requirements that follow the American Association of State Highway and Transportation Officials (AASHTO) recommendations. FHWA and State DOT agencies are interested in the concept of a "forgiving" roadside: a roadside environment that allows a driver to recover safely if they drive off the road onto the roadside. The agencies expect a clear zone of low vegetation adjacent to the road, preferably low grassy surfaces, or shrub masses instead of trees. The roadside distance required to make a roadside forgiving depends on the speed limit of the highway, the traffic volume, and surrounding conditions. The AASHTO Roadside Design Guide (RDG) recommends clear zone widths based on the road design speed, average daily traffic, the up or down slope of the roadside and horizontal curve radius. The presence of curbs does not affect the clear zone distance along high speed roadways. Highway clear zones are generally are in the 20-46 foot range, but vary based on speed and noted conditions.

Preliminary Phase

The preliminary development phase involves collecting information and initiating contacts with "stakeholders". Stakeholders are individuals or parties who are interested in or affected by the road construction (local and adjacent landowners, resource agencies, regulatory agencies, and any other potentially affected parties). The local jurisdiction will often be able to provide a detailed contact list of stakeholders who will likely be interested in the road project. The preliminary phase is necessary to refine purpose and need, to develop a range of alternatives to address purpose and need, and to obtain the approvals and clearances to allow the project to proceed. This includes commitments for CSS safety, cultural, aesthetic, functional, and environmental mitigations. The preliminary phase takes the road construction plans to about 30 percent completion. Once approvals and clearances are obtained, funds can typically be committed to continue development of the project.

Usually the preliminary phase will include the development and identification of:

- Preliminary construction plans (usually drafts about 30 percent complete) of the proposed alternatives (plan/profile sheets, typical sections, major work items identified and located)
- Preliminary construction cost estimates for alternatives
- Resource surveys (wetlands, archaeological sites, and biological assessments)
- Preliminary construction schedule
- Identification of impacts and mitigation
- Environmental approvals and selection of alternatives for implementation
- List of contacts for the project

For the revegetation designer, the preliminary phase is a crucial one. This phase represents the best opportunity for input regarding issues associated with revegetation, including disturbances planned for existing soil and vegetation on the site. Significant features of the preliminary revegetation plan will need to be incorporated during this road planning phase. By the time of environmental approvals, the vegetative concepts and the necessary commitments of resources and funds will need to be integrated with the documents, as revegetation is an important aspect of environmental protection and mitigation. The appropriate level of detail for the revegetation plan during the preliminary phase depends on the project. The State and local environmental guidelines predetermined by legislation will specify goals and requirements for the project regarding issues of soil stabilization, percent native vegetative cover, and protection of water quality (Inset 2-2). The designer is often asked to assist in preparation of the Storm Water Pollution Prevention Plan (SWPPP) for the project based on these guidelines, and to design them into the final revegetation plan. Environmental approvals are key milestones for the project team in order to maintain the project schedule, and for some designer teams, important in regard to availability of funds to carry out site assessments and revegetation planning work including preliminary mapping and seed collections.

Intermediate Phase

The next phase of road development moves towards 50 to 70 percent completion of the road construction documents. This phase involves refining plans and specifications, obtaining rights-of-way and permits, and creating detailed plan and profile sheets. The intermediate set of documents will include major budget items and quantities, final information pertaining to environmental concerns (such as SWPPP or erosion control plans), and major elements such as grading, drainage, and other issues defined.

At the intermediate stage, the designer is typically far along in the development of the revegetation drawings. The SWPPP is submitted to the State or local jurisdiction for review and

Inset 2-2 | **Example of an environmental regulation requirement**

"Final stabilization" means that all soil disturbing activities at the site have been completed and that a uniform perennial vegetative cover with a density of at least 70 percent of the native background vegetative cover for the area has been established on all unpaved areas and areas not covered by permanent structures, or equivalent permanent stabilization measures.

"Final Stabilization" (adapted from EPA 2006) means that:

- All soil disturbing activities at the site have been completed and either of the two following criteria are met:
  - *a uniform (i.e., evenly distributed, without large bare areas) perennial vegetative cover with a density of 70 percent of the native background vegetative cover for the area has been established on all unpaved areas and areas not covered by permanent structures, or*
  - *equivalent permanent stabilization measures (such as the use of riprap, gabions, or geotextiles) have been employed.*
- When background native vegetation will cover less than 100 percent of the ground (e.g., arid areas, beaches), the 70 percent coverage criteria is adjusted as follows: if the native vegetation covers 50 percent of the ground, 70 percent of 50 percent (0.70 X 0.50 = 0.35) would require 35 percent total cover for final stabilization. On a beach with no natural vegetation, no stabilization is required.
- In arid and semi-arid areas only, all soil disturbing activities at the site have been completed and both of the following criteria have been met:
  - *Temporary erosion control measures (e.g., degradable rolled erosion control product) are selected, designed, and installed along with an appropriate seed base to provide erosion control for at least three years without active maintenance, and*
  - *The temporary erosion control measures are selected, designed, and installed to achieve 70 percent vegetative coverage within three years.*

approval. Mitigating measures have been identified for affected areas and owner or design-build contractor contracts for seed and seedling production have begun. The intermediate set of road documents will include specifications for how the road project will be carried out. These specifications and contract requirements are key tools for the designer.

Special Contract Requirements: A Key Tool for Revegetation

In every phase of road development, there are two key components of contract documents: (1) drawings (plans) and (2) specifications (contract descriptions). The drawings are visual representations of the proposed work with dimensions, labels, and notes as described later in this chapter. Specifications describe and define materials, equipment, systems, procedures, performance, workmanship, standards, provisions, and requirements for the work that each agency provides to contractors or employees to carry out the work. A "special provision" (FHWA, State DOT) or "special contract requirement" (US Forest Service) is a type of specification. Standard specifications are uniformly carried out for most projects.

Special provisions or special contract requirements address local, project specific, context-sensitive concerns for a particular project. They are modifications of existing specifications found within the agency manual, or newly written specifications that are designed to address special concerns not adequately addressed in the standard contract specifications. For example, a standard specification may exist for chipping woody debris; however, the standard specification does not address size requirements of the chipped material. A project may require a uniform size of material that should be shredded and screened, rather than chipped, to create optimal mulch for the project. To meet this requirement, the designer can create a special

For the Designer
Special Provisions and special contract requirements require pre-approval by the reviewing agency prior to inclusion in construction documents. The approval process can take several months.

provision or special contract requirement that will specify the required size (such as three inches or less in length) and processing needs (such as shredded and screened rather than chipped). Careful research is often needed to adequately develop and describe a special provision or special contract requirement, but it is essential in order to achieve the desired results in the field. In the future, generically applicable special provisions or special contract requirements may become adopted as standard specifications if they come to be utilized on most projects.

Special provisions or special contract requirements are an important tool for designers to communicate special expectations with contractors, to clearly define contracting responsibilities to reduce duplicate efforts, and to set standards for performance. The designer can specify to contractors what the requirements are, and how requirements might be met, measured, and paid for. Special provisions or special contract requirements will be part of the contract, but need to be reviewed and approved by the agency with jurisdiction over the specifications. The reviewing agency typically takes weeks or months to review and approve a specification and assign it a specification number. It is recommended that attention be given to modifying or creating special provisions or special contract requirements to meet the revegetation needs of the project by the intermediate phase. Special provisions or special contract requirements that are approved may be included in the final contract documents for the road construction project.

Final Phase

The final set of road construction documents will include the detailed design elements of the Revegetation Plan, as well as all the details for road construction. Drawings and contract specifications will be fully developed. Special provisions and special contract requirements will have been submitted and approved. Environmental approvals and permits will have been accomplished. Final cost estimates will be provided along with a comprehensive schedule. The work of the designer in developing the revegetation plan, as well as efforts to reduce the construction footprint and protect native vegetation on the project site, will be an integral part of the road construction documents. At this point, finalizing the revegetation documents, including budget, will be necessary. Final road construction documents will be submitted for distribution to bidders or in the case of design-build, will be submitted to the contractor who will distribute to his team of sub-contractors. Once the documents are in the contractor's hands, this is a good opportunity for the revegetation designer to connect and coordinate with the contractor, landscape sub-contractor, and agencies in order to confirm plant material sources and to schedule availability of plant materials with outplanting windows.

2.3.3 CONSTRUCTION

Following project development, the construction phase begins. Road construction can take one to three years. Sometimes there is a formal milestone when the project is handed off to construction personnel. If so, the construction manager or project engineer becomes an essential contact for the designer, who may attend some of the weekly meetings that will take place during road construction. The construction phase of a road is completed when there is a formal acceptance of the road by the road owning agency. For the designer, implementation and monitoring phases of revegetation may begin before road construction (with plant materials procurement, etc.) and continue following completion of construction.

2.3.4 MAINTENANCE

Following construction of the road, the work of the designer will usually continue for an additional one to three years until the revegetation is fully implemented. Also, the activities centered on monitoring and adaptive management of the establishing vegetation will continue to take place. These types of activities may continue for up to five years after the road construction is complete. The submission of a final monitoring report is the milestone marking the end of the designer's formal efforts on the project. Although the designer's efforts are contractually complete, valuable information can be obtained by periodic visits to the project site in order to see how the restoration efforts develop over time.

Coordination with the road owning agency and the individuals who carry out road maintenance will be essential to ensure that native vegetation continues to thrive on the site. In many instances once the state DOT hands off the project to the county, the state DOT does not provide further input. For example, the agency taking ownership, often the county, could have maintenance methods that may ultimately undo portions of the revegetation, such as blanket herbicide use as standard practice along roadsides. The designer can protect the revegetation plan by identifying the ultimate roadside vegetation management agency in the planning phase, checking what maintenance methods are currently utilized, and to continually coordinate efforts with the ultimate maintaining agency in order to ensure that future management is appropriate for the native vegetation. The transportation agencies will continue to monitor the road to ensure that the problem that led to the road modification (infrastructure decay, safety issues, etc.) was adequately addressed by the project.

2.4 ROAD CONSTRUCTION PLANS

This section explains how to use roadway engineering views for revegetation planning, including determining the vegetation zones that begin where the pavement ends. A glossary with illustrations is provided in order to understand technical concepts and terminology for effective communication with others involved in road design and construction. This section explains how to read and interpret:

- Plan views
- Profile views
- Cross-section views
- Typical views
- Summary of quantities tables

The plan set consists of construction drawings and specifications for each section of road or project. The four most common views of plans utilized by the designer are plan views, cross-section views, profile views, and typical views. Each of these is defined in Table 2-1. Examples and descriptions for interpreting each of these views are provided below. Each engineering plan includes a legend defining abbreviations and symbols as well as a summary of plan quantities table.

Table 2-1 | **Definitions of views**

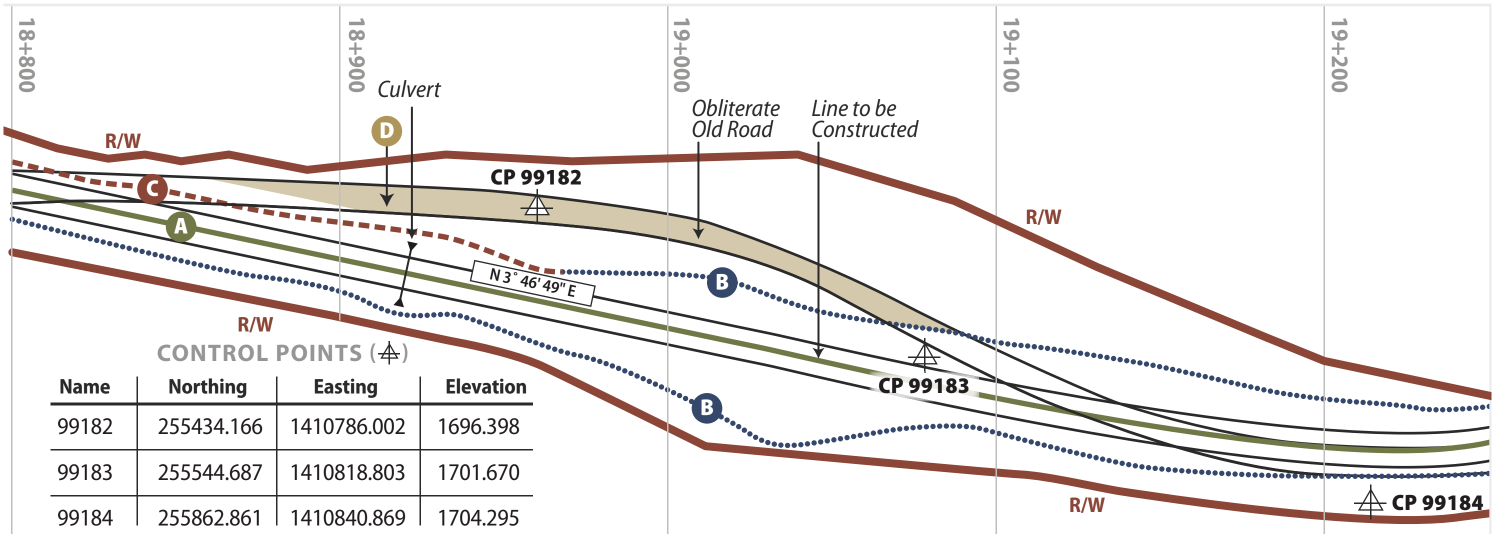
View	Definition
Plan	A drawing depicting a portion of the road project from a bird's eye view.
Profile	A drawing depicting the vertical plane section along the longitudinal centerline of the road, expressed in elevation or gradient.
Cross-section	A drawing depicting a horizontal section of the road viewed vertically, as if cut across the width of the road.
Detail	A drawing depicting features of a particular design, installation, construction or methodology.

Source: Keller and Sherar 2003

2.4.1 PLAN VIEW

The plan view shows the existing and proposed road locations from a bird's eye view. It is important to note that plan sets, in particular road plans, historically displayed distances in meters. This practice was discontinued nationwide in the early 2000s and distances are now displayed in US Customary Units (feet). The proposed road is usually designated with solid lines (Figure 2-2A). The solid centerline (of the road to be constructed) is divided into 100 foot sections (large ticks), often with 20 foot subdivisions also designated (small ticks—not shown). Each 100 foot division is called a station, representing a discrete, surveyed, and identifiable point within the road corridor. Each station is identified with a unique number that indicates its distance from the beginning of the project. For example, the station 19+000 indicates this point is 19,000 feet from the start of the project; 19+040 indicates this point is 19,040 feet from the start. This short-hand identifier is also used to indicate the placement of road-related infrastructure, such as culverts, the beginning and end of guard-rail construction, or the placement of a sign. In the field, stations are identifiable as vertically aligned numbers written on wooden stakes and driven into the ground, facing the roadway. Detailed location of elements off of the roadway can then be identified by station along the centerline of the alignment plus the offset distance dimension from the edge of roadway pavement. This will appear as a +0.00 note on the field stake. Not only do the stations provide locations, they help to locate revegetation units. The plans also show the top of the cut slope (Figure 2-2B, dotted line), bottom of the fill slopes (Figure 2-2C, dashed lines), and the location of the original road, which will be obliterated in this example (Figure 2-2D, shaded area). Plans also include temporary construction easement lines (Figure 2-2D (outside line)) and right-of-way lines (ROW or R/W). These are, in effect, the property lines of the roadway and an important boundary for the designer.

Figure 2-2 | Example plan view

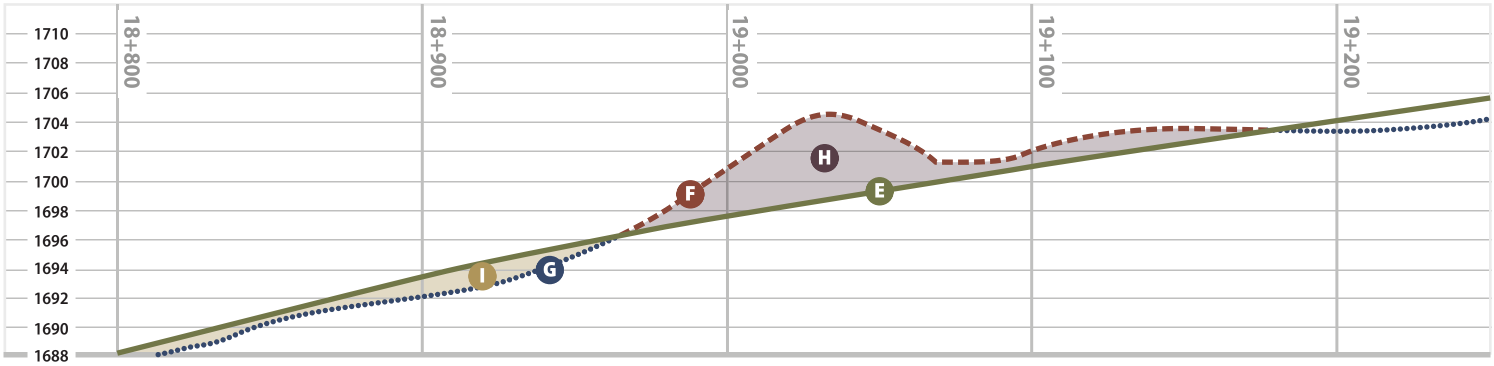


Name	Northing	Easting	Elevation
99182	255434.166	1410786.002	1696.398
99183	255544.687	1410818.803	1701.670
99184	255862.861	1410840.869	1704.295

2.4.2 PROFILE VIEW

The profile view is a trace of a vertical plane intersecting a particular surface of the proposed road construction (Figure 2-3E). It corresponds to the longitudinal centerline of the road bed in the plans. Profile grade means either elevation or gradient of the trace, depending on the context. The trace of the existing road is shown as a dashed line (Figure 2-3F) and a dotted line (Figure 2-3G). A vertical scale provides useful information about the profile of construction grades throughout the project. This view shows where the proposed road will be lower than the existing road (Figure 2-3H) and areas where it will be higher (Figure 2-3 I). Where the planned road is lower, material will usually be removed and used in areas needing fill. Additional information is often displayed adjacent to and locatable by the station numbers, such as volumes of excavation and embankment work, guard-rail placement, or wall placements.

Figure 2-3 | **Example profile view**



2.4.3 CROSS-SECTION VIEW

Cross-sections are views of the slopes perpendicular to the direction of the road. They display a vertical section of the ground or structure at right angles to the centerline or baseline of the roadway. Depending on the length and topographic complexity of the road, there can be hundreds of cross-sections. Each cross-section is referenced back to a station. For example, the cross-section shown in Figure 2-4 depicts the slope at Station 18+940. It shows the proposed road (Figure 2-4J), and the natural ground line as a dotted line (Figure 2-4 K). This section will have material brought in and placed as fill (Figure 2-4L). The cross-section in Figure 2-5 shows a through cut at 19+000. Material will be removed from the natural ground line (Figure 2-5K) to the proposed ground line – solid line (Figure 2-5 M).

Figure 2-4 | **First example cross-section**

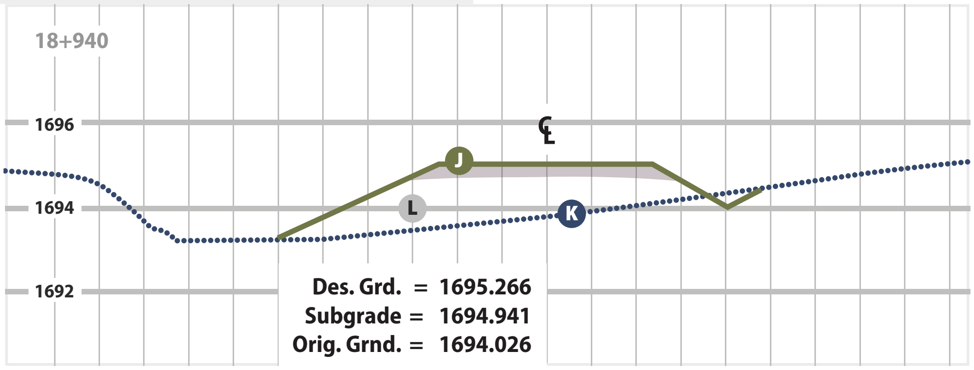
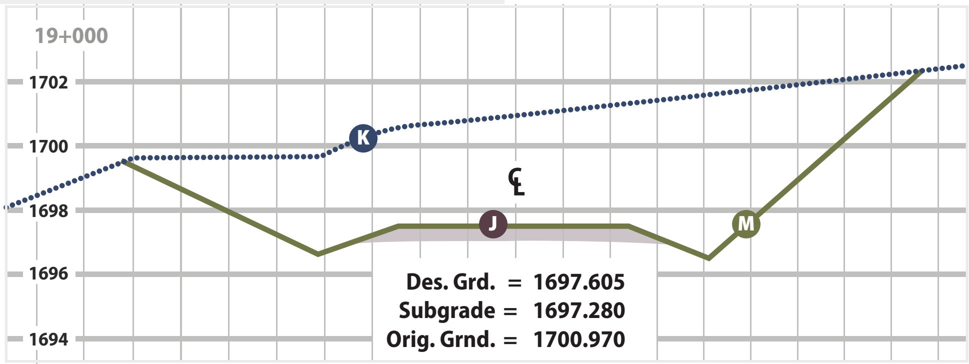


Figure 2-5 | **Second example cross-section**



Cross-section and plan views are used together to view the proposed road three-dimensionally. From these views, a more detailed revegetation plan can be developed. Each cross-section can be reviewed and a set of revegetation criteria can be developed for similar cross-sections throughout the project.

Cross- sections show the proposed slope gradients for cut and fill slopes and provide the designer a means to determine slope steepness. Like stationing, the method of depicting slopes has changed over the years. Older plan sets often depicted slopes as a ratio of one unit horizontal to one unit vertical. Several years ago, however, slope ratios were brought more in line with other disciplines and are now depicted as one unit vertical to one unit horizontal (vertical:horizontal). When slopes are flatter than 1:1 (45° or 100 percent), the slope is expressed as the ratio of one unit vertical to the number of units horizontal. For slopes steeper than 1:1, the slope ratio is expressed as number of units vertical to one unit horizontal. To avoid confusion, it is wise to notate the ratio by indicating the vertical and horizontal, for example 1V:2H, and to think in terms of rise over run (Figure 3-61).

2.4.4 TYPICAL VIEWS

Typical views graphically illustrate the design or construction details of the structures or other components that will be encountered in the road project (Figure 2-6). They can cover such structures as retaining walls, road surfaces, guardrails, ditch lines, plant installation, etc. They may be shown in profile, cross-section, or plan views (Figure 2-7). Like special contract requirements (see above), typical views are useful in helping communicate a new or modified approach to an existing methodology or construction technique.

2.4.5 SUMMARY OF QUANTITIES TABLE

Tabulation of plan quantities tables contain details on quantities, types of materials, and performance specifications. Standardized specifications for construction of federal roads are described in the FHWA handbook: Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects. The specifications are cited as “FP-03,” or “FP-14”, indicating “Federal Project” Standard Specifications issued in 2003 or 2014, respectively. The state departments of transportation have analogous manuals. Tabulation of plan quantities references not only the particular item specification number in the FP manual, but also the station number(s) of the planned work. Information of special interest for the designer includes the number of hectares of clearing and grubbing, hectares of obliterated roads listed by station, and the number of cubic meters of wood mulch to be produced. The summary of quantities table provides a summary of all tabulation of plan quantity tables contained within the plan. It generally does not include station numbers.

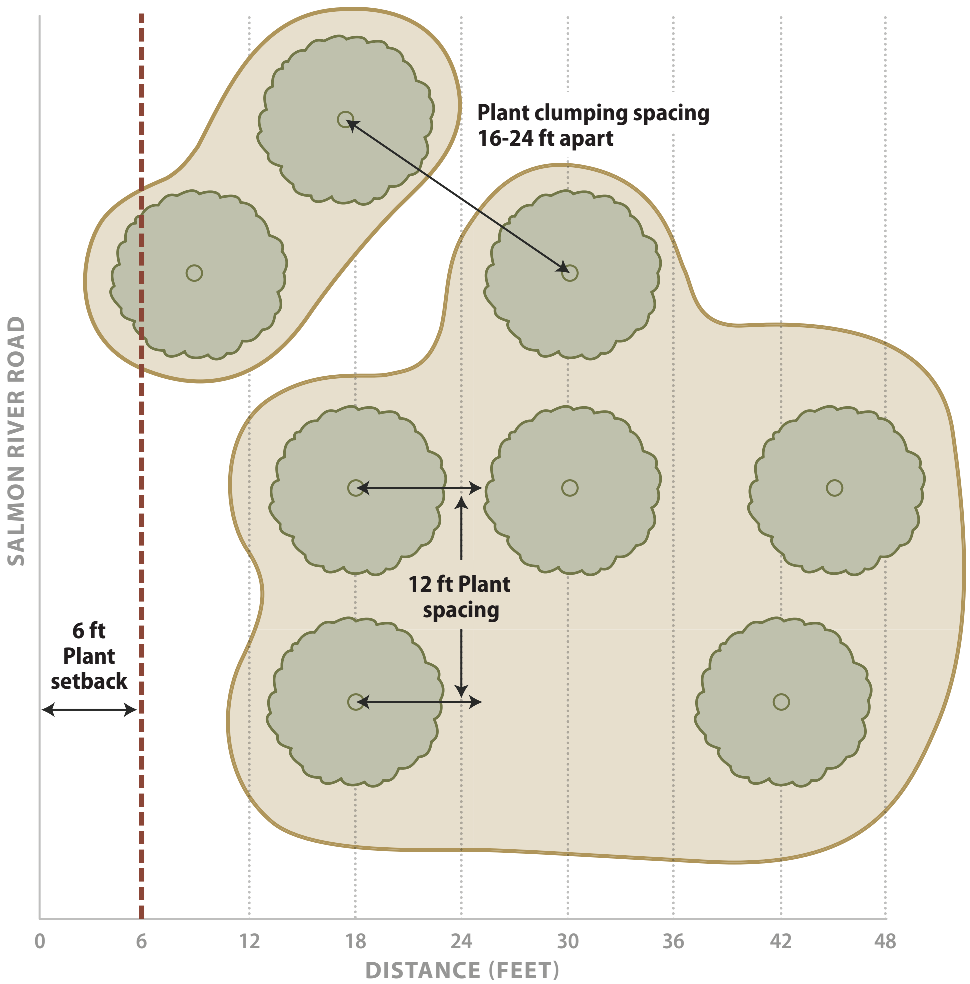


Figure 2-6 | **Example typical view**

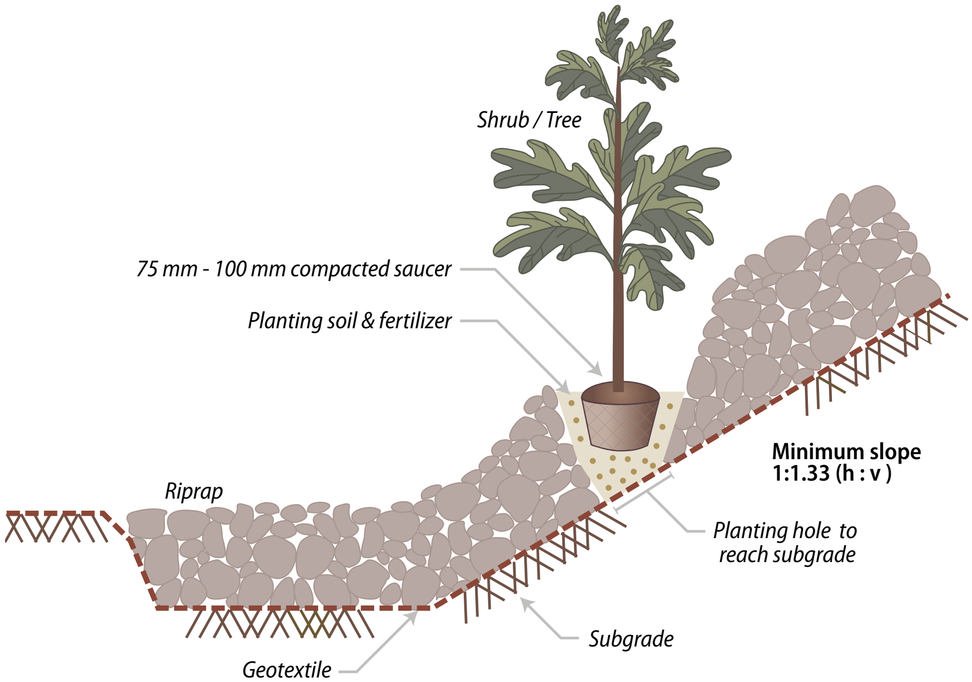


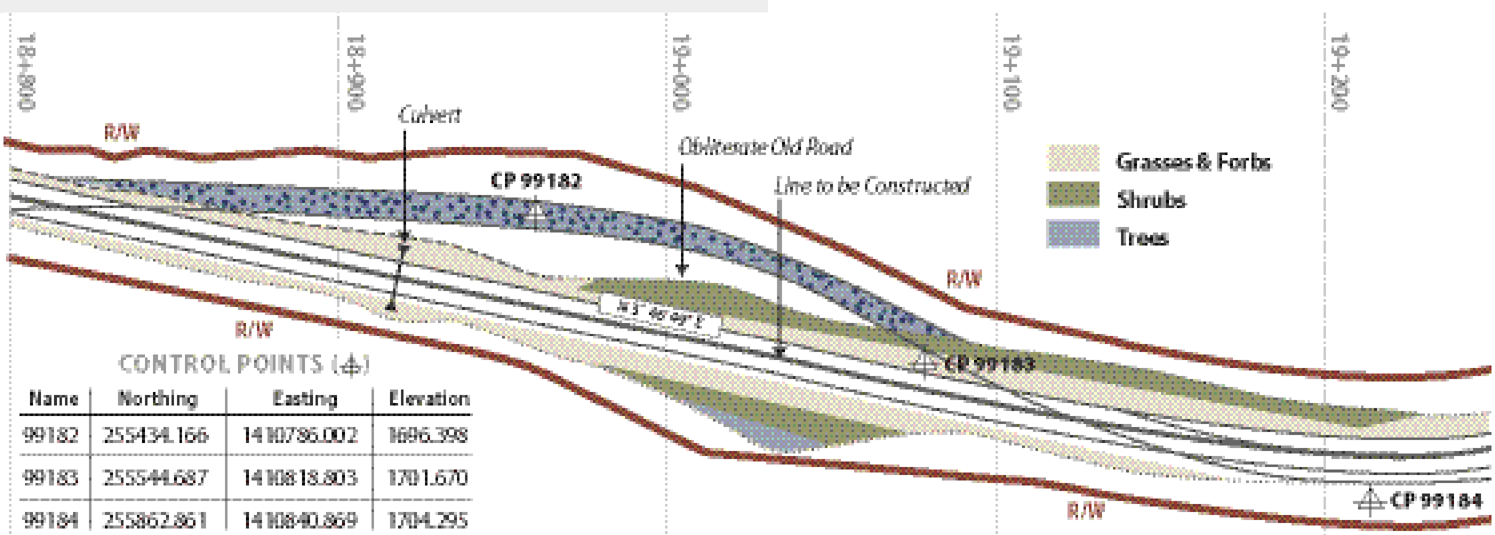
Figure 2-7 | **Example typical view of installation trail and turnout**

2.5 **INTERPRETING ENGINEERING VIEWS FOR REVEGETATION PLANNING**

Road construction, management, and safety concerns result in distinct revegetation zones along roadsides. Properly interpreting plans helps define where these zones may be located and what types of vegetation should be established. While the sizes and characteristics will vary, the zones that parallel the road can be grouped into four categories. Zone 1 begins immediately adjacent to the road surface (concrete or asphalt) and includes the road shoulder (concrete, asphalt, compacted gravel, coarse subsoil, etc.), the bottom of the drainage ditch, and portions of cut and fill slopes. This first zone is generally considered to be up to 10 feet from the pavement edge and is often barren of vegetation due in part to herbicide application, road salts, frequent ditch cleaning, and/or mowing. Local, state, and federal road managing agencies will have limitations to the types and proximity of vegetation that can be established next to the road. Zone 2 begins at roughly 10 feet from the pavement edge and continues laterally to about 30 feet. This zone may begin at the ditch bottom or at some point on a cut or fill slope, and may continue to the limit of the construction zone. Within Zone 2, grasses and forbs can thrive, but larger forbs, shrubs, and trees usually are not planted or encouraged due to safety, maintenance, and visibility issues. Beyond 30 to 50 feet from the pavement edge, Zone 3 begins in which larger forbs and shrubs can be planted. Past about 75 feet from the pavement edge, Zone 4 begins with largely unrestricted revegetation potential. Understanding these zones is necessary to coordinate revegetation with road management practices and safety considerations (Forman and others 2003).

To define the zones and begin to interpret engineering plans for revegetation work, information from plan sheets and quantity tabulations is applied to the plan map as shown in Figure 2-8. Each area can be considered a revegetation unit or subunit. An estimate of the area in each of these units can be calculated and used in determining how many seedlings or pounds of seeds will be needed. These criteria can be graphically displayed on a typical cross-section (Figure 2-9). On this cross-section, the criteria can be expressed as follows: from 20 to 60 feet grasses/forbs will be hydroseeded; from 60 to 100 feet shrubs will be planted; and on obliterated roads, trees will be planted. The slopes given in cross-sections can help define the types of revegetation methods available.

Figure 2-8 | **Interpretation of plan view showing revegetation zones**



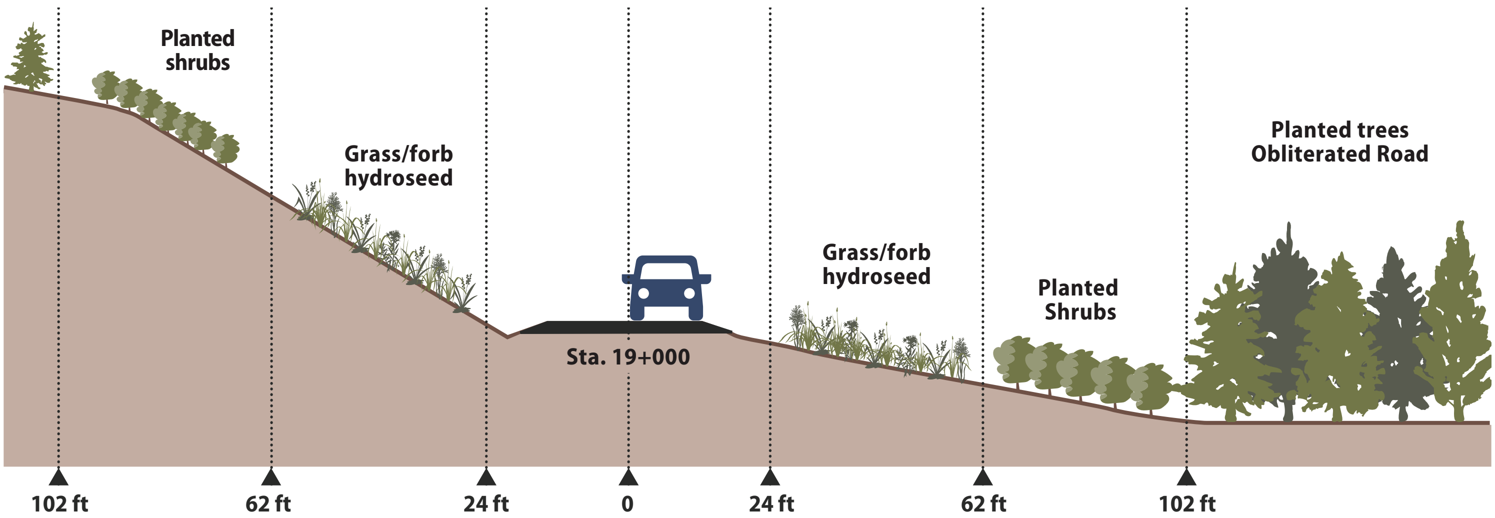


Figure 2-9 | **Cross-section showing revegetation zones as interpreted from engineering plans**

2.6 UNDERSTANDING TECHNICAL CONCEPTS AND TERMINOLOGY

The ability to understand and utilize the technical concepts and terminology used by road engineers is essential to roadside revegetation planning. This ability enables the designer to contribute effectively to road design and construction processes, as well as to communicate revegetation needs and goals to others involved with the project. The following section introduces key technical concepts and terminology relating to road design and construction

Road Concepts and Terminology

The following terminology was adapted from Keller and Sherar 2003.

2.6.1 ROAD COMPONENTS

- **Berm**—A ridge of rock, soil, or asphalt, typically along the outside edge of the road shoulder, used to control surface water. It directs surface runoff to specific locations where water can be removed from the road surface without causing erosion.
- **Buttress**—A structure designed to resist lateral forces. It is typically constructed of large riprap rock, gabions, or well-drained soil to support the toe of a slope in an unstable area.
- **Cross-Section**—A drawing depicting a section of the road sliced across the whole width of the road. Can also apply to a stream, slope, or slide.
- **Cut Slope (Back Slope or Cut Bank)**—The artificial face or slope cut into soil or rock along the inside edge of the road
- **Cut-and-fill**—A method of road construction in which a road is built by cutting into the hillside and spreading the spoil materials in adjacent low spots and as compacted or side-cast fill slope material along the route. A "balanced cut-and-fill" utilizes all of the "cut" material to generate the "fill." In a balanced cut-and-fill design there is no excess waste material and there is no need for hauling additional fill material. Thus cost is minimized.
- **Ditch (Side Drain)**—A channel or shallow canal along the road intended to collect water from the road and adjacent land for transport to a suitable point of disposal. It is commonly along the inside edge of the road. It also can be along the outside edge or along both sides of the road.

- **End Haul**—The removal and transportation of excavated material off-site to a stable waste area (rather than placing the fill material near the location of excavation).
- **Fill Slope (Embankment Slope)**—The inclined slope extending from the outside edge of the road shoulder to the toe (bottom) of the fill. This is the surface formed when excavated material is placed on a prepared ground surface to construct the road subgrade and roadbed template.
- **Grade (Gradient)**—The slope of the road along its alignment. This slope is expressed as a percentage and is the ratio of elevation change compared to distance traveled. For example, a +4percent grade indicates a gain of 4 units of measure in elevation for every 100 units of measure traveled.
- **Natural Ground (Original Ground Level)**—The natural ground surface of the terrain that existed prior to disturbance and/or road construction.
- **Plan View (Map View)**—View seen when looking from the sky towards the ground (bird's-eye view).
- **Reinforced Fill**—A fill that has been provided with tensile reinforcement through frictional contact with the surrounding soil for the purpose of greater stability and load carrying capacity. Reinforced fills are comprised of soil or rock material placed in layers with reinforcing elements to form slopes, walls, embankments, dams, or other structures. The reinforcing elements range from simple vegetation to specialized products such as steel strips, steel grids, polymeric geogrids, and geotextiles.
- **Retaining Structure**—A structure designed to resist the lateral displacement of soil, water, or any other type of material. It is commonly used to support a roadway or gain road width on steep terrain. They are often constructed of gabions, reinforced concrete, timber cribs, or mechanically-stabilized earth.
- **Right-of-Way**—The area or footprint of land over which facilities such as roads, railroads, or power lines are built. Legally, it is an easement that grants the right to pass over the land of another.
- **Road Center Line**—An imaginary line that runs longitudinally along the center of the road.

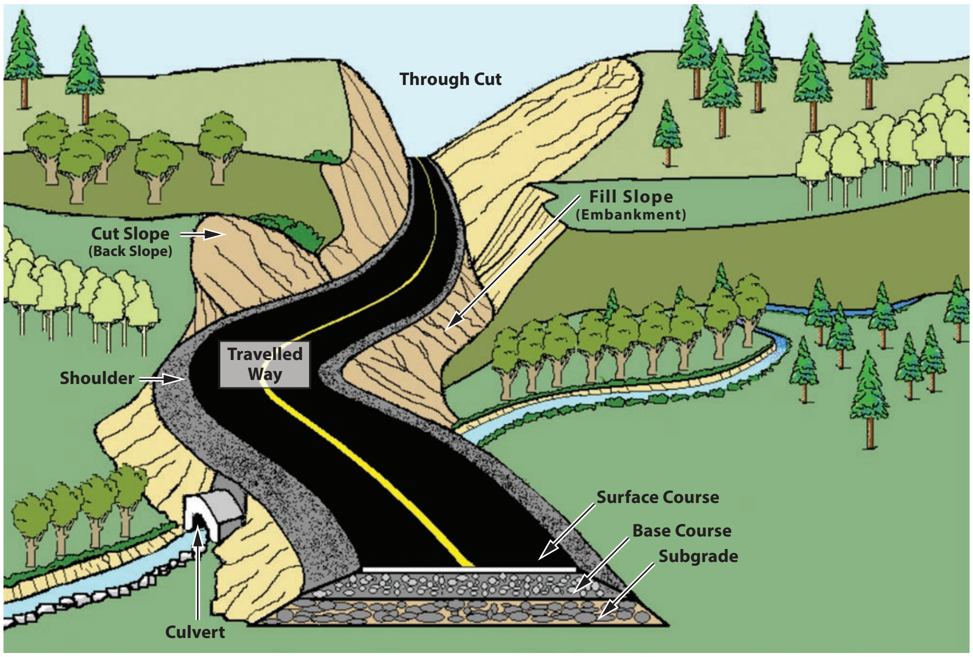


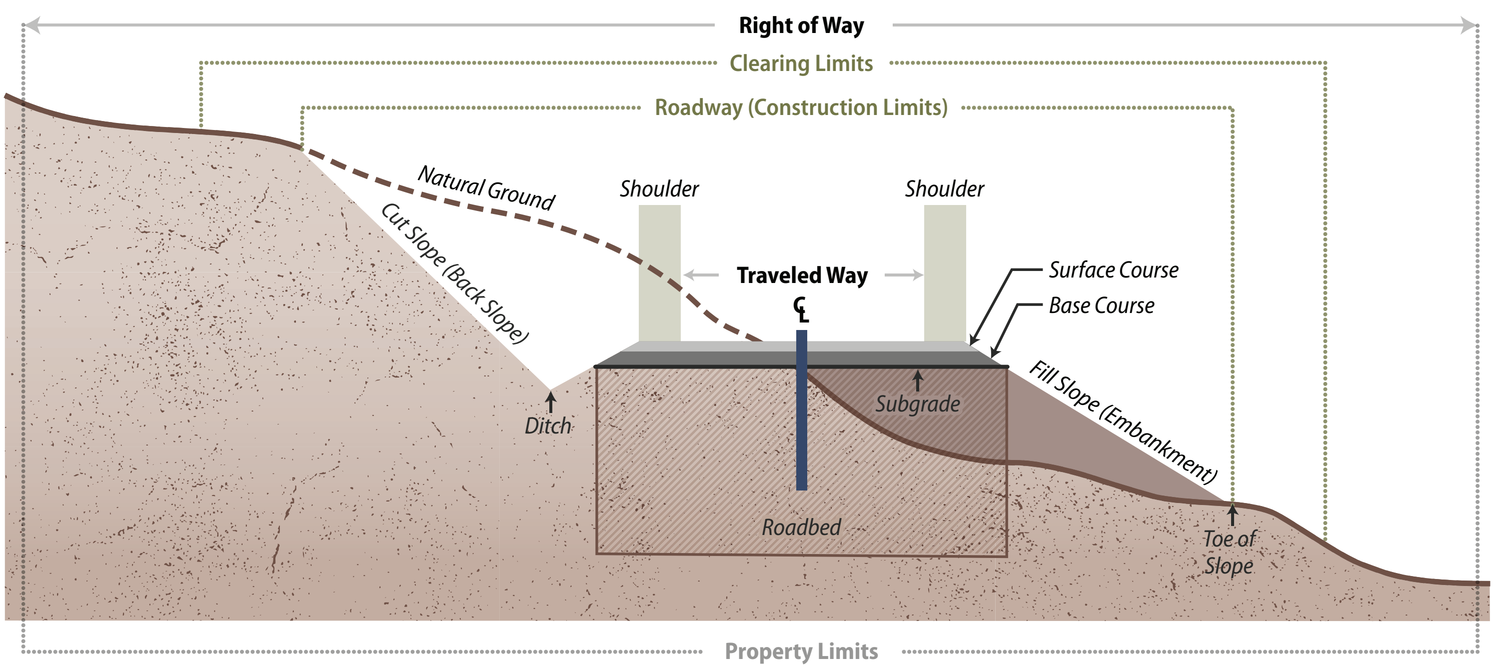
Figure 2-10 | **Terms used to define roads**

- **Roadbed**—Width of the road used by vehicles, including the shoulders, measured at the top of subgrade.
- **Roadway (Construction Limits or Formation Width)**—Total horizontal width of land affected by the construction of the road, from the top of cut slope to the toe of fill or graded area.
- **Side-Cast Fill**—Excavated material pushed on a prepared or unprepared slope next to the excavation to construct the roadbed. The material is usually not compacted.
- **Shoulder**—The paved or unpaved area along the edge of the traveled way of the road. An inside shoulder is adjacent to the cut slope. An outside shoulder is adjacent to an embankment slope.
- **Traveled Way (Carriageway)**—That portion of the road constructed for use by moving vehicles including traffic lanes and turnouts (excluding shoulders).
- **Through Cut**—A road cut through a hill slope or, more commonly, a ridge, in which there is a cut slope on both sides of the road.
- **Through Fill**—Opposite of a through cut, a through fill is a segment of road that is entirely composed of fill material, with fill slopes on both sides of the road.

2.6.2 ROAD STRUCTURAL SECTION AND MATERIALS

- **Borrow Pit (Borrow Site)**—An area where excavation takes place to produce materials for earthwork, such as a fill material for embankments. It is typically a small area used to mine sand, gravel, rock, or soil without further processing.
- **Quarry**—A site where stone, riprap, aggregate, and other construction materials are extracted. The material often has to be excavated with ripping or blasting, and the material typically needs to be processed by crushing or screening to produce the desired gradation of aggregate.

Figure 2-11 | **Terms used to define roads: cross-section**



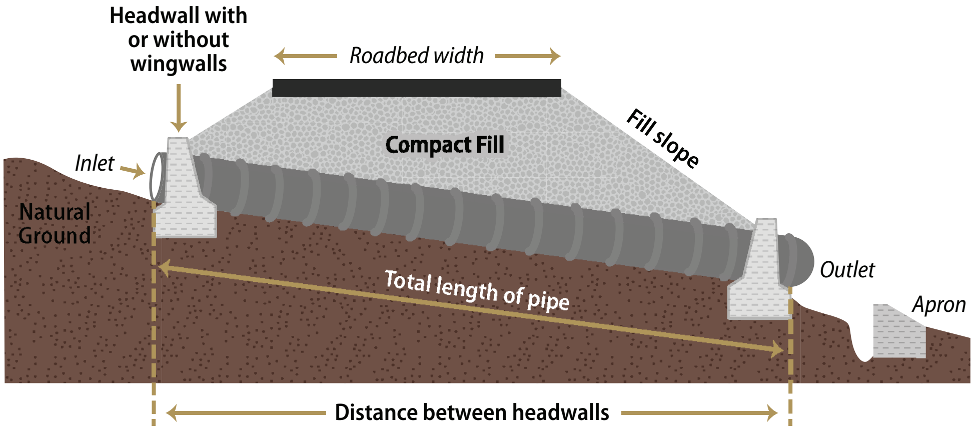
2.6.3 SURFACE DRAINAGE

- **Armor**—Rocks or other material placed on headwalls, on soil, or in ditches to prevent water from eroding and undercutting or scouring the soil.
- **Drainage Structure**—A structure installed to control, divert, or move water off or across a road, including but not limited to culverts, bridges, ditch drains, fords, and rolling dips.
- **French Drain (Underdrain)**—A buried trench, filled with coarse aggregate, and typically placed in the ditch line along the road to drain subsurface water from a wet area and discharge it to a safe and stable location. French drains may use variable sizes of rock but do not have a drain pipe in the bottom of the trench.
- **Inslope**—The inside cross-slope of a road subgrade or surface, typically expressed as a percentage. Inslope is used to facilitate the draining of water from a road surface to an inside ditch. An insloped road has the highest point on the outside edge of the road and slopes downward to the ditch at the toe of the cut slope, along the inside edge of road.
- **Outslope**—The outside cross-slope of a road subgrade or surface, typically expressed as a percentage. Outslope is used to facilitate the draining of water from a road directly off the outside edge of the road. An outsloped road has the highest point on the uphill or inside of the road and slopes down to the outside edge of the road and the fill slope.
- **Riprap**—Well-graded, durable, large rock, ideally with fractured surfaces, sized to resist scour or movement by water and installed to prevent erosion of native soil material.

2.6.4 CULVERTS AND DRAINAGE CROSSINGS

- **Catch Basin**—The excavated precast, or constructed basin at the inlet of a culvert cross-drain pipe for storing water and directing it into the culvert pipe.
- **Culvert**— A drainage pipe, usually made of metal, concrete, or plastic, set beneath the road surface to move water from the inside of the road to the outside of the road, or under the road. Culverts are used to drain ditches, springs, and streams that cross the road. The invert is the floor or the bottom of the structure at its entrance.
- **Headwall**—A concrete, gabion, masonry, or timber wall built around the inlet or outlet of a drainage pipe or structure to increase inlet flow capacity, reduce risk of debris damage, retain the fill material, and minimize scour around the structure.
- **Inlet**—The opening in a drainage structure or pipe where the water first enters the structure.

Figure 2-12 | **Culvert components**



- **Outlet**—The opening in a drainage structure or pipe where the water leaves the structure. The outlet is usually lower than the inlet to ensure that water flows through the structure.

2.6.5 MISCELLANEOUS TERMS

- **Angle of Repose**—The maximum slope or angle at which a granular material, such as loose rock or soil, will stand and remain stable.
- **Gabions**—Baskets (usually made of heavy-gauge wire) filled with rocks or broken pieces of concrete (~10-20 cm in size), used for building erosion control structures, weirs, bank protection, or retaining structures.
- **Road Decommissioning**—Permanently closing a road through techniques that may include blocking the entrance, scattering limbs and brush on the roadbed, replanting vegetation, adding waterbars, removing fills and culverts, or reestablishing natural drainage patterns. The basic road shape, or template, is still in place. The end result is to terminate the function of the road and mitigate the adverse environmental impacts of the road.
- **Road Obliteration**—A form of road closure that refills cut areas, removes fills and drainage structures, restores natural contours, revegetates the area, and ultimately attempts to restore the natural ground shape and condition. Most adverse environmental impacts of the road are eliminated.
- **Silt Fence**—A temporary barrier used to intercept sediment-laden runoff from slopes. It is typically made of porous geotextile material.
- **Streamside Management Zone**—The land, together with the associated vegetation, immediately in contact with the stream and sufficiently close to have a major influence on the total ecological character and function of the stream. It is a buffer area along a stream where activities are limited or prohibited.

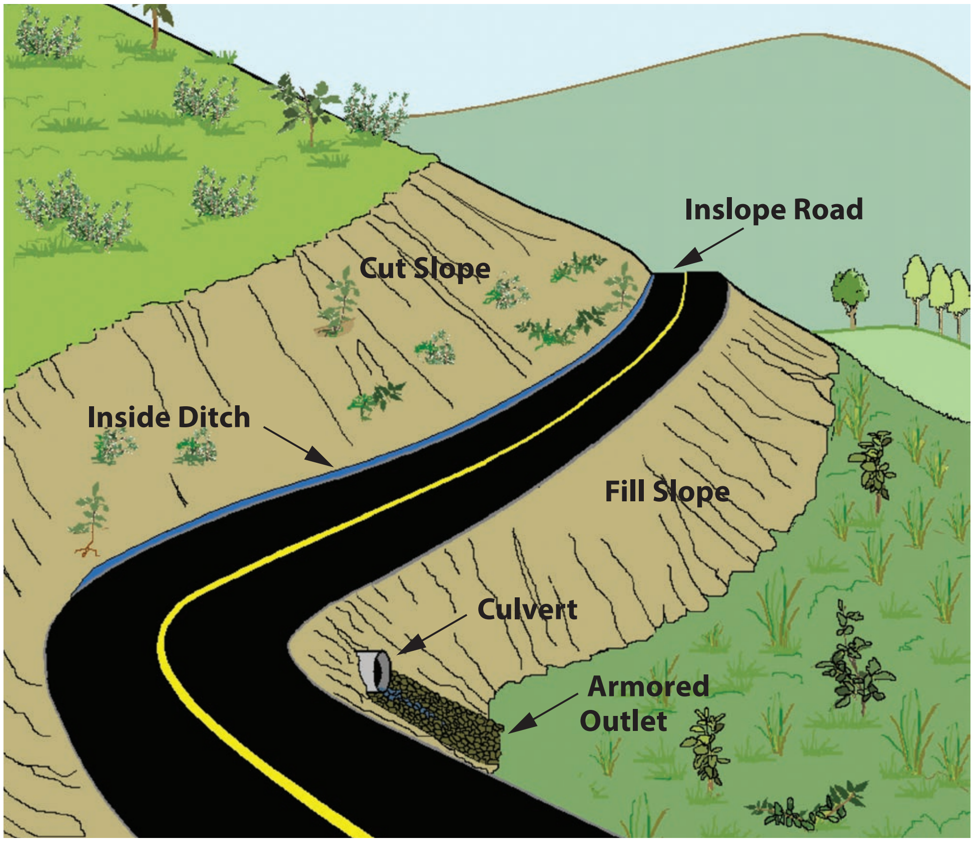


Figure 2-13 | **Terms used to describe road slopes**

3— Planning

3.1 INTRODUCTION

Careful planning is essential to the success of any roadside revegetation project. There are a series of steps that are important to consider in developing a comprehensive revegetation plan. These are shown in Table 3-1 and outlined in this chapter.

Table 3-1 | **Planning Phase Steps**

Activity	Definition
Defining revegetation objectives	Description of the general purpose and goals of the road project as determined by societal, ecological, and transportation needs, environmental regulations, and other factors. Development of revegetation objectives, including pollinator habitat enhancement, erosion control, water quality enhancement, weed control, and carbon sequestration.
Gathering pre-field information	Prior to field surveys, the review of reports and websites that describe soils, vegetation, climate, and pollinators for the project area.
Defining revegetation units	Classification of areas within the project site that are similar enough to be appropriate for similar strategies and treatments. Homogenous sites will have only a few units; sites with greater diversity (different soil types, microclimates, vegetation types, and management needs) will have more revegetation units. Each revegetation unit should be distinct in terms of ecology, management requirements, or both.
Identifying reference sites	Location of natural or revegetated areas that will serve as models for desirable recovery of native plant communities and pollinator habitat. One or more reference sites are identified for each revegetation unit in the project area.
Gathering field information	Survey of reference sites, as well as the road project area, for vegetation, soils, climate, and pollinator habitat that will provide baseline ecological data for developing the revegetation plan.
Defining the desired future condition (DFC) target	Creation of specific, measurable goals for each revegetation unit, usually defined in terms of the percentage of vegetative cover, ground cover, species composition, plant growth, plant density, and pollinator diversity and abundance.
Identifying limiting factors to plant establishment	Review of pre-field and field information to determine which site factors may be limiting for plant growth based on water input, water storage, water loss, nutrient cycling, surface stability and slope stability.
Identifying factors that affect pollinators	Review of pre-field and field information to identify the limiting factors affecting pollinators. These include nectar and pollen sources, breeding habitat, water sources, shelter, landscape connectivity, nesting habitat, and vegetation management.
Inventory of site resources	Assessing physical resources that may be available or generated for use in the revegetation plan. These resources include topsoil, duff, litter, woody materials, logs, and plant materials
Developing a vegetation management strategy	A maintenance strategy is developed to assess how the revegetation project will affect the management and maintenance of the roadside after the road project has been completed and integrate this into the revegetation plan. Ideally, the planning team or designer meets with local maintenance personnel, to learn what problems can be expected in reestablishing roadsides with native plants.
Selecting site improvement treatments	The treatments that will improve the site for plant growth or pollinator enhancement are selected.
Selecting plant species for propagation	Native plant species that will be used on the project are selected based on project objectives and how well they will perform on the site. Genetic diversity and local adaptation is considered in the reproductive sources that will be used to propagate the plant materials.

Activity	Definition
Selecting plant establishment methods	Optimal propagation methods are determined for each plant species. These include the plant materials that will be produced (seeds, cuttings, plants), the method of plant material installation, and when to install the plant materials (seeding and planting windows).
Developing a revegetation plan	A written revegetation plan captures the most important information and decisions that were made on revegetating the project site. It typically outlines project objectives, revegetation units, treatments, plant species, planting methods, roles, responsibilities, timelines, and budget.

3.2 DEFINING REVEGETATION OBJECTIVES

The design objectives of a road project guide the development of the revegetation plan. As discussed in Chapter 2, road objectives usually involve goals of improving safety and efficiency, as well as environmental health. Revegetation objectives develop from road objectives and become the foundation of the revegetation and monitoring plans. It is important to develop a clear set of revegetation objectives early in the planning phase. When these objectives are understood and expectations are clear, the development and implementation of a revegetation plan are easier and more successful. Most roadside revegetation projects share the common objective of initiating and/or accelerating the process of natural succession near the roadside in order to establish self-sustaining native plant communities (Brown and Amacher 1999; Clewell and others 2005). This objective usually reflects larger project goals, stated in terms of increasing pollinator habitat, protecting soil and water resources, carbon sequestration, enhancing roadside aesthetics, limiting invasive plants, and improving road safety and function while protecting environmental health. Later in the planning process, revegetation objectives are used to develop specific goals (stated as DFC targets) for evaluating the success of the revegetation work. Table 3-2 defines some terms commonly used in defining revegetation objectives. Clarifying whether the overall goal is reclamation or restoration, for example, is an essential distinction for defining revegetation objectives.

Table 3-2 | **Terms used in defining revegetation objectives**

Term	Definition
Revegetation	To reestablish vegetation on a disturbed site. This is a general term that may refer to restoration, reclamation, and rehabilitation.
Restoration	This is the re-creation of the structure and function of the plant community identical to that which existed before disturbance. The goal of restoration is conservation, with the intention of maximizing biodiversity and functioning.
Reclamation	This is the re-creation of a site that is designed to be habitable for the same or similar species that existed prior to disturbance. Reclamation differs from restoration in that species diversity is lower and projects do not re-create identical structure and function to that before disturbance. However, a goal of long-term stability with minimum input is implied.
Rehabilitation	This process creates alternative ecosystems that have a different structure and function from the pre-disturbance community, such as a park, pasture, or silvicultural planting.

Adapted from Allen and others 1997

Table 3-3 illustrates some of the most common road-related revegetation objectives as they relate to the road design goals. Most revegetation projects state several objectives to address both short-term and long-term outcomes. For example, short-term, immediate revegetation objectives on most projects include erosion control and water quality protection through mulch and vegetative cover. A long-term revegetation objective would be to establish a native plant community, with a range of plant species that benefit pollinators by increasing foraging, breeding, and nesting habitats. Table 3-4 outlines roadside objectives specific to enhancing pollinator habitat. While short-term objectives might rely on quick-growing ground covers such as grasses and forbs, long-term objectives are often broadened to include such revegetation treatments as planting deep-rooted tree and shrub seedlings to stabilize roadsides, creating visual screens of road infrastructure, and/or supporting sustained native plant community development.

Table 3-3 | **Native plants are used to meet road and revegetation objectives**

Revegetation objective	Function of native plants
Pollinator habitat enhancement	An important revegetation objective is to improve pollinator habitat by selecting a mix of plant species and site improvements that encourage foraging, breeding, nesting, and overwintering of a variety of pollinator species (Table 3-4).
Erosion control	Controlling surface erosion and thereby protecting soil and water quality is a high priority on road construction projects. Native grasses, forbs, and other herbaceous plants can help meet this challenge, particularly when they are accompanied by appropriate mulching treatments. Deep-rooted native trees and shrubs can also enhance stability of cut and fill slopes.
Water retention	Runoff from road surfaces and cut slopes concentrate water into ditches during rainstorm events, increasing the amount of water that normally enters natural drainage ways. Practices that use native plants in the design, such as constructed wetlands and bioretention swales, amended ditches and fills, filter strips, can help retain much of this water on the project site, reducing the amount of sediments and road pollutants from entering stream courses. The additional water increases the productivity of the established plants.
Weed control	Roadsides can be corridors for the transport and establishment of noxious or invasive weed species. Once established, weeds are hard to eradicate and become seed sources for further encroachment. Revegetating with desirable native species minimizes opportunities for problem species to establish.
Carbon sequestration	Roadside revegetation with native plants can help improve air quality and the health of the public and environment by plants taking in and reducing the amount of carbon dioxide in the atmosphere. Plants store the carbon in the soil long-term and release beneficial oxygen. Native roadside vegetation requires less mowing maintenance, herbicides and pesticides, which reduces carbon in the atmosphere and reduces maintenance costs and associated emissions.
Visual enhancement	Vegetation is often used to enhance the aesthetic experience of the traveler. Wildflowers add color and beauty throughout the growing season; deciduous trees provide shade, vertical structure, and change color in fall; and evergreen species stay green all year, adding visual interest, structure, and green color all year. Vegetation can also be used to frame views, soften views or hide structures such as gabion walls or slopes covered by riprap.
Wildlife enhancement	Many roads intercept animal corridors. Designing native plantings into animal underpasses or overpasses can make roads more permeable to wildlife. The presence of birds and small animals can be enhanced when appropriate plant species are reestablished.
Cost management	Advanced planning, an integrated approach, and the use of appropriate stocktypes and equipment all facilitate successful and cost-effective revegetation.

Table 3-4 | **Roadside objectives for enhancing pollinator habitat**

Roadsides planted with native plants also can provide pollinators with shelter, sites for nesting or egg-laying, and overwintering habitat. Pollinators have complex life cycles, with different needs at different stages of their lives. Roadsides can provide resources for a portion of the life cycle of some species, while providing resources needed for the entire life cycle of other species.

<table>
<tr><th>Pollinators</th><th>Food</th><th>Shelter</th><th>Revegetation Goals</th></tr>
<tr><td>Bats (nectar feeding species)</td><td>Nectar, pollen, fruit</td><td>Caves and mines</td><td>▪ Include food plants</td></tr>
<tr><td>Bees: Bumble</td><td>Nectar for adults; nectar and pollen collected as provisions for larvae</td><td>Nest in small cavities, underground in abandoned rodent nests, under clumps of grass, or in hollow trees, bird nests, or walls</td><td rowspan="3">▪ Increase density and diversity of native flowering plants
▪ Provide native bunch grasses for bumble bee nesting habitat
▪ Provide areas with partially vegetated well-drained soil
▪ Provide living and dead pithy and woody vegetation</td></tr>
<tr><td>Bees: Ground-nesting</td><td>Nectar for adults; nectar and pollen collected as provisions for larvae</td><td>Nest in bare or partially vegetated, well-drained soil</td></tr>
<tr><td>Bees: Tunnel-nesting</td><td>Nectar for adults; nectar and pollen collected as provisions for larvae</td><td>Nest in narrow tunnels in dead standing trees, or excavate nests in pith of stems and twigs. Some construct domed nests of mud, plant resins, saps, or gums on the surface of rocks or trees</td></tr>
<tr><td>Beetles</td><td>Pollen and nectar as adults; vegetation or prey such as aphids, slugs, insect eggs, as larvae or adults</td><td>Larvae overwinter in loose soil or leaf litter; Adults shelter under rocks, logs, brush</td><td>▪ Increase density and diversity of native flowering plants
▪ Provide refuge from burning and grazing during dormant season and early spring</td></tr>
<tr><td>Butterflies/moths: Caterpillar</td><td>Leaves of larval host plants</td><td>Host plants</td><td rowspan="2">▪ Increase density and diversity of native flowering plants
▪ Include host plants
▪ Provide refuge from burning and grazing during dormant season and early spring</td></tr>
<tr><td>Butterflies/moths: Adult</td><td>Nectar; some males obtain nutrients, minerals, and salt from rotting fruit, tree sap, animal dung and urine, carrion, clay deposits, and mud puddles</td><td>Protected site such as a tree, bush, tall grass, or a pile of leaves, sticks, or rocks</td></tr>
<tr><td>Flies</td><td>Nectar and sometimes pollen as adults; insect prey such as aphids, scales, mites, thrips</td><td>Larvae found on plants near prey; pupae and adults overwinter in soil or leaf litter</td><td>▪ Increase density and diversity of native flowering plants
▪ Provide refuge from burning and grazing during dormant season and early spring</td></tr>
<tr><td>Hummingbirds</td><td>Nectar, insects, tree sap, spiders, caterpillars, aphids, insect eggs, and willow catkins</td><td>Trees, shrubs, and vines; typically need red, deep-throated flowers, such as twin berry or penstemons</td><td>▪ Increase density and diversity of native flowering plants, particularly species with deep throats</td></tr>
<tr><td>Wasps</td><td>Nectar as adults; insect prey such as caterpillars, aphids, grasshoppers, planthoppers, and true bugs as larvae</td><td>Many nest in the ground; others nest in tunnel nests in wood or cavities in mud or resin</td><td>▪ Increase density and diversity of native flowering plants
▪ Provide areas with partially vegetated well-drained soil
▪ Provide living and dead pithy and woody vegetation</td></tr>
</table>

Revegetation objectives are often developed by the designer and design team and are supported by, or integrated with, public documents such as Environmental Assessments or Environmental Impact Statements. The objectives sometimes originate from a state or federal agency and motivated by environmental concerns and regulations regarding water quality, erosion control, and vegetation establishment. In the early stages of planning, revegetation objectives are broad and general. As the project evolves, objectives are translated into more precise and measurable goals (DFC targets). After the installation is complete, DFC targets and revegetation objectives will be used to monitor, evaluate, and manage the project.

3.3 GATHERING PRE-FIELD INFORMATION

The revegetation plan is developed by obtaining an understanding of the road design and by gathering pre-field information on the soil, climate, vegetation, and pollinators of the project site. Much of this information can be obtained prior to visiting the project site. A good pre-field review of information can make the time in the field more efficient and effective.

3.3.1 CLIMATE PRE-FIELD ASSESSMENT

Local climate plays a dominant role in the success or failure of the revegetation effort. Knowledge of local climate factors, including historic climate data and recent trends, can inform the designer and help delineate the appropriate revegetation units and develop achievable DFC targets. In later phases of the planning process, climate data will be used to determine appropriate revegetation treatments.

Obtaining climate records from a variety of sources is the first step in conducting a climate assessment. There are many sources of climate records for the United States (Figure 3-1). One source is the Western Regional Climate Center website that displays the location of the National Oceanic and Atmospheric Administration (NOAA) Cooperative Stations in the United States and provides historical weather data for most stations. Each weather station has helpful graphics, such as spring and fall "freeze probabilities" (Figure 3-2) that can be used to determine the best dates for sowing seeds and planting seedlings. Another available graphic is the probability of precipitation throughout the year, which can be used to determine if supplemental irrigation is necessary (Figure 3-3).

Figure 3-1 | **NOAA and NRCS weather stations**

The United States has an extensive system of weather stations maintained by National Oceanic and Atmospheric Administration (NOAA) and Natural Resources Conservation Services (NRCS). These maps show the locations of weather stations in the Puget Sound area. Stations administered by NOAA are shown on the left (A) and those by NRCS on the right (B). Historic climate summaries and interpretative graphs for each station can be downloaded from each website.

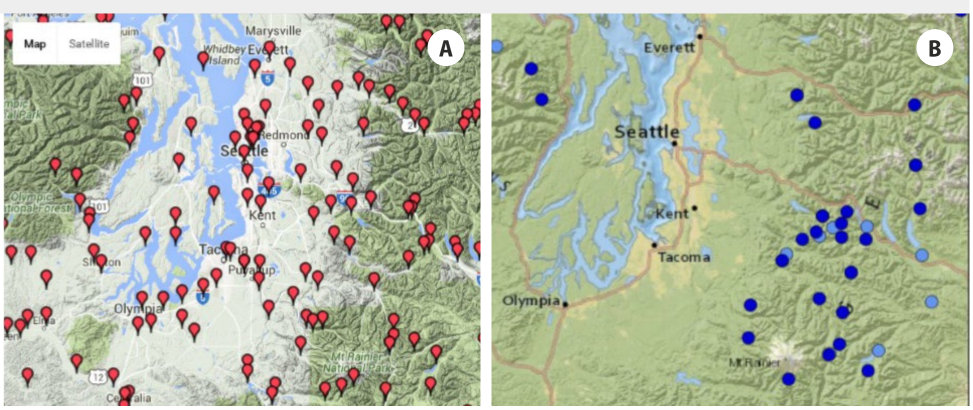
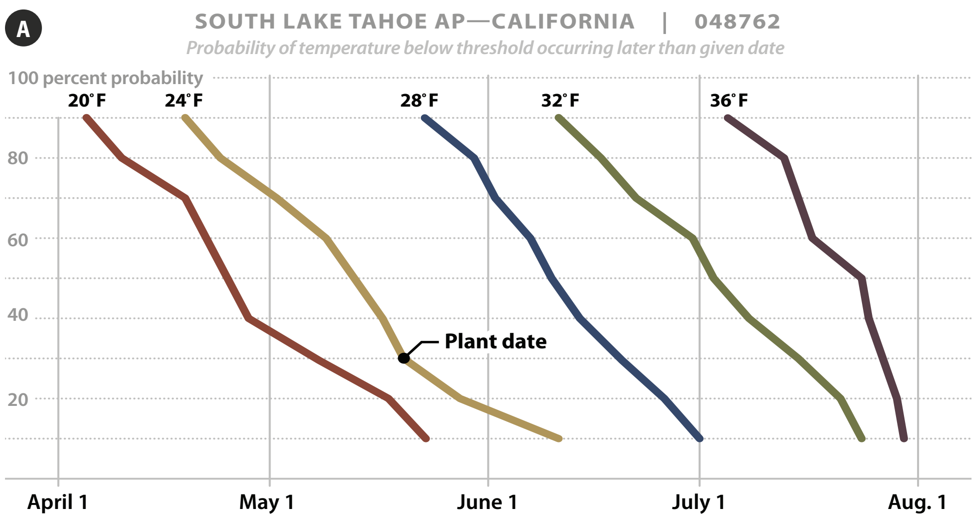
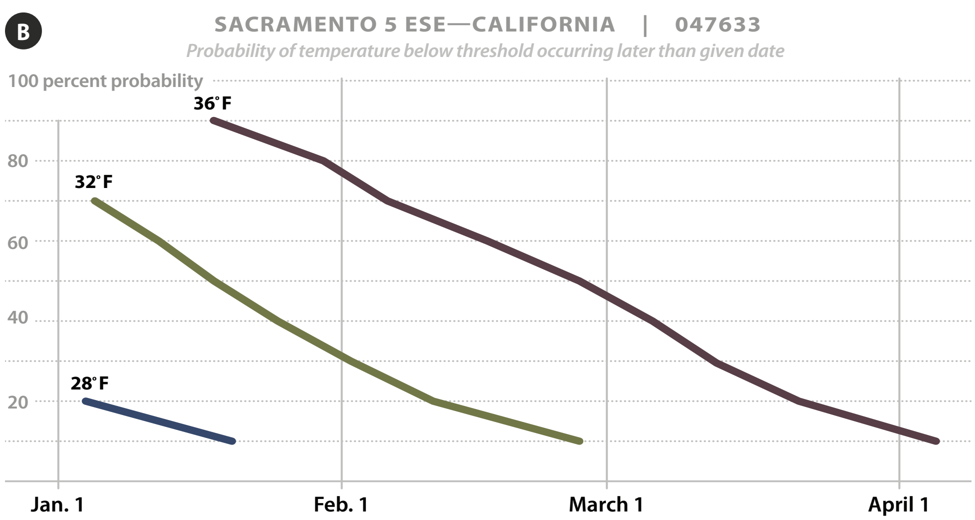


Figure 3-2 | **Spring and fall freeze probability graphs**

In addition to historic weather station data, the Western Regional Climate Center has many useful graphs (located on the left-hand side of the weather station data screen), such as the "Spring and Fall Freeze Probability" curves. The Graph A shows the probability of temperatures dropping to sub-freezing temperatures during the winter through summer in South Lake Tahoe, California. At this site, planting might be planned when there is less than a 30-percent probability that temperatures will drop below 24° F to reduce the risk of seedling damage as the plants are coming out of dormancy. This would put the planting date sometime around the middle of May. In contrast, Sacramento, California, to the west and near sea level has a very different climate as shown in Graph B. According to these curves, it is improbable that temperatures ever reach 24° F in winter and spring; therefore, plants could be installed at any time during the winter.

Source: Western Regional Climate Center



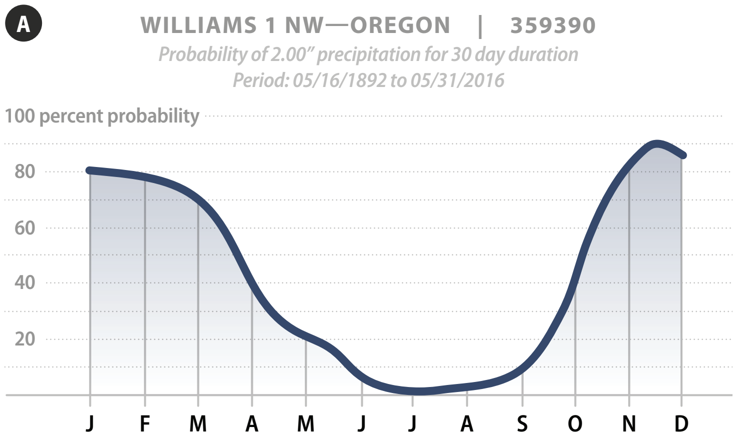


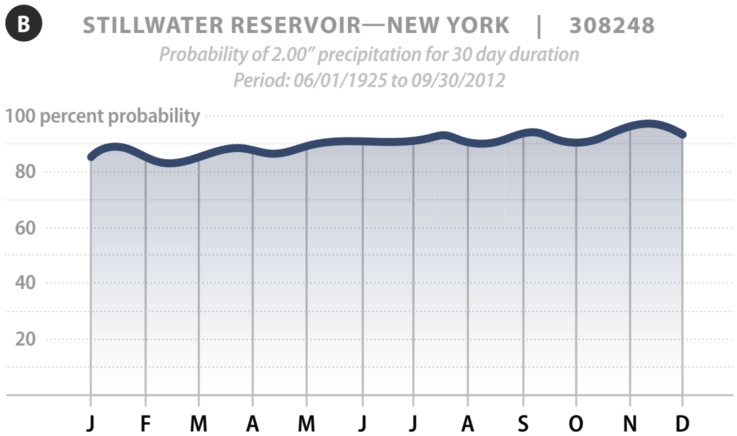
Finding a weather station closest to the project site will be helpful in understanding the influence climate will have on the project. The PRISM website allows the user to locate the project site on a map of the United States, so instead of using data from a single weather station located miles away from the project, this website creates a weather profile specific to the project site. It does this by extrapolating data from surrounding weather stations using a digital elevation model and expert knowledge of complex climatic patterns. This website also

Figure 3-3 | **Rainfall probability graphs**

Another helpful graph from the Western Regional Climate Center displays the probability of receiving precipitation through the year. The probability of receiving 2 inches of rainfall in a 30-day period for a station in southwestern Oregon (A) indicates that it is highly unlikely this will ever happen during the summer, which may lead the practitioner to consider supplemental watering or some other measure to keep plants alive during the first year after the seedlings are planted. In comparison, the probability that 2 inches of precipitation would occur in 30 days in upstate New York (B) any time of the year is more than 90 percent, indicating that irrigation of newly planted seedlings may not be necessary.

Source: Western Regional Climate Center





displays weather trends and anomalies (e.g., extreme heat) that can be helpful in planning (Figure 3-4). NRCS maintains the National Water and Climate website that reports historic and real-time weather data from automatic weather stations located in remote mountainous areas of the western United States. If a project is located near one of these stations, then it is easy to monitor current weather conditions. Historic data and more recent climate trends can be a valuable tool for the designer to consider when developing a revegetation plan. Recent studies of climate trends have noted changes that are affecting pollinators and their habitat and have offered recommendations on how designers can adapt revegetation plans to these changing conditions.

Planning for Climate Change

Climate change effects, including increased frequency of extreme weather events, wildfires, invasive species, drought, increased temperatures, and altered stream flows, can affect native plants and revegetation success on both temporal and spatial scales. Measurable effects of climate change have been observed such as spring events arriving earlier, shifts in species distribution, and disruption of plant-pollinator dynamics. Parmesan and Yohe (2003) showed spring events such as budburst in plants, the arrival of migratory birds and butterflies, bird nesting, and others occurred an average of 2.3 days earlier per decade over 123 years. This same review revealed that the latitudinal and elevational range limits of several alpine plant populations had shifted northward 3.79 miles and upward approximately 20 feet per decade over the past 1,000 years. As a result of these effects of climate change plants, in particular long-lived perennials, are forced to either adapt or migrate (Parmesan 2006).

The migration of plants or changes in plant phenological events have been observed to disrupt or decouple pollinating insect interactions with their host plants. For example, host plants may senesce more quickly than caterpillars develop and other asynchronies between

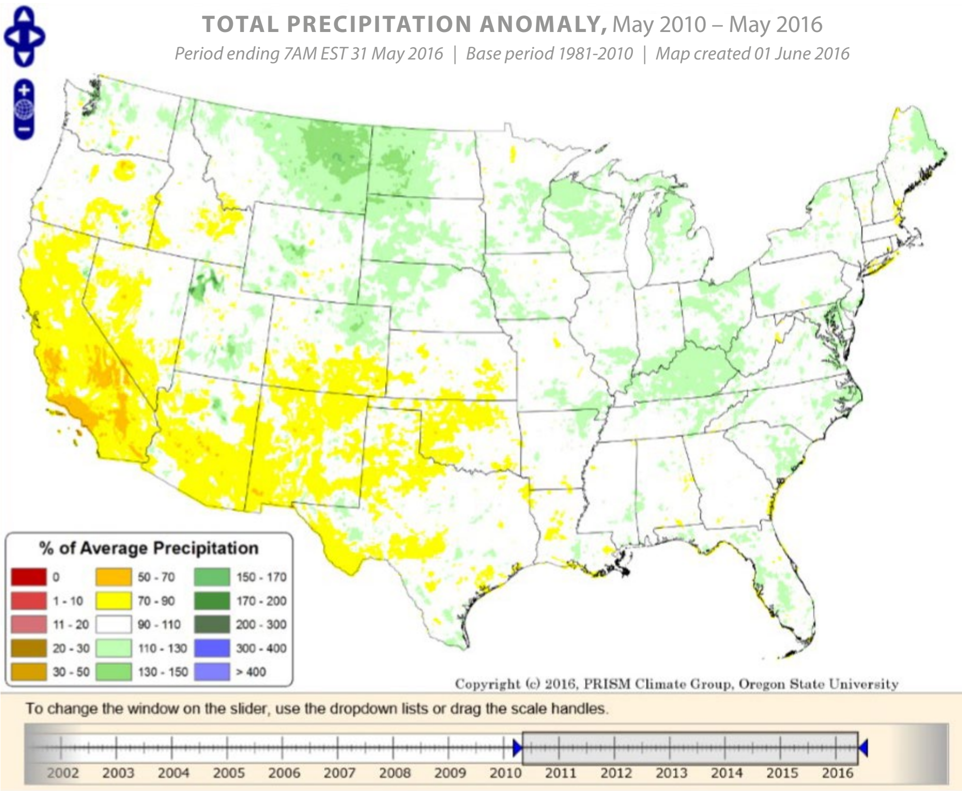


Figure 3-4 | **Precipitation trends**

The PRISM website allows the user to obtain extrapolated weather data for any point in the United States. By identifying the project location on an interactive map of the U.S., a report is generated that summarizes site-specific climate information for that area. In addition, this website displays climate information in a variety of ways that may be helpful in revegetation planning. This map, for instance, shows precipitation trends for the past five years across the U.S., which can be useful during the development of the revegetation plan.

butterflies and their host plants (Parmesan 2007). Some species of pollinators have undergone range contractions due to climate change (Kerr and others 2015). Limitations of dispersal and establishment may mean that many species of pollinators will not be able to keep up with predicted climate change scenarios and that climate change will exacerbate other threats to pollinators, including habitat loss (Settele and others 2016).

Revegetation project designers have an opportunity to address many of these effects of climate change during all phases of their projects. Doing so can increase the overall robustness and health of restorative plant populations, thereby increasing the success of projects. Ways in which designers might address climate change in their revegetation projects include the following.

Diversifying Plant and Seed Sources

Revegetation efforts often occur where previously intact habitats have been disrupted or fragmented. If the area of disturbance is small, such as a localized landslide, the fragmentation might be minimal. It is often the case in roadside revegetation projects however, that the disruption to the original habitat can span miles and remain in place for decades. With these projects the original habitat has often been bisected, the hydrology disrupted, and the area might have experienced multiple disturbances or uses over time. In these instances, it's often valuable to collect plant materials along the entire length of the project area, including reference and adjacent sites, within each provisional seed zone.

Observations of, and collections from, mosaic populations of similar aged plants of the same species often provide opportunities to capture pre-disturbance genetic diversity and mimic natural gene flow patterns. Collecting and sourcing plant material in the direction of climate change conditions (i.e., up the elevation or latitudinal gradient) can potentially incorporate traits needed to compensate for predicted changes due to climate (Breed and others 2013). The Seedlot Selection Tool (SST) is a new mapping application that can assist designers in considering options for obtaining seed and matching seed sources to planting sites based

For the Designer

The development of climate change decision support tools and their application to revegetation practices is rapidly evolving and generally beyond the scope of this manual. Designers should consult geneticists and other experts for the most current guidance and best management practices for their specific project goals and site conditions. Resiliency, diversity, and adaptability will remain important strategies for both short- and long-term revegetation success (Havens and others 2015). Monitoring will also be critically important for informing and adjusting revegetation.

on climatic information. The climates of the planting sites can be chosen to represent current climates, or future climates based on selected climate change scenarios. SST can also be used to identify planting sites that are appropriate for a particular seed source, now and into the future.

Utilizing a Mix of Annual and Perennial Species to Meet Short- and Long-term Goals

There is often a desire to provide quick green up and stabilization to projects with annual plant species. Benefits of annual plants include quick germination and establishment, their seeds can be relatively inexpensive, and they are abundant in the current market. Disadvantages of annual species include the fact that they are short-lived, are often seeded in monocultures, their parental lineage and nativity may be difficult to ascertain, and they can out-compete perennial seeds. Importantly, in the context of climate change, using only annual species does not create a resilient plant community with long term persistence.

At times designers and managers can become frustrated at the slow germination and establishment of perennial seeds. Perennial plants tend to establish deeper, persistent roots and therefore provide longer lasting stabilization than do annual plants however. Native perennials are often seeded in a mixture of grasses and flowering forbs, a practice not impossible with annuals but one that seems underutilized. Due to their outcrossing, one disadvantage of long-lived perennial plants tend to be more susceptible to fitness impacts of inbreeding (Breed et al. 2013).

Developing seed mixes that contain both native annual and perennial seeds, proportional to what is appropriate for the individual project in order to avoid deleterious effects of competition and to mimic the vegetation of the surrounding environs, can exploit the best traits of each while minimizing risks.

Developing Monitoring Plans with Climate Change in Mind

Regular assessments of plant survival and recruitment will assist designers and managers in understanding potential effects of climate change on revegetation success and outcomes. To facilitate adaptive management, detailed records should be kept on plant material sources, the planting scheme (e.g. seeding prescription or seedling numbers and density by species), and site preparation and seeding/planting methods. To make this information available to designers in the future, it must be clearly summarized in the monitoring report (Section 6.6).

Some projects, in particular those that involve wetland construction or enhancement, have monitoring plans ten years into the future or more. Given that plant responses to climate change trend toward upward or northward migration, stratified monitoring may be appropriate for some projects. Designers can stratify monitoring units by elevation band, latitudes, degree days, etc. in an effort to identify any changes in plant communities early. Including adaptive management strategies within the monitoring plan will help identify possible solutions to trends that are learned from monitoring.

3.3.2 SOILS PRE-FIELD ASSESSMENT

More than 95 percent of the counties in the United States have soil surveys either completed or in the process of completion by Natural Resources Conservation Services (NRCS). Information from these surveys is available on the Web Soil Survey website. By delineating the road project area on the Web Soil Survey map, a customized soils report specific to the project area is generated (Figure 3-5). Included in the report are profile descriptions, characteristics, and capabilities for each soil mapping unit. A typical profile description is provided and includes topsoil depth, soil textures, rock content, soil depth, available water holding capacity, permeability rates, and drainage classes. More detailed information on each soil series, such as laboratory results for

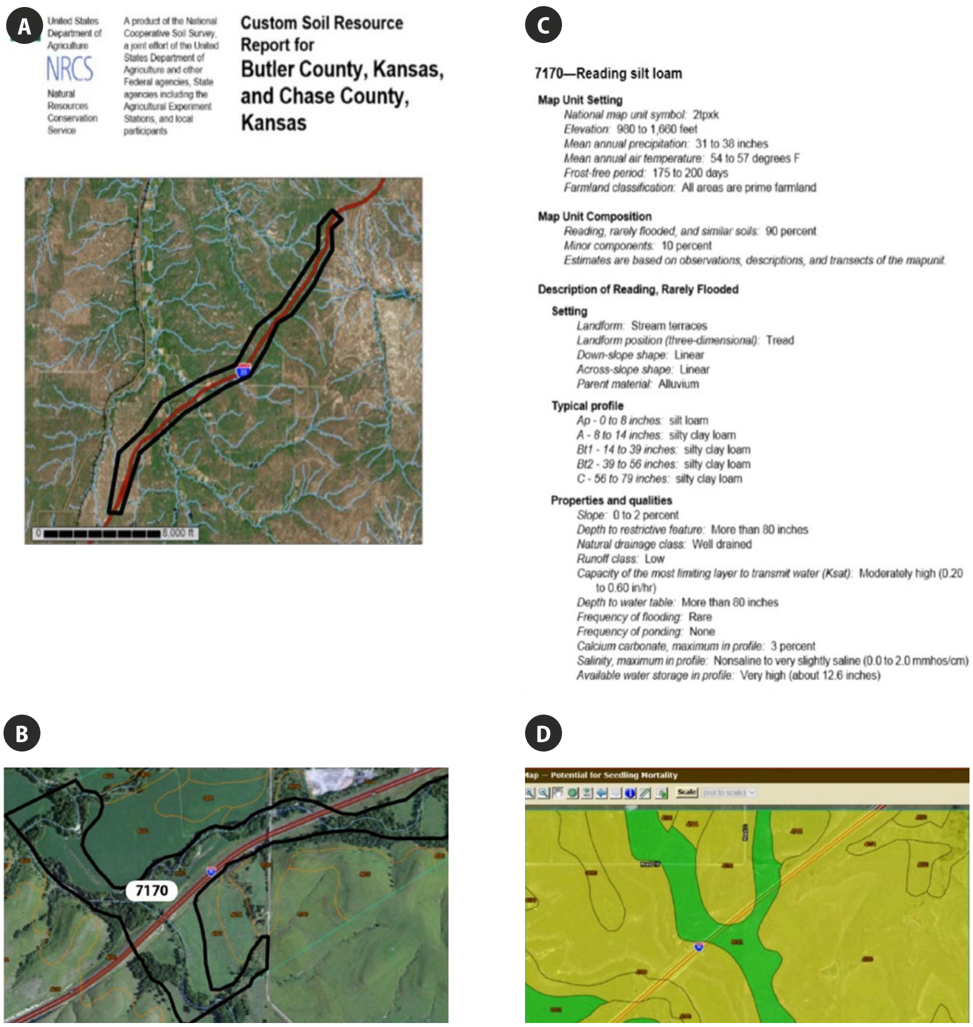


Figure 3-5 | **Soils maps generated from the Web Soil Survey website**

The Web Soil Survey can be used to develop a custom soils report for most highway projects in the U.S. In this example, a 10-mile stretch of road is being proposed for reconstruction through several counties in Kansas. To understand the soils, the study area is delineated on the Web Soil Survey Interactive Map of the U.S. which generates a site-specific soil report (A). Within the report is a map of the project area with the locations of each soil mapping unit. For each mapping unit, the report describes the soil profile and soil characteristics (C). In this example, a prominent soil mapping unit in the planning area is "7170—Reading silt loam" (B). It is a deep stream terrace soil described in the report (C). The Web Soil Survey also allows the user to query the project site for areas of similar land capabilities or limitations. For this project site, one of the maps generated was areas where high seedling mortalities may be expected (D). Grouping of soil mapping units can also be used in the development of revegetation units.

nutrients, water retention curves, and other soil properties, is available at the NRCS National Cooperative Soil Survey Soil Characterization Data website.

The information generated from these reports is for undisturbed soils, therefore the use of this information needs to be adapted to the type of disturbance expected to occur within the project. For example, on a project where topsoil is to be removed, it can be assumed that the soil remaining after construction will be the subsoil and not topsoil. The designer would consider the characteristics of the subsoil (B horizon) described in the Web Soil Survey report rather than the topsoil. If the topsoil is to be salvaged, the Web Soil Survey report can provide a general characterization of the topsoil that will be removed. It can also give a good description of an undisturbed reference site soil which may be helpful if restoration of the original site is the objective.

In addition, the Soil Data Explorer portion of the website creates a series of maps based on soil interpretations. Depending on the county the survey was conducted in, a wide range of maps are available, including suitability for hand planting, potential for seedling mortality, forest and range productivity, soil pH, hydrologic soil groups, depth to restrictive layers, and more.

Most lands administered by the USDA Forest Service have separate soils reports in addition to, or in lieu of, the NRCS soils report. These reports are often referred to as a Soil Resource Inventory report and can be obtained at the Forest Service District Office. The agency also maintains a national inventory and mapping ARC-GIS application that includes a soil database as well as information on geology, potential natural vegetation, and Terrestrial Ecological Units Inventory (TEUI).

Ecoregions and Seed Zones

Ecoregions are defined areas in North America that have similar geographic, vegetative, hydrologic, and climatic characteristics. Several ecoregion systems are available; however, for the purposes of this publication, the ecosystem maps developed by the U.S. Environmental Protection Agency are used. The United States is divided into four ecoregion levels, each level representing increasing degrees of detail:

- **Level I**—12 broad ecoregions
- **Level II**—25 ecoregions
- **Level III**—105 ecoregions
- **Level IV**—967 ecoregions

Because ecoregion maps identify areas with similar environmental characteristics, they are useful in planning, monitoring, information sharing, and management. The Level III ecoregion map has also been used to provide recommendations for seed use and movement of species and geographic areas where empirical genetic information is lacking (Bower and others 2014). Used in conjunction with climate data, such as minimum winter temperature and aridity, Level III ecoregions are a good starting point for guiding source selection of revegetation species. See Chapter 3.13 for a more detailed discussion of seed zones and seed transfer guidelines.

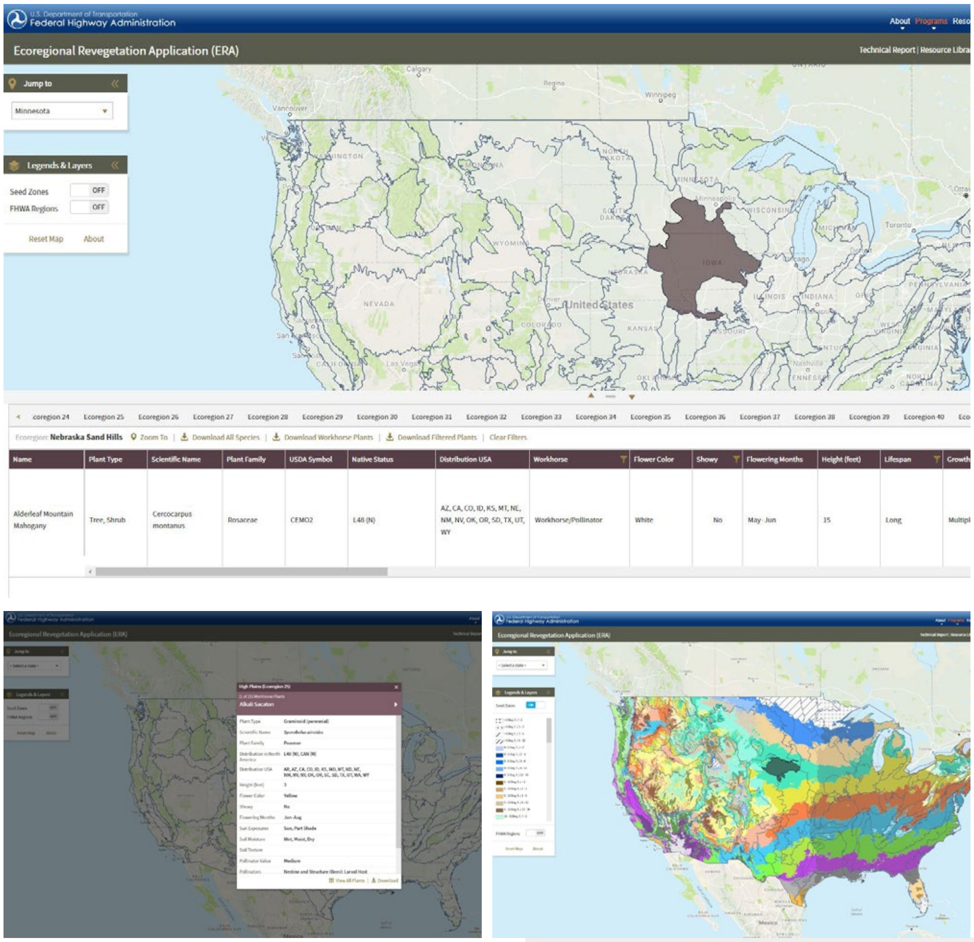


Figure 3-6 | **ERA—An online planning tool to select workhorse and pollinator-friendly species**

The Ecoregional Revegetation Application (ERA) allows the designer to obtain a list of appropriate workhorse and pollinator-friendly plant species for any location in the United States. Each workhorse species will display the plant attributes important for plant establishment and pollinator habitat enhancement.

Ecoregional Revegetation Application (ERA)

A spatially explicit online planning tool called the Ecoregional Revegetation Application (ERA) has been developed by the FHWA that will list the recommended workhorse and pollinator-friendly plant species for all EPA Level III ecoregions in the continental United States (Figure 3-6). The data used to create these lists were vetted by botanical experts and gathered from reliable sources such as the scientific literature, USDA PLANTS database, the USDA Agricultural Research Service pollinating insect unit, and the Xerces Society for Invertebrate Conservation. For each plant species, the ERA will provide attributes such as flowering season and preference for sun that will denote whether a given species is a workhorse (i.e., a reliable and available revegetation plant), or pollinator-friendly (e.g., supports larval or adult pollinators). For pollinator-friendly plant species the selector will denote which general groups of pollinators the plant species will benefit. Moreover, using data generated at the Chicago Botanic Garden (White and others 2016) the ERA will also indicate if a species of interest is commercially available. The first step in revegetation planning, specific to developing pollinator habitat, will be to use ERA to identify potential workhorse plant species for the project area. From this list, other plant species may be selected based on development of a site-specific pollinator working group (Section 3.13.1).

3.3.4 POLLINATORS PRE-FIELD ASSESSMENT

During the early stages of planning, it is important to identify "at-risk" pollinator species that may be affected by the project so that special measures can be taken to protect or enhance populations. A good source for identifying at-risk species is the Xerces Society Red Lists website. This site lists bees, butterflies, and moths that are at-risk by state. It also provides links to recovery plans for species listed under the Federal Endangered Species Act. NatureServe Explorer is a searchable database of plant and animal species in the U.S. that includes conservation status information. Other sources of information for at-risk pollinators are the wildlife and forestry departments of state and federal agencies.

Figure 3-7 | **BAMONA website displays pollinator sightings for locations around the US**

Websites, such as the BAMONA, can display specific locations where pollinators have been sighted. The search for a specific county in Maine, for example, brings up a list of butterfly and moth sightings.

Many good websites are devoted to pollinator species. The BAMONA (Butterflies and Moths of North America) (Figure 3-7) and eButterfly websites are citizen scientist websites that provide access to data about butterflies and moths in North America. Sightings of butterfly and moth species are shown on maps of the U.S. for many species on these websites, including a description of each species. These maps allow the designer to determine if specific pollinator species are near the project area. The crowd-sourcing website, BugGuide, is an online citizen science group that collects images of North American insects and offers an insect identification service for submitted images. Specific to the monarch butterfly is the Monarch Joint Venture website. This is a good resource for monarch butterfly biology, and the site also presents a map that displays current monarch butterfly sightings throughout the U.S.

3.3.5 ROAD PLANS

Understanding the design of the road project and how the site will appear after construction are important in developing a revegetation plan. Prior to a field review, an evaluation of road plans and reports should be conducted. Road plans show road cuts, road fills, drainages, ditches, disposal areas, abandoned roads, and engineered structures, which typically require different revegetation strategies. As discussed in the next section, these road components often become the basis or foundation of the revegetation unit map. Most road plans include a series of cross sections that provide slope steepness and shape, components that directly guide revegetation design. Many road projects include Storm Water Pollution Prevention Plans (SWPPP) that describe how water will be controlled, directed, and treated. These reports address the requirements and expectations for soil cover and revegetation and should be understood prior to developing a revegetation plan. Refer to Section 2.4 for how to read road plans, profiles, cross-sections, and typical views.

3.4 DEFINING REVEGETATION UNITS

Revegetation units are areas with similar revegetation treatments and environment (e.g., soils, climate, and vegetation potential). In mountainous terrain, there may be several revegetation areas in a mile of roadside due to changes in aspect, soil type, and road drainage. Roads in mid-western states, however, often have only one revegetation unit that may encompass much of a project area because of the uniformity of the landscape. The first step in developing a revegetation unit is grouping major soil types together with similar characteristics important for reestablishing native plant communities. For example, a project site with a group of soils that are less than a foot deep would have a different set of revegetation treatments than deeper soils and for that reason would be identified as a revegetation unit based on soil depth. Grouping soils into revegetation units can also be done through the Ecological Sites section of the Web Soil Survey. As described in Figure 3-5, a soils map and report are created on the Web Soil Survey by delineating the project area on the interactive map of the U.S. At the same time, a map can also be produced that groups soils by similar capabilities to create distinct plant communities called "ecological sites". The ecological sites section of the Web Soil Survey also lists the major native species for each ecological site for many parts of the U.S.

Revegetation units also designate areas that have the same revegetation objective. For example, a road project may include a constructed wetland for maintaining or improving water quality. In another area, the objective may be to enhance pollinator habitat. These areas would be designated as separate revegetation units because they would have different revegetation treatments and species, which might include a pollinator species mix for the pollinator habitat unit and an erosion species mix for the wetland unit. In addition, soil improvement treatments for the wetland would be developed to enhance wetland species and maintain the proper functioning of a constructed wetland. This may include creating manufactured soil that is specific to wetland species and water filtration.

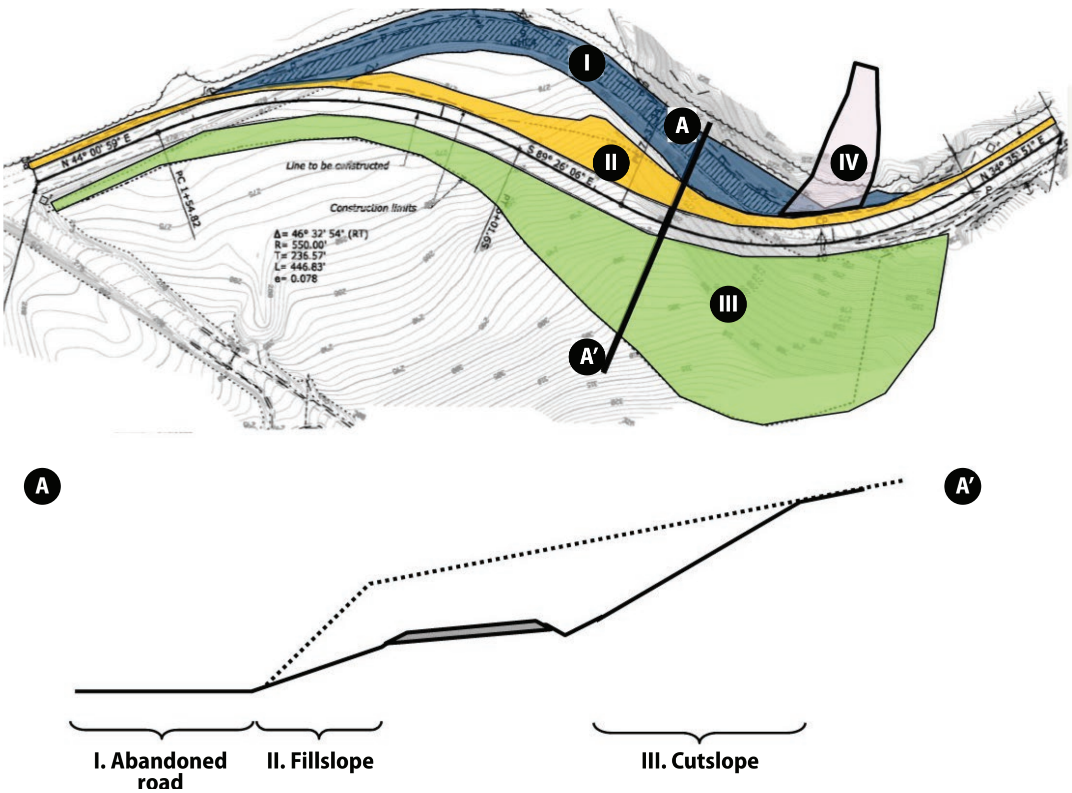
Road components also play a large role in delineating revegetation units. In mountainous terrain, cut slopes and fill slopes are often designated as separate revegetation units because of the differences in soil depth, slope gradient, and road drainage between the two slopes. Table 3-5 shows revegetation units commonly associated with the components of a road.

Table 3-5 | **Common revegetation units often associated with road components**

Road component	Types of revegetation units
Cut slopes	Cutslopes, living snow fence, pollinator habitat
Ditches	Amended ditches, wetlands, biorention swales, bioswales
Shoulders	Shoulders
Fill slopes	Fill slopes, filter strips, amended fill slopes, wave-attennuating bioscreens, living snow fence, pollinator habitat
Culvert outlets	Vegetated culvert outlets
Engineered slopes	Reinforced soil slopes, vegetated MSE walls, bioengineered slopes
Bridges	Stream restoration terraces and slopes
Disposal or staging areas	Restored areas, pollinator habitat
Abandoned roads	Restored obliterated road, pollinator habitat

Figure 3-8 | **Example—cut and fill slopes often define revegetation units**

Major road components such as cut slopes, fill slopes and abandoned road sections often define revegetation units because of similar soils, objectives, and revegetation treatments. The road project in this example has four revegetation units that correspond to cut slopes, fill slopes, abandoned road, and bioretention swale. The objective for the road reconstruction project was to reduce existing curves for traffic safety while increasing pollinator habitat and decreasing the effects of road runoff and soil erosion on water quality. The road plans call for realigning the road, leaving an abandoned section of road, and greater area in cut slopes. During the planning phase, the revegetation units were identified based on soils and road objectives. Revegetation Unit I is the abandoned section of road to be restored by removing pavement, subsoiling the subbase, adding fill, and applying salvaged topsoil. Because the area is a pollinator habitat emphasis area, the seed mix will have more than 50 percent pollinator forb species. Flowering shrubs and trees will be planted in clumps. Salvaged logs from the road clearing operation will be randomly placed upright and on the ground for pollinator nesting habitat. Unit II includes fill slopes that will be amended with shredded wood to increase infiltration rates and capture and filtrate road surface runoff water. A low-growing native grass and forb seed mix will be applied. Unit III includes steep-cut slopes with high erosion potential that will be terraced and a seed mix primarily composed of grasses for erosion control will be applied in a bonded fiber matrix (BFM). Unit IV is a shallow draw where all road ditch water collects. It will be constructed as a bioretention swale to retain and filter sediments and road pollutants from the water before entering the stream. Wetland seedlings will be planted.



Revegetation Unit Descriptions

I. **Abandoned road (pollinator habitat emphasis area)**
Deeper soils covered with 10 inches of salvaged topsoil. Large wood placed upright or down for pollinator nesting. Application of pollinator seed mix. Planting in clumps of flowing shrubs and trees.

II. **Amended fill slopes**
Deeper soils with incorporated wood fiber for road water infiltration. Native grass/forb seed mix.

III. **Cut slopes**
Steep, shallow soils
have a high runoff potential. Erosion control seed mix applied with a Bonded Fiber Matrix.

IV. **Bioretention swale**
Engineered soils and slopes.
Wetland species seed mix or plants.

The revegetation plan includes a revegetation unit map that locates revegetation units on the road project map (Figure 3-8). The revegetation plan further describes the soils, climate, and vegetation of each revegetation unit and how the revegetation objectives will be met.

3.5 IDENTIFYING REFERENCE SITES

Reference sites provide a natural model for possible vegetation outcomes and are important for defining DFC targets, as well as evaluating and monitoring the project following implementation (SER 2004). They can also be used to document the types and amounts of pollinator species that may be present in putatively natural environments near the project area.

Each revegetation unit should have at least one corresponding reference site that models the expected outcome or DFC target of the unit. Ideally the reference site shows how a revegetation unit might recover from disturbances at different points in time after road construction. Reference sites can be considered a snapshot, or series of snapshots, of possible future outcomes. They demonstrate a point in time along a desirable developmental trajectory for a plant community. Using reference sites to understand the possible vegetative outcomes after disturbances will help the designer develop realistic expectations and provide a guide to the development of appropriate revegetation strategies for each revegetation unit. The most important aspect of reference sites is that they provide examples of plant communities from which designers can chose individual species for use in the revegetation project. The designer may sometimes choose to obtain baseline ecological data from several reference sites and then assemble DFC targets (SER 2004).

The two types of reference sites are disturbed and undisturbed. Disturbed reference sites are areas, typically old road cuts and road fills that have recovered, whereas undisturbed reference sites are relatively pristine sites that lack major disturbances in the recent past. For most road projects, disturbed reference sites are the most helpful because they represent sites that are ecologically similar to the revegetation unit and have recovered from disturbances similar to those planned. Undisturbed reference sites may also be used when ecological restoration is an objective or when suitable disturbed reference sites are not available.

Disturbed reference sites can be categorized several ways:

- Type of disturbance
- Length of time after the disturbance
- Desirability of the recovered vegetation

Disturbed reference sites can be old road cuts and fills, abandoned roads, ground-based logging sites, waste areas, rock source sites, ski runs, or other areas that have recovered from major soil disturbances. Disturbed reference sites often show a range of possible vegetative outcomes years after disturbance. Some sites will show good recovery and include stable soil, be visually pleasing, and populated by functioning communities of native plants. Others might show what can go wrong if revegetation is not carried out properly, including erosion, poor ground cover, weed infestation, and a lack of native vegetation. Understanding the conditions that lead to these vegetative outcomes can be a guide to avoiding them in the future.

Disturbed reference sites are the best models to demonstrate what is possible on the site in terms of vegetation, what trajectories succession might take (with or possibly without human intervention), and ways to effectively intervene in order to facilitate desired outcomes. Disturbed reference sites are invaluable in developing realistic DFC targets. Ideally, the type of disturbance on a disturbed site should match the type of road construction disturbance that will occur on the revegetation unit. For example, if the road cut after construction will be denuded of topsoil, then a disturbed reference site should be found that lacks topsoil.

The stage of recovery is also important. It is ideal to find several disturbed reference sites that represent different successional stages of site recovery (Figure 3-9). For instance, a revegetation unit would ideally be represented by a recently disturbed site (several years after disturbance), a recently recovered site (5 to 25 years after disturbance), and a fully recovered site (over 25 years since disturbance).

While there is no such thing as a “pristine” plant community, an “undisturbed” reference site is an area that has not been heavily affected by ground-disturbing activities. Undisturbed reference sites indicate the highest potential of a revegetation unit and are most often used as models when the goal is ecological restoration (re-creation of a plant community identical to that which existed before disturbance). The description of soil, climate, and vegetation in an undisturbed reference area often become the framework for the DFC target. It provides the designer with an understanding of those site characteristics or components necessary for healthy ecological functioning.

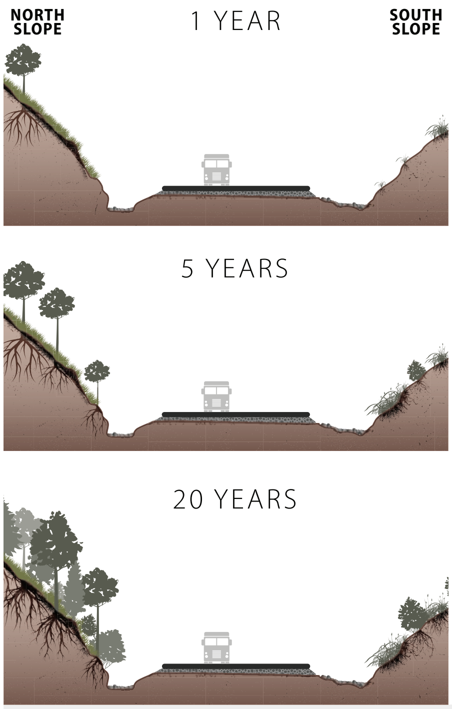


Figure 3-9 | **Successional processes vary by microsite**

Successional processes and plant communities vary considerably based on microsite conditions. In this example, plant communities developed differently on north-facing and south-facing slopes.

The process of selecting and describing reference sites is best accomplished in an interdisciplinary manner. The discussions that are generated between soils and vegetation specialists are generally far more thorough in knowledge and understanding of recovery processes than if surveys were conducted separately. Disturbed reference sites can be located by driving the roads in and around the project area and finding areas that appear similar to the type of road construction being planned for a revegetation unit. Revegetated road cuts of various ages are good reference sites for cut slope revegetation units.

3.6 GATHERING FIELD INFORMATION

Surveying reference sites, as well as the project area in general, for soils, climate, and vegetation will provide baseline ecological data for developing the revegetation plan. If creating pollinator habitat is a revegetation objective, then reference sites and the project area are also surveyed to assess pollinator habitat quality and pollinator populations. This survey will provide insight into which pollinator species might be supported or enhanced by the revegetation project. The goal of the field survey is to obtain sufficient information from reference sites to realistically define DFC targets. During an initial survey, the appropriate survey intensity can be determined based on information needs and knowledge gaps. For example, if one of the revegetation objectives is to restore an abandoned road to a DFC target similar to a neighboring forest, then a survey of vegetation and soils of an undisturbed and disturbed neighboring forest would be conducted to describe the site characteristics and species composition.

The data used to define revegetation units (Section 3.3) should be reviewed prior to the field surveying of reference sites. Information regarding land ownership, site history, resources, and past and current management is also valuable. Specialists who might have knowledge of the soils, vegetation, climate, and hydrology, as well as locals who can provide information on the site's history, should be contacted.

3.6.1 VEGETATION FIELD ASSESSMENT

The objective of assessing the vegetation of a reference site is to create a comprehensive species list that will guide in the selection of species to be used for revegetating the project area. A good method for compiling a comprehensive species list is to choose a representative cross section of each reference site that will characterize the range of plant species for that unit. Intuitively controlled surveys, such as these, maximize floristic knowledge yet are less time and effort intensive than complete floristic inventories. Usually, a few plant species are not easily identified in the field. Samples of these species can be brought back to the office for identification by specialists. If more detailed data collection is desired, such as a complete floristic inventory, surveys along transects or grids may be conducted.

Once species are identified, a comprehensive species list is developed for the project (Table 3-6). This list will be used throughout the life of the project for selecting species for plant propagation, weed control, and plant protection. It includes some or all of the following attributes:

- **Species name (common and scientific)**—Because common names for plant species change throughout the country, it is important to list both the scientific and common names of each species. The USDA PLANTS database is a good source for obtaining the current scientific and common names. The database also includes the short species code symbol for field documentation.
- **Revegetation unit**—Identify the revegetation units where the species occurred.
- **Ecological settings**—Plants are identified by the ecological setting they are most commonly found in. A relative rating by temperature (cold, cool, warm, hot) and moisture (dry, moist, wet) gives a quick profile of the ecological setting. Some portions of the U.S. are covered by plant association maps or reports that were developed by

federal agencies and are good sources for identifying the ecological setting of a species. Another way to describe the ecological setting of a species is by using the Ecological Site Assessment section of the Web Soil website (Section 3.3.2). This part of the website groups soil mapping units into ecological site units and dominant plant species.

- **Amplitude**—Ecological amplitude is the recurrence of a species across a wide array of ecological settings. A species found in all ecological settings would have a high ecological amplitude, while a species found in only one ecological setting would have a low ecological amplitude.
- **Abundance**—The quantity, dominance, or cover of a species found in a revegetation unit is the abundance.
- **Life form**—Group each species by life form: (1) tree, (2) shrub, (3) annual grass, (4) perennial grass, (5) annual forb, (6) perennial forb, or (7) wetland species (e.g., sedges, rushes)
- **Nativity**—Identify whether the species is native to the local area or introduced. The USDA PLANTS database identifies the nativity of all plant species in the U.S.
- **Weed status**—The USDA PLANTS database identifies the noxious weeds for each state. State-listed noxious weeds are found under the heading "Introduced, Invasive, and Noxious Plants" under the "PLANTS Topics" sidebar. Contacting the local State agency in charge of maintaining the lists, usually state departments of agriculture, is recommended.
- **Threatened and endangered species**—State and federal protected plants are found in the USDA PLANTS database under the heading "Threatened & Endangered" on the "PLANTS Topics" sidebar.
- **Succession**—Determine the seral stage a species is most commonly associated with: (1) early, (2) mid, (3) late, or (4) climax. Visiting reference sites and adjacent areas at different ages of recovery following disturbance will help provide an understanding of where each species fits into ecological succession. Figure 3-9 illustrates how plant communities develop differently over time depending on site conditions and successional processes.
- **Pollinator friendly**—Reference the ERA to determine if a species is beneficial to pollinators. Use the ERA lists of pollinators associated with each plant species to build a highly diverse pollinator community; flower color is also helpful in this regard—the more the merrier. Flowering periods for plant species can be obtained from the ERA. Use these to maximize the seasons flowers are available to pollinators; a good minimum rule is three to five different species each of early, mid, and late bloomers. In addition to the ERA, other sources of reliable information such as species distribution maps by county from the USDA PLANTS website, or the I-35 Corridor plants list can give more detailed guidance to selection of appropriate species.

Table 3-6 | **A comprehensive species list**

Upon completion of a vegetation survey of the reference sites, a comprehensive species list is developed for the project. The spreadsheet will be used to determine the plant species mix that will be used in each revegetation unit.

Scientific name	Common name	Revegtation unit	Amplitude	Abundance	Life form	Nativity	Weed status	Threatened & endangered	Succession	Ecological setting	Pollinator friendly
Achillea millefolium	**Common yarrow**	2,3	High	High	Perennial Forb	Native	–	–	Early	All	Yes
Abies grandis	**Grand fir**	1	High	High	Tree	Native	–	–	Late	All	No
Abies lasiocarpa	**Subalpine fir**	1	High	Mod	Tree	Native	–	–	Late	Cool	No
Agastache urticifolia	**Horsemint**	2,3	High	High	Perennial Forb	Native	–	–	Early	All	Yes
Agoseris aurantiaca	**Orange agoseris**	2,3	High	Mod	Perennial Forb	Native	–	–	Early	All	Yes
Agoseris glauca	**Pale agoseris**	2,3	High	Mod	Perennial Forb	Native	–	–	Early	All	Yes
Agoseris grandiflora	**Bigflower agoseris**	2,3	High	Mod	Perennial Forb	Native	–	–	Early	All	Yes
Allium acuminatum	**Tapertip onion**	4	Low	Low	Perennial Forb	Early	–	–	Early	Wet	?
Allium fibriatum	**Fringed onion**	4	Low	Low	Perennial Forb	Native	–	–	Early	Warm/Dry	?
Allium macrum	**Rock onion**	4	Low	Low	Perennial Forb	Native	–	–	Early	Wet	?
Allium madidum	**Swamp onion**	4	Low	Mod	Perennial Forb	Native	–	–	Early	Wet	?

3.6.2 SOILS FIELD ASSESSMENT

Understanding the soil characteristics of each reference site is essential to effectively define DFC targets and develop revegetation treatments. The soils report that is generated from the Web Soil Survey website for a road project gives a close approximation of the characteristics of undisturbed soils for the project area and should be checked in the field. It is important to remember that the soil condition after road construction will not resemble the natural soils found in the soil survey. For this reason, it is important to find disturbed reference sites that are similar to the disturbance of the revegetation unit. The following information can be collected for topsoil and subsoil:

- Soil texture
- Rock fragments
- Rooting depth
- Topsoil depth
- Nutrient levels
- Soil structure
- Litter and duff layers (Section 5.2.3, see Litter and Duff)
- Site organic matter
- Infiltration rates

3.6.3 POLLINATOR FIELD ASSESSMENT

Habitat Assessment

During the field review, an assessment of the pollinator habitat and pollinator species populations may be conducted for the project area. The pollinator habitat assessment includes evaluating the road project plans within the context of the larger planning area for creating habitat supportive for general and at-risk pollinator species. Table 3-7 is a checklist that can be used to identify those factors important for creating pollinator-friendly habitat. Factors that improve pollinator health or habitat can be considered in design plans while factors that limit pollinator health can be mitigated or improved through management treatments or practices, presented in Section 3.9.

One approach to using this checklist is for the designer to visit the project site during planning and evaluate both the current condition of the roadsides and the undisturbed reference sites (Section 3.5). Ideally these assessments can be conducted during the same visits as the vegetation assessment (Section 3.6.1) and the soil assessment (Section 3.6.2). Evaluating the quality of pollinator habitat of the existing roadsides will give some indication of what the designer can expect if standard construction practices are employed. Comparing these findings to those of undisturbed reference sites gives the designer an idea of what is possible. Comparisons of the current condition and the reference site can help the designer develop a revegetation plan for improving pollinator habitat.

The Pollinator Habitat Assessment checklist provides eight characteristics important for most pollinator habitats. The designer may want to modify the checklist based on project objectives, pollinators of interest, and the unique ecology of the roadside. Another valuable use of the checklist is that it can be used to develop target DFCs for the revegetation project (Section 3.7). For example, a DFC target from this list may state that "at least three native species will be in bloom during spring, summer, and fall". Field visits during the growing season would be conducted after revegetation to determine if this target was met.

Pollinator Monitoring

Revegetation projects, especially those specific to improving pollinator habitat, may require a pre- and post-construction assessment of pollinator species. As discussed earlier, it may be helpful to know which pollinators are present prior to project design. If imperiled pollinator species are suspected in the project area, it is important to survey for pollinators before undertaking construction. See Section 3.3.4 for resources for determining imperiled pollinators in the project area and check with the state Natural Heritage Program and land managing agency, as applicable, for a list of species of conservation concern.

Table 3-7 | **Pollinator habitat assessment checklist**

This guide can be used to assess the pollinator habitat conditions at any time during the life span of a road project. The checklist gives eight characteristics important for most pollinator habitats, however, the designer may want to modify the checklist so that it addresses the climate, soils, vegetation, and pollinator species of interest specific to the project area and project objectives. It is important when using the checklist to identify the purpose of the assessment, such as whether it is describing a reference site, pre-disturbance or post-revegetation conditions.

Components of pollinator habitat	Steps to improve pollinator habitat conditions
Nectar/Pollen sources	▪ At least three blooming species in each season (spring, summer, fall) ▪ Species have overlapping and sequential bloom periods ▪ Presence of both wildflowers and woody blooming plants ▪ Aim for 45 percent plant cover of blooming plants available across seasons
Breeding habitat	▪ Host plants present for target butterfly and moth species ▪ Presence of vegetation, leaf litter that can serve as egg-laying sites for other species. At least three blooming species in each season (spring, summer, fall)
Nesting habitat	▪ Patches of bare ground present at site ▪ At least three species of woody plants or pithy stemmed plants that support tunnel-nesting bees ▪ Snags or downed wood present in safe location for traveling public ▪ Unmown bunch grasses present throughout growing season to support bumble bee nests
Water source	▪ Water sources such as culvert outlets, ditches, draws, gullies, intermittent streams, and topographic enhancements
Shelter and overwintering	▪ Trees and/or shrubs present at the site ▪ Diversity of grasses to provide vegetation structure
Vegetation management	▪ Mowing and herbicide use is timed to reduce impact to pollinator life cycles ▪ Mowing and herbicide use is timed to support plant diversity ▪ Herbicide use in roadside beyond the safety strip is targeted to noxious and nonnative plants and other undesirable species rather than using broadcast applications ▪ Weeds are controlled before and during construction to aid in plant establishment, as well as during the establishment phase ▪ If haying (mowing and removal of biomass) by adjacent landowners is permitted on the roadside, it is conducted once at the end of the growing season ▪ Prescribed fire and prescribed grazing are timed carefully to avoid damage to life cycles of imperiled or sensitive species of pollinators ▪ Brush removal is tapered to soften transition to denser vegetation at edge of ROW, opening up the canopy to allow understory plants to bloom and leaving some stems or other sites for tunnel-nesting bees ▪ Biological and cultural control methods are integrated into vegetation management to reduce use of herbicides to control noxious and invasive weeds
Landscape connectivity	▪ Site increases landscape connectivity by linking existing habitat parcels on nearby land ▪ Site increases roadside connectivity by linking roadside habitat ▪ Site increases diversity within the landscape and benefits agricultural activity on adjacent lands
Road mortality	▪ Site is not isolated within areas of high road density in which there are multiple barriers to pollinator movement ▪ Sites have reduced mowing and high plant diversity ▪ Clear zone width is increased within AASHTO guidelines along roadsides with high salt use and high volumes of traffic (reduces exposure of pollinators to salts, heavy metals)

It can also be helpful to monitor pollinators before construction and following revegetation in order to assess the success of the project or to perform comparisons of the effectiveness of seed mixes or revegetation techniques for different pollinators. Monitoring techniques for these assessments are discussed in Section 6.4.

3.7 DEFINING THE DESIRED FUTURE CONDITION

Once revegetation units and corresponding reference sites have been described, the DFC targets can be defined for each unit. The DFC target is the translation of the revegetation objectives into measurable goals for each revegetation unit. Specifically, the DFC target defines the desired or expected composition of vegetation at a particular point in time after the completion of the revegetation work.

An example DFC target would be, "one year after seeding, vegetative ground cover will be 40 percent and of this cover, 50 percent will be composed of native forb species beneficial to pollinators." Stating expectations in this manner will (1) clarify how the site will appear after treatments, (2) narrow down the appropriate revegetation treatments to meet the DFC target, and (3) define measurable criteria, or thresholds, for monitoring the success of a project.

Commonly stated DFC criteria include the following:

- Vegetative ground cover
- Bare soil cover
- Native grass cover
- Number of species of native grasses
- Native forb cover
- Number of species of native forb species
- Seedling survival
- Seedling density (plants per area)
- Tree growth (height per year)
- Coarse pollinator diversity
- Pollinator abundance

Stating the DFC in measurable terms and with a time frame ensures that the project team, regulatory agencies, and the public have similar expectations of how the project will appear in the years following its completion. Quantifying the objectives also focuses the monitoring plan to collect only the information necessary to determine if project objectives were met. For example, if one of the objectives is erosion control, a DFC target might be, "the amount of bare soil one year after road construction will be less than 20 percent." Monitoring procedures would focus on measuring bare soil after one year. If another objective is to increase pollinator species, then a measurable threshold for success might be, "an increase of 50 percent pollinator abundance over reference site populations three years after seeding." Monitoring, in this case, would measure general pollinator types in reference sites and revegetation unit three years after completion of the project.

Another benefit in defining DFC targets is that it often will generate a discussion of whether they are achievable without investing in soil improvement or additional plant establishment methods. Unless DFC targets are stated and discussed, individual team members will develop their own concept of what success looks like. For example, a road project was being proposed next to a river with high fisheries values. The Storm Water Pollution Prevention Plan that had been prepared for the project stated that the cut slopes would have 100 percent ground cover, which would result in very low sediment delivery to the stream after construction. Team members discussed this DFC target and concluded that it was unachievable because of the lack of topsoil and shallow soils. This left the team the choice of either modifying the DFC target or improving the soil quality.

When developing DFC targets, it is important to consider the plant community succession that is likely to occur on each revegetation unit. In some cases, planting early seral species at the outset may work. By year 3, when the early seral species begin to decline, the late seral species may be increasing. In other cases, it may be necessary to intervene immediately after seeding or planting in order to meet the revegetation objectives of the project. For example, short-term revegetation planning might call for seeding grasses and forbs to stabilize the site. One year later, the site might be revisited to remove any invasive species before they produce seeds. Two years later, the site might be revisited to interplant conifers and shrubs. These three intervention points (seeding, weeding, and planting trees) speed succession in the desired direction.

3.8 IDENTIFYING LIMITING FACTORS TO PLANT ESTABLISHMENT

Site conditions that affect plant establishment and growth are referred to as limiting factors (Figure 3-10). Odum (1971) defines limiting factors as “any condition which approaches or exceeds the limits and tolerance (of a plant species).” He further states that “the chief value of the concept of limiting factors lies in the fact that it gives the ecologist an ‘entering wedge’ into the study of complex situations. Environmental relations of organisms are apt to be complex, so that it is fortunate that not all possible factors are of equal importance in a given situation or for a given organism.” Not only does this simplify a complex analysis, it requires the designer to systematically consider all site factors, focusing on those of greatest concern. For example, typical revegetation treatments conventionally call for the blanket use of fertilizers without assessing if nutrients are really limiting to plant growth. In many cases, other limiting factors to revegetation, such as low rainfall, compacted soils, low organic matter, and poor rooting depth, are more limiting. Applying fertilizer without an assessment of limiting factors, is like a physician prescribing medicine before the patient has been properly diagnosed. While soil fertility is often important on many highly-disturbed sites, it might not be the primary limiting factor to revegetation on this particular site.

This manual has grouped the site characteristics essential for plant growth into six limiting factors to revegetation typically encountered in the United States. These factors are further broken down into component parts, or parameters (Figure 3-11). In this section, each limiting factor to revegetation and corresponding parameters are discussed in terms of why they are important to plant establishment and growth, how they are assessed, and what mitigating measures or treatments can be applied to make them less limiting.

The information used in defining limiting factors for each revegetation unit can be obtained from the surveys and reports conducted during the field surveys. It is important that an assessment of every limiting factor and corresponding parameter be made for each revegetation unit based on the expected condition of the site after road construction. Figure 3-11 can be used as a checklist—a means of quickly assessing a site for its potential to grow plants while preventing the possibility of overlooking factors important for successful revegetation. Much like pilots or surgeons use checklists, the designer can use the limiting factors list to simplify a “complex situation” and quickly identify what is important from what is not.

From the limiting factors identified for a project, a list of mitigating measures is developed. Mitigating measures are the site treatments that will reduce or eliminate the site conditions limiting to revegetation. For example, if rainfall is limiting, a mitigating measure is to irrigate. There are usually several ways to mitigate each limiting factor. While some of the mitigating measures might seem impractical for a particular revegetation project, they are at least considered.

For the designer
Defining the limiting factors is an essential process in developing a revegetation plan because it identifies, from a multitude of site factors, only those that are roadblocks to successful revegetation. A Limiting Factor table is available in this Planning workbook.

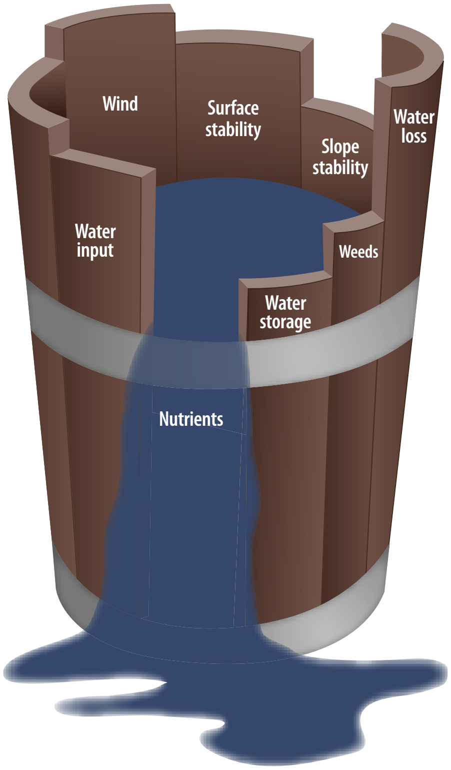


Figure 3-10 | **Limiting factors to revegetation**

Limiting factors to revegetation can be displayed as unequal boards of a barrel. Water can only be held to the level of most limiting factor.

How to approach this chapter—This chapter is organized by limiting factors. It is not important to read the whole chapter, but it can be helpful to read portions, especially those that pertain to the limiting factors identified for a project. Each limiting factor section discusses how to assess or record the factor and how to mitigate for it. Many of the mitigating measures discussed in this section are presented in further detail in Chapter 5. The mitigating measures described in this report are not a complete list and other practices should be considered based on local or regional experience. Section 3.12 discusses how to select the appropriate site improvement measures from the mitigating measures list.

3.8.1 WATER INPUT

Water input refers to the moisture supplied to the soil through rainfall, snowmelt, and road drainage. This moisture recharges the soil and becomes the primary source of water for plant establishment and growth. Water input is influenced by obstacles that capture, or intercept, water before it can enter the soil, including standing live or dead vegetation and soil cover (litter, duff, and mulch). Surface infiltration rates also regulate entry of surface water. If infiltration rates are low, water that would normally enter the soil runs off the surface and is unavailable.

The primary site factors that affect water input are as follows:

- Precipitation
- Rainfall interception
- Infiltration
- Road drainage

In the western United States, water input is at its lowest levels from late spring through early fall. This is also the period when plants require the most soil moisture for survival and growth. During the summer, when water input is low, the soil profile dries out as vegetation withdraws moisture. As soil moisture is depleted, plants cease growing; if soil moisture is not recharged, plants will go into dormancy or die. It is critical that any water from precipitation arriving during the dry season enters the soil and is stored for later plant use.

Precipitation

In wildlands revegetation, the only source of soil water comes through precipitation in the form of rainfall or snowmelt. In the western United States, this typically occurs from late fall through mid-spring, a period when plants are dormant and least able to utilize soil moisture for growth. Water that is not stored in the soil during these events is lost from the site either to ground water or runoff. The period when plants need soil moisture the most occurs during a five- to six-month period, from April through October. For most sites in the western United States, the amount of moisture that occurs in this period is less than a quarter of the total annual rainfall. Precipitation is also extremely low during the middle of the summer (Figure 3-12).

Plant survival and growth hinge on the precipitation that occurs in the years following planting or seeding. Very low precipitation in summer is common in the western United States (those areas west of the 1-inch line) but less common in the eastern United States, as shown in this map of the U.S. which depicts normal precipitation over a 30-year period for the month of August. Much of California, Oregon, Nevada, Idaho, and Washington receive less than one-half inch of rainfall in August as compared to many areas in the mid-western and eastern United States that receive more than 4 inches of rainfall in the same month. This pattern is typical of other months during the growing season (map generated from PRISM).

Vegetation native to the western United States has evolved to compensate for the limited supply of moisture during the growing season (Figure 3-13). During spring, when soils are charged with moisture from winter precipitation and soil temperatures increase, plants

Water input

- Precipitation
- Interception
- Infiltration
- Road drainage

Water storage and accessibility

- Soil texture
- Rock fragments
- Soil structure
- Rooting depth
- Myrrrohizal fungi

Water loss

- Wind
- Aspect
- Competing vegetation
- Soil cover

Nutrient cycling

- Topsoil
- Site organic matter
- Nitrogen and carbon
- Nutrients
- pH and salts

Surface stability

- Rainfall
- Wind
- Freeze/thaw
- Soil cover
- Surface strength
- Infiltration
- Slope gradient
- Surface roughness
- Slope length

Slope stability

- Permeability
- Restrictive layer
- Water input
- Slope length
- Slope gradient
- Soil strength

Figure 3-11 | **Factors that can limit plant growth**

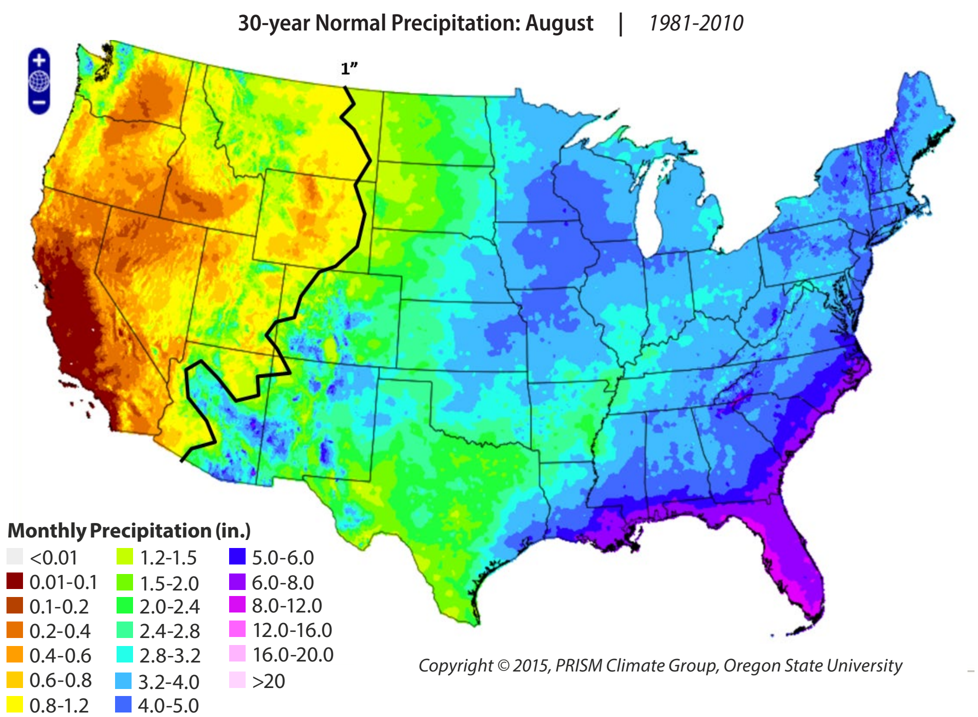


Figure 3-12 | **30-Year Normal Precipitation: August (1981–2010)**

Plant survival and growth depend on the precipitation that occurs in the years following planting or seeding. Drought periods in the summer are common in the western United States (west of the 1-inch line) but less common in the eastern United States, as shown in this map of the U.S. which depicts normal precipitation over a 30-year period for the month of August. Much of California, Oregon, Nevada, Idaho, and Washington receive less than one-half inch of rainfall in August as compared to many areas in the mid-western and eastern United States that receive more than 4 inches of rainfall in August.

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produce new roots, followed by new foliage. As the soil dries out and plants undergo mild moisture stresses, new root and foliage growth cease. During summer, soil continues to dry and plants respond to even greater moisture stress by shutting down their physiological functions and becoming dormant. By mid to late summer, when available soil moisture is depleted and evapotranspiration rates are high, plants will show stress symptoms (browning, loss of needles and leaves); under extreme circumstances, plants will die. By late summer and early fall, rain returns and the soil slowly moistens again, reducing plant moisture stress and signaling plants to grow new roots.

The primary characteristic of precipitation for plant survival is the quantity of rainfall delivered in each storm event during the dry season. Storm events that deliver more than one-quarter inch of rainfall can wet the surface portion of the soil profile and reduce plant moisture stress. Precipitation events that deliver less than this amount rarely supply enough water to enter the soil, especially if interception and runoff rates are high.

How to Assess Precipitation—Average monthly rainfall for a project area can be accessed through climate websites, as discussed in Section 3.3.1. For more site-specific information, precipitation can be collected on-site using rain gauges that capture and record precipitation.

Two types of precipitation gauges are available: digital and non-digital. The advantages of digital gauges are that they record the amount and intensity of rainfall at the time it occurred; the downside is cost (although prices are falling). Many types of digital rain gauges are available, ranging in price and quality. It is important to select a digital rain gauge that is rugged, self-maintaining, and can record for long periods of time. In addition, many remote stations have the capacity to transmit data via the web so it is easy to keep current on weather events.

Non-digital rain gauges are basically cylinders that collect and store precipitation while preventing evaporation. The gauges are monitored by simply measuring the water in the cylinder. The disadvantage of non-digital rain gauges is that they only report the rainfall that has occurred between site visits. They do not provide the dates when rainfall occurred and do not record rainfall intensities.

Mitigating for Low Precipitation—For projects where rainfall is limited during the growing season, making the most of rain and snowmelt that falls throughout the year is an important

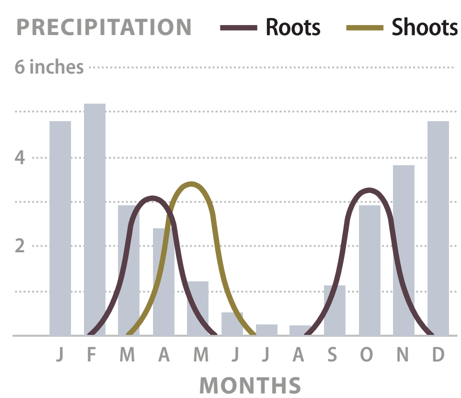


Figure 3-13 | **Root and shoot growth**

In the western United States, root and shoot growth occur when moisture is available in the spring. Growth ceases by early summer when there is very little rainfall. Root growth takes place again from late September through November when soils are recharged by fall rainstorms.

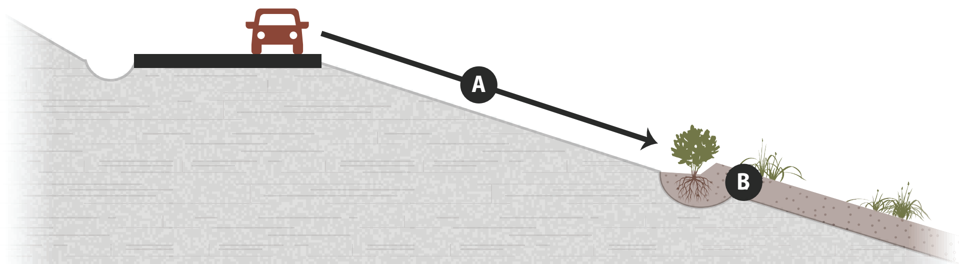


Figure 3-14 | **Fill slope microcatchments**

Fill slope microcatchments take advantage of the low infiltration rates of compacted fill slopes. Water moves off impervious road surfaces and compacted road shoulders during rainstorms (A), and is captured in berms or flattened areas below the road shoulder (B). If this area is ripped and amended with organic matter (e.g., filter strips, amended fill slopes), it becomes a very good environment for establishing shrubs and trees. Soil and compost berms and/or flattened areas are also catchments for sediments.

part of successful revegetation planning. In most cases, supplemental watering will not be feasible. However, if very little water input occurs during the summer, temporary supplemental water could be considered during plant establishment. This can take an active form, such as irrigation, or a passive form, such as redirecting surface water to planted seedlings.

Irrigation—Irrigation can be expensive, and it is generally used only on projects with high visibility or when rapid establishment is necessary for slope stability. These are projects where revegetation objectives include minimizing the risk of seedling failure or enhancing vegetation growth.

Several basic types of irrigation systems are used in roadside revegetation. They are grouped into fixed systems, such as overhead sprinkler and drip irrigation, and manually applied systems. Fixed systems are discussed in Section 5.5.5 (see Drip Irrigation). Manual systems require water to be delivered directly to each plant, either from a hose or water container.

If only a few applications are necessary, the entire project can be irrigated by hand. Personnel can water each seedling or seeded area using a water truck or hydroseeding equipment (with water only), although care must be taken to avoid pulling hoses over establishing plants. Creating basins around seedlings will pond the surface-applied water and keep it concentrated in the seedling root zone. However, a better way to be certain that water will be delivered directly to the roots is to integrate the deep pot irrigation system into drip or manually applied irrigation methods (Bainbridge and others 2001). Pipes made from polyvinyl chloride (PVC) or other materials are placed at depths of 1 to 2 feet beside the seedling at the time of planting. The pipes are then filled with water when the soils dry out in summer. The advantage of deep pipe irrigation is that water is delivered directly to the root system and, because the water is placed deeper in the soil, roots are forced to extend farther into the soil for moisture. Refer to Section 5.5.5 (see Deep Pot Irrigation) for how to install this system.

For any irrigation method, it is important to monitor the wetting pattern of each irrigation. This will ensure that water is applied at the appropriate rates. Digging a hole where the water has been applied at least several hours after irrigation will show how far the water has moved into the soil profile. Duration of irrigations can be adjusted accordingly.

Water Harvesting—Water harvesting is the alteration of local topography to capture runoff water and concentrate it in areas where it can be used by plants. Water harvesting designs can be applied to roadside revegetation in several ways. They include, but are not limited to, contour bench terraces, runoff strips, and fill slope microcatchments. Fill slope microcatchments take advantage of water that drains off road surfaces and shoulders during intense rainstorms by capturing runoff in berms or depressions created at the base of the road shoulder (Figure 3-14). Shrubs and trees planted in these catchment areas will receive greater soil moisture. Contour bench terraces are structures carved out of cut and fill slopes that collect and store runoff water. When filled with topsoil or amended soil, they are referred to as planting pockets. Figure 3-15 shows how planting pockets collect water. Even very low rainfall events, which would normally be of insufficient quantity to moisten the soil surface, can recharge soil in planting pockets and fill slope microcatchments. Sediments will also be deposited on the benches and pockets during rainstorms, building the soil up over time and reducing soil erosion. Water harvesting not only supplies additional water to plants but reduces sediment

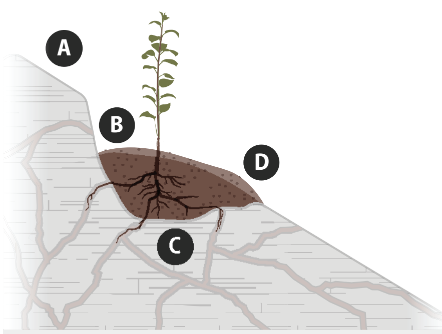


Figure 3-15 | **Planting pockets**

Planting pockets are designed to capture water from upslope runoff (A), which collects in a slight depression (B). Captured water wets the soil after each rainstorm and drains into the fractured bedrock (C). Soil is protected from surface erosion on the downhill side of the pocket with mulch or erosion fabric (D).

and peak flow water to the stream system. Road practices that intercept water and sediments from the road surface for water quality improvement are also a source of additional water for plant growth. These include amended slopes, filter strips, amended ditches, bio-retention swales, and constructed wetlands. In addition, some of these structures create surface-water sources for pollinator species.

Rainfall Interception

The amount of water entering the soil profile from a rainfall event can be significantly reduced by the interception of live or dead vegetation cover. Rainfall is captured through a series of layers, beginning with the tree and shrub canopy, the ground cover, litter, and duff, and is returned to the atmosphere through evaporation. During the dry season, moisture from a low rainfall event might not reach the soil.

How to Assess Rainfall Interception—Rainfall interception can be determined by the soil cover and vegetation that exist on the site after construction. In most cases, there will be very little vegetation and ground cover. It is therefore important to understand the effects of various types of ground cover used in revegetation on the rainfall interception. The depth and water-holding capacity of the material will determine the effect on water input.

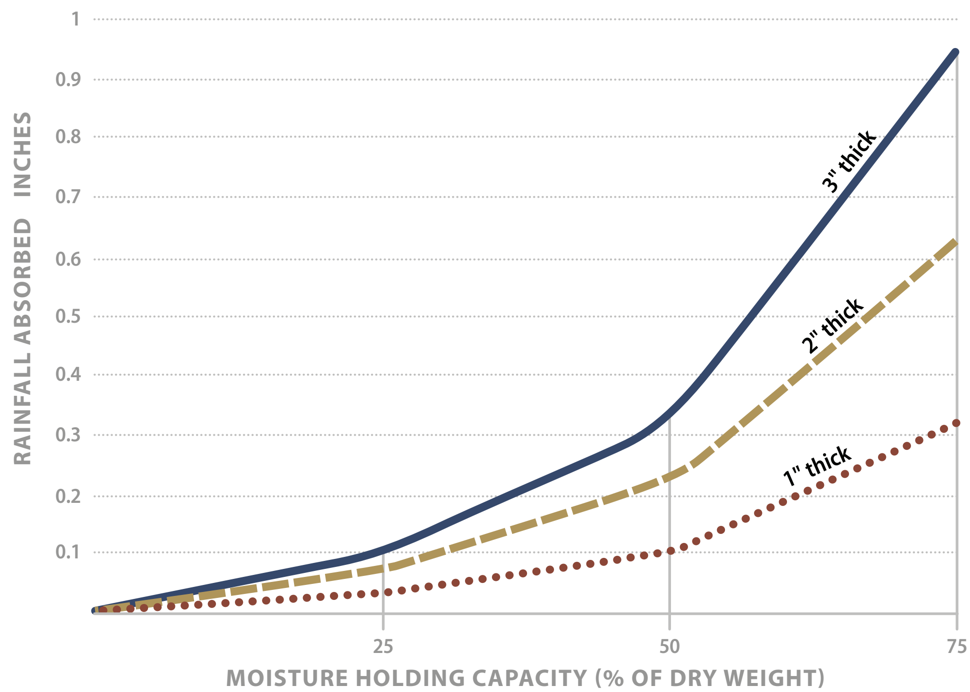


Figure 3-16 | **Moisture holding capacity of mulch or litter**

The amount of rainfall intercepted by soil cover (e.g., mulch or litter) is dependent on its water- holding capacity and thickness.

Water-holding capacity of a surface cover can be measured through testing labs specializing in composts. Alternatively, it can be measured by collecting the soil layer (duff, litter, mulch) and drying it at 230° F in a drying oven (a crockpot can be used, adjusting the temperatures using a meat thermometer). When the sample is dry, it is placed in a 5-inch-long by 3-inch-round PVC pipe with a flat piece of cardboard secured to the bottom of the tube to prevent the material from falling out. The PVC pipe is weighed and placed in a bucket that is filled with water to the top of the pipe. The sample is removed and allowed to drain.

After several hours, the pipe is reweighed. The material in the pipe is removed and the pipe plus cardboard is weighed. The moisture holding capacity of the material (by percentage of dry weight) is as follows:

$$\frac{(\textit{Wet weight of container and cardboard}) - (\textit{Dry weight of container and cardboard})}{(\textit{Dry weight of container and cardboard}) * 100}$$

Figure 3-16 can be used to approximate how much rainfall is intercepted based on the moisture-holding capacity of the soil cover.

Mitigating for High Rainfall Interception—It is important to consider the water-holding capacities of the mulches or soil covers to be used, especially on arid sites. Highly decomposed, fine-textured composts have high water-holding capacities compared to coarser-textured composts and hold more moisture after a rainstorm. Coarser materials, such as shredded wood, bark, wood chips, and wood strands, hold less water, allowing more rainwater to enter the soil. In addition, because fine-textured composts hold more water than course mulches or soil, they are good growing media for desirable native plants as well as undesirable weed species. The question that should be asked when selecting a soil cover is whether it is to be used as a mulch or a growing media. If a mulch, then a coarse material should be used; if growing media, a fine compost should be used.

Infiltration

Infiltration is the ability of the soil surface to absorb water from rainfall, snowmelt, irrigation, or road drainage. When infiltration rates are slower than the amount of water applied to the surface of the soil, runoff will occur and this water will not be available for plant uptake. In addition, runoff can detach and transport soil, causing soil erosion, decreased water quality, and increased peak flows. Refer to Section 3.8.5 (see Infiltration Rates) for a discussion of infiltration rates on surface stability.

The size, abundance, and stability of soil aggregates in the surface soil determine the infiltration rates. Large stable pores created by worms, insects, and channels left behind from decayed roots will absorb water quickly and have high infiltration rates; soils that have been compacted, had their topsoil removed, or are low in organic matter will have poor infiltration rates.

Under undisturbed conditions, infiltration rates are typically high, especially where a litter and duff cover exists. When soil cover is removed, the impact from rain splash can seal the soil surface, creating a crust that will significantly reduce infiltration rates. Infiltration rates are also reduced when the soil is compacted by heavy equipment or traffic.

How to Assess Infiltration—The most accurate method to measure field infiltration rates the rainfall simulator (Section 3.8.5, see Infiltration Rates). This equipment is calibrated to simulate the appropriate drop size and impact velocity of many rainfall events (Grismer and Hogan 2004). The rainfall simulator is expensive to operate and is not routinely used by the designer. The most common application for this technology is in comparing different mitigating measures, such as mulches and tillage methods, on infiltration capacity.

Without conducting rainfall simulation tests, infiltration rates must be inferred by measuring soil strength using a soil penetrometer, bulk density measurements (Section 3.8.6, see Soil Strength), and from site characteristics such as visual observation of compaction and the percentage of soil cover. For most construction activities that remove surface cover or disturb the topsoil, it can be assumed that infiltration rates will be reduced to levels that will create overland flow under most rainfall intensities.

Mitigating for Low Infiltration Rates

Minimize Compaction—Driving heavy equipment over soils causes compaction and reduces infiltration rates. After sites have been prepared for seeding or planting, heavy equipment must not be driven over soils. Such practices that are often recommended for erosion control, such as trackwalking, can actually decrease infiltration rates and adversely affect the establishment and cover of native plants. These practices may not be appropriate on all soil types and should be assessed on a site-specific basis (Grismer and Hogan 2007).

Tillage—Infiltration rates can be increased through soil tillage, including subsoiling, ripping, and disking (Section 5.5.2). In most cases, tillage will reduce compaction and increase macro-pore space in the surface soil, as well as create surface roughness that further increases infiltration rates. Depending on the stability of the surface material and the level of organic matter, the effects of tillage on infiltration might only be effective for a short time. Under some conditions, tillage needs to be planned into the design of the road. Concentrated water from poorly designed road drainage or inadequate road maintenance has the potential to create deep gullies on tilled soils. Steep slopes in areas of high precipitation have a higher risk of slope failure if tilled slopes are not designed appropriately (Section 3.8.5, see Mitigating for Steep Slope Gradients). Deeper tillage and sculpting the subsoil are some methods to reduce these risks (Section 5.5.2).

Organic Amendments and Tillage—Incorporating organic amendments into the soil surface using a bucket of an excavator can create large, stable pores. However, unless the pores are interconnecting, they will not drain well (Claassen 2006). One method for creating continuous pores is to use long, slender organic material, such as shredded bark or wood,

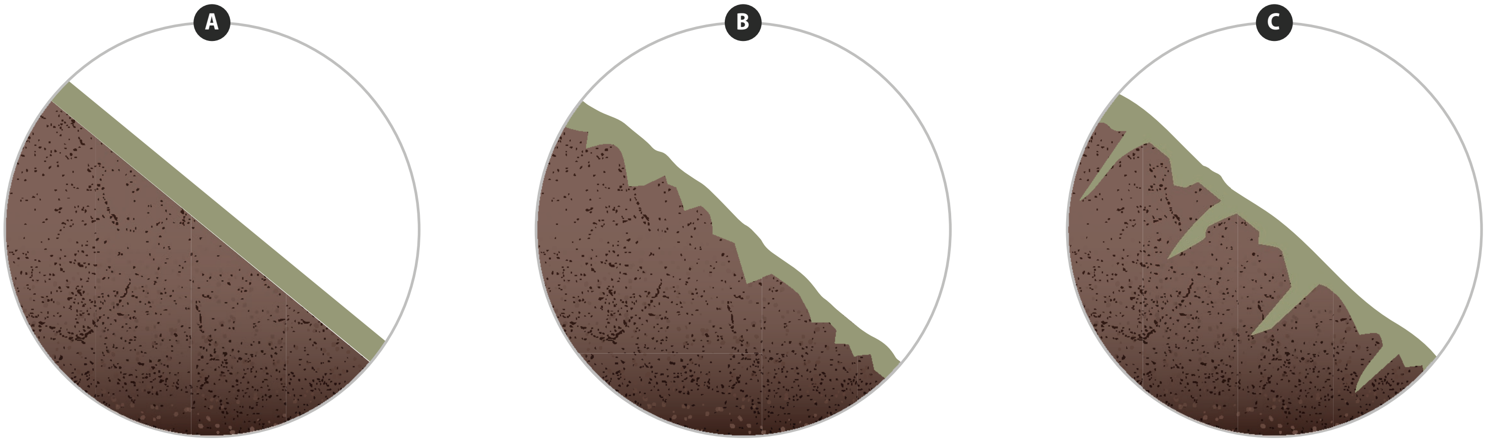


Figure 3-17 | **Surface-applied compost**

Surface-applied compost has greater surface area contact with the soil when it is applied to roughened surfaces (B), compared to smooth surfaces (A). Creating a rough surface prior to the application of compost creates better rooting, greater surface stability, and faster organic matter decomposition. Tilling the soil, through subsoiling and ripping, to depths of 1 to 2 feet (C) will break up compaction and create channels for compost to move into the soil, increasing soil contact and creating greater infiltration rates.

composted yard waste, straw, or hay (Section 5.2.5). Compared to short organic materials such as wood chips, longer materials can increase infiltration rates. Incorporating higher quantities of organic matter in the soil will also increase porosity because of the potential of the organic material to overlap and interconnect.

Mulch and Tillage—Applying mulch by itself does not necessarily increase infiltration rates, although it can reduce sediment yields (Hogan and Grismer 2007). However, combined with surface tillage in the form of subsoiling or ripping prior to application of mulch, infiltration rates can be significantly increased. Mulch fills in the micro-basins left from the tillage operation (Figure 3-17).

Establish Vegetation—Ultimately, the best method to increase infiltration is to create conditions for a healthy vegetative cover. Good vegetative cover will produce soils with extensive root channels, aggregated soil particles, and good litter layers.

Road Drainage

Depending on how the road is designed, surface road water from precipitation events is either dispersed or concentrated. Dispersed water is often seen on outslope or crowned roads, where water moves in sheets over the road surface during rainstorms and into the fill slopes. This water can be captured by water harvesting methods (Section 3.8.1). Concentrated water occurs where runoff from the road surface and cut slopes, as well as intercepted water from seeps and streams, is collected in ditches that flow into culverts or other road drainage structures. When designed into the road drainage system, this water can be available for plant growth. Live silt fences, bio-retention swales, and constructed wetlands are some structures that take advantage of this additional water.

How to Assess Road Drainage—Road drainage is assessed by identifying drainage patterns on the road plans. Often the Storm Water Pollution Prevention Plans will show the detailed direction of surface road water. Culvert outlets are the areas most likely to have concentrated water that can be considered for use for plant establishment and standing water for pollinator habitat.

Mitigating for Road Drainage

Species Selection—In areas below culverts, soil moisture is typically higher than surrounding areas after rainstorms or snow melt. These areas may be suitable for more moisture-sensitive plant species that require increased soil moisture. When planted with plant species that support pollinators, these sites will increase pollinator habitat.

Large Wood—Obstacles, such as large wood, can be placed at the base of culverts or perpendicular to the slope to slow concentrated water and increase soil moisture in these areas. Large wood also provides nesting habitat or shelter for many pollinator species.

Biotechnical Slope Protection—Gullies can form below culvert outlets and, for this reason, these sites are often armored with rock. Moisture-loving vegetation, such as willows, sedges, and rushes, can be integrated into the hardened surfaces, such as live silt fences, as shown in Figure 3-18 and as discussed in Section 5.4.3.

Water Harvesting—Road surfaces, shoulders, and to a lesser extent, cut and fill slopes are impermeable surfaces that create runoff water during precipitation. Utilizing this water for plant growth, as shown in Figure 3-14, is a form of water harvesting.

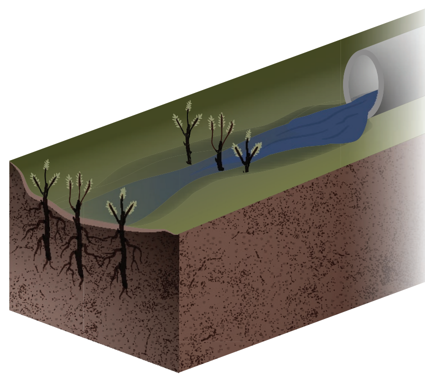


Figure 3-18 | **Live silt fence**

In gullies, draws, intermittent streams, or below culvert outlets, live willow stakes are placed in rows, creating what is referred to as a live silt fence, to slow water velocities and catch sediment and debris (Polster 1997). The stakes root and establish into plants over time.

3.8.2 AVAILABLE WATER STORAGE AND ACCESSIBILITY

The previous section discussed how water enters the soil surface. This section describes how water is stored in the soil and how soil water is accessed by roots. Where precipitation is low or infrequent during the growing season, the amount of water a soil can hold between rainstorms is important from a plant survival and growth standpoint.

The total available water-holding capacity (TAWHC) is the sum of all water stored in the soil profile that is available to plant roots. The amount of water that a soil can store is primarily a function of the following:

- Soil texture
- Rock fragments
- Soil structure
- Rooting depth
- Mycorrhizal fungi

The amount of water a soil stores and how easily it is accessible by roots determines the types of species and the amount of vegetative cover a site can support.

Soil Texture

Soils are composed of minerals of varying sizes, ranging from clays (the smallest) to sands (the largest). Each mineral particle in a soil sample can be grouped into one of three categories depending on its size:

- **Clay**— <0.00008 in (0.002 mm)
- **Silt**— 0.00008-0.002 in (0.002 to .05 mm)
- **Sand**— 0.002-0.08 in (0.05 to 2.0 mm)

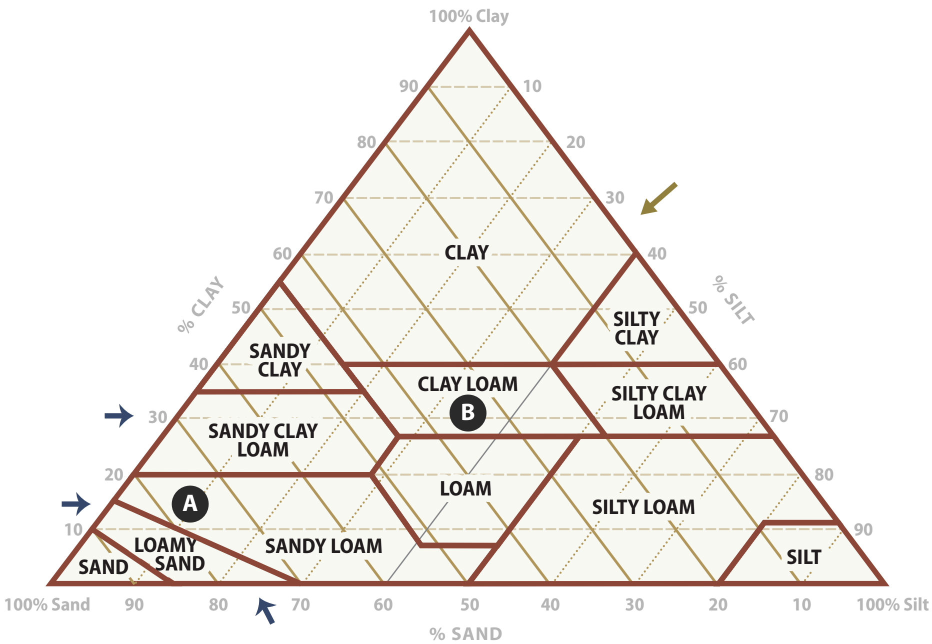
The proportion of these size groups in a soil is called the soil texture.

Figure 3-19 shows 12 soil textural classes by their proportions of sand, silt, and clay as defined by the U.S. Department of Agriculture classification system (Soil Survey Staff 1975). Two other soil classification systems, the American Association of State Highway and Transportation Officials (AASHTO) and the Unified Soil Classification systems, are used for geotechnical engineering. These two systems use different particle size ranges and include parameters such as liquid limit and plasticity in classifying soils. There is no accurate way of converting values from these systems to the USDA textural classes.

Soil texture is an important function of soil water storage because the unique arrangement of pores created in each texture class holds differing quantities of moisture. Clays are typically thin, wafer-like particles with highly charged surface areas that retain large amounts of water.

Figure 3-19 | **Soil textural triangle**

The soil textural triangle defines 12 textural classes based on the percentage of sand, silt, and clay in a soil sample. The textural classes make it easy to describe soils without having to state percentage of sand, silt, and clay. To use the textural triangle, locate the percentage of sand on the bottom side of the triangle and trace the line up to the left-hand side of the triangle. Do the same with either the silt or clay percentages on the other two sides of the triangle (follow silt diagonally down to the lower left and clay across from left to right). Where the two lines intersect is the textural class for that soil. For example, a soil with 75 percent sand and 15 percent clay would be a sandy loam (A). A soil with 30 percent clay and 35 percent silt would have a clay loam texture (B).



Clay particles are often arranged to form small void spaces, or micropores, that also store water. Sands, on the other hand, are large, rounded particles that have a very low surface area and therefore do not hold as much water. The large pores (macropores) that are created when sand particles are adjacent to each other are good for air and water flow but poor for storing water. Soils high in silts hold more water than sands because of the greater quantity of micropores. However, silt particles are not charged, therefore holding less water than clays.

How to Assess Soil Texture—Soil texture can be determined fairly accurately in the field using the "feel" test. This is done with the aid of a soil sieve (2 mm opening size) and a bottle of water. Obtain a fairly dry field sample and separate the fine fraction from the coarse fragments with the sieve (note the volume of gravel in the sample). Take a sample of the fine fraction in the palm of the hand and moisten it with water. The soil is rubbed between the fingers and thumb and classified using the decision tree in Figure 3-20.

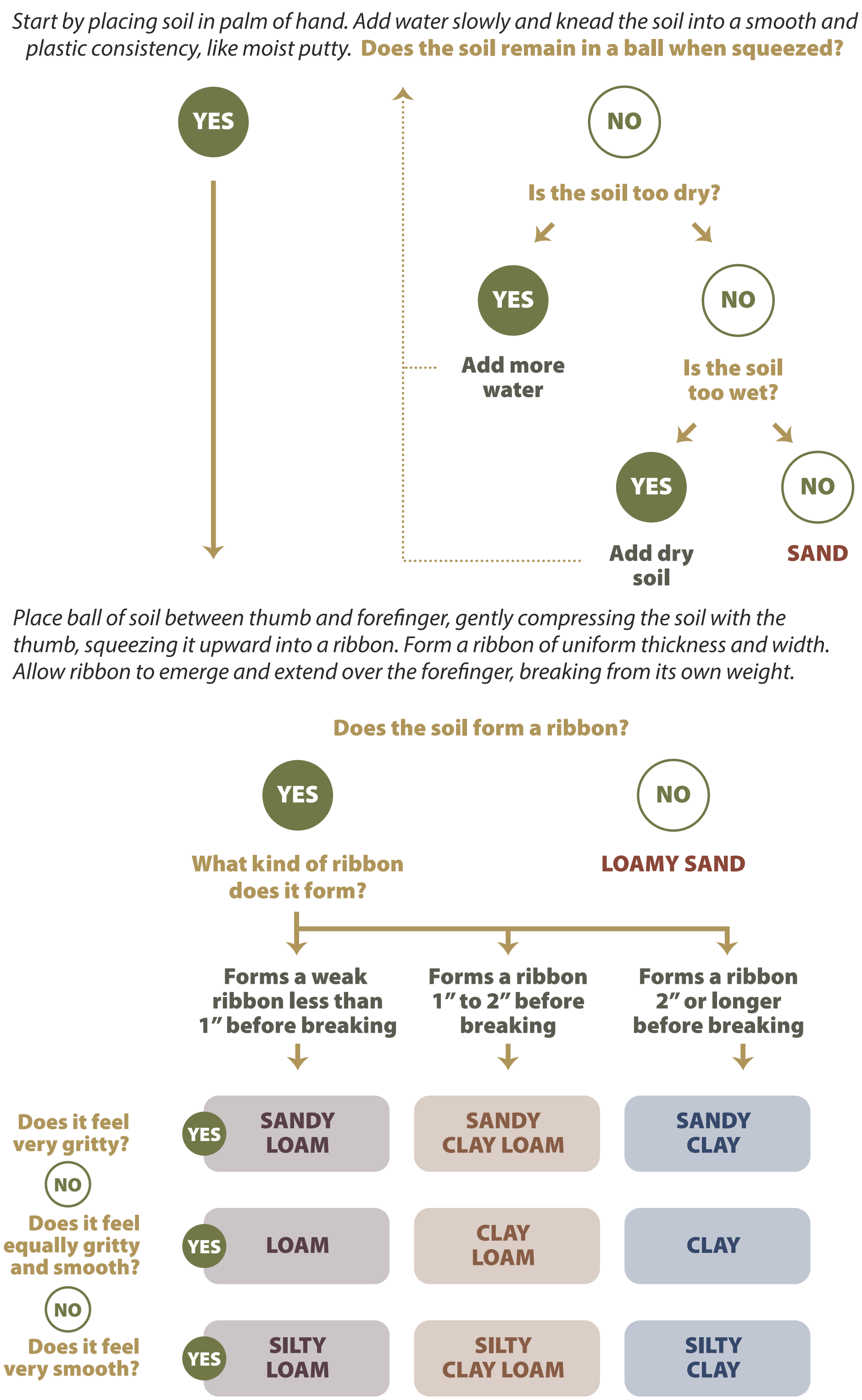
For a more exact determination of soil texture, a sample of soil can be sent to a soils laboratory for a particle size distribution test. This test will report the percentage of sands, silts, and clays in the sample. A Web Soil Survey report (Section 3.3.2) generated for the project area will also provide a good estimate of the soil textures.

Knowing soil texture is essential for estimating the available water-holding capacity (AWHC) of a soil. Figure 3-21 shows some typical available water-holding capacities for various soil textures. The values in this figure are generalized, but are acceptable for making recommendations on most revegetation projects. The Web Soil Survey and Soil Characterization Data websites (Section 3.3.2) may have available water-holding capacities for soils in the project area. For a

Figure 3-20 | **Soil texture by feel method**

With some practice, soil textures can be determined using the following guide.

Adapted from Colorado State University Extension Publication — #7.723



Inset 3-1 | **Measuring available water-holding capacity**

Modified after Wilde and others 1979

Available water-holding capacity (AWHC) can be measured in the field by collecting soil samples from a reference site or disturbed site in mid- to late summer when soils are presumably at their driest. Collect samples in bulk density rings in the same manner as sampling for bulk density (Section 3.8.6, see Soil Strength). After removing the ring from the soil, secure a piece of cardboard at each end of the ring to keep the soil from falling out, then place it an airtight plastic bag to ensure the sample stays intact during transport. When ready to take measurements, remove the top cardboard piece and weigh the sample. Place the sample in a bucket and fill with water to just the top of the ring. Allow the sample to saturate with water. Once the soil is fully saturated, remove the ring and allow it to drain. After 24 hours, remove the soil from the ring and weigh the soil (this is the wet weight), also weigh the ring and cardboard (allow the cardboard to dry first). To calculate the dry weight, subtract the weight of the dry cardboard and ring from the original dry sample weight.

Available water-holding capacity (inches of available water per foot) =

$$\frac{(\textit{wet weight} - \textit{dry weight})}{(\textit{volume of cylinder}) * 12}$$

more accurate assessment, samples can be sent to soils labs for moisture determination. This is a specialized test and not all labs offer this test; therefore, it is important to contact the lab prior to collecting samples. Water-holding capacity can also be measured using the methods outlined in Inset 3-1.

Mitigating for Textures with Low Water-Holding Capacities

Organic Amendments. Incorporation of organic amendments (e.g., compost, biochar, biosolids) can increase the water-holding capacity of a soil. Because the water-holding capacity of each type of organic matter varies by composition and degree of weathering, the effect on soil water-holding capacity by any organic matter being considered is assessed prior to application (see Section 5.2.5 for assessment methods). Sandy textured soils benefit most from organic matter additions, especially those with plant available water of 9 percent or less (Claassen 2006), which are typically sands, loamy sands, and sandy loam soils. Testing several different rates of incorporated organic matter on soil moisture-holding capacity prior to selection will help determine the appropriate amount of material to apply.

Clay—The water-holding capacity of sandy textured soils can be increased by incorporating soils with higher clay fractions into the sandy soils. These soils should have no more than 40 percent clay fraction (e.g., clay loam, sandy clay loam, and silty clay loam textures). The addition of clays should be at rates that result in new soil textures similar to loams, silt loams, or sandy clay loams. Higher rates of clay addition are not recommended. It is always important to test the additions of any soil to another to understand what the effects on water-holding capacity and structure might be. Ideally this should be done in the field in small plots.

Polyacrylamides—Polyacrylamides are hydrophilic polymers that absorb many times their weight in water. They are used to increase the water-holding capacity of greenhouse growing media. The value of using these materials in revegetation projects, however, is questionable based on the low plant response rates, high material costs, and difficulty of incorporating these materials evenly into the soil. A study, located at several semi-arid sites, showed that two rates of polyacrylamide crystals incorporated into road fills had no differences in native grass cover and survival and growth of outplanted pine seedlings from the controls (Riley and others 2013). Any full-scale use of polyacrylamides should be tested at different rates on the sites being revegetated. In addition, determining how polyacrylamide crystals would be evenly mixed into the soil is an important consideration when considering use of these materials.

Rock Fragments

Mountain soils and highly disturbed sites are typically high in rock fragments. The presence of rock fragments is important because rock reduces the amount of water and nutrients a soil can hold. At high volumes in the soil, rock fragments will limit the biomass and vegetative cover a site can support.

The rock classification system classifies rock fragments into the following five size ranges:

- **Fine gravels**—0.08 to 0.2 in (0.2 to 0.5 cm)
- **Medium gravels**—0.2 to 0.8 in (0.5 to 2.0 cm)
- **Coarse gravels**—0.8 to 3 in (2.0 to 7.0 cm)
- **Cobble**—3 to 10 in (7.0 to 20.0 cm)
- **Stone**—>10 in (20.0 cm)

Highly weathered rock can retain some soil moisture depending on the size of the rock fragments and degree of weathering (Flint 1983). For practical purposes, however, it is usually assumed that the presence of cobbles and stone rock fragments in the soil will reduce the available

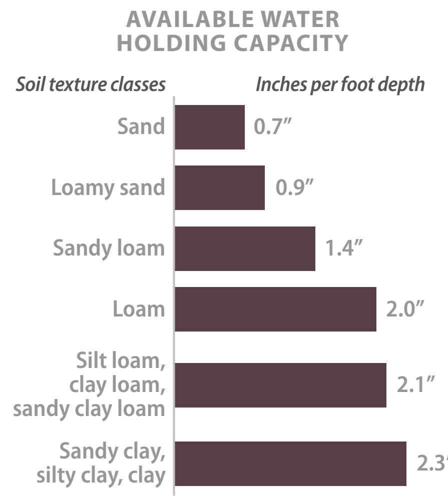


Figure 3-21 | **Soil texture and available water-holding capacity**

This chart shows the general relationship between soil texture and available water-holding capacity soils (adapted after Ley and others 1994). As clays increase in a soil, so does water-holding capacity. Typically, clay loam soils hold more than twice as much water as sandy textured soils. The presence of humus in topsoil increases water-holding capacity of loams and sandy loams at a rate of 2.25 percent water to each percent rise in soil humus (Jenny 1980), which equates to an approximately 0.75 percent increase in water holding capacity for every 1 percent increase in organic matter.

water-holding capacity of the soil proportionally. For example, a sandy loam soil without rock fragments has a water-holding capacity of 1.4 inches per foot of soil (Figure 3-21). When 30 percent large rock fragments are added to the soil profile, the available water-holding capacity is reduced to 70 percent, or 0.98 inches of available water ($1.4 * 0.7 = 0.98$). Alternatively, fine and medium gravels (0.08 to .8 inches in diameter) hold some moisture. A rule of thumb is that these fine and medium gravels reduce water-holding capacity by two-thirds of their volume. In the above example, if 30 percent of the soil were composed of medium and fine gravels, the available water in this soil would be 1.12 inches per foot ($1.4 - (1.4 * 0.3 * 0.66)$).

How to Assess Rock Fragments—Rock fragment content is usually determined in the field. Large rock fragments, such as cobble and stones, are estimated in a variety of ways. The most common methods are surveying freshly exposed road cuts or observing soil excavation during road construction. Estimating the volume can be difficult, and often the amount of rock is over- or under-estimated. One method of estimating large rock in road cuts is to take a digital picture and lay a grid over the surface, as shown in Figure 3-22. Whenever rock is estimated from old road cuts, it must be discerned whether a portion of the rock is masked by soil that might have moved over the rock. A freshly exposed road cut provides the most accurate approximation of rock content.

Rock encountered while digging a soil pit will provide a more accurate estimate of larger coarse fragments. Cobbles and stones, if they can be moved, are set apart from the soil when the pit is excavated. The volume of cobbles and stones is then visually compared to the volume of soil excavated from the soil pit to estimate the percentage of rock fragments.

Gravel content is determined from the excavated soil by sieving it through several soil sieves. Sieves are available through most engineering equipment companies (Figure 3-23). The 2-mm sieve (also referred to as a #10 sieve) is the most important sieve to use because it separates the gravels from the soil fraction. Another useful sieve is the ¾-inch sieve because it separates the fine and medium gravels from the coarse gravels. This sieve can be used in the field to remove larger rock fragments from the soil sample to reduce the weight of the sample. When soils are dry, they are easier to sieve in the field; however, when they are moist, they must be air dried first before they can be sieved. The gravel and soil volumes are visually estimated.

It is important to include the volume of cobbles and stones estimated in the field with the gravels estimated through sieving to calculate the total rock fragments in a soil:

*% rock fragments in profile = (100 - % cobbles and stone) * % gravels in sample*

For example, a soil is estimated to have 25 percent cobbles and stones from observing road cuts and from several soil pits. Sieving shows that 50 percent of the sieved soil is composed of gravels. The soil would be composed of 25 percent cobbles and stones, 37.5 percent gravels ($(100 – 25) * 0.50$), and 37 percent soil.

Figure 3-22 | **Estimating rock fragment content from roadcuts**

The amount of rock in a section of soil can be roughly estimated from road cuts. Large rock can be determined by laying a grid of 20 circles over a photograph of a road cut and recording the number of circles intercepting rock (in the center of the circle). This value is divided by the total number of circles in the grid to obtain the percentage of subsoil in rock fragments. In the picture below, subsoil contains approximately 25 percent large rock (5 intercepted rocks divided by 20 points).

Photo credit: David Steinfeld

Figure 3-23 | **Soil sieves for estimating rock content**

The number 10 sieve (2 mm opening) on the right separates soil particles (C) from rock particles (B and A). The 3/4-inch sieve on the left separates the fine and medium gravels (B) from the coarse gravels (A).

Photo credit: David Steinfeld

Mitigating for High Rock Content

Rock Removal—Screening rock fragments from the soil will increase the available water-holding capacity of a soil. The greatest benefit from screening is with soils that are very high in cobble and stone, where the reduction in volume of rock in the soil would be significant. One type of screen is the "grizzly feeder" which acts as a giant sieve to sort out rock of any size depending on the screen opening widths. Screened soils have the greatest benefit where soils are shallow or a good ground cover is required (e.g., grasses and forbs).

Incorporate Compost—Compost incorporated in the soil at high rates will increase the water-holding capacity of a rocky soil. Depending on the size of the coarse fragments, incorporation can be difficult.

Surface Apply Compost—A more practical method to mitigate for rocky soils is to apply composts to the soil surface without mixing. When surface applied, composts can be good growing media for seeds of grasses and forbs (Section 5.2.3). At rates greater than 3 inches applied to the surface, seeds germinate well and establish into seedlings that can access moisture and nutrients not only from the compost, but also some moisture from the rocky soil below the compost. Be aware that on steep slopes, if the site is not prepared correctly, the layer between the compost and soil can become a slip plane on slopes when compost becomes saturated with water (Section 3.8.6, see Mitigating for Low Permeability).

Apply Topsoil—If topsoil is available, it can also be applied over a rocky soil (Section 5.2.4). Topsoil will have to be placed deep enough to compensate for the quantity of rock in the soil being covered. On steep slopes, preparation of the site prior to application of topsoil is important to avoid slope stability problems (Section 3.8.5, see Mitigating for Steep Slope Gradients).

Planting Islands—On very rocky sites, rocky soils can be mitigated by focusing mitigating measures into planting islands (Section 5.2.8). Where topsoil, compost, or screened soil is limited, this material can be concentrated in mounds, pockets, or benches strategically located throughout a revegetation.

Soil Structure

Just as soils are composed of many-sized mineral particles, they are also composed of different-sized voids (also referred to as pores) whose influence is responsible for water movement, water storage, air flow, and root penetration. Small pores (micropores) strongly influence the moisture-holding capacity of soils, while large pores (macropores) are responsible for water movement, air flow, and root penetration. Soil structure is the arrangement of soil particles into aggregated units that gives rise to the macro-porosity in the soil. It is qualitatively observed as cracks, channels, aggregates, crumbs, and clods in the soil, and described by alternative terms such as friability and tilth. Water flow and root penetration depend on good soil structure. If soil structure is poor or compacted, roots are less able to penetrate the soil to access water. Soil structure is important for other soil functions such as air flow, drainage, permeability, infiltration, and essential habitat for most soil organisms.

Soil structure is significantly reduced by operating heavy equipment over soils. The pressure applied by heavy equipment compacts the macropores, reducing soil volume and increasing soil density. This impact is called soil compaction (Figure 3-24). The effects of soil compaction on tree growth are well documented (Poff 1996). Trees growing on highly compacted soils have far less root, stem, and leaf production than those growing on non-compacted sites. Studies have shown a linear relationship between the increase in surface soil bulk density and decrease in height growth of young Douglas-fir and ponderosa pine trees (Froehlich and McNabb 1984).

It should be assumed that soils will be highly compacted after construction due to the use of heavy equipment. In addition to reducing the potential of a construction site to grow vegetation, compaction also increases runoff and sediment during rainstorm events, which can impact

Figure 3-24 | **Compacted soil**

Compacted soils are created by heavy equipment operating over soil. The large pore spaces are compressed and the impacted soils often form a platy structure as shown in this photograph.

Photo credit: Tom Landis

Figure 3-25 | **Poor draining soils due to soil compaction**

Compacted soils drain very slowly, as the puddles on the surface of the obliterated road in this photograph indicate. During rainfall or snowmelt, soils can stay saturated for days and even weeks. Establishing seedlings during this period can be very difficult because roots of most species cannot survive when soils are poorly drained. Seedlings shown in this photograph were dead within three months.

Photo credit: David Steinfeld

water quality. On sites where summer rainfall is limiting, there will also be less water entering the soil, reducing the amount of water available for plant growth.

Compaction can occur several feet below the soil surface, depending on soil texture, moisture, and the type and weight of equipment being operated. Very compacted soil layers can significantly reduce or eliminate root penetration. Where compacted layers occur, downward water movement is restricted and water may saturate the soil layers above the compacted layer. The resulting saturated soil conditions can be very restrictive to root growth because of the lack of oxygen and the propensity for higher incidence of disease (Steinfeld and Landis 1990) and seedling mortality (Figure 3-25). Compacted layers will naturally recover to their original porosity through root penetration, animal activity, and freeze-thaw events, but recovery can take 20 to 70 years (Wert and Thomas 1981; Froehlich and others 1983).

How to Assess Soil Structure—It is easy to qualitatively differentiate good soil structure from compacted soil, but measuring it quantitatively can be difficult. Indirect field tests to quantify soil structure include bulk density and penetrometer tests.

The bulk density test measures the dry weight of a standard volume of soil. If the soil has a high porosity, the bulk density values will be low; if the soil is compacted, the bulk density will be high. In this method, a cylindrical tube is driven into the soil with a portable bulk density sampler and a soil core is removed (Figure 3-26). The soil is shaved evenly on both ends so that the soil is exactly the shape and volume of the cylinder. The soil is then removed from the cylinder, oven-dried, and weighed.

Bulk Density = *Weight of dry soil (g) / Cylinder volume (cc)*

Figure 3-26 | **A soil core is used to assess soil compaction**

Soil compaction can be assessed by measuring bulk density of a soil. The most common method is to drive a cylindrical tube into the soil, as shown in the photograph, and weighing the soil after it has been dried.

Photo credit: David Steinfeld

Bulk density values of a disturbed site must be related back to the bulk density of an adjacent reference site to make the values meaningful. Remaining within a 15 percent increase in bulk density over reference site values is ideal. Unfortunately, the bulk density method is time consuming and cannot be conducted on soils with high rock fragments.

A less quantitative, but more practical, method of measuring soil porosity is with a soil penetrometer. This equipment measures soil strength instead of density. Compacted soils have greater strength, and greater resistance to penetration by a penetrometer, than non- compacted soils. Several types of penetrometers can be purchased for field work—penetrometers that measure the resistance as a continuous pressure is applied to the probe and penetrometers (impact penetrometers) that measure the number of blows of a hammer to drive the penetrometer into a specified depth. A monitoring procedure for assessing compaction using an impact penetrometer has been developed by the NRCS (Herrick and others 2005b). The most practical and economical field method for assessing compaction, however, is simply using a long shovel, as shown in Figure 3-27. In this method, a site is traversed and, at predetermined intervals, a shovel is pushed into the ground to determine how loose the soil is. By applying the entire body weight to the shovel and observing the distance the shovel penetrates the soil, a qualitative measurement of soil compaction can be made. A rule of thumb is that a shovel penetrating over 12 inches deep indicates a soil with a very high porosity; penetration below 3 inches deep indicates a very low porosity.

Whether a shovel is used or a soil penetrometer, the readings are affected by rock content and soil moisture. When soils are dry, they have greater strength and higher resistance to penetration. This is why any comparative sampling (e.g., comparing reference site to construction site soils) using a penetrometer must be done at the same moisture levels. Encountering large rocks can be confused with hitting a compacted layer. When this occurs, sampling should be done at several adjacent points until the penetrometer can be pushed into the soil without hitting rock. On very rocky soils, the penetrometer is not a practical tool.

Figure 3-27 | **A shovel can be used to determine depth to compaction**

A simple, qualitative method of determining compacted layers is to mark the face of a long shovel with a ruler. Pushing the shovel in the ground with the entire body weight and observing the distance the shovel penetrates can indicate the depth to a compacted layer.

Photo credit: David Steinfeld

Mitigating for Poor Soil Structure

Tillage—Breaking up compacted layers can be done effectively when deep tillage equipment is operated correctly (Section 5.2.2).

Incorporate Organic Matter—The effectiveness of deep tillage can be enhanced if organic matter is incorporated into the soil prior to tillage (Section 5.2.5). Organic matter can keep the soil from settling back to higher, pre-tillage densities. Application rates at which organic matter showed positive effects on soil structure was observed at a ratio of 25 percent incorporated organic matter to 75 percent soil by volume (Claassen 2006). Longer shreds of organic matter are preferred over smaller, chip sizes because the longer strands create interconnecting pathways for water, air, and roots while increasing soil strength (Claassen 2006). The additions of non-composted organic matter, however, will tie-up nitrogen for a period of time. While this might be problematic in the short term, the importance of developing soil structure for long-term site recovery often overrides concerns about the lack of immediately available nitrogen.

Operate Heavy Equipment with Care—Soil compaction is greatest when soils are moist. To limit the amount of soil compaction, schedule equipment operation during times when soils are dry. Compaction can also be minimized by using smaller equipment (Amaranthus and Steinfeld 1997) or leaving slash or deep mulch on the soil surface (which provides cushion).

Avoid Last Minute Compaction—Soil compaction is unavoidable during construction, but compacting soils after mitigating treatments have been implemented, such as tillage, must be avoided. In many cases the benefits of mitigating treatments have been nullified by the lack of attention to heavy equipment operations after topsoil additions or tillage treatments have been made. For example, topsoil salvage and placement, as discussed repeatedly in this manual, benefit the site in many ways. But this expensive mitigating measure loses much of its value if the soils are compacted during or after soil placement. Once topsoil is deep-tilled, every effort should be made to avoid any further equipment operation on the site.

Encourage Mycorrhizae Establishment—Mycorrhizal fungi build soil structure through hyphae and water stable organic glues (e.g., glomalin). Section 3.8.2 (see Mitigating for Lack of Mycorrhizal Fungi) covers methods beneficial for establishing mycorrhizae.

Rooting Depth

Rooting depth is the distance from the surface of the soil to the lowest point that roots can penetrate. It encompasses any strata (e.g., topsoil, subsoil, and parent material) that can be accessed by plant roots. The deeper the rooting depth of a disturbed site, the greater the total available water storage and the higher the productivity of the site.

Rooting depth is affected by restrictive layers that block root penetration to lower strata (Section 3.8.5, see Mitigating for Steep Slope Gradients). For example, the rooting depth of a post-construction site is estimated at 6 feet deep. However, further investigation finds that there is a highly-compacted layer at 12 inches, which would limit most, if not all, root penetration below that point. The rooting depth under these conditions has been reduced to only 1 foot of soil instead of 6 feet. Restrictive layers also include soils with very high or very low pH, toxic materials, or a high-water table.

Rooting depths vary by plant species and age of the vegetation. Most mature tree species have deep root systems that access subsoil and parent material; roots of grasses and forbs are predominantly limited to surface soils. Annual grasses and forbs require less rooting depth than perennial grasses and forbs, with the roots of these species growing in the upper surfaces of the soil. The age of the vegetation also determines the abundance and location of roots. Newly established seedlings have shallow roots but, as the plants mature, root systems expand to access moisture deeper in the soil.

Rooting patterns and root morphology play a role in how plants access soil water. Some species have finer-textured root systems that access tightly held soil moisture; other species have aggressive root systems that can penetrate deeply into cracks between rock fragments. Grasses, for instance, have shallower root systems than trees and shrubs, but their small size and high density in the surface soil gives them an advantage in shallow soils.

How to Assess Rooting Depth—Rooting depth should be estimated from reference sites during planning and post-construction, but it is not always an easy parameter to measure. Observing road cuts is often the best means to determine rooting depth. Rock type (e.g., granite, sandstone, and schist), fracturing patterns, rock weathering, and the degree of rock fracturing will provide an indication of rooting depth. Observing the amount and type of roots in the fractures of existing road cuts will give a good idea of rooting depth.

Fracturing and weathering of rock can also be determined from geotechnical analysis. If the bedrock has been drilled, the drill log report can provide an indication of degree and depth of rock fracturing and weathering. One way that rock quality is assessed is through a classification called the Rock Quality Designation Index (RQD). This system rates the bedrock by how much fracturing is observed in the cores. It is calculated by measuring the pieces of rock in the core sample that are longer than 10 cm, summing the length of these pieces, and dividing by the total length of the core (Deere and Deere 1988). A small RQD means that the bedrock is highly fractured whereas a high RQD means the bedrock is massive. A RQD may be poor from an engineering standpoint because of the high fractures, but favorable from a revegetation standpoint because cracks will hold some moisture and allow root penetration. A RQD rated as "very poor," "poor," and even "fair" should be somewhat favorable to root penetration.

Rooting depth is also affected by the presence of a restrictive layer caused either naturally or by compaction. How to determine the presence of these layers is addressed in Section 3.8.2 (see Rooting Depth) and Section 3.8.5 (see Mitigating for Steep Slope Gradients).

The literature contains many references to defining the depth of soil needed to support different plant communities. For example, 18 inches of soil has been shown to support simple grassland ecosystems, but more diverse native grassland communities are reported to require up to 4 feet or more (Munshower 1994). These figures can be misleading if they are not put in the context of site climate and soil type. In many respects, it is more useful to state the TAWHC of a site rather than the rooting depth. The TAWHC is the total amount of moisture that a soil can store for plant growth when fully charged with water.

Table 3-8 shows how the TAWHC is calculated. Using the same format and equations, a similar spreadsheet can be created by copying the equations into the "Results" column. In this example, there is 1 foot of topsoil and 2 feet of subsoil over a highly-fractured basalt. The topsoil has a loam texture and available water-holding capacity of 2.0 inches (estimated from Figure 3-21 or obtained from lab results) but, because of the rock fragments, it is reduced by approximately 0.4 inch. The subsoil has a high water-holding capacity because of high

Soil strata	Data		Soil characteristics	Results	Equations
0 to 1′	A	2	AWHC of texture (inches / foot)	2	From Figure 3-21 or lab results
	B	20	Small Rock (%)	0.264	*= A * (B / 100) * 0.66*
	C	5	Large Rock (%)	0.1	*= A * (C / 100)*
	D	1	Thickness (ft)	1	Thickness of soil section
	E		Available water by section	1.6	*= (A - B - C) * D*
1 to 2′	F	2.2	AWHC of texture (inches / foot)	2.2	From Figure 3-21 or lab results
	G	35	Small Rock (%)	0.5082	*= F * (G / 100) * 0.66*
	H	25	Large Rock (%)	0.55	*= F * (H / 100)*
	I	1	Thickness (ft)	1	Thickness of soil section
	J		Available water by section	1.1	*= (F - G - H) * I*
2 to 5′	K	2.2	AWHC of texture (inches / foot)	2.2	From Figure 3-21 or lab results
	L	35	Small Rock (%)	0.5082	*= K * (L / 100) * 0.66*
	M	70	Large Rock (%)	1.54	*= K * (M / 100)*
	N	3	Thickness (ft)	3	Thickness of soil section
	O		Available water by section	0.5	*= (K - L - M) * N*
	Total available water holding capacity (inches)			**3.2**	*= E + J + O*

Table 3-8 | **Calculating total available water-holding capacity**

The total available water-holding capacity (TAWHC) is the total amount of moisture that a soil can store for plant growth when fully charged with water. TAWHC values for each revegetation unit are helpful for determining which species will perform well and in developing the mitigating measures necessary to increase water-holding capacity or rooting depth. TAWHC is calculated by determining the texture, rock fragment content, and depth of each soil layer, and calculating how much water each layer will optimally store. The water-holding capacity of each soil layer is added together to obtain the TAWHC for the soil profile.

clay content, but the available water-holding capacity is reduced by half due to rock. Highly fractured basalt is encountered at a depth of 2 feet, and it is estimated from the road cut that approximately 30 percent is actually fractured. Within these weathered fractures is a gravelly clay loam textured material storing approximately 0.5 inch of water. The TAWHC for this site would be the sum of all sections of soil (approximately 3.2 inches).

TAWHC is useful for comparing water relationships between revegetation units and reference sites. For example, the TAWHC for a post-construction soil is 3.6 inches compared to an adjacent reference site, which is 6 inches. If the desired future condition of the post-construction soil is to be similar to the adjacent reference site, then the TAWHC of 3.6 inches must be increased upward toward 6 inches for the site to be capable of supporting the vegetative community occurring on the reference site. If this is not possible, then the DFC target needs to be changed to reflect the plant community that the soil can support.

Mitigating for Poor Rooting Depth

Increase Available Water-Holding Capacity—Improving the water-holding capacity of the existing soil will increase TAWHC. Mitigating measures discussed in Section 3.8.2 can be used to increase soil moisture.

Tillage—If restrictive layers due to compaction are encountered, deep tillage should be considered. Section 5.2.2 provides guidelines for deep tillage.

Apply Topsoil—Increasing rooting depth and TAWHC can be accomplished by applying topsoil (Section 5.2.4).

Planting Islands—Mitigating measures, such as applying topsoil, organic matter incorporation, deep tillage, and other measures that increase water-holding capacity, can be focused in strategic locations, such as planting islands. This will conserve materials and reduce costs (Section 5.2.8).

Blasting—Strategic blasting to shatter the parent material has been suggested as a possible means of increasing rooting depth (Claassen 2006).

Mycorrhizal Fungi

The discussion to this point has addressed the primary factors responsible for soil water storage (soil texture, rock, and rooting depth) and ease of a plant through its roots to reach this water (soil structure). In this section, the discussion turns to how plants increase the efficiency of accessing water through mycorrhizae. While mycorrhizae provide many other benefits to the site in addition to water enhancement, they are covered in depth in this section because of the importance of water to establishing vegetation on highly disturbed sites in the western United States.

Mycorrhizae is the unique symbiotic relationship between fungi (called mycorrhizal fungi) and host plants. To the naked eye, many mycorrhizal fungi appear as a fine web or netting that seems to connect the root system to the surrounding soil (Figure 3-28), and in essence, this is exactly what is occurring. The extremely small hyphae of the mycorrhizal fungi are actually taking on the form and function of an extended root. Because mycorrhizal hyphae are up to five times smaller, they are able to access spaces in the soil not easily accessible by larger plant roots. Mycorrhizal hyphae not only provide the plant with greater access to soil moisture and nutrients, they also surround and protect roots from soil pathogens. In return, the host plant supplies carbohydrates to keep the mycorrhizal fungi alive.

Mycorrhizae play a critical role in site restoration by building soil structure. Hyphae and water stable organic “glues,” such glomalin, are excreted by the mycorrhizal fungi and bind soil particles together into aggregates. These aggregates stabilize the soil (Section 3.8.6, see Soil Strength) and are important for good air exchange and water permeability. This basic soil building process, or repair, facilitates the creation of nutrient reserves and nutrient cycling essential for restoring ecosystems (Miller and Jastrow 1992). Mycorrhizal fungi can also improve survival of tree and grass seedlings (Steinfeld and others 2003; Amaranthus and Steinfeld 2005). A healthy population of mycorrhizal fungi has also been shown to increase plant biomass and cover (Wilson and others 1991; Brejda and others 1993; Sobek and others 2000), and increase the diversity of native species (Smith and others 1998; Charvat and others 2000).

Ninety percent of all terrestrial plants form symbiotic relationships with mycorrhizal fungi. Of the thousands of known species, most generally fall into two categories—ectomycorrhizal fungi and arbuscular mycorrhiza fungi.

Arbuscular mycorrhizal fungi (AMF), formerly called endomycorrhizae, are the most commonly occurring mycorrhizal fungi, forming on 75 to 85 percent of plant species. These include legumes, composites, grasses, bulbs, most shrubs, and ferns. In addition, AMF occur on many tree species, including redwoods and some cedars, and many types of tropical trees. AMF grow inside the roots of the host plant and extend hyphae out into the soil. These fungi are

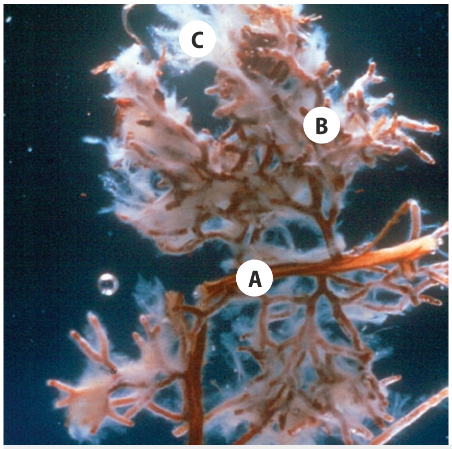


Figure 3-28 | **Mycorrhizal fungi extend root systems**

Mycorrhizal fungi can greatly increase the surface area of the root system. The ectomycorrhizal fungi attached to the pine root system (A) comprise most of the absorptive surface shown in this photograph. The mycorrhizae include brown branched structures (B) and white hyphae or filaments (C).

Photo credit: Mike Amaranthus, Mycorrhizal Applications Inc more general in their association with plant species, meaning that one mycorrhizal species can form an association with a broad spectrum of plant species. AMF reproduce in two ways: by forming single spores outside of the root and from fungal structures (vesicles and hyphae) present inside a colonized root system. Arbuscular mycorrhizal fungi do not disperse their spores in the wind, but instead are dispersed from root to root or by animals. For this reason, recolonization of drastically disturbed sites by arbuscular mycorrhizal fungi can be slow, especially if there are limited sources of healthy, undisturbed soils nearby to repopulate the site.

Unlike arbuscular mycorrhiza fungi, ectomycorrhizal fungi, as the name implies, coat the outside of the roots with hyphae that extend out into the soil. Ectomycorrhizal fungi form on 5 to 10 percent of plant species, the majority of which are forest trees in the western United States. Species include Douglas-fir, western larch, true firs, spruce, hemlock, oak, manzanita, willows, and cottonwood. These fungi form a netting of fine hyphae around the root system that is often observable on nursery produced seedlings inoculated with mycorrhizal spores. Unlike AMF, the relationship between ectomycorrhizal fungi and host species is very specific. Many ectomycorrhizal fungi species have evolved to associate with only one plant species. Ectomycorrhizal fungi produce fruiting bodies, such as mushrooms, puffballs, and truffles, which yield reproductive spores for wind or animal dispersal.

AMF and ectomycorrhizae do not associate with all plant species. For instance, in the western United States, arbutoid mycorrhizae forms on manzanita and madrone, while huckleberry form ericoid mycorrhizae. Still another 10 to 15 percent of the plant species in the United States do not form mycorrhizae at all. Many of these plant species have evolved root systems that function similarly to mycorrhizae and therefore give them an advantage over many mycorrhizal plant species, especially during early plant establishment when mycorrhizae inoculum may be limiting. This advantage is why many plant species, considered highly aggressive weeds, are non-mycorrhizal species.

How to Assess Mycorrhizal Fungi—Where soils have been drastically disturbed, it can be assumed that the mycorrhizal fungal propagules are drastically reduced or absent from the site. The size and severity of the disturbance determine the diversity and quantity of mycorrhizal fungi. As the level of disturbance increases, the density of viable fungi propagules typically decreases. Small disturbances surrounded by native forests or rangelands often reestablish quickly; in larger disturbances, where topsoil has been removed, recolonization by mycorrhizal fungi may take years.

Some laboratories offer testing for mycorrhiza fungi, but these are expensive tests. Because it is unlikely that mycorrhizal fungi will be found in recently disturbed sites lacking topsoil, conducting these tests for most projects is unnecessary.

Mitigating for Lack of Mycorrhizal Fungi

For most construction projects, the management of mycorrhizae should be considered in the early stages of project planning. Several strategies are available to enhance mycorrhizal colonization.

Minimize Soil Disturbance—Operations that maintain topsoil will often preserve mycorrhizal inoculum and maintain soil nutrition. Partially disturbed topsoil is often adequate for reestablishing mycorrhizal plant species. Partial disturbances include clearing and grubbing of road right-of-way vegetation, ground-based logging, and light to moderate intensity burns. Colonized root systems left behind in these operations are sources of inoculum for endomycorrhizae.

Leave Undisturbed Areas—The movement of AMF into highly disturbed sites is slow. Spores are transported by soil erosion and animal movement but not by air. Leaving small areas of native vegetation and undisturbed soils within the larger disturbance reduces the travel distance of AMF, facilitating a quicker repopulation of the disturbed site. This practice is especially important where the size of the disturbance is large.

Salvage Topsoil—Salvaging topsoil and reapplying it to drastically disturbed sites is commonly done when quality native topsoil is available (Section 5.2.4). Topsoil obtained from non-forested sites, such as meadows, rangelands, and unforested clear-cuts, is typically high in AMF which is important for grass and forb establishment. Salvaged topsoil forested sites will have mycorrhizae suitable for tree species as well as grass and forbs.

Apply Topsoil to Planting Holes—If topsoil is very limiting, placing healthy topsoil into holes prior to planting seedlings is an effective method of introducing an inoculum to a disturbed site. Collecting soils as inoculum from young, actively growing forests has been shown to be suitable inoculum for young tree seedlings (Amaranthus and Perry 1987).

Apply Commercially Available Mycorrhizal Fungi Inoculums—Applying commercially available mycorrhizal fungi inoculum is another method used to repopulate highly disturbed sites (Section 5.2.7). Commercially available sources of mycorrhizal inoculums are available for ectomycorrhizal and AMF plant species. These inoculums can be applied in hydroseeding slurries, as seed coats and root dips, through irrigation systems, or incorporated into the soil by broadcasting or banding. Fine grades of mycorrhizal inoculum are applied to the surface of the soil and will move into the soil surface with rainfall. Coarser-textured commercial inoculums must be incorporated in the soil to make them effective. When purchasing live plants from a nursery, rooting media can be inoculated with mycorrhizal fungi during nursery culture (Figure 3-29).

Reduce Fertilizer Use—While the application of fertilizer can increase plant biomass in the short term, it can also suppress mycorrhizal infection (Jaspers and others 1979; Claassen and Zasoski 1994). However, at lower rates, fertilizers have been shown to help plant establishment and improve mycorrhizal colonization (Claassen and Zasoski 1994).

Figure 3-29 | **Non-mycorrhizae inoculated seedlings versus inoculated seedlings**

The response of adding mycorrhizae spores to non-inoculated seedlings (right) can sometimes be dramatic. Both sets of sticky currant (*Ribes viscosissimum*) seedlings shown in this photograph were stunted for months after seed germination. AMF spores were applied to the surface of each seedling container on the left with immediate growth response, while those on the right without mycorrhizae remained stressed (photo taken 50 days after inoculation).

Photo credit: David Steinfeld

3.8.3 WATER LOSS

Water loss is the depletion of soil moisture through transpiration (loss of water through leaves/needles) and evaporation of soil moisture from the soil surface. The rate at which evaporation and transpiration draw moisture from the soil profile is the evapotranspiration (ET) rate. ET rates change daily (rates rise through the day with increasing temperatures and winds speeds and decrease at night), weekly (as weather systems move through), and seasonally (rising in spring and summer and decreasing in fall and winter) (Figure 3-30).

The plant is a conduit for water transport between the atmosphere, which demands water from the plant, and the soil, which acts as a bank of water. When ET rates are low, plants can easily pull water from the soil through the leaves to the atmosphere. As soil moisture is depleted through time, there is less moisture to draw from and plants come under greater stress. With rising temperatures, lower humidity, and lack of rainfall, plants will be under very high

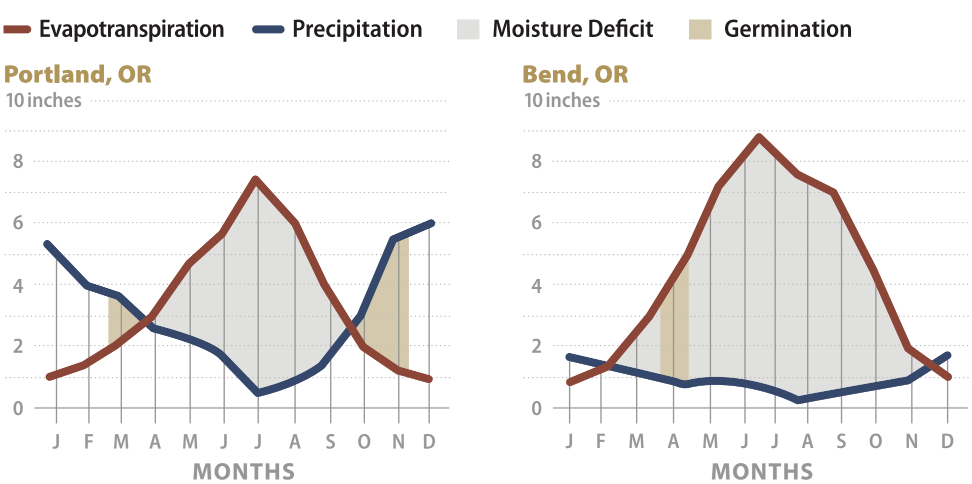


Figure 3-30 | **Evapotranspiration rates**

Evapotranspiration (ET) rates can be found for many NOAA weather stations. Plotting monthly evapotranspiration rates with precipitation rates (also found on the website) gives a good indication of the climate during plant establishment and growth phases. The graphs on the left show that the climate in Portland, OR, has a very favorable environment (low evapotranspiration and high precipitation) for seed germination in March; therefore, plant establishment should be adequate without the need for extra mitigating measures. The weather in the fall is also conducive to germination and plant establishment. The climate in Bend, OR, during April and May when seeds in that area germinate has very high ET rates and very low rainfall; mitigating measures such as applying mulch over the seeds at sowing might be critical for success.

moisture stress levels (Figure 3-31). The amount of stress that a plant is under is referred to as plant moisture stress (PMS) (Figure 3-32). PMS is at its highest from middle through late summer in the western United States, when the ET rates are at their highest and soil moisture levels at their lowest.

Water loss due to ET can be influenced by a number of abiotic and biotic factors, primarily:

- Wind
- Site aspect
- Competing vegetation
- Humidity
- Soil cover

Wind

Wind is often overlooked as a factor in the success or failure of establishing native vegetation, but it can play a major role, especially on sites where summers are hot and dry and soil moisture levels are low. Until seedlings become established, wind can place extremely high demands for moisture on newly planted seedlings, severely limit growth, and ultimately lead to death. Wind can also be an important factor for surface stability, as discussed in Section 3.8.5.

How to Assess Wind—Wind speed equipment is available but is most likely too costly for most designers. Site visits during different times of the year, especially in the summer, can give some indication whether wind is a problem. Visiting the site during the afternoon is important because this is the time of day when hot, dry winds negatively affect plants the greatest. Other site characteristics, such as position on the slope (e.g., ridgelines are more prone than valley floor), or proximity to forested

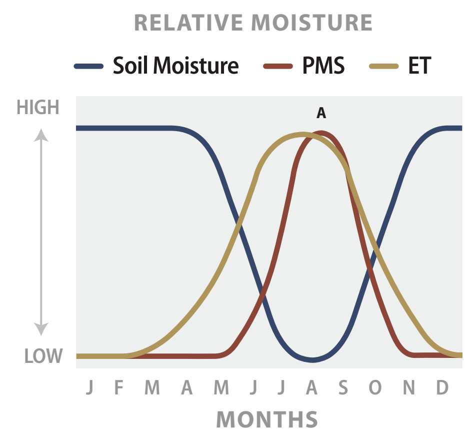


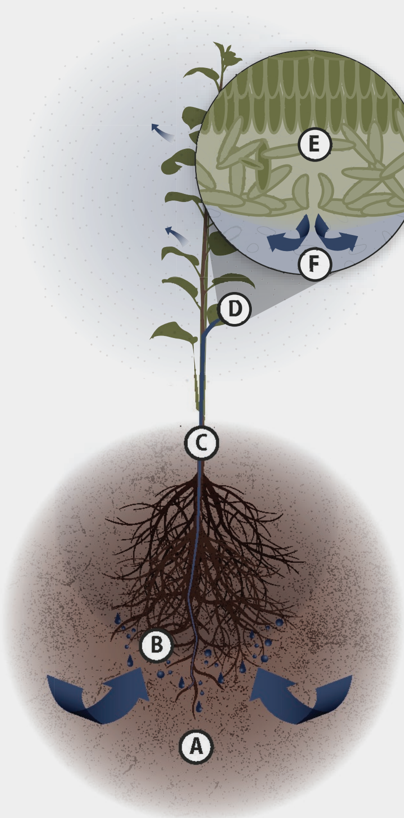
Figure 3-31 | **Relationships among evapotranspiration, soil moisture, and plant moisture stress**

Conceptual relationship between evapotranspiration (ET), soil moisture, and plant moisture stress (PMS). In the western United States, PMS lags behind ET in late spring because soil moisture is still moderate to high from the winter rains. By mid summer (A), plant moisture stress has increased to its greatest level in the year because soil moisture is at its lowest. Newly planted seedlings undergo extreme stress during this period. Unless the seedlings are dormant or their root systems have grown deeper into the soil, where there is greater access to soil moisture, seedlings will die. In late summer and early fall, cooler weather returns and rains wet the soil, driving ET and PMS rates down again.

Figure 3-32 | **Plant moisture stress**

Plant moisture stress (PMS) is a measure of the tension or pull of moisture through a vascular plant. Much like a straw, when the demand for moisture at the surface of leaves is high, moisture is drawn from the stomata. This creates a pull of water through the leaves, stem, and down to the roots, which draws water from the soil.

	Location	Water Potential (MPa)
A	Soil	-0.1
B	Plant roots	-0.3
C	Plant stem	-0.6
D	Plant leaf	-0.9
E	Plant stomata	-25.0
F	Atmosphere	-125.0



environments—as forests often reduce wind speeds—can be used to infer wind strengths and directions.

Mitigating for High Wind

Road Design—Designing islands of undisturbed vegetation to help break up wind patterns can aid vegetation establishment. The taller the plants left undisturbed, the greater the wind protection. Established trees, particularly those with low-growing branches, provide the greatest protection from wind.

Wind Barriers—Obstacles that block wind at the soil surface can be effective for early seedling survival. These obstacles can include trees and tall shrubs, shelterbelts, filter fabric, stabilized logs, large rocks, berms, and stumps. In using these structures, seedlings should be planted on the windward side.

Tree Shelters—Tree shelters completely surround seedlings and block them from the wind (Section 5.5.4). They are an effective means of reducing ET rates created by high winds during early establishment. Once the vegetation has emerged from the top of the tube, however, tree shelters no longer protect the emerging foliage from the wind.

Shade Cards—Shade cards are sometimes used to block wind, but they are less effective than the fully enclosed tree shelter (Section 5.5.3). When used to block wind, shade cards must be placed on the windward side of the seedling, which is not necessarily the same location that cards would be placed if protection from sun is the objective. Often two shade cards are placed around the seedling for added protection against the wind. Placement of the shade cards at the height of the foliage affords greater protection to the seedling.

Appropriate Species Selection—The drying and damaging effects of wind are important considerations in appropriate species selection. A simple assessment of soil type and rainfall may not account for the effects of wind. Choosing hardier, wind-tolerant, and more drought-tolerant species may be necessary to establish vegetation on windswept sites. Find reference sites in windy locations to indicate which species are adapted to wind.

Leave Surface Roughened—A roughened soil surface can create a micro-basin or relief that protects young germinants from the drying effects of wind during the establishment phase (Section 5.2.2).

Aspect

Aspect is the direction a slope is facing and is one of the predominant site characteristics affecting evapotranspiration. South and west aspects receive more solar radiation during the day and are warmer and drier, with higher ETs than north and east aspects. Soils on these south and west aspects dry out faster than north and east slopes. In spring, during seed germination, south and west aspects can dry very quickly between rainstorms, reducing the rates of germinating seeds. As seedlings emerge and grow through spring and early summer, temperatures on the south and west slopes continue to rise to very high levels, creating very unfavorable conditions for seedling establishment. Even with planted seedlings, high surface temperatures can damage stems near the ground line, severely affecting seedling survival and establishment (Helgerson and others 1992).

In climates where moisture is not the limiting factor, south and west slopes are often very productive and have greater cover. Warmer soil and air temperatures create a longer growing season, offsetting the effects of moisture stress on plant growth.

On high elevation sites, north and east aspects are cool, with much shorter growing seasons, compared to the south and west aspects, resulting in very different compositions of species. At high elevations, soils on south and west slopes stay warmer longer in the fall, providing an opportunity to plant in the late summer in time for seedlings to become established before winter arrives. During spring, at all elevations, south and west slopes warm up much sooner than north slopes, resulting in earlier seed germination and plant growth. The difference in soil temperatures between north and south aspects is a consideration for determining when to plant and what species to use.

How to Assess Aspect—Aspect is measured in the field by facing the fall line of the slope (the imaginary line a ball would roll) and taking a compass bearing downslope. A "northeast slope," "northeast aspect," "northeast exposure," or "northeast-facing slope" all refer to an aspect with a compass bearing facing northeast.

Aspect can also be measured from topographic maps by drawing an arrow perpendicular to the contour lines and pointing the tip of the arrow downslope. Aspect is often a factor for delineating one revegetation unit from another due to the strong influence it has on the growth and survival of seeds, seedlings, and cuttings.

Soil and air temperatures differ greatly between aspects, and taking temperature measurements can be important for assessing the effects of aspect on revegetation. There are many types of recording devices available on the market, but only equipment that can download data to spreadsheets for analysis and graphing should be considered. Some equipment has become so inexpensive that more than one unit can be purchased (Figure 3-33).

Figure 3-33 | **Temperature recording device**

Temperature recording technology has become smaller and very inexpensive. The iButton® shown next to the nickel can record more than a year of temperature data.

Photo credit: David Steinfeld

Mitigating for South and West Aspects

For most sites, any treatment that will shade vegetation on the south and west slopes from intense solar radiation should increase survival and growth of establishing plants.

Overstory Vegetation—Keeping overstory trees at a minimum density of one tree per tenth acre is a rule of thumb for reducing soil temperatures below lethal levels on south aspects (Helgerson and others 1992).

Shade Cards—Shade cards can significantly increase seedling survival on south aspects (Hobbs 1982; Flint and Childs 1984) (Section 5.5.3). They must be placed close to planted seedlings so that the stem and lower portion of the seedlings are shaded from the afternoon sun (Helgerson and others 1992).

Obstacles—Large obstacles that cast significant amounts of shade on young seedlings will create a more favorable environment for seedling establishment and increase seedling survival (Minore 1971). These include stabilized logs, large rocks, berms, and stumps. Seedlings should be planted on the north and east side of these features to be shaded from the afternoon sun.

Mulch—On south exposures, the use of mulches as a moisture barrier should be considered for seedlings, seeds, and cuttings (Section 5.2.3). Avoid placing mulch in direct contact with the stem of the seedling.

Species Mix—The composition of species will probably be different for north and south aspects. Species adapted to hotter and drier environments are used for revegetating south exposures; those adapted to cool, moist environments are used on north aspects. Elevation can offset the effects of aspect. For example, species that grow on low elevation, north aspects often occur several thousand feet higher on south aspects because of the difference in temperatures. Reference site vegetation surveys will guide in the selection of appropriate species for each exposure.

Plant Material Rates—South aspects often require a higher density of seedlings, cuttings, and seeds than north aspects to offset the expected higher mortality rates. Adjusting for increased mortality rates is made when calculating plant materials rate for seeds (Section 5.4.1), cuttings (Section 5.3.5), and plants (Section 5.3.6).

Planting and Sowing Windows—Take advantage of warmer spring and fall soil temperatures on the south exposures by sowing and planting earlier on these sites (Section 3.14.2).

Competing Vegetation

Controlling competing vegetation around planted seedlings, whether native or non-native, reduces the rate at which water is withdrawn from the root zone and increases the potential for survival and growth. The rate at which water is depleted is a function of the type and amount of competing species. Grass species, for example, have a very fibrous root system in the upper soil horizon that allows them to withdraw moisture very quickly and efficiently during dry weather. Unless grasses are controlled, especially in the western United States, it is very difficult to achieve good survival or growth of planted seedlings in areas with high densities of grass. Perennial forbs are generally less competitive than grasses because their root systems are deeper and less concentrated in the surface where the seedlings are withdrawing moisture.

Revegetating with a seed mix is also affected by the type and quantity of competing vegetation. Those species that germinate earlier than the seeded species in the spring or fall will deplete soil moisture before the seeded species can establish. Cheatgrass is an example of an annual species that establishes quickly when soil temperatures are cool during early spring, depleting the surface soil moisture just as perennial species are beginning to germinate. How to assess and mitigate for competing vegetation is discussed in detail in Section 3.11.

Soil Cover

The thickness and composition of material that covers the soil surface influence many important soil properties covered in this manual, such as infiltration rates, interception losses, soil temperatures, surface erosion, runoff, and soil moisture loss. The following discussion focuses on soil cover as it affects soil moisture loss through evaporation.

Under undisturbed conditions, soil cover is predominantly composed of duff, litter, and stems that block the escape of soil moisture through evaporation (Figure 3-34). Mulches are also unfavorable seedbeds for weed seeds because duff and litter dry out quickly. Disturbed soils, on the other hand, are mostly composed of bare soil. Evaporation from the surface of bare soil can be high, extending to at least 6 inches below the soil surface, affecting seed germination and seedling establishment rates. Until roots of planted or seeded seedlings have extended farther into the soil profile, surface drying will negatively affect seedling establishment, especially on sites where water input and storage are already limiting.

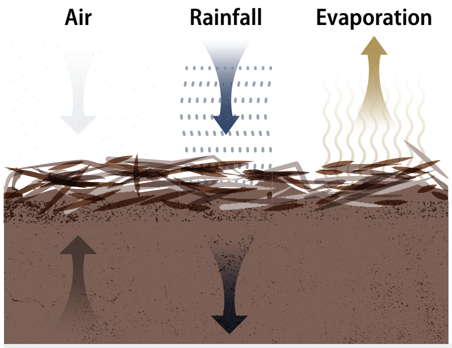


Figure 3-34 | **Effective mulch cover**

An effective mulch for seed cover is one that is stable and allows good airflow and rainfall entry, while reducing evaporation from the soil surface.

How to Assess Soil Cover—Soil cover can be measured on undisturbed and disturbed reference sites or post-construction sites through the ground cover monitoring procedures outlined in Section 6.3.1. In this procedure, the percentage of area in litter, duff, rock, vegetation, and bare soil is recorded and periodic measurements of litter and duff thickness are made.

Mitigating for Low Soil Cover

Mulches for Seedlings and Cuttings—Mulches create a more favorable environment for establishing seedlings and cuttings not only by reducing surface evaporation, but also by decreasing the amount of competing vegetation. There are three types of mulches for seedlings and cuttings—organic aggregate, sheet mulches, and rock mulches. The organic aggregates are thickly applied ground wood or bark, while the sheet mulches are made from non-permeable or slightly permeable plastic, newspaper, or geotextile. Rock mulches are composed of gravels, cobbles and stone. Mulches are placed around the base of the seedling and cover at least a radius of 1.5 feet from the base of the seedling (Section 5.2.3 for how to install).

Mulches for Sown Seeds—Selecting and applying mulches over sown seeds differ from those selected for planted seedlings and cuttings. Mulch application for seedlings and cuttings is typically too thick for seeds to germinate and grow through. An ideal seedbed mulch is one that is applied at the highest rates without affecting seedling emergence. Long-fibered mulches, such as straw, hay, shredded wood, or wood strands, create the greatest loft or thickness. At the optimum thickness, these mulches allow some light to penetrate and space for seedlings to emerge. Short-fibered mulches, such as wood fiber and paper found in hydromulch products, are more compact and create less loft. While these products reduce erosion rates, they are not necessarily good as seed covers (Section 5.4.1, see Determine Seedling Methods).

3.8.4 NUTRIENT CYCLING

Nutrient cycling is the process by which sites store and release essential nutrients for plant survival and growth. There are 13 elements, or mineral nutrients, and each fills a specific role or function in plant development and each possesses individual characteristics of movement and storage in the soil. This manual will not attempt to explain the role and function of each mineral nutrient (there are many good textbooks on this subject). It will instead focus on how nutrients cycle through vegetation and soils; how they are captured, stored, and released; and what site components are essential to support these processes. In contrast to an agricultural system of managing optimum growth in crops through fertilization, the goal in wildlands revegetation is to create an environment that will support a self-sustaining native plant community that can develop through successional processes. This includes facilitating the establishment of nutrient cycles in a way that conserves, cycles, and builds nutrients in the system.

Mineral nutrients are stored in: soil, live or dead vegetation, and rock. They are slowly released over time at varying rates. The rates at which nutrients are released from each source will determine their availability for plant uptake. Rock and fallen trees, for example, both hold essential nutrients but release them to the soil at significantly differing rates. The fallen tree can take up to 100 years to decompose and release its nutrients; the weathering of rock might take over 100,000 years. Soil, on the other hand, can release nutrients in the order of weeks and months. Once released, these nutrients are taken up by plants, lost through leaching or erosion, or reabsorbed in the soil.

On undisturbed sites, there is a dynamic exchange of nutrients throughout the year. Plants absorb nutrients from the soil through the root system and assimilate them into vegetative biomass. As plants, or portions of plants, die, they drop leaves, branches, and stems to the ground where they eventually decompose and return nutrients to the soil. The nutrients are stored in the soil and once again become available for plant uptake. This natural process of nutrients moving from soil to vegetation and back again is referred to as nutrient cycling. The factors important in nutrient cycling are as follows:

- Topsoil
- Site organic matter
- Soil nitrogen and carbon
- Nutrients
- pH
- Salts

In a healthy plant community, nutrients are constantly recycled with a minimum amount of nutrients lost from the site. On drastically disturbed sites, however, nutrient cycling functions poorly, if at all. The topsoil, which holds the greatest concentrations of available nutrients and supports the primary microbial activity on the site, is missing or mixed with the subsoil. Organic matter, which is a primary source of long-term nutrient supply and an energy source, has also been removed. Soil nitrogen, the most critical nutrient for plant growth and site revegetation, is lacking. Soil nitrogen governs how quickly vegetation will return to a disturbed site and how much biomass it will ultimately support (Bloomfield and others 1982). Its availability is closely regulated by the amount of carbon present in the soil, which is also in flux on highly disturbed sites.

For many sites that lack topsoil, the subsoil in its place may have pH values that are higher or lower than the pH of the original topsoil. pH values at extreme ranges affect nutrient cycling by making many nutrients insoluble and unavailable for plant uptake. In addition, increased soil salinity, which can be caused by soil disturbance and amendments, can disrupt nutrient availability and provide unfavorable conditions for plant establishment.

Topsoil

The topsoil is the horizon directly below the litter layer that is characterized by high organic matter, abundant roots, healthy microbial activity, good infiltration rates, high porosity, high nutrient content, and high water-holding capacity (Jackson and others 1988; Claassen and Zasoski 1998). Most nutrient cycling takes place in the topsoil where the greatest biological activity occurs. Decomposing microorganisms flourish, feasting on dead vegetation and roots, releasing stored nutrients back to the soil. Most life forms occur in forest, prairie, and range topsoils, including mammals, reptiles, amphibians, snails, earthworms, insects, nematodes, algae, fungi, viruses, bacteria, actinomycetes, and protozoa (Trappe and Bollen 1981). The top 6 inches of an acre of forest topsoil can contain as much as a ton of fungi and a half of a ton of bacteria and actinomycetes apiece (Bollen 1974). Topsoil depth is highly correlated with the nutritional status of the soil and, in forests of the western United States, has been found to be highly correlated to site productivity (Steinbrenner 1981). Topsoils possess humus, which is what gives topsoils their dark color (Figure 3-35). Humus is a stable end-product of decomposition, important for nutrient storage, soil structure, and water-holding capacity.

Sites lacking topsoil have significantly reduced productivity, and obtaining even minimal revegetation can be very difficult. Planted seedlings often fail or growth is significantly reduced, resulting in inadequate plant cover to protect the soils from erosion. Growth of planted trees can be reduced by one-third to one-half when planted in subsoil instead of topsoil (Youngberg 1981). Restoring these sites to functioning plant communities is unlikely without mitigating measures.

Figure 3-35 | **Topsoil**

Topsoil is the upper soil horizon and is generally darker, more friable, and has more roots than subsoil.

Photo credit: Thomas D. Landis

How to Assess Topsoil—On undisturbed sites, topsoil is visually differentiated from the underlying subsoil by having darker colors, less clay, better soil structure, and higher abundance of fine roots. In forest soils, topsoil depths can be more difficult to differentiate from subsoils because the color changes are not always distinct. Other attributes, such as the abundance of roots, lack of clays, soil structure, and lower bulk density, can be used instead. On construction sites, topsoil has either been removed and stockpiled or mixed in with the subsoil.

Mitigating for Lack of Topsoil

Minimize Soil Disturbance on "Fragile Soils"—Where soils are especially fragile and reconstructing topsoil conditions is difficult, it is particularly important to keep the "disturbance footprint" to a minimum (Claassen and others 1995). Sites with fragile soils include decomposed granitic soils, serpentine soils, high elevation soils, and very acidic or basic soils.

Salvage and Reapply Topsoil—An effective practice in revegetating highly disturbed sites is salvaging and reapplying topsoils (Section 5.2.4). This practice has been found to greatly increase plant growth and ground cover (Claassen and Zasoski 1994). Topsoil salvage and application require good planning, implementation oversight, and topsoil surveys. In the planning phase, a survey of the planned road corridor identifies the location of topsoil, the depth, and nutrient status through laboratory testing (Section 3.10.1, see Laboratory Testing). After topsoil is removed and appropriately stored, it is reapplied to the disturbed site, ideally at depths similar to pre-disturbance reference sites.

Create Manufactured Topsoil—When topsoil is not available, "manufactured topsoil" can be created in situ or produced offsite and imported (Section 5.2.4, see Manufactured Topsoil). Manufactured topsoil will lack the native seed bank and some of the biological components of topsoil, but it can re-create a rooting zone high in nutrients and organic matter, with good water-holding capacity, porosity, and infiltration.

Create Planting Islands—If sources of manufactured or natural topsoil are scarce or too costly for broad scale applications, placing available topsoil in strategic locations, such as planting islands, can create a mosaic of productive growing sites.

Site Organic Matter

Site organic matter (OM) consists of plant materials in all stages of decomposition, including wood, bark, roots, branches, needles, leaves, duff, litter, and soil organisms. From a nutrient cycling standpoint, site organic matter assimilates nutrients drawn from the soil into live vegetation. Depending on the type of vegetation and the productivity of the site, the amount of nutrients held in organic matter can be significant. Figure 3-36 shows the quantities of four major nutrients held in the organic matter of a young Douglas-fir stand, and Figure 3-37 shows the quantity of major nutrients found in the application of 2 inches of material derived from Douglas-fir and alder. These two examples show the possible nutrient reserves that organic matter can contribute to a disturbed site if they are kept on the site or processed into mulch or soil amendments and reapplied.

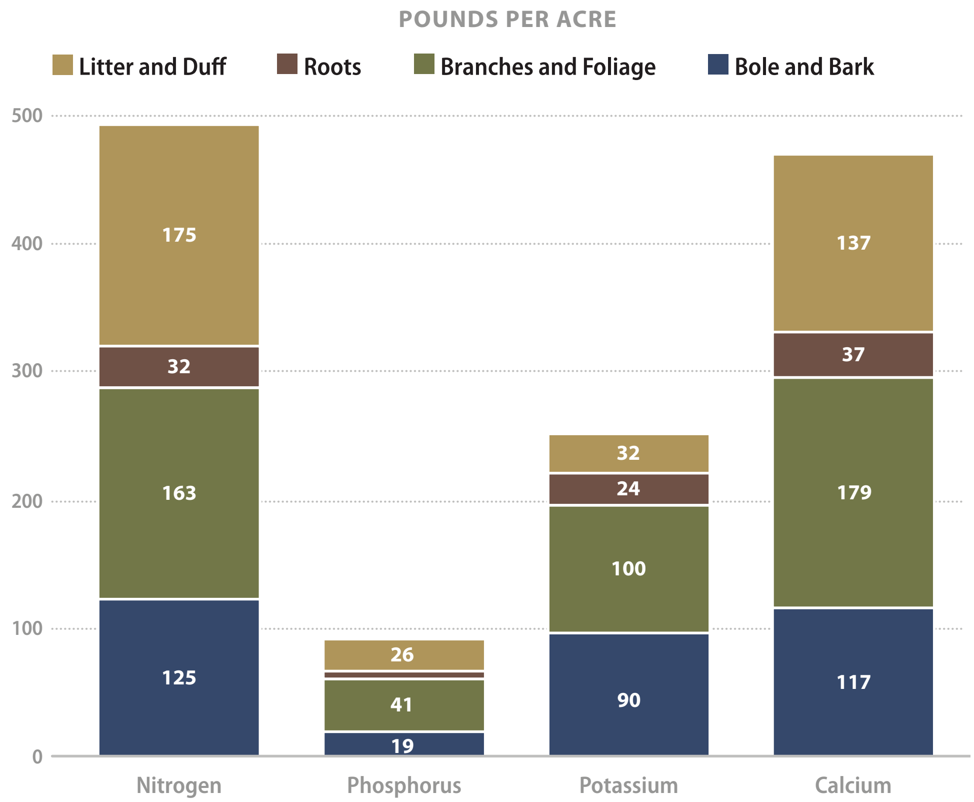


Figure 3-36 | **Nutrients in forests stands**

Most of the nutrients found in a young Douglas-fir stand reside in the litter, duff, and branches (adapted from Cole and Johnson 1981).

While plants are essential in nutrient cycling, equally important are the decomposing organisms that release nutrients to the soil. Decomposers consist of thousands of specialized species of animals, insects, fungi, bacteria, and actinomycetes that survive on organic matter. Decomposing organisms not only release nutrients but are essential to the development of soil structure (Section 3.8.2, see Soil Structure).

On an undisturbed site, organic matter is in all stages of decomposition, from recently dead trees to soil humus, the end product of hundreds of years of decomposition. This understand-

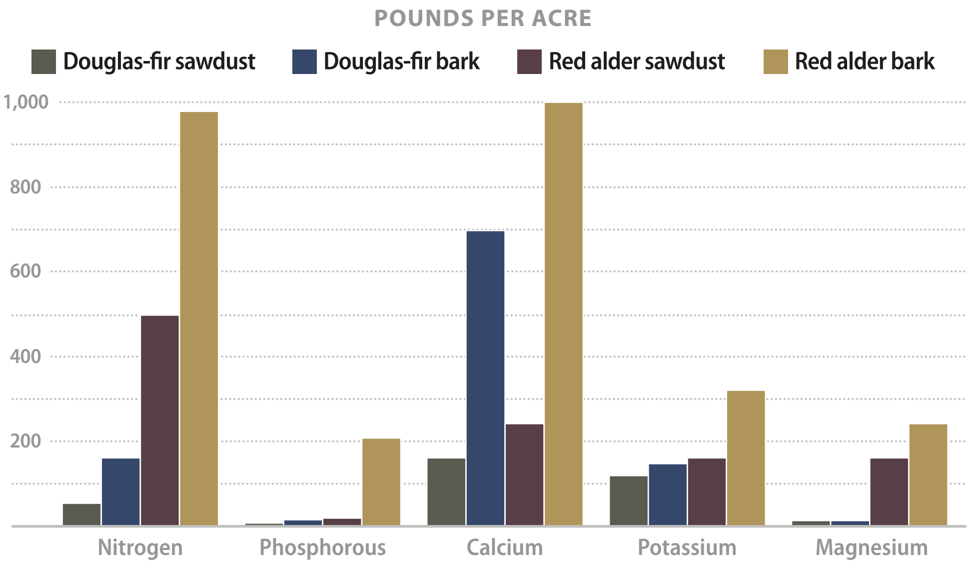


Figure 3-37 | **Nutrients in Douglas-fir and alder**

Comparison of pounds per acre of nutrients resulting from bark or wood from Douglas-fir and alder trees, based on 2 inches of applied organic matter (Rose and others 1995).

ing is important for restoring a site to a functioning plant community because it is a reminder that nutrients are released throughout the life cycle of a plant community, not just at the beginning of a revegetation project. A site that has a range of organic matter in all stages of decomposition not only conserves nutrients but slowly meters them out over time. In addition, organic matter is an essential nesting habitat for many pollinator species. For example, tunnel-nesting bees nest in dead standing trees or piths of stems and twigs of shrubs, grasses, and forbs.

The rate at which organic matter decomposes and releases nutrients is a function of: soil to OM contact, OM particle size, the ratio of carbon to nitrogen (C:N ratio), temperature, and moisture. Decomposition rates of organic matter are highest in soil because the greatest microbial activity occurs when soil is in direct contact with OM (Slick and Curtis 1985; Rose and others 1995). Organic matter placed on the surface of the soil as mulch will decompose at a much slower rate than organic matter incorporated into the soil because there is less contact with the soil.

Organic matter particle size plays an important role in the rate of decomposition. Within the soil profile, the smaller-sized OM fractions decompose faster than the larger fractions due to greater surface area in contact with soil. Roots, leaves, needles, and very finely ground sawdust or bark often decompose much faster than larger materials, such as buried logs or large diameter branches. Materials with C:N ratios, such as wood or bark, decompose much slower than materials with low C:N ratios, such as green leaves and grass cuttings. As Figure 3-38 illustrates, high C:N organic matter will take much longer to decompose than low C:N material, but both will decompose faster when they are reduced in size.

Moisture and temperature also control decomposition rates; cold and dry environments have very slow rates compared to warm, moist sites.

How to Assess Organic Matter—Duff and litter on reference sites can be measured through transects or plots (Section 5.2.3, see Litter and Duff). Estimating forest biomass of down, woody materials in different size classes can be done using photo series guides (Maxwell and Ward 1976a, 1976b, 1979). Fire specialists are experienced in estimating the amount of biomass in forested environments.

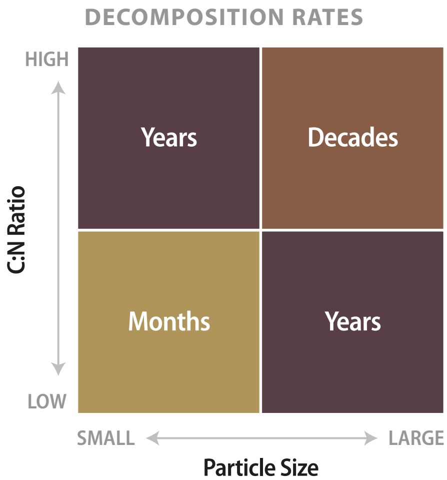


Figure 3-38 | **Relative rates of decomposition by C:N ratio and particle size**

Mitigating for Lack of Site Organic Matter

Salvage and Reapply Litter and Duff—Duff and litter can store a significant amount of nutrients, especially on sites where layers are deep. It can be salvaged separately (Section 5.2.3, see Litter and Duff) or mixed together when topsoils are salvaged (Section 5.2.4).

Process and Apply Organic Matter—Road projects constructed through forested sites can generate high amounts of biomass. These materials can be good sources for slow-release nutrients and carbon. Methods of processing this material and reapplying it to constructed slopes are discussed in Section 5.2.3 (see Litter and Duff). Processed organic matter can be applied directly to the soil surface as a mulch or mixed into the soil as a soil amendment. High C:N organic materials, such as sawdust and bark, can be placed on the soil surface to prevent long-term nitrogen tie-up in the soil or composted for several years to lower the C:N ratio before adding as a soil amendment. Lower C:N materials, such as leaves, needles, and branches, can be incorporated in the soil with some addition of slow-release nitrogen to reduce the effects of nitrogen tie-up.

Apply Composts to Soil Surface—When compost is applied to the surface of the soil (compost blanket), it functions as a soil cover to protect the soil from surface erosion while slowly decomposing and adding nutrients as the plant community develops. Decomposition rates of surface-applied compost are slower than if it were incorporated into the soil because there is very little soil contact at the soil surface. Nutrients are released at a slower rate and are available to the site longer. Leaving the soil surface very rough prior to the application of compost creates more soil-to-compost contact, which can increase the rate of decomposition of the compost. Tackifiers are added to compost to reduce the potential for the material to move off the site. Compost blankets function very differently than mulches; compost blankets are great media for seed germination and plant establishment whereas mulches are not (Section 5.2.3).

Salvage and Place Large Wood—Large wood can be salvaged and placed in areas such as abandoned roads for long-term site productivity, microsite planting, pollinator nesting habitat, and soil erosion control structures (Figure 3-39). When placed in contact with the soil, large wood helps stabilize the surface of the soil from sheet and wind erosion, and can be used as buttresses to stabilize slopes. Seedlings planted on the north side of the logs can be protected from wind and sun during establishment. Large and small wood can be placed at the outlets of culverts as obstacles to capture and store sediments, reducing the amount of sediment reaching live streams (Burroughs and King 1989; Ketcheson and Megahan 1996). When large wood is placed upright, it can be used as barriers to off-road vehicle traffic, nesting habitat for many pollinator species, and feeding and nesting habitat for a range of wildlife species.

Figure 3-39 | **Large wood creates pollinator habitat and reduces soil erosion**

Placement of large wood adds long-term organic matter while creating microsites for planting seedlings and habitat for pollinators and wildlife. Large wood can also slow runoff and detain sediments from surface soil erosion.

Photo credit: David Steinfeld

Soil Nitrogen and Carbon

Nitrogen (N) is discussed separately from the other mineral nutrients because of its critical importance to plant growth and long-term development of plant communities. Carbon (C) is included in this discussion because of its unique relationship to nitrogen availability. Carbon governs the amount of available nitrogen in the soil while nitrogen regulates the rate at which carbon is broken down. Both factors play a critical role in microbiological activity and the development of soil properties.

Carbon to Nitrogen Ratio (C:N Ratios)—Carbon is the energy source for soil microorganisms, and practically all site nitrogen eventually passes through these microorganisms (Woodmansee and others 1978). The rate at which carbon (or organic matter) decomposes is directly related to the amount of available nitrogen and the type of dominant microbes present in the soil. The greater the nitrogen, the greater the decomposition rates. If decomposing organisms do not find sufficient nitrogen in the organic matter, they will withdraw it from the soil, leaving little or no nitrogen for plant growth. This is usually a temporary condition but could last several years. The tie-up of nitrogen can greatly affect the establishment of vegetation if organic amendments, such as wood chips, are incorporated into the soil without supplemental nitrogen.

With time, nitrogen is eventually released from the organic matter by microbial activity. This nitrogen, plus nitrogen released from dead and decomposing microorganisms, becomes available for plant growth. As organic matter breaks down further, there becomes a net increase in available nitrogen. In the last stage of decomposition, microorganisms move to a steady rate of decomposition, releasing a constant nitrogen supply (Figure 3-40). This process can take several years or more depending on site factors and organic matter levels. The C:N ratio is an indicator of whether nitrogen will be limiting or in surplus. A C:N ratio of 30:1 or greater indicates that decomposing organisms have consumed the available nitrogen in the soil, leaving little if any available nitrogen for plant growth. Plants respond by turning yellow and stunted. A C:N ratio below 18:1 is an indication that the decomposing organisms are releasing available nitrogen from the breakdown of organic matter at rates that exceed their need, thereby increasing nitrogen for plant uptake (Claassen 2006). For example, undisturbed topsoils typically have ratios of 10:1 to 12:1, which indicates that nitrogen is sufficiently available for plant growth (Tisdale and Nelson 1975). Dry hay, on the other hand, has a C:N ratio around 40:1, indicating nitrogen will probably be limiting for some period of time if the hay is incorporated into the soil.

The use of high C:N materials is often discouraged because of concerns about tying up nitrogen. However, there are strategies where the use of high C:N materials can aid in achieving project goals. One use of high C:N materials is to apply it to the soil surface or incorporate it into the top several inches of soil to intentionally tie up nitrogen. The lower availability of N at the surface creates a less than optimum growing environment for the establishment of annual weedy species, which thrive on high nitrogen environments.

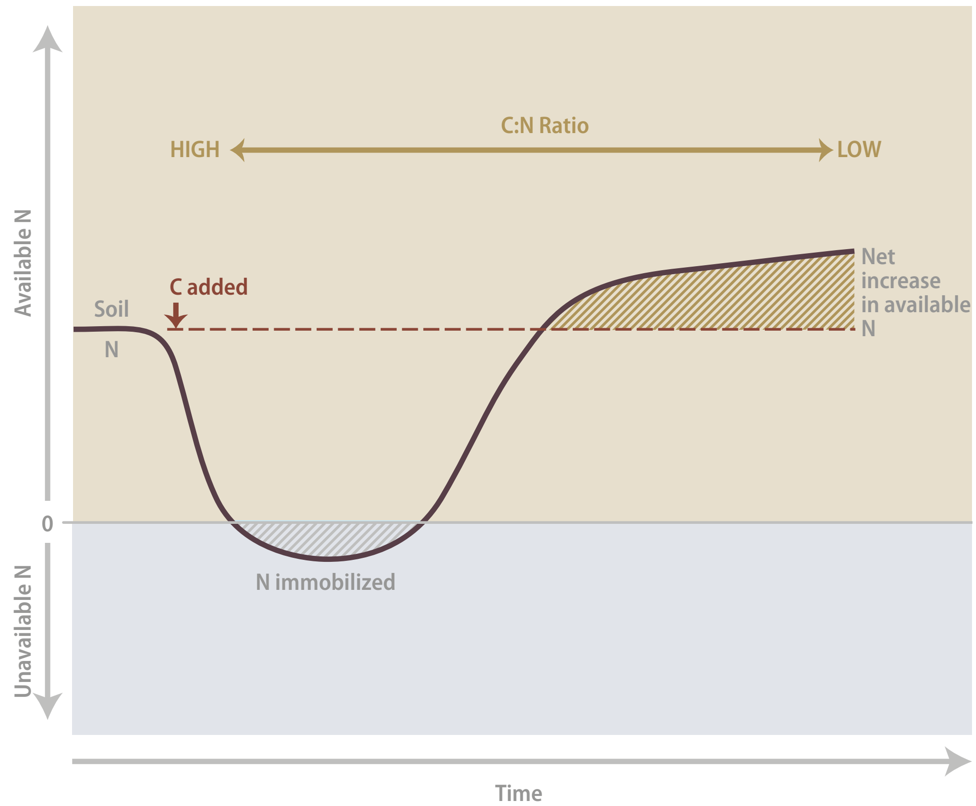


Figure 3-40 | **Release of available nitrogen through decomposition**

Available nitrogen (N) levels change as organic matter carbon (C) is added to the soil. High ratios move to low ratios during decomposition. Nitrogen is tied up in microorganisms during the immobilization phase (blue shaded area) and unavailable to plants. With time, nitrogen becomes available again and, at some point, exceeds the original level (green shaded area). Nitrogen is then released at a constant rate (modified after Havlin and others 1999).

Soil Nitrogen Capital

Soil nitrogen capital can be categorized into three nitrogen pools, or reserves, based on its availability in the soil:

- Available nitrogen (referred to as "extractable nitrogen")
- Slowly available nitrogen (referred to as "mineralizable nitrogen")
- Unavailable nitrogen ("humified organic" or "fresh" forms)

Nitrogen capital can be viewed much like our banking system. Cash received from the bank teller is comparable to "available nitrogen." When money runs low, the teller replenishes it with money from the bank vault (similar to "slowly available nitrogen"). Banks are backed up by money held in an extremely large banking reserve system ("unavailable nitrogen"). While this money is not accessible, it is very important for the long-term stability of the banking system. Unavailable nitrogen is like the banking reserve system in that it backs up the nitrogen system and ultimately releases nitrogen to the plant community.

As with the banking reserve system, having high reserves of both slowly available and unavailable nitrogen ensures that available nitrogen levels will be released at constant rates over time which is necessary for the development of a sustainable plant community. Figure 3-41 shows the relationship of different revegetation treatments on nitrogen capital.

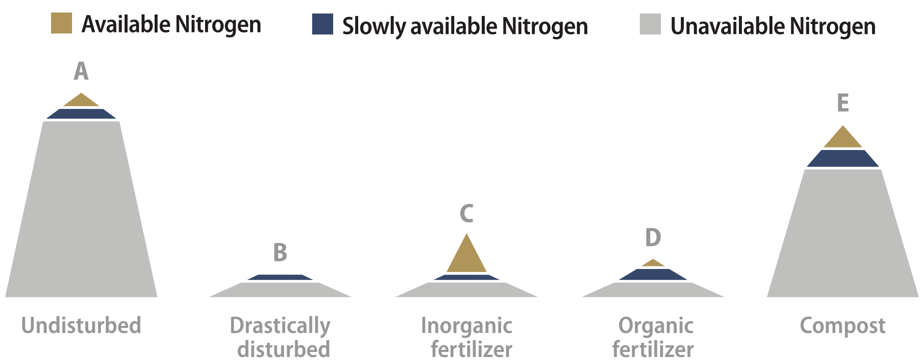


Figure 3-41 | **Managing nitrogen capital**

Undisturbed sites (A) have very high total nitrogen levels, with over 95 percent tied up in organic matter and not available (gray). Slowly available nitrogen (blue) makes up 1 percent to 3 percent of the total nitrogen; available nitrogen for plant uptake (tan) is less than 2 percent of the total nitrogen. Nitrogen capital is essentially removed on drastically disturbed sites (B). The addition of inorganic fertilizer (C) dramatically increases available nitrogen but does little to build nitrogen capital. The application of organic fertilizers (D) raises the available and the slowly available nitrogen but does not add to the long-term reserves. Adding compost to the soil can increase available, slowly available, and total nitrogen reserves (E) to levels comparable to undisturbed soils (A).

On highly disturbed sites, all nitrogen reserves are low. The course of action in typical revegetation projects is to apply inorganic fertilizers during the seeding operation. While this immediately makes nitrogen available, it does little for increasing long-term nitrogen reserves. Within a year of application, most soils will need more available nitrogen to sustain plant growth. Alternatively, organic fertilizers provide a combination of available and slowly available nitrogen. These fertilizers release nitrogen over several years but are typically applied at rates not great enough to bring the nitrogen reserves up to levels for long-term plant community establishment (Claassen and Hogan 1998). Applying topsoil, composts, or low C:N organic matter into the soil are mitigation treatments that create the reserves of unavailable and slowly available nitrogen important for a constant supply of available nitrogen over time.

Minimum Soil Nitrogen Levels

Total soil nitrogen is the sum of available, slowly available, and unavailable nitrogen reserves. The level of total soil nitrogen varies by plant community and ecoregion. It can range from 20,000 lb/ac in deep forest soils of the Washington and Oregon coast (Heilman 1981) to as low as 800 lb/ac in desert grasslands of southern New Mexico (Reeder and Sabey 1987). Shortgrass prairies in northeastern Colorado and shrub-steppe prairies of the Great Basin have a range of total nitrogen from 4,000 to 5,000 lb/ac (Reeder and Sabey 1987). Sites that are drastically disturbed often have nitrogen rates below 700 lb/ac. These sites cannot fully support vegetative cover. A minimum, or threshold, level of total soil nitrogen required for a self-sustaining ecosystem has been suggested at 625 lb/ac (Bradshaw and others 1982) to 670 lb/ac (Dancer and others 1977) for drastically disturbed sites. But Claassen and Hogan (1998) suggest much higher rates might be necessary. In their research on granitic soils in the Lake Tahoe area, they found a good relationship between total soil nitrogen and the percentage of plant cover. Sites with greater than 40 percent ground cover contained at least 1,100 lb/ac total soil nitrogen in the surface foot of soil. This implies that to maintain a minimum of 40 percent plant cover, sites like these must contain at least 1,100 lb/ac of nitrogen, with higher nitrogen levels necessary for higher plant cover (Figure 3-42).

Target levels for available nitrogen released annually from nitrogen sources for plant growth range from below 27 to 50 lb/ac (Munshower 1994). These are nitrogen levels that should be considered when calculating fertilizer rates (Section 5.2.1, see Determine Fertilizer Application Rates).

How to Assess Soil Nitrogen and Carbon—Soil testing for nitrogen can be conducted for: topsoils that will be salvaged, reference sites, and post-construction soil materials. Procedures for collecting soil samples are presented in Inset 3-2. The following nitrogen tests are available:

- **Total nitrogen**—Total nitrogen is an important test to request; the results will be used to determine nitrogen thresholds and nitrogen amendment needs. The common total nitrogen tests are Leco and Kjeldahl. Total nitrogen has been found to correlate well with plant cover (Claassen and Hogan 1998).
- **Mineralizable nitrogen**—This test requires the soil samples to be incubated for a period of time and then tested for available nitrogen. The results indicate the amount of slowly available nitrogen present in the sample. While this test is not widely used, it nevertheless is a very good test to perform because the results correlate well with expected plant cover (Claassen and Hogan 1998). There are several types of incubation tests, so it is good to confer with the soil laboratory as to which tests would be most appropriate.
- **Extractable nitrogen**—This test is less meaningful because it only indicates available nitrogen, not what is in reserve. This test is often included in a soil testing package. The extractable N pool has the lowest correlation to the amount of plant cover growing on a site (Claassen and Hogan 2002). The most common test for extractable nitrogen is 2N KCl extract.

Nitrogen testing for composts and organic matter should be done by laboratories specializing in these tests. These laboratories should follow the testing procedures outlined in the Test Methods of the Examination of Compost and Composting (TMECC) explained in Inset 5-6.

Nitrogen Analysis—Soils laboratories report nitrogen in a variety of units, such as gr/l, ppm, mg/kg, ug/g, and percent. Unless these values are converted to pounds per acre, it is difficult to determine rates of fertilizer, compost, or topsoil necessary to restore site nitrogen. Use Table 3-9 (Line E) to convert lab values to total pounds per acre of nitrogen. These calculations account for soil bulk density, soil thickness, and coarse fragment content, which affect the total nitrogen levels of a site.

Nitrogen Thresholds and Deficits—Each plant community has a total nitrogen requirement that must be met in order to develop into a functioning and self-sustaining system. For successful revegetation efforts, a practical goal is to meet the minimum target, or threshold level, for total nitrogen. Threshold values, however, are not found in textbooks and must be developed from soil tests of disturbed and undisturbed reference sites. Conducting nitrogen tests on disturbed reference sites where revegetation efforts have succeeded, as well as reference sites where revegetation efforts have failed, can help determine a threshold value (Figure 3-42). Alternatively, conducting soil tests on undisturbed reference sites will define the optimum nitrogen levels and also bracket target nitrogen levels. Converting soil test results into total nitrogen per acre is shown in Table 3-9, line E.

Post-construction soils are typically deficient in nitrogen. In order to develop a strategy for bringing soil nitrogen above threshold levels, it is important to determine the approximate nitrogen deficit. Table 3-9 shows how this is calculated by subtracting the total nitrogen value of post-construction soils (Line E) from the threshold nitrogen value (Line F).

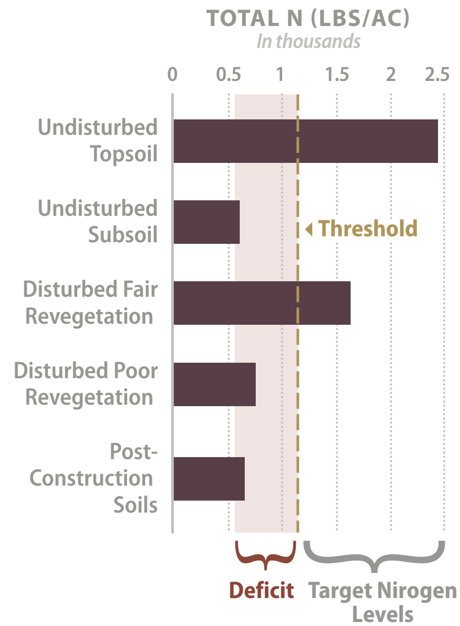


Figure 3-42 | **Determining total N threshold values from reference sites**

In this example, the total N threshold was estimated at 1,100 lb/ac (average of disturbed reference sites with "poor" and "fair" revegetation). Total N in post-construction soils was 650 lb/ac, making these soils deficient by 450 lb/ac. The undisturbed topsoils of reference sites showed a total N of 2,430 lb/ac, which set the target levels of nitrogen between 1,100 and 2,430 lb/ac.

Inset 3-2 | **Soil testing**

Soil testing is a means of describing those soil characteristics that cannot be observed or accurately measured in the field. The tests include analysis of chemical properties, including pH, soluble salts, macronutrients, micronutrients, and organic matter, as well as physical properties such as density, water-holding capacity, and texture. Soil testing is costly and if not sampled, analyzed, and interpreted properly can lead to unneeded and expensive soil amendments and application practices. In many respects, it is better not to test soils than to test them or interpret the results incorrectly. Some laboratory test results found for many soil series in the U.S. is available at the National Cooperative Soil Survey Soil Characterization Data website.

Soil testing is performed with topsoil recovery surveys and reference site surveys (discussed in other sections) to identify soil physical and chemical factors that will limit plant growth, develop site-specific soil quality targets, and develop a set of revegetation treatments that will increase short- and long-term soil productivity targets. The three components of soil testing are soil sampling, lab analysis, and interpretation of lab results. Adhering to an established procedure for each component of soil testing is critical for developing appropriate revegetation treatments.

Sampling soil—Soil sampling is the field collection of soils in a manner that best represents the soils of an area. The number of soil samples taken within a project area is usually kept to a minimum because of the expense of collecting and handling the samples and the cost of laboratory analysis. Taking too few samples to describe a project site, however, can be misleading, especially if the soils are extremely variable. This leaves the designer with the challenge of determining the best approach to collecting soil samples in a way that most accurately represents the sites being described.

The following guidelines are useful in developing a sampling strategy for soil testing:

- **Determine the area to be sampled**—The areas to be sampled are called sampling areas and they typically encompass a vegetation unit, an individual topsoil stockpile, similar topsoil salvage areas, or a reference site. For most projects, only one soil sample is collected from a sampling area. For this reason, it is important to select a collection site (an area where soil samples are collected) that best represents the sampling area. Only for small sampling areas, such as topsoil stockpiles or reference sites, will the collection site be the same as the sampling area. For larger sampling areas, such as revegetation units or topsoil salvage areas, the collection site will be a smaller, representative area within the sampling area.
- **Collect multiple subsamples**—Once a collection site has been identified, a set of subsamples are collected. Collecting soil from one point is never enough. The number of subsamples to collect within a collection site should be based on the site's variability. Small collection sites generally require fewer subsamples than larger areas because these sites are usually less variable. Undisturbed sites are typically more homogenous than disturbed sites and therefore require fewer subsamples. Guidelines for the numbers of subsamples to collect range from 6 for very homogenous sites to 35 for large, heterogeneous sites.
- **Randomly collect subsamples**—Subsamples should be collected randomly within the collection site. For small areas like reference sites or stockpiled soil, the samples can be collected on a grid system. For very large areas, samples can be collected in a zigzag or "W" pattern at predetermined intervals.
- **Determine sampling depth**—The objectives for soil sampling are reviewed and the sampling depth is determined. If the objective is to characterize the soil for topsoil recovery, then the soil samples must be collected only in the topsoil horizon, in which case the depth of the topsoil will have to be determined prior to sampling. If it is known that the surface soil including duff and litter will be removed to 15 inches during topsoil salvage, then collection depth would be a sample 15 inches deep that included the duff and litter layers. If soil sampling objectives are to determine the nutrient levels of a topsoil pile, the entire pile becomes the collection site and the subsamples are collected from various depths within the piles, as well as around the pile to obtain a representative sample. If the designer felt that the interior of the pile was significantly different in nutrient status or mycorrhizae, then the pile could be stratified into two collection sites—the exterior of the pile and the interior—and sampled separately. It may also be important to sample the subsoil because this will be the condition of the soil after construction and before mitigation.
- **Collect a representative slice of soil**—It is important to evenly sample the predetermined depth of soil. For example, if the sampling depth is 0 to 15 inches deep, then the entire section of soil must be equally sampled for each subsample.
- **Mix subsamples**—Subsamples for a sampling area are placed in a clean bucket and mixed thoroughly. From the composite subsamples, the required amount of soil is removed to send to the lab for analysis.
- **Determine coarse fragment content**—If the soils are high in coarse fragments, the samples can be sieved in the field. If the soils are dry, a 2mm sieve can be used. This will reduce the amount of soil to haul out of the survey area and also give an estimate of the coarse fragment content. Soils can be sieved back at the office prior to sending to the lab. If the samples are wet or moist, they will need to be air dried prior to sieving. The percent coarse fragment content is recorded, which includes large and small coarse fragments. This information will be used later to modify the lab results.
- **Selecting a lab**—The criteria for selecting a soil lab is typically based on costs, turnaround time, analytical tests, and consulting services. Most labs offer pH, nutrients, nitrogen, and organic matter tests for under $80 per sample (2016 prices) and deliver the results within two weeks of receiving the soil samples. For an added fee, laboratories will interpret the results of the analysis. While these are important reasons for selecting a lab, the primary

criteria for selecting a lab should be based on the quality of the testing facilities.

A common assumption is that all labs are of similar quality in their analytical testing, and that if a group of labs were sent the same soil sample they would report similar results for most tests. This is not typically the case, as several university reviews of laboratories have shown (Neufeld and Davison 2000; Rose 2004). In one comparison, eight reputable laboratories reported widely differing results for all soil nutrients when sent identical soil samples (Rose 2004). One reason for the variation in results is that usually several testing procedures can be used to quantify a soil parameter. Some methods have greater accuracy and precision than others. The soil testing industry at this time has not settled on an agreed upon set of analytical methods to use. Even when the same tests are performed, labs often report different levels of accuracy (Rose 2004).

Soil laboratories can voluntarily participate in the North American Proficiency Testing (NAPT) program that will assess the quality of their analytical procedures. In this program, NAPT periodically sends all participating labs identical soil samples. Each lab analyzes the samples for mineral nutrients using established analytical procedures, then sends the results back to NAPT. The results from all labs are compiled and analyzed statistically and each lab is sent a report on how their results compared to the other participating labs. NAPT suggest that the accuracy be less than 10 percent of industry values and precision no greater than 15 percent of industry values (Neufeld and Davison 2000). These reports are not available to the public, but laboratories might share them if asked. NAPT is not a certification program but is often a basis for a soil lab quality control program.

The following is a checklist for selecting a high-quality lab (modified from Neufeld and Davison 2000):

- Does the lab have a quality control program? If they do, ask them to explain it.
- Does it participate in a proficiency testing program (such as NAPT)?
- Will they share the results of proficiency testing program?
- Does the lab use established analytical methods (the most appropriate for soils in the geographic area being tested)?

If a "no" is given for the answers to any of these questions, another soil testing facility should be considered. If the selection is between a couple of labs, consider sending duplicate soil samples with known properties ("checks") to each lab and compare the results using the NAPT suggested standards for accuracy and precision. Soil "checks" can be purchased through a proficiency testing program. Once a lab is selected, continue to ask for quality control reports. If the budget allows, periodically send duplicate "check" soil samples with regular soil samples to assess accuracy and precision.

Table 3-9 | **Calculating the nitrogen deficit of a site—an example**

	Parameter		Source
A	Total soil nitrogen (N)	0.025%	From soil test of post construction soils (if rates are expressed as gr/l, ppm, mg/kg, ug/g, divide by 10,000 to convert to percentage)
B	Thickness of soil layer	0.5 feet	The thickness of soil represented in (A).
C	Soil bulk density	1.4 gr/cc	Unless known, use 1.5 for compacted subsoils, 1.3 for undisturbed soils, 0.9 for light soils such as pumice
D	Fine soil fraction	70%	100% minus the rock fragment content (from estimates made from sieved soil prior to sending to lab)
E	N in soil layer *A * B * C * D * 270 =*	331 lbs/ac	Calculated amount of total nitrogen in soil layer. To convert to kg/ha: *E * 1.12*
F	Minimum or threshold N levels	1,100 lbs/ac	Determined from reference sites or literature
G	N deficit: *F - E =*	769 bs/ac	Minimum amount of N to apply to bring up to threshold

Carbon Analysis—Carbon is determined directly using the combustion method (Leco instrument) or indirectly with the Walkley-Black and/or loss-on-ignition methods. Depending on the testing methods, carbon will either be reported as percent of organic matter or percent of carbon. To convert percent of organic matter to percent of carbon, multiply the value by 0.5 to 0.58 (Tisdale and Nelson 1975).

When soils laboratories receive soils samples, they sieve out any materials greater than 2 mm. For this reason, it is important to sieve rock fragments, but not larger organic matter, from the soil samples prior to sending them to the lab. Request that the lab not sieve the larger organic matter from the sample so that the results report out in total carbon and nitrogen.

C:N Ratio—The C:N ratio is calculated by dividing the percent of carbon by percent of nitrogen from the laboratory results obtained for nitrogen and carbon tests.

Mitigating for Low Soil Nitrogen

Develop a Strategy—It is important to develop a strategy for increasing nitrogen over time, especially on sites that are deficient in nitrogen. The strategy takes into account the accumulation of nitrogen by all available sources—topsoil, mulch, compost, fertilizers, and nitrogen-fixing plants. Figure 3-43 shows an example of a strategy for increasing total soil nitrogen to a threshold level.

Topsoil—Salvaging and reapplying topsoil is an excellent way to increase total soil nitrogen on drastically disturbed sites. The depth to apply topsoil should be similar to the soil depth found in undisturbed reference sites or pre-construction soils. If topsoil material is limited, then using the calculations shown in Table 3-9 can help determine the minimum depths to apply topsoil. Section 5.2.4 discusses methods to salvage and apply topsoil. To determine if there is a tie-up or surplus of nitrogen in the salvaged topsoil, soil tests can be conducted for C:N ratios. Topsoils with C:N ratios greater than 25:1 could benefit from the addition of nitrogen, while ratios less than 8:1 will have the necessary nitrogen for plant growth.

Composts—Applied on the soil surface and incorporated, composts can supply sufficient soil nitrogen for long-term site needs. Application rates for composts can be calculated using the methods shown in Table 3-9. Testing and application methods for compost are discussed in Section 5.2.3 and Section 5.2.5.

Nitrogen-Fixing Plants—Significant quantities of nitrogen can be supplied by nitrogen-fixing plants (Section 5.2.7, see Nitrogen-Fixing Bacteria). Establishing nitrogen-fixing plants is a means of meeting short-term goals by reducing the need to apply fertilizers and long-term goals by increasing the total nitrogen on the site.

Fertilizers—Applying nitrogen-based fertilizers to drastically disturbed soils is another means of increasing nitrogen levels, but it requires an understanding of fertilizers (composition and release), how the soils will capture and store nutrients, and how plants will respond to increased levels of available nitrogen. As the calculations in Table 3-9 demonstrate, nitrogen-based fertilizers cannot deliver enough nitrogen in one application for long-term site recovery of drastically disturbed sites. However, applied judiciously within an overall nitrogen strategy using topsoil, composts, and nitrogen-fixing plants, nitrogen-based fertilizers can be an effective tool in site recovery.

Not all sites or conditions require fertilizers. It might not be necessary to fertilize soils that have high total N levels and low C:N ratios. In fact, applying fast-release fertilizers may be a disadvantage on some sites by favoring weedy annuals over perennial species. A discussion on selecting fertilizers, calculating application rates, and determining methods of application is provided in Section 5.2.1.

Biosolids—Biosolids are rich in slow and fast releasing nitrogen and, if sources are available nearby, are a good means of raising soil nitrogen (Figure 5-5).

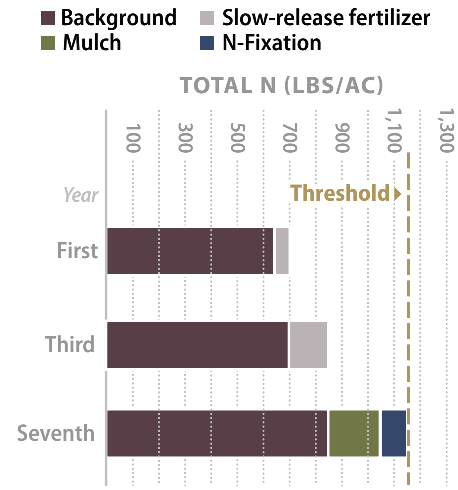


Figure 3-43 | **Raising nitrogen levels**

Raising nitrogen levels on nitrogen-deficient sites to threshold levels requires developing a long-term strategy. In this example, the site began with a background N of 650 lb/ac. After application of a slow-release fertilizer at 1,000 lb/ac during the first year, the site accumulated 50 lb N (assumes N was captured by plants or soil microorganisms and not leached from the soil). In the third year, an additional 3,000 lb slow-release fertilizer was applied, which increased total N to 850 lb/ac. By the seventh year, woody mulch that was applied during sowing had mostly decomposed, releasing approximately 200 lb N. Nitrogen-fixing plants were well established by then and had contributed approximately 100 lb N.

Nutrients

Macronutrients	**N** *Nitrogen*	Major fertilizer element most commonly limiting in disturbed soils Easily leached from soils. Legumes and other plants can fix atmospheric nitrogen in natural plant communities
	P *Phosphorus*	Major fertilizer element frequently unavailable in disturbed soils. Mycorrhizal fungi can improve uptake in natural plant communities
	K *Potassium*	Major fertilizer component that can be leached from soils
Secondary Macronutrients	**Ca** *Calcium*	Besides being plant nutrients, calcium and magnesium can be applied as dolomitic limestone to raise soil pH
	Mg *Magnesium*	
	S *Sulfur*	Besides being a plant nutrient, sulfur can be applied to lower soil pH
Micronutrients	**B** *Boron*	More important for subsequent plant grwoth than for establishment. Micronutrients are frequently unavailable in disturbed soils, but can be amended with organic fertilizers or specially formulated micronutrient fertilizers
	Mn *Manganese*	
	Fe *Iron*	
	Zn *Zinc*	
	Mo *Molybdenum*	
	Cu *Copper*	
	Cl *Chloride*	

Figure 3-44 | **The 13 essential mineral nutrients**

Success in wildland restoration is determined by its species richness, not biomass production or whether it is a self-sustaining and resilient system, not a system that requires constant energy inputs. By these standards, applying the basic agricultural model to wildland revegetation is limited.

This section broadly discusses the remaining mineral nutrients essential for plant growth (Figure 3-44). There are many references devoted to the role of nutrients in plant nutrition and the designer is directed to these sources for a more detailed discussion of each nutrient (Tisdale and Nelson 1975; Thorup 1984; Munshower 1994; Havlin and others 1999; Claassen 2006). Historically, the majority of research in soil fertility and mineral nutrients was conducted with the agricultural objective of optimizing crop yields through annual inputs of fertilizers, soil amendments, and irrigation. The primary objective of wildland restoration, however, is to restore or re-create self-sustaining plant communities that, once established, require very little input of resources. Unlike agriculture, revegetation of highly disturbed sites is not approached with the objective of optimizing the site for a single, high-yielding crop, but to develop a system of interrelated species that have evolved and adapted to site conditions. In wildland restoration, it is more important to re-create the components of the local soils than to change nutrient status based on agricultural models. For example, from an agricultural perspective, a serpentine soil has an imbalance of calcium and magnesium. Unless fertilizers containing a "correct" ratio of calcium and magnesium are applied to adjust this imbalance, the soils will be unsuitable for crop species. In wildland restoration, the approach is guided by the nutrient needs of the species endemic to the site, not to a generic agricultural crop. Because serpentine plant species have evolved on soils with these nutrient ratios, their nutrient requirements are vastly different than those of agricultural crops, or even native vegetation growing on adjacent, non-serpentine soils. In this example, the calcium-to-magnesium ratio would not be seen as an imbalance for native serpentine plant establishment, but perhaps as a "requirement" for certain endemic species to recolonize the site. This requires the designer to compare post-construction mineral nutrient status to that of undisturbed or recovered reference sites to determine if there are deficiencies. Amendments can then be applied to bring nutrients and other soil factors to pre-disturbance levels or to levels that meet project revegetation objectives.

How to Assess Nutrients—The objective of nutrient analysis is to compare nutrient levels of post-construction, disturbed soils with those of pre-disturbance, or reference site, soils. Where there are large discrepancies, a strategy can be developed to bring low post-construction levels up to minimum nutrient levels. Because this is a comparative analysis, it is essential that the sampling, collection, and testing methods are identical.

Nutrient tests are often performed on salvaged topsoil, reference sites, post-construction slopes, and areas where there have been failures in revegetation. A guide to sampling soils for nutrient analysis is presented in Inset 3-2. Nutrient testing can be used to evaluate total soil nutrient levels for long-term nutrient availability, as well as available levels, for immediately available nutrients for plant growth. Table 3-10 lists common soil tests.

Table 3-10 | **Soil testing methods**

Common soil testing methods for the western United States (Horneck and others 1989; Munshower 1994; Teidemann and Lopez 2004).

Note: Composts use a different set of tests due to high organic matter (Table 5-9).

Tests	Type	Test method	Notes
Boron	Available	Hot-Water	
Boron	Available	Aqueous extract of a soil paste	
Calcium, Magnesium	Available	Ammonium Acetate	
Calcium, Magnesium	Available	Aqueous extract of a soil paste	In semi-arid to arid soils
Molybdenum	Available	Ammonium oxalate-oxi acid extraction	
Nitrate	Available	Aqueous extract of a soil paste (Saturated paste)	Accepted extrant for western soils
Nitrate	Available	CaO extract & Cd reduction	
Nitrogen (ammonium and nitrate)	Available	KCL Extraction	
Nitrogen (mineralizable)	Slowly - Available	Anaerobic Incubation	
Nitrogen (total)	Total	Kjeldahl N	
Nitrogen (total)	Total	Combustion (Leco Instrument)	
Organic matter	Total	Loss - Ignition	Best used for soil high in or-ganic matter
Organic matter	Total	Walkley-Black Method	
Organic matter	Total	Combustion (Leco Instrument)	Reports out in Total C
pH		Aqueous extract of a soil paste (saturated paste)	
Phosphorus	Available	Olsen Sodium Bicarbonate	For arid and semi-arid soils
Phosphorus	Available	Dilute Acid-Flouride (Bray-P1)	For mesic sites
Phosphorus	Available	AB-DIPA	Reports out at half the rates of Olsen method
Potassium	Available	Sodium Acetate	
Potassium	Available	Olsen Sodium Bicarbonate	For arid and semi-arid soils
Potassium	Available	Ammonium Acetate	
Sodium	Available	Ammonium Acetate Displacement	
Sodium	Available	CTPA	
Sulfate Sulfur	Available	Aqueous extract of a soil paste (saturated paste)	
Sulfate Sulfur	Available	$CaHPO_4$ & ICP	
Zinc, Copper, Manganese, Iron	Available	CTPA	Iron is not performed in Oregon because not found deficient

With soil laboratory results from reference sites and post-construction sites, determine which nutrients, if any, are deficient using the process outlined in Section 5.2.1 (see Develop Nutrient Thresholds and Determine Deficits). If a nutrient is found deficient, fertilizers, composts, topsoil, or other organic amendments can be applied to the soil to bring the nutrient above threshold levels. A process for determining fertilizer type, application rates, and application methods is presented in Section 5.2.1.

Mitigating for Low Nutrients

Topsoil—Salvaging and reapplying topsoil are important for restoring nutrients to pre-construction levels, especially on sensitive soils (e.g., serpentine and granitic soils). The depth to apply topsoil should be at levels found in undisturbed reference sites or pre-construction soils, or can be calculated by methods described in Figure 5-27 in Section 5.2.4.

Compost—Incorporating composts is a good method for increasing nutrients to pre-disturbance levels. Determining which type of compost to select and how much to apply is discussed in Section 5.2.5.

Fertilizers—As discussed in Section 3.8.4, fertilizers should be used within an overall nutrient strategy. See Section 5.2.1 for a discussion on application methods, fertilizer types, timing, and other important aspects of fertilization.

Biosolids—Biosolids are rich in nutrients. If sources are available and transportation economical, this is a good way to add nutrients to disturbed sites (Figure 5-5).

pH

pH (potential of hydrogen) is the measurement of soil acidity or alkalinity based on a logarithmic scale of 0 to 14. Soils with pH values below 7 are acidic, and those above 7 are basic. Basic soils have high amounts of bases (positively charged ions), such as calcium, magnesium, potassium, sodium, and phosphates. Basic soils have developed under arid and semi-arid climates and are found throughout the Basin and Range, Colorado Plateau, and portions of the Great Plains. Acidic soils have formed in wetter climates, where the continued movement of water through the soil profile leaches bases from the soil. Acidic soils are common in the eastern United States, the coast range and mountains of the Pacific Northwest, and the Gulf states (Figure 3-45). Topsoils are typically more neutral when compared to underlying subsoil, whether the soils are acidic or basic. In some cases, the topsoil buffers the plant root systems from the underlying, inhospitable subsoil conditions. When topsoils are removed during construction, subsoils become the growing environment and, unless mitigating measures are taken, plant establishment and productivity of the site is greatly reduced.

Soil acidity and alkalinity affects mineral nutrient availability, mineral toxicity (Palmer 1990), and nitrogen fixation (Thorup 1984). In acid soils, the ability of plants to utilize many nutrients decreases, especially for calcium and magnesium. As soil pH becomes more acid (less than 4.5), aluminum becomes more soluble and more toxic to plant growth. Low pH soils also hinder the establishment of nitrogen-fixing plants, such as legumes (Bloomfield and others 1982). Significant loss of rhizobia viability has been documented at pH levels less than 6 (Brown and others 1982).

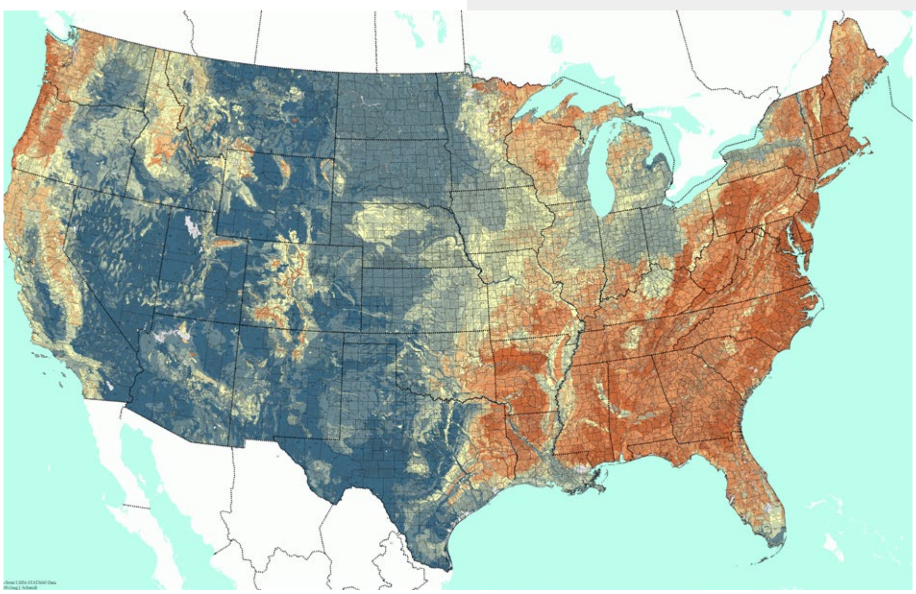


Figure 3-45 | **Soil pH levels across the US**

The soils of the United States have a range of soil pH values, from less than 5.0 to greater than 8.0. Basic (high pH) soils shown in blue are widespread in areas of the United States that receive low rainfall. Acidic soils (low pH) shown in red occur in areas of very old soils common in the eastern United States or in areas of high rainfall common to the Pacific Northwest.

Source: Bonap.org

Soil with pH values of 8.0 or greater indicate the presence of calcium carbonate (Thomas 1967). Calcium and magnesium are at such high levels that they interfere with the uptake of other nutrients, notably phosphorus, iron, boron, copper, and zinc (Campbell and others 1980). High pH soils typically have high salt levels, which can also restrict the growth of many plants. For example, as soil pH approaches 9.0, sodium concentrations become toxic to plants (Tisdale and Nelson 1975).

How to Assess pH—The pH test is a standard analytical measurement that is typically run on soil samples sent for nutrient analysis. The pH test is also conducted on soil organic matter amendments considered for mulch or incorporation into the soil. The pH test is accurate, with values differing between laboratories by 0.1 to 0.2 points (Thomas 1967). pH can also be tested by the practitioner on site or back at the office using reasonably priced equipment. Most portable pH meters can measure soluble salts and this dual capacity is important in areas with high salts (Section 3.8.4, see pH). It is important when selecting a pH meter that has a tip that can be submerged easily in a soil slurry.

The most accurate method of assessing pH is through lab analysis. However, quick, reliable estimates can be made with a hand-held pH/electrical conductivity meter using the Saturated Media Extract (SME) method for preparing samples (Figure 3-46). This method requires a small amount of soil (50 cc) be placed in a jar. Just enough distilled water is stirred into the soil to make the surface "glisten" but not readily flow. After the mixture rests for approximately 15 minutes the pH probe is inserted into the soil so that the sensors are completely covered and the pH reading is made.

Figure 3-46 | **pH meter**

Most portable pH meters will also measure salts (electrical conductivity). Many probes can be directly inserted into the saturated media.

Photo credit: David Steinfeld

Mitigating for Low pH Soils

Apply Liming Materials—Raising the pH through the application of liming materials is a common agricultural practice that can be applied to revegetating road sites (Section 5.2.6).

Apply Appropriate Fertilizers—Some commercial fertilizers, especially ammonium-based fertilizers such as ammonium nitrate, ammonium sulfate, and ammonium phosphate, will reduce pH (Havlin and others 1999) and should be limited on acidic soils. Fertilizers that have calcium, magnesium, or potassium in the formula are more appropriate for low pH soils. Examples of these fertilizers are calcium nitrate, potassium nitrate, and magnesium sulfate.

Apply Lime with Organic Matter—Incorporation of organic matter will lower pH. On acid soils, application of lime with organic matter will raise the pH of the soil (Section 5.2.6).

Apply Topsoil—Where topsoils have been removed leaving very basic or very acidic subsoils, reapplying topsoil or manufactured topsoil can moderate pH levels.

Mitigating for High pH Soils

Apply Organic Matter—Incorporated composts or other types of organic matter can lower soil pH as the organic matter decomposes (Havlin and others 1999). For arid sites, however, the pH and conductivity of the organic matter must be tested prior to purchase to avoid the possibility of introducing organic matter high in salts.

Add Nutrients—To compensate for the tie-up of certain nutrients, the addition of nutrients through fertilization may be considered, however, the benefits of using fertilizers on arid soil must be offset by the possibility of creating fertilizer salt problems.

Apply Sulfur—Agricultural soils can be treated with sulfur to lower pH, but high quantities of sulfur and irrigation must be applied to lower the pH just slightly (Havlin and others 1999). The use of sulfur in roadside revegetation therefore is not a widely practiced method.

Irrigation

Applying irrigation water is another method of reducing soil pH by leaching out bases. However, the amount of water needed to lower pH levels can be very high; in most cases, using irrigation is not a viable mitigating measure on roadsides. It is also difficult to find irrigation water in arid environments that is low in bases and salts. Applying irrigation water that is high in bases will raise pH and salt levels in the soil, compounding the problem.

Salts

Soil salinity is the measure of the total amount of soluble salts in a soil. The term soluble salts refers to the inorganic soil constituents, or ions, that are dissolved in the soil water. The principal soluble salts in most soils contain the cations—sodium, calcium, and magnesium, and the anions chloride, sulfate, and bicarbonate (Landis and Steinfeld 1990).

Almost all plants are susceptible to salt injury under certain conditions, with germinants and young seedlings being particularly susceptible to high salt levels (Figure 3-47). Soluble salts can injure plants in several ways:

- **Reduced soil moisture**—Salts can lower the free energy of water molecules, causing an osmotic effect and thereby reducing the moisture availability to plants.
- **Reduced soil permeability**—High salt concentrations (specifically sodium salts) can change the soil structure by reducing the attraction of soil particles, causing them to disperse. Pore space is lost and air and water movement within the soil profile are restricted.
- **Direct toxicity**—High levels of certain ions, including sodium, chloride, and boron, can injure plant tissue directly.
- **Altering nutrient availability**—Certain nutrients as salts can change the availability and utilization of other plant nutrients (Landis 1981; Landis and Steinfeld 1990).

High salt levels are common in arid regions of the United States where there is inadequate precipitation to leach salts out of the plant root zone (Figure 3-48). As a result, salts move out of the topsoil and accumulate in the subsoil. At high enough concentrations, a layer of calcium carbonates form, creating an impermeable horizon call caliche. This layer restricts root growth and soil drainage. When topsoil is removed, the resulting surface soils may be very high in salts or where a caliche horizon is present, may expose a hardened calcium carbonate surface.

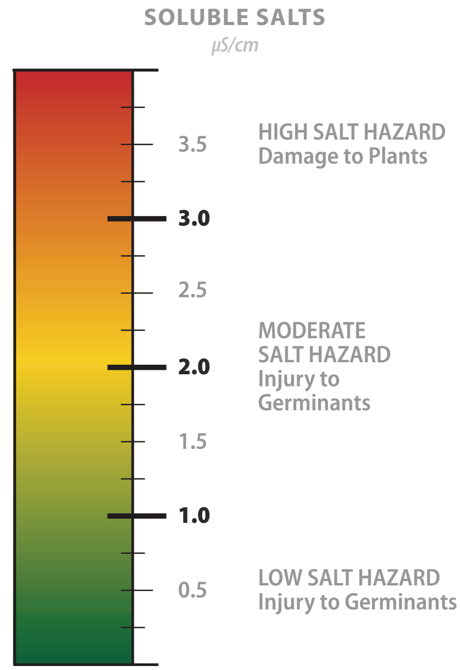


Figure 3-47 | **Soluble salt effects on plants**

Soluble salts will injure germinants and, at higher concentrations, damage established plants. Values are based on the saturated media extract method of conductivity measurement reported in mS/cm (microSiemens per centimeter).

Modified from Fisher and Argo 2005

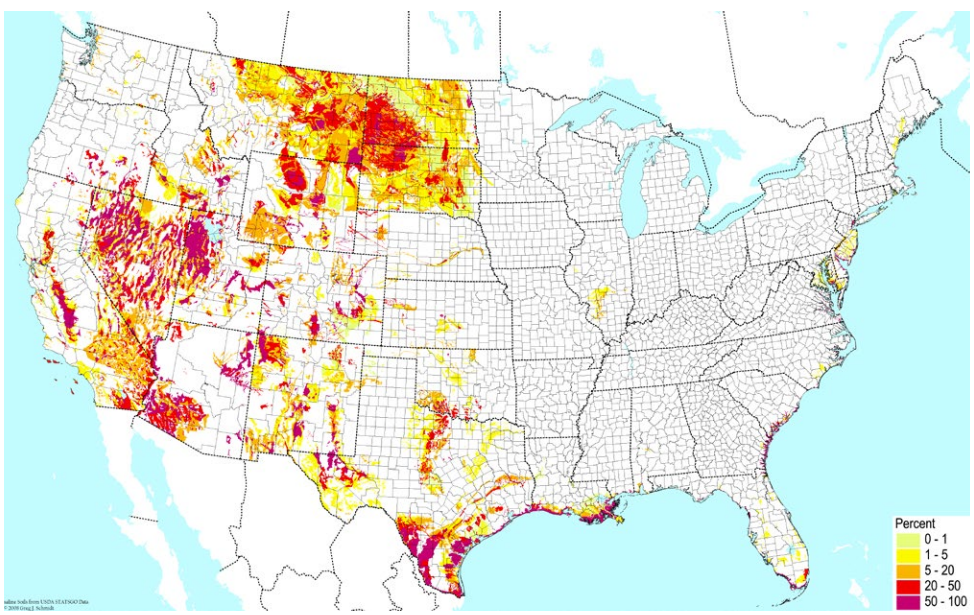


Figure 3-48 | **Soils with high salts**

Soils with naturally high salt content typically occur in regions of the United States with low annual precipitation.

Source: Bonap.org

High salt concentrations can also be created by poor soil drainage resulting from compaction; when excessive amounts of fertilizer, manure, or compost are applied; or when de-icing chemicals applied to roads run off and enter the soil (Parent and Koenig 2003).

Deicing salts can pose a problem to plant establishment depending on the annual quantity of salt applied, distance from the road, type of salt applied, annual precipitation, and soil type (Section 3.11.9, see Deicing for Winter Safety). The sensitivity of a plant species is also important and it may be necessary to revegetate with plant species that are less sensitive to salts. These can be selected using the ERA tool.

How to Assess Salts—There are two methods of measuring salts: Electrical Conductivity (EC) and Total Dissolved Salts (TDS).

EC is a relatively easy test to run and is the most commonly used test in nurseries, forestry, and agriculture. Most pH meters are equipped to measure EC. Electrical conductivity measures how strongly electrical current flows between two metal plates. The more dissolved salts there are in solution, the greater the current and higher the electrical conductivity. EC is reported as the conductance over the distance between plates. The standard unit of measure is microSiemens per centimeter (μS/cm), though there are many ways that it can be expressed which can be confusing. To convert these units to μS/cm:

- μS/cm = 0.001 dS/m
- μS/cm = 0.001 mS/cm
- μS/cm = 0.1 mS/m
- μS/cm = 0.001 mmho/cm
- μS/cm = 1 μhos/cm

The most accurate method of assessing salinity is through lab analysis, however, quick estimates can be made with a hand-held pH/electrical conductivity meter using the Saturated Media Extract (SME) method for preparing samples as described in Section 3.8.4 (see pH). Landis and Dumroese (2006) provide a more detailed discussion on EC and measuring methods.

The second method of measuring salinity is the TDS. In this method, a known sample (water or soil solution) is evaporated and the remaining salt is weighed. This test is more difficult to run but it is often used in reporting salinity levels in road deicing studies. Test values are reported in milligrams per liter of water (mg/l) which is equivalent to parts per million (ppm). To convert TDS values to EC:

$$EC\,(\mu S/cm) = TDS\,(mg/L)/0.6$$

Mitigating for Salts

Because high levels of soluble salts are often caused by poor soil management, the key to mitigating high salinity is to avoid creating the conditions that could cause those levels. In soils where internal drainage is poor, prevention may be the only feasible approach for reducing salt problems. Reducing the quantity of road deicing salts can also lower the amount of salts that enter the soil.

Avoid Mulch or Soil Amendments with High Salinity—Testing all materials to be applied to the site will aid in the prevention of increased salt levels in the soil. Amendment materials with electrical conductivity readings more than 1 μS/cm should be avoided.

Reduce Commercial Fertilizers—Some commercial fertilizers, such as control-release fertilizers (CRF), can significantly increase the soluble salts found in the soil. This can be a major problem when using CRF in arid conditions. The fertilizer will begin to release following wet, warm spring conditions, but will not be leached through the soil without significant rainfall through the summer. Salts can build up to damaging levels, both on the surface and in the plant root zone.

Apply Gypsum with Irrigation—Incorporation of gypsum (calcium sulfate) followed by leaching can be effective in situations where sodium is the cause of high soluble salts (e.g., de-icing materials have been applied to roads). The calcium in gypsum will displace sodium, and the sodium will then leach out of the soil profile with irrigation or rainfall (UMES 2004).

Irrigation—Application of irrigation water if often used to leach salts from the soil. The amount of water depends on the soil type. In arid soils, application of 6 inches of water can reduce salinity levels by 50 percent; 12 inches can reduce salinity levels by 80 percent; and 24 inches can reduce salinity levels by 90 percent (UMES 2004). However, for most sites roadside project, this is not practical due to high costs.

Select salt resistant plant species—If salts are present or are expected to be present through deicing practices, selecting species from the ERA that are less sensitive to the effects of salts may improve revegetation.

3.8.5 SURFACE STABILITY

Surface stability is the tendency of the soil to remain in place under the erosive forces of rain, wind, and gravity. Good surface stability is essential for establishing plants, reducing erosion, and maintaining high water and air quality. When seeds are applied to unstable surfaces, they often move off the site through water or wind erosion leaving the site barren of vegetation. Soil is also removed in this process, which reduces the productivity of the site. Excessive erosion also affects the survival of planted seedlings by removing soil and exposing roots.

Site factors that influence surface stability and soil erosion are as follows:

- Rainfall
- Wind
- Freeze-thaw
- Soil cover
- Surface strength
- Infiltration rates
- Slope gradients
- Surface roughness
- Slope lengths

All surface erosional processes start first with the detachment of soil through the forces of rainfall, wind, or frost heave. These forces loosen seeds and soil, making them more susceptible to movement off the site. Surface runoff, during rainstorm events, is the primary factor in moving seeds and soil into stream channels, resulting in lost seeds and water quality problems. This occurs when infiltration rates (the rate water moves through the soil surface) are lower than rainfall rates. If slope gradients are steep, slope lengths are long, or surface roughness is low, surface water picks up energy and transports greater amounts of soil and seeds downslope. As this energy increases, water becomes concentrated with enough force to cut through the surface of the soil, creating rills and gullies. The degree to which soils detach is directly related to the percentage of soil cover protecting the soil (more cover, less erosion) and to the soil strength, or the capacity for individual soil particles to hold together under erosional forces. The result of soil erosion can often be detected on road cuts by noting how much sediment is in the ditch line. If the ditch is full of recently deposited sediment (recently deposited sediment usually lacks vegetation), there is a good chance that sediment came from the cut slope. An inspection of the surface of the cut slope will indicate if the sediment originated there. Gravels, cobbles, and even small plants will show the results of soil movement (see Figure 3-52, Figure 3-54, and Figure 3-55).

Rainfall

Each project site has a unique rainfall pattern that will affect the stability of the soil surface. Periods of high rainfall intensities can move seeds and soil particles off-site through erosional processes which begins with the raindrop. Raindrops have been likened to small bombs. In heavy rainstorms, they fall with such speed (up to 20 miles per hour) that, when they hit the soil surface, they create an impact that can blast the soil or seeds several feet away and leave behind small craters. After such events, the soils surface is compacted and sealed with fine soil particles that can significantly reduce surface infiltration rates.

The intensity of a rainfall event determines how much soil is detached. A high intensity rainfall will detach more soil particles than a low intensity rainfall. But detachment is only one aspect of erosion; it takes surface runoff to move soil and seeds downslope. If an intense rainstorm lasts only a short period, there may be insufficient water to exceed infiltration rates and water will absorb into the soil. If the duration is long, some water will not enter the soil, and run over the surface as overland flow, carrying soil and seeds downslope. The most critical weather events are those that bring high intensity rainstorms of long duration. High intensity rainfall is common in the central and eastern United States, whereas in the western U.S., high intensity storm events are less frequent and typically occur during summer thunderstorms or major winter storm systems (Figure 3-49). Precipitation in the form of snow is not typically a problem for surface erosion because snow cover protects the soil surface from rainfall splash and water from snowmelt usually occurs at such slow rates that even soils with low infiltration can absorb it, reducing the likelihood of runoff.

How to Assess Rainfall—It is unlikely that climate reports or weather records will give the duration and intensities of rainfall events for site level planning. Digital rainfall gauges are available that record the amount of rainfall and the time it occurred. This information is used to determine duration and intensity. While the cost of this equipment is high, it is becoming more affordable. Many types of digital rain gauges are available, ranging in price and quality. It is important to select a digital rain gauge that is rugged, self-maintaining, and can record for long periods of time. Some systems upload weather data to the internet where it can be accessed remotely through smart phones and computers for data summary and analysis.

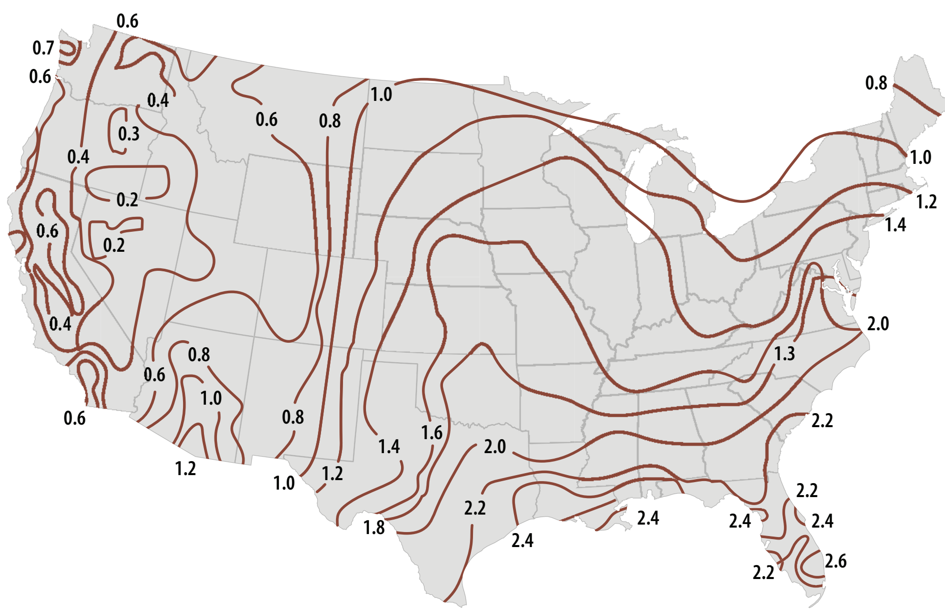


Figure 3-49 | **Rainfall intensities across the US**

Rainfall intensities increase moving from western to eastern United States. The differences in intensities can be dramatic, ranging from 0.2 inches/hour in Nevada to 2.6 inches/hour in Florida for a 2-year, 1-hour storm event.

Source: FHWA

Mitigating for High Rainfall

Minimize Disturbance—In areas of high rainfall or sites where water quality values are high (near streams or rivers), the best engineering design is to keep the footprint of the construction project disturbance to a minimum. Not only does this reduce the risk of delivering sediment to the aquatic system, it can reduce project costs by reducing the amount of area needing revegetation.

Integrate Erosion Practices—On disturbed sites, especially those near streams, the integration of erosion practices with plant establishment techniques offers the best approach to stabilizing the soil surface. These include practices such as increasing soil cover, shortening slopes, reducing slope gradients, leaving roughened surfaces, reducing compaction, increasing infiltration rates, and quickly establishing native vegetative cover.

Use Appropriate Mulching Practices—Applying a surface mulch is one of the best practices for controlling surface erosion because it protects the soil surface from rainfall impact and reduces overland flow. The types of mulches are described in Section 5.2.3.

Wind

Wind erosion can be a major limiting factor in establishing native plants (Figure 3-50), especially in the Great Plains and portions of the Eastern Temperature Forests ecoregions (Figure 3-51). Wind erosion begins with a process called saltation in which a soil particle is lifted by the wind and bounced along the ground surface, dislodging other soil particles in its path. The resulting dislodged particles either become airborne or continue to roll or hop along the surface of the soil, dislodging more particles. Saltation occurs with very fine to medium sands, ranging from 0.003 to .04 inches (.07 to 1 mm). Particle sizes smaller than that (silts and clays) become airborne and can be carried long distances (Fifield 2004).

Wind erosion affects revegetation in several ways. Newly sown seeds and seed cover can be removed in high winds, resulting in poor germination and plant establishment. Plants that do establish, can be damaged through saltation, where dislodged soil particles continually abrade the plant stems. In extreme conditions, topsoil is removed, reducing the soil productivity and plant growth. This is more severe where topsoils are thin. Where plants are established, loss of topsoil can also expose roots, causing reduced growth and in some cases, mortality.

How to Assess Wind—Permanent wind speed equipment is available but is most likely beyond the reach of most project budgets. Site visits during different times of the year provide some indication if wind is a problem. Site characteristics, such as position on slope (ridgelines are more prone to high winds than a valley floor) or proximity to forested environments (forests often reduce wind speeds). Observing soil surfaces for signs of erosion can be helpful and include appearance of bare soils, exposed roots, and fine soils deposited behind stable structures. Local residents may also provide some information on local weather events.

Assessing risk of wind erosion can be determined by:

- **Wind speed**—The rate of soil movement is proportional to wind velocity. Wind speeds are considered erosive when they exceed 13 miles per hour measured 1 foot above the soil surface for loose sands (Lyles and Krauss 1971).

Figure 3-50 | **Wind erosion removes topsoil and exposes roots**

Wind erosion not only blows seeds, soil, and mulches off the soil surface, it will also expose roots of established plants, as shown in this photograph. Non-cohesive soils, like sands and silts, are most prone to wind erosion.

Photo credit: David Steinfeld

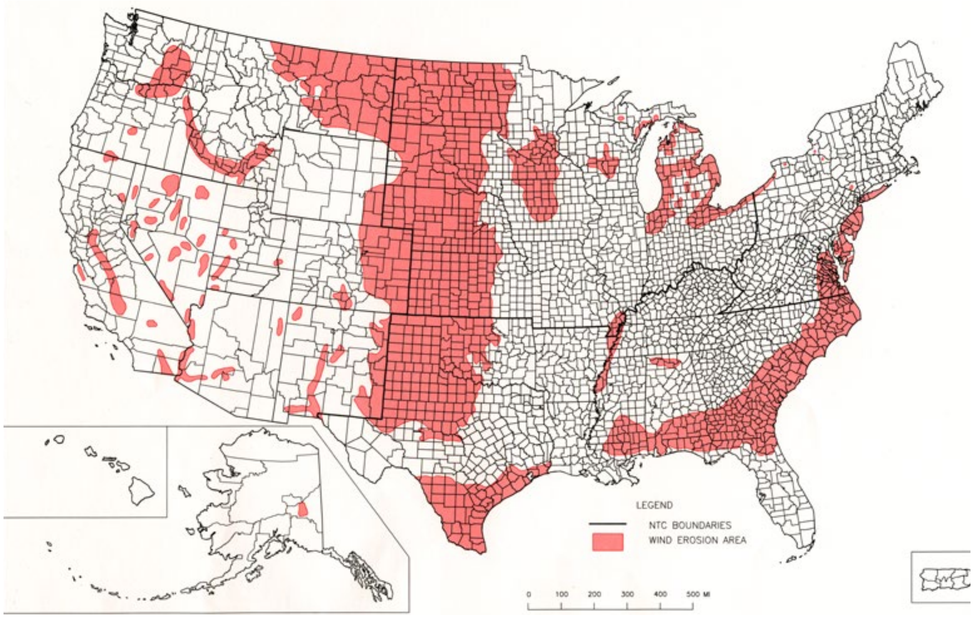


Figure 3-51 | **Areas in the United States that have high winds**

High winds are the primary cause of soil erosion in many areas of the United States. This map shows areas where wind erosion could strongly influence the establishment of native plants (areas in red) (FHWA 1992). The effects of wind on revegetation are very site specific, the potential of which can be determined during field surveys.

- **Soil Texture**—Silt contents have the most potential to be dislodged and become airborne. Clays can be susceptible when soils have been continually disturbed and clods have been destroyed. Sandy texture soils are less susceptible to becoming airborne but will move through surface creep and saltation.
- **Rock fraction**—The amount of rock fragments in a soil affects the severity of wind erosion; the more rock, the greater the protection of the soil surface. In addition, surface rocks may also collect windblown silts and sands over time, increasing soil depth.
- **Organic matter**—Soils that are higher in soil organic matter, especially organic cements that produce stable aggregates, have greater stability.
- **Water content**—water holds soil grains together through cohesion so when surface soils have a high moisture content, they have greater strength.
- **Surface roughness**—a roughened soil surface composed of a microtopography of ridges and valleys will trap and suspend soil particles, especially if the ridges are predominantly perpendicular to the direction of the wind.
- **Vegetative cover**—The height and density of vegetation affects the air flow on the surface of the soil; the greater the height and density the lower the wind velocity. Windbreaks, such as shelterbelts, can significantly reduce wind velocities (see Inset 3-3).
- **Soil cover**—Soils that are covered with a stable material are more resistant to wind erosion.

Mitigating for High Wind

Maintain vegetative cover—Keeping the construction footprint to a minimum is one of the best practices for controlling wind erosion. Minimizing the width of the disturbances perpendicular to the direction of the prevailing winds will also reduce the effects of strong winds.

Install shelterbelts—A shelterbelt is a line of trees that reduce the wind velocity and reduce the potential for wind erosion (Inset 3-3). The ERA tool can be consulted for appropriate trees and shrubs suitable for shelterbelts, depending on the ecoregion.

Create microtopography of ridges and furrows—When the soil surface is left in a roughened condition of ridges and furrows, wind erosion can be reduced significantly, however the effectiveness depends on the stability of the soil (Fryrear and Skidmore 1985). Ridges formed in non-cohesive soils or soils that do not form clods when tilled, will have a short life span.

Tillage, using a land imprinter (Section 5.2.2, see Roughen Soil Surfaces), may be a good alternative to loosening soils with traditional tillage equipment (e.g. disks, harrows) because imprinting compresses the soil while it forms depressions, thereby creating a roughened surface and increasing soil strength that will increase resistance to wind erosion (Dixon and Simanton 1977).

Mulch—Applying a mulch is one of the best practices for controlling surface erosion (Section 5.2.3), however, mulches be removed with strong winds. Some materials, such as wood strand mulches (Section 5.2.3, see Wood Strands and Wood Wool), have been tested under high wind conditions and, because of higher weights and interlocking particles, may be more resistant to high winds.

Lighter mulch materials, such as straw and hay, are more susceptible to wind erosion and must be crimped into the soil to keep them in place. Hydromulch with tackifier or just tackifier applied with hydroseeding equipment can be effective in stabilizing hay mulches in areas with lower wind speeds.

Place Large Woody Material—Downed woody material, such as trees and large branches, can be used to block the soil surface from wind and rainfall.

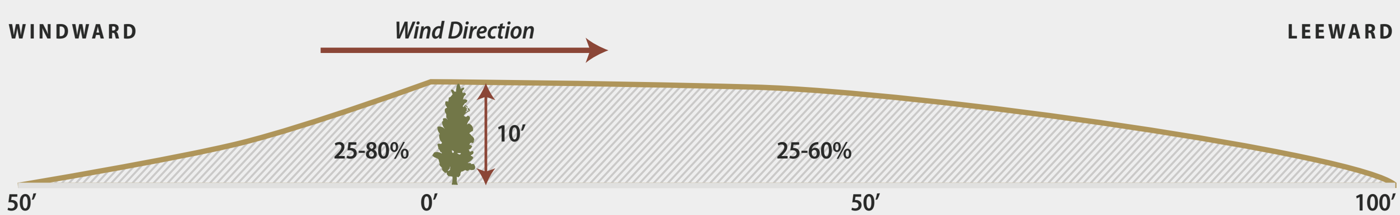
Inset 3-3 | **Wind breaks—shelterbelts and living snow fences**

Shelterbelts. A shelterbelt is a vegetative barrier that reduces wind speeds, resulting in lower soil erosion. Shelterbelts also provide excellent pollinator and wildlife habitat. Shelterbelts work by creating wind resistance in the face of the prevailing wind. The reduction in wind velocity can be significant depending on the height of the shelterbelt. Depending on the wind speed, the effect on the leeward side of the shelterbelt (the side away from the wind), can be up 10 to times the height of the shelterbelt and on the windward side (the side toward the wind), as much as 5 times the height (see illustration below).

For greatest effectiveness, shelterbelts are designed perpendicular to the direction of the prevailing winds. Shelterbelts with multiple rows of vegetation have a greater reduction in wind speeds than single row shelterbelts because there is more vegetation to block wind flow. A two-row shelterbelt composed of shrubs and trees not only provides more wind resistance, it provides better wildlife and pollinator habitat. The effectiveness of a windbreak depends on the selection of tree and shrub species and planting density. It is important to understanding wind speeds, shelterbelt effectiveness, and appropriate species specific for the project area to develop an appropriate shelterbelt design.

Wind speeds can be reduced on the leeward side of a shelterbelt by 25 to 60 percent within a distance that is 10 times the height of the shelterbelt. It also can reduce wind speeds on the windward side by 25 to 80 percent within a distance 5 times the height on the windward side. In the example shown below, a 10-foot-high shelterbelt reduces the wind velocity significantly 50 feet before the shelterbelt and 100 feet beyond the shelterbelt (modified from Casement and Timmermans 2007).

Living Snow Fence. When vegetation is installed for snow management, it is referred to as living snow fences. Densely planted trees and shrubs along highways can reduce the amount of snow drift on roadways and subsequently, lower winter maintenance costs. These living snow fences create a barrier which reduces wind speeds and drops snow in front of and downwind of the break. Designing an effective living snow fence requires an understanding of the wind speed, wind direction, and annual snowfall. Some of this information can be obtained from historic climate data from local weather stations (**Section 3.3.1**) but in most cases, it can be obtained from local maintenance personnel. Visiting existing snow fences during the winter can help in designing living snow fences. The most effective living snow fence is planted perpendicular to the prevailing wind direction at a minimum of 175 feet from the road centerline (South Dakota Department of Agriculture (2006). Other States and municipalities may have guidance on the design of natural or man-made snow fencing for their area. Shrub and tree species that grow at least 6 to 8 feet tall are good for living snow fences. Optimum snow storage capacity is achieved when individual rows have a density of 50 to 60 percent cover as viewed through the winter vegetation. Density is determined by how closely plants are spaced and whether the vegetation is deciduous or evergreen. When vegetation densities are low, more snow moves through the living snow fence while snow fences with high densities run the risk of being damaged by deep snow drifts (Brandle and Nickerson accessed 2017). The most effective living snow fences are those with at least two rows of shrubs or trees.



Freeze-Thaw

Freeze-thaw is the process of ice formation and ice melting that occurs in a 24-hour cycle within the surface of the soil. At night, temperatures drop at the soil surface and water begins to freeze within the soil pores, creating ice crystals. As ice crystals continue to form, water is drawn from the soil below through capillary action to replace the water that created the ice crystals. During freezing, ice crystals expand in the soil and push soil aggregates apart (Ferrick and Gatto 2004), weakening the internal structure of the soil. When soils thaw the following day, soil strength is greatly reduced (Gatto and others 2004), leaving the soil surface significantly less resistant to erosional forces. Freeze-thaw is considered one of the least understood aspects of soil erosion (Ferrick and Gatto 2004) and yet accounts for significant annual soil losses (Froese and others 1999).

The formation of ice crystals will destabilize the seed germination environment. Freeze-thaw cycles affect germinating seeds by creating ice crystals that physically push the new seedlings above the soil surface, exposing the emerging roots to extremely harsh conditions for

Figure 3-52 | **Freeze-thaw effects on planted seedlings**

Continual freeze-thaw conditions can push root systems of planted seedlings out of the ground, reducing growth and potentially killing seedlings.

Photo credit: David Steinfeld

seedling establishment, including low humidity, high temperatures, and sunlight. On steeper slopes, soil particles and germinating seeds move downslope after each freeze-thaw cycle, further destabilizing the seed germination environment. Freeze-thaw processes can also affect seedling establishment. Long periods of freeze-thaw cycles can push seedlings out of the ground, exposing roots and, in many cases, killing seedlings (Figure 3-52).

Soils most susceptible to freeze-thaw effects are those with a high silt content or soils that are compacted. Soils are most susceptible when they are cold and wet. Silt-sized particles have pore sizes that are small enough to pull moisture to the layers that are freezing through capillary action, yet large enough to form ice crystals (Ballard 1981). Sandy soils do not draw moisture to the freezing layer because the pores are too big. Clays, on the other hand, have good capillary characteristics, yet do not have large enough pores for ice crystals to form (Ferrick and Gatto 2004). Sands are susceptible to freeze-thaw when they are compacted because the size of the pores is reduced, encouraging capillary rise (Gatto and others 2004). Soil cover, which includes litter, duff, and organic mulches, does not typically have good capillary rise characteristics, and therefore are less frost-susceptible. In addition, soil cover offers good thermal protection, which moderates the degree of freezing and thawing at the soil surface. The effects of freeze-thaw on surface stability increases as slope gradients steepen; the steeper the slopes, the greater the movement of seeds and soil downslope each day. For example, a seed or soil particle on a steep slope rises 2 inches on top of an ice crystal (Figure 3-53) but when the crystal melts, the seed or soil particle drops to a different point farther downslope. After many freeze-thaw cycles, the distance traveled by the seed or soil particle can be significant.

How to Assess Freeze-Thaw—Freeze-thaw processes typically occur in the spring and fall, when soil moisture levels are high and soil temperatures are cold. Soil surfaces that have undergone freeze-thaw cycles will have a very loose crust that will collapse when touched or walked upon. Gravels are often perched on pedestals, but give way under light pressure.

Project areas with bare surface soils high in silts or compacted sands should be considered prone to freeze-thaw processes, while soils with deep mulch or litter layers are less susceptible.

Mitigating for Freeze-Thaw

Apply Mulch—Available research on the mitigation of freeze-thaw effects is slim, but it can be assumed that practices, such as applying an organic mulch, will insulate the soil surface and minimize the effects of freeze-thaw. The deeper the mulch layer, the less propensity for freeze-thaw at the surface. Hydromulch applications at typical rates of 1,000 to 2,000 lb/ac are too thin to moderate surface temperatures or strong enough to resist the destabilizing effects

Figure 3-53 | **Freeze-thaw ice crystals**

Ice crystals that form under freeze-thaw conditions can lift soil particles over 2 inches above the original surface. Later in the day the crystals will melt and the particles will drop.

Photo credit: David Steinfeld

Figure 3-54 | **Soil erosion affects seed germination**

Soil cover protects the surface from rainfall impact. Not only is soil removed during rainstorms, affecting germination and seedling establishment, but seedlings that do emerge can be covered with soil that splashes from rainfall impact. Seedlings will not grow through an encasement of soil.

Photo credit: Thomas D. Landis

of ice crystal formation on surface strength. Deep application of most mulches however, will bury seeds, resulting in poor seedling emergence. An alternative to is to apply needles or wood strands because these materials can be applied at greater depths and still allow light through for seedling emergence. For planted seedlings, the application of very deep mulches will reduce the effects of freeze-thaw. Gravels, cobbles, and stone can provide a stable soil cover. These materials are often left over after rock has been screen from the soil and designed into the slope can add surface stability and reduce evaporation.

Till Compacted Soils—Sandy soils are very susceptible to freeze-thaw if they are compacted. Loosening soils through tillage is perhaps the best method of mitigating the effects of freeze-thaw on these soil textures (Section 5.2.2).

Avoid Wet Soils—Planting or sowing in soils with high water tables and poorly draining soils should be avoided. The extra moisture in these soils will continue to supply water for ice crystal formation. Planted seedlings can be pushed out of the soil in these environments (Figure 3-54).

Maintain Some Overstory Canopy—Trees and shrubs will moderate surrounding temperatures, reducing the potential for freeze-thaw.

Soil Cover

Soil cover is the layer directly above the surface of the soil. In an undisturbed environment, soil cover is composed of a combination of duff, litter, live plants, and rock. Soil cover is very important for surface stability because it dissipates energy from rain drop impact, protecting the soil from high intensity rainfall events. Furthermore, soil cover will slow the movement of runoff and capture sediments and seeds, preventing them from moving downslope. Section 3.8.3 discusses how soil cover is important for reducing evaporation; this section will discuss its role in stabilizing the soil surface and reducing erosion.

When the soil surface lacks cover, it is subject to the direct forces of raindrop impact, overland flow, wind, and gravity. These forces not only move soil offsite, affecting water and air quality, but they also displace seeds or remove soil from around newly developing seedlings (Figure 3-54). A lack of soil cover will impact revegetation objectives by reducing the quantity of seeds that will germinate. Seedlings that do emerge will be negatively affected by soil splash and sheet

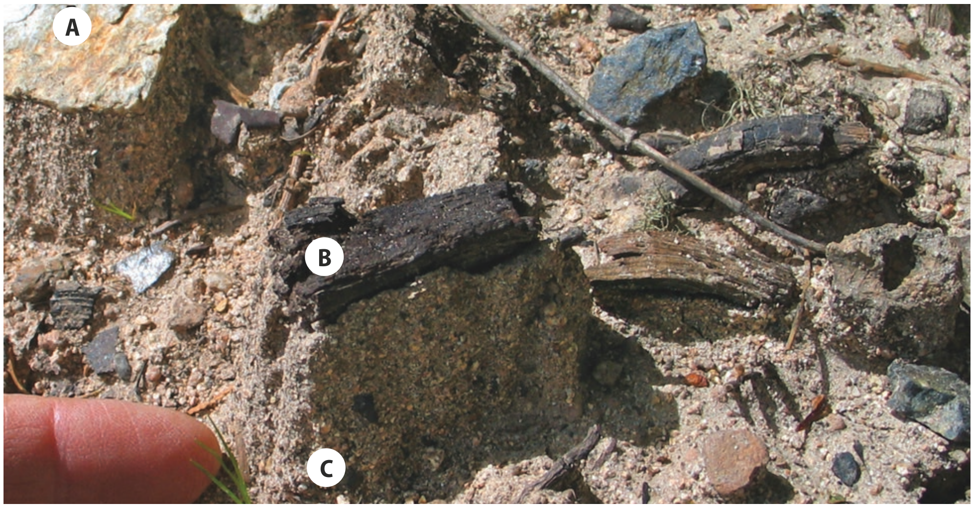


Figure 3-55 | **Soils are protected by a soil cover**

Larger materials, such as gravels (A) and wood chips (B), protect the soil and sown seeds by absorbing the energy of rainfall impact. While unprotected soil and seeds are removed through splash and sheet erosion, protected soil remains in pedestals, sometimes several inches above the surface of the soil. Seeds that do remain on or near the surface have a difficult time germinating through the surface crust created by rainfall impact (C). Plants that do establish will have roots exposed by successive rainfall events.

Photo credit: David Steinfeld

erosion that remove soil from around the seedling roots. The severity of soil erosion and seed movement is directly related to the percentage of bare soil.

After construction, most organic soil cover is removed. What remains is bare soil and coarse fragments (gravel, cobble, and stone). Left unprotected, bare soil will erode during rainstorms, leaving a pavement of coarse fragments (Figure 3-55). If the amount of coarse fragments in the soil is high, then the percentage of the soil surface covered by coarse fragments will also be high. By the third year, erosion rates on unprotected bare soils typically fall to a tenth of the rate of the first-year rate because of the formation of a coarse fragment surface (Megahan 1974; Ketcheson and others 1999). While this process produces less sedimentation to stream systems, the high coarse fragments at the soil surface are a poor environment for seed germination. For this reason, it is important to quickly stabilize the soil surface after soil exposure and why most road contracts call for temporary road stabilization during the construction period.

How to Assess Soil Cover—Soil cover can be measured by establishing transects and recording the percentage of rock, vegetation, litter, duff, and bare soil. A monitoring procedure for measuring soil cover is presented in Section 6.3.1.

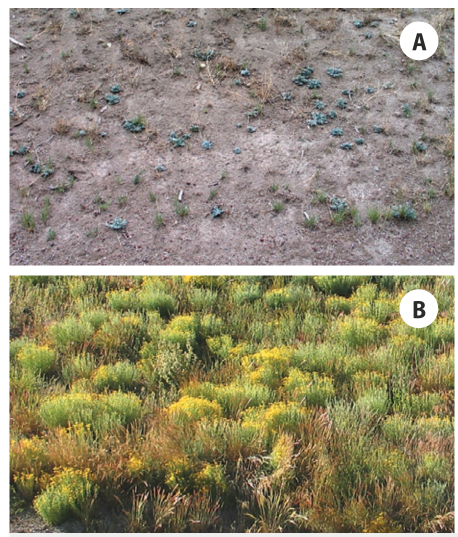


Figure 3-56 | **Many sites take more than one year to fully revegetate**

Semi-arid, arid, and cold sites often take more than one year to fully revegetate. Photo A shows the vegetative establishment one year after hydroseeding on a semi-arid site; bare soil exceeds 60 percent. Photo B shows the same site almost two years after sowing; vegetation has fully established. Soil cover methods in these cases must last several years for soil protection and plant establishment.

Photo credits: David Steinfel

Mitigating for Low Soil Cover

The primary objective of most revegetation projects is to stabilize the soil surface and create an optimum environment for seeds to germinate and plants to establish. Initial surface stabilization must remain effective until plants become established and can protect the surface from erosion through vegetative cover. Therefore, the selection of surface stabilization methods must be based on: how effectively does the material stabilize the soil surface, does the material allow good seed germination and plant establishment, and how long does it remain effective (longevity).

Apply an Organic Mulch—A variety of mulches with varying qualities and longevities should be considered based on the erosional potential and revegetation needs of each site (Section 5.2.3). Short-fiber materials, such as wood fiber and paper products found in hydromulches, applied with a tackifier are a very effective short-term surface cover for protecting soil from rainfall impact. However, after a few months, these products are usually no longer effective. Higher rates of hydromulch and tackifier, which make up BFM products, have a higher degree of soil protection and greater longevity (up to a year). On many sites where the environment is optimum for establishing native plants, protection for less than a year is adequate. However, on sites that are cold, arid, or semi-arid, the establishment of vegetative cover can take longer than one year (Figure 3-56) and soil surface protection will require longer-lasting mulches such as straw, pine needles, hay, shredded wood, wood strands, or erosion fabrics.

Apply a Rock Mulch—Gravels, cobbles, and stone can provide a stable soil cover. These materials are often left over after rock has been screen from the soil and designed into the slope can add surface stability and reduce evaporation.

Surface Strength

When soil cover is removed, the surface of the soil is exposed to the erosive forces of raindrop impact, overland flow, freeze–thaw, and wind. How strongly soil particles bind together will determine the degree by which soil particles are detached and moved through soil erosion. Topsoils with good aggregation and high organic matter will be more stable than subsoils or soils low in organic matter. Clay soils have greater strength than soils dominated by sands and silts which are non-cohesive. Seeds have no cohesive properties and, when sown on the surface of the soil without mulches or tackifiers, are very susceptible to erosive forces.

How to Assess Surface Strength—Determining the soil texture of the surface soil is a simple way to determine soil strength (Section 3.8.6, see Soil Strength). Soils low in clays (<15 percent) and high in sands will have low surface strength (Figure 3-57). In most cases, soils lacking topsoil will have reduced surface strength due to the lack of roots and organic matter that hold the soil particles together. The rainfall simulator is an indirect indicator of soil strength because it measures the amount of sediment that is detached from surface soils under various rainfall intensities (Section 3.8.5, see Rainfall). The USDA Natural Resources Conservation Service has developed a field test for determining surface stability for water erosion (Inset 3-4). This method rates how well surface soil samples maintain their stability after being agitated in water.

Figure 3-57 | **Sandy soils have low surface strength**

Soils low in clays and high in sands have very low surface strength. Not only are they prone to surface erosion, but even walking on them can leave the surface in a highly disrupted condition.

Photo credit: David Steinfeld

Inset 3-4 | **Bottlecap test for surface stability**

From Herrick and others 2005a

Place a soil fragment in a bottle cap filled with water. Watch it for 30 seconds. Gently swirl the water for 5 seconds. Assign one of three ratings:

M = Melts in first 30 seconds (without swirling)—Not stable

D = Disintegrates when swirled (but does not melt)—Moderately stable

S = Stable (even after swirling)—Stable

Mitigating for Low Surface Strength

Apply Tackifier and Hydromulch—Surface strength can be increased for up to a year by applying tackifiers by themselves, with hydromulches, or to bond straw onto the site (Section 5.4.2). These products strengthen the bonds between surface soil particles and between the soil particles and the products. Seeds applied with a tackifier are held tightly to the soil surface, reducing the likelihood that seeds will be detached and moved.

Apply Long-fiber Mulch—Applying a long-fiber mulch to the soil surface can increase the overall surface strength because of the direct contact of the material with the soil surface and the interlocking nature of the fibers (Section 5.2.3). The application of erosion mats can increase surface strength by an order of magnitude when in contact with the soil surface.

Infiltration Rates

Infiltration is the ability of the soil surface to absorb water from rainfall, snowmelt, irrigation, or road drainage. A high infiltration rate indicates that the soil surface can transmit high rates of water; a low rate indicates that the surface has low capability of absorbing water. When infiltration rates are lower than the rate of water input, runoff or overland flow will occur. Under these conditions, runoff can detach and transport soil particles, resulting in soil erosion and, in many cases, off-site water quality problems (Figure 3-58). Overland flow can also remove sown seeds.

The size, abundance, and stability of soil surface pores determine the infiltration rates of a soil. Large stable pores created by worms, insects, and channels created by decaying root systems will absorb water quickly and have high infiltration rates, while surfaces that have been compacted, have had their topsoil removed, or are low in organic matter will have poor infiltration rates.

Under undisturbed conditions, infiltration rates are usually high, especially where a litter and duff cover exists. When soil cover is removed, the impact from raindrops can seal the soil surface, creating a crust that will significantly reduce infiltration rates. Infiltration rates are also reduced when soil is compacted by heavy equipment traffic.

How to Assess Infiltration Rates—The most accurate equipment for measuring infiltration rates is the rainfall simulator. This equipment simulates rainstorms of different intensities under controlled conditions and measures how the soil surface responds. Infiltration rates are determined at the point when runoff occurs. The amount of runoff water is measured at the bottom of the plot to calculate runoff rates and sediment yields (Figure 3-59). While most rainfall simulators were developed for agricultural operations, several have been developed specifically for wildland conditions. These simulators were built for transportability and conservation of water because construction sites are often in remote locations and far from water sources. The "drop-forming" rainfall simulator, developed for wildland use, delivers rainfall at the drop size or impact velocity determined for the climate of the project site (Grismer and Hogan 2004).

Figure 3-58 | **Infiltration rates**

When precipitation exceeds infiltration rates, water collects on the surface of the soil and begins to move downslope, causing erosion. On this site, litter and duff layers that typically protect the surface from rainfall impact have been removed, causing low infiltration rates.

Photo credit: David Steinfeld

Figure 3-59 | **Portable rainfall simulator**

A portable "drop-forming" rainfall simulator developed by scientists at the University of California Davis (Grismer and Hogan 2004) delivers water droplets through hundreds of needles (A). Pressure is increased or decreased to simulate rainstorm events. Droplets hit the soil surface within a plot frame (B) and runoff water is collected in a bottle at the bottom of the frame (C) to measure runoff rates and sediment production.

Photo credits: David Steinfeld

Using the rainfall simulator in revegetation planning is expensive, yet it is an important tool and should not be discounted because of the cost. Specifically, rainfall simulation used to compare the effects of different mitigating measures, such as mulches or tillage, on runoff and sediment production takes the guess work out of whether such measures are effective. This quantitative evaluation of erosion control methods might be essential in areas where water quality objectives are critical.

In most cases, infiltration rates are estimated under routine field investigation by inference from site conditions. Infiltration rates can be considered high when the soil surface has not been disturbed and has a high percentage of cover. With compaction and loss of surface cover, infiltration rates are proportionally reduced. It is often assumed that construction activities that remove surface cover or disturb the topsoil will have very low infiltration rates that will create overland flow under most rainfall intensities.

Mitigating for Low Infiltration Rates

Avoid Compaction—Where possible, avoid operating heavy equipment on undisturbed soils or soils that have been tilled. Coordinate with project engineers to verify that site preparation does not compromise the compacted roadbed prism which is engineered as a structural entity.

Tillage—Infiltration rates can be increased through soil tillage (Section 5.2.2) which reduces compaction, increases macropore space, and creates surface roughness. Depending on the erosional characteristics of the site, the positive effects of tillage on infiltration rates might only remain effective through a series of rainfall events.

Incorporating Organic Matter—Incorporating organic matter into the soil surface can increase the longevity of infiltration rates created through tillage by forming stable macropores (Section 5.2.5). Unless macropores are interconnecting or continuous, however, they will not drain well (Claassen 2006). One method for creating continuous pores is to incorporate long, slender organic material, such as shredded wood or hay that overlaps and interconnects within the soil. Higher application rates of shredded wood or straw will result in greater porosity and infiltration rates.

Surface Mulch—Applying surface mulch will reduce the effects of rainfall impact on surface sealing and reduce soil erosion rates (Section 5.2.3). It does not, however, necessarily increase infiltration rates. Studies have shown that, while sediment yield can be less with the application of mulches, runoff rates are not necessarily reduced (Grismer and Hogan 2007).

Plant Cover—The best long-term way to increase infiltration is to create conditions for a healthy vegetative cover. Good vegetative cover will produce soils with extensive root channels, aggregated soil particles, and good litter layers.

Slope Gradient

Slope angle or gradient is important in surface stability because it directly affects how soil particles will respond to erosional forces; the steeper the slope, the greater the erosional forces will act on the surface of the soil. Slope gradient is a dominant factor in water erosion and dry ravel erosional processes. In water erosion, the rate of soil loss and runoff from disturbed soil surfaces increases incrementally as slope gradient steepens. In dry ravel erosion, the surface remains stable until a specific slope gradient is reached, and then soil particles move downslope under the direct effects of gravity. This critical angle is called the angle of repose and it can be likened to the angle that accumulated sands make in an hourglass. Only non-cohesive soils, composed of sands, silts, or gravels, have an angle of repose; soils with significant amounts of clays typically do not.

Dry ravel is the downslope movement of individual particles by rolling, sliding, and bouncing (Rice 1982). It occurs more frequently as soils dry out and is triggered by vibrations from vehicles, animals, planes, and wind turbulence. Dry ravel creates a constant supply of material to the ditches at the bottom of the slopes making these slopes very difficult to revegetate unless the surface is stabilized. Seeds that germinate on steep, raveling slopes typically will not have enough time to put roots down deep enough to stabilize the surface before the emerging seedling moves or is buried by soil particles rolling down from above. Figure 3-60 shows dry ravel on a cut slope composed of a sandy soil.

Figure 3-60 | **Dry ravel**

Steep, non-cohesive soils move downslope at a continuous rate. The soil surface is constantly moving and never stable long enough for seeds to germinate and plants to become established. These slopes can remain barren for years. Soils that are high in sands and gravels are the most susceptible to dry ravel. In this picture, trees became established below rock outcrops, where the surface was protected from dry ravel.

Photo credit: David Steinfeld

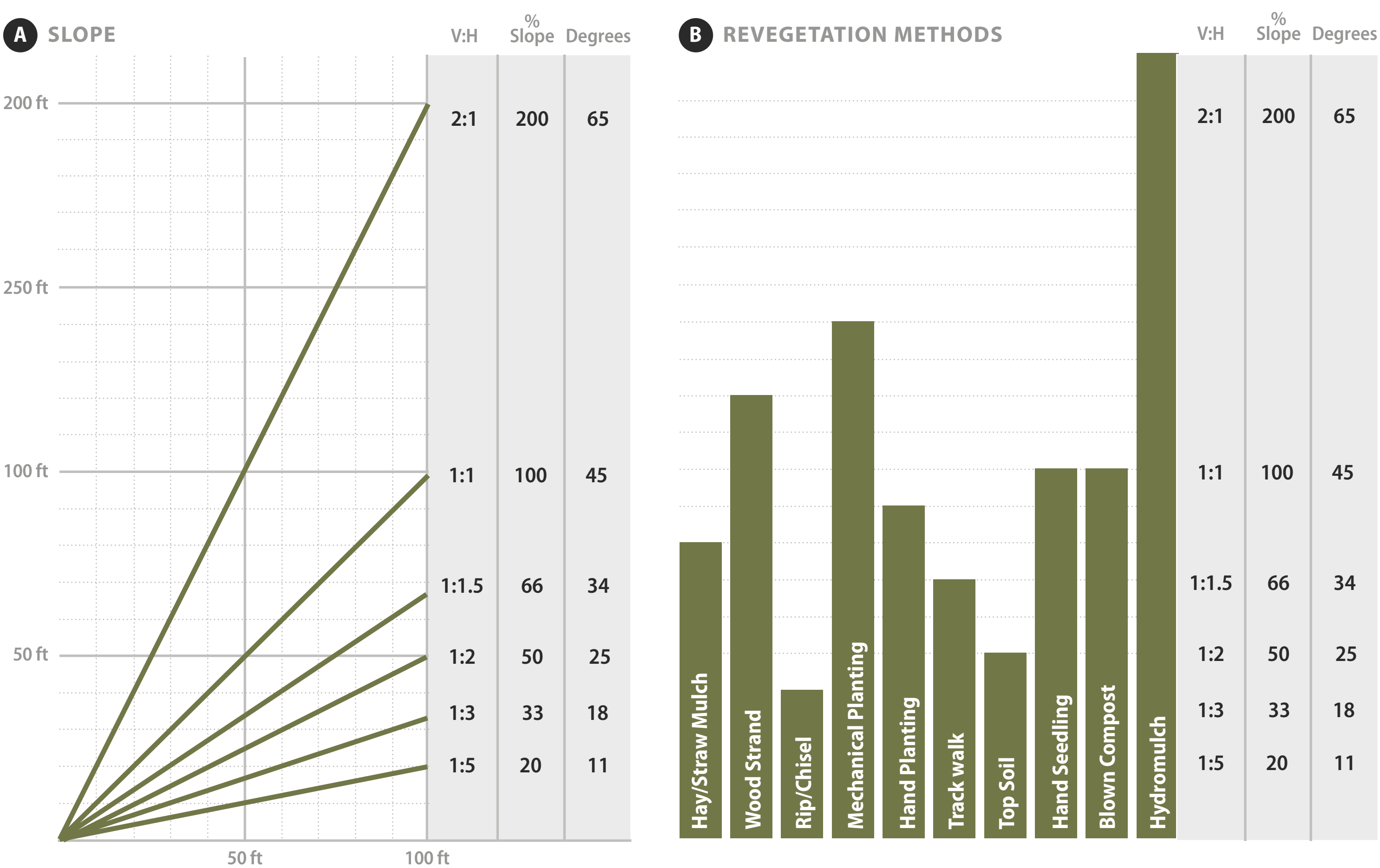
How to Assess Slope Gradient—Slope gradient is quantified in several ways, as shown in Figure 361. For road construction projects, slope is usually expressed as the rise (vertical distance) over run (horizontal distance). A 1:3 road cut, for example, defines a slope that rises 1 foot over every 3 feet of distance. Biologists, including range, forest, and soil scientists, use percent slope as a measure of slope angle. This is calculated by measuring the number of feet rise over a 100-foot length. Slope gradient as expressed in degrees is not commonly used.

Slope gradient can be measured in the field using a handheld instrument called a clinometer. This equipment reads slope angle in percent slope and in degrees. Readings from a clinometer can be converted to rise over run notation using the chart in Figure 3-61. Road construction plans display the slope gradients for every cross-section corresponding to road station numbers (refer to Section 2.4 and Figure 2-4). Using these cross-sections, slope gradients can be identified on the plan map by color coding the run:rise for cut and fill slopes. For instance, 1:1 cut and fill slopes might be highlighted red for areas of concern, while those areas with gradients 1:3 or less might be light green, favorable areas for mitigation work. This exercise can quickly identify areas with the highest risk for soil erosion and difficulty in establishing vegetation.

Slope angle plays a key role in revegetation planning because of its potential limitation on the types of mitigation measures that can be implemented. Figure 3-61 shows which practices are generally limited to gentle slopes and which can be implemented on steep slopes.

Figure 3-61 | **Revegetation methods and slope gradients**

For engineering work, slope is generally expressed as the rise (V) over run (H). For slopes flatter than 1:1, (45° or 100%), slope gradient is expressed as the ratio of one unit vertical to a number of units horizontal. For example a 1:2 slope gradient indicates that there is one unit rise to 2 units horizontal distance. For slopes steeper than 1:1, it is expressed as the number of units vertical to one unit horizontal (e.g., 2:1 indicates that there is a 2 unit rise to 1 unit horizontal distance). In general to avoid confusion, it is wise to notate the ratio by indicating the vertical (V) and horizontal (H), when defining gradient (e.g., 2V:1H). Range and forest sciences use % slope gradient to describe slope angle. Slope gradient refers to the number of feet elevation rise over 100 feet. A 66 percent slope gradient indicates that for every 100 feet, there is a 66 foot vertical distance rise. Slope gradient controls what type of revegetation treatments can be used (B). The steeper the slope gradient, the fewer tools are available.



Mitigating for Steep Slope Gradients

Lengthen Cut or Fill Slopes—Slope gradient can be reduced by increasing the length of the disturbance. This will make the revegetation effort easier and more successful, but will increase the amount of area, or construction footprint, of the project.

Road planners consider many factors when they design the steepness of cuts and fills. A common strategy is to create cut and fill slope gradients as steep as possible. This practice disturbs far less land, resulting in less area to revegetate, and because there is less exposed soil, the potential for soil erosion is considerably reduced. Furthermore, there is a substantial cost savings with less excavation and revegetation work. Figure 3-62 shows an example of how increasing the steepness of a cut slope on a typical 1V:2H natural ground slope substantially decreases the length of disturbed soils.

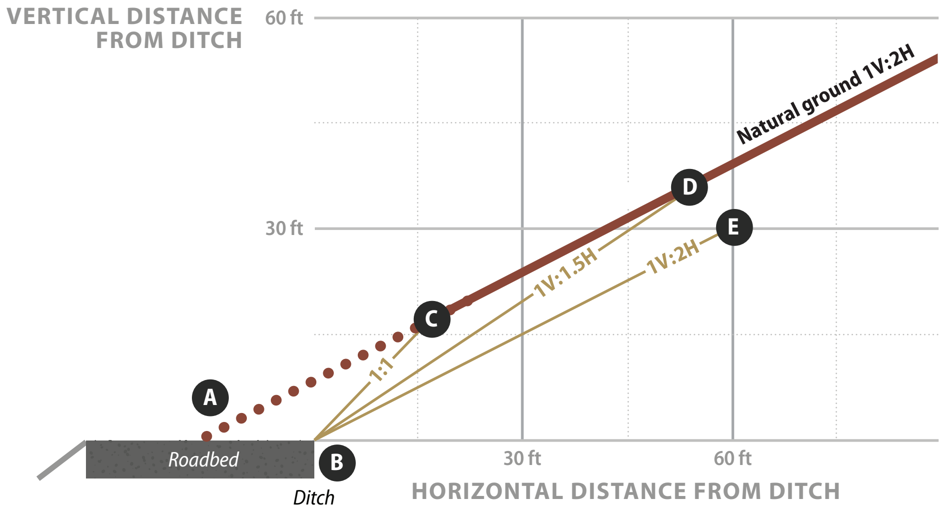


Figure 3-62 | **Effects of designing steep and gentle gradient slopes on size of disturbance**

The trade-off between designing steep cuts that are difficult to revegetate or creating gentle slopes that disturb more area but are easier to revegetate is demonstrated in this example. The centerline (A) of a new road intersects the 1V:2H natural ground (A to D). Fifteen horizontal feet of material must be excavated from the center of the road (A) to the ditch (B) to create the road bed. The resulting road cut will have varying lengths depending on how steep it is designed. A 1:1 cut slope will expose a 25 ft cut from the ditch (B) to the top of the cut slope (C). A 1V:1.5H slope (B to D) will lengthen this exposure threefold to approximately 80 ft. A 1V:2H slope (B to E) is not achievable because it remains parallel to the natural ground slope.

The main drawback of steepening slopes from a designer's standpoint, however, is that steeper slopes are much harder to revegetate and the selection of revegetation practices available are reduced as the steepness of the slope increases. Vegetation on steeper slopes are also harder to maintain using practices such as mowing. On sites with 1V:5H slopes or less, all revegetation practices are possible; on slopes approaching 1:1, the threshold of most revegetation practices has been reached, as well as the limit of what can be successfully revegetated. It is important to work with the design engineers early in the planning stages to consider the effects of slope gradient on meeting revegetation objectives.

Create Steep, Hardened Structures—Creating hardened structures or walls, such as retaining walls, crib walls, gabion walls, mechanically stabilized earth walls, or log terrace structures at the base of a steep slope, will allow gentler slope gradients to be constructed above the structure. With adequate planning, these structures can be revegetated.

Surface Roughness

Slopes that have roughened surfaces trap water during the initial stages of runoff (Darboux and Huang 2005). Roughened surfaces consist of microbasins that capture and store soil particles and seeds that detach in the erosional processes. Seeds that have been transported short distances into these depressions are often buried by sediments. Moderate seed covering from transported soil can enhance germination as long as the seeds are not buried too deeply. Microbasins can also be relatively stable during the period for seed germination and seedling establishment.

Surface roughness also reduces the effects of wind by reducing wind speed at the soil surface. Seeds may be blown into the depressions and become covered by transported soil. For both wind and water erosion, however, as the microbasins fill up with sediments, they become less effective in capturing sediments and seeds (Figure 3-63).

How to Assess Surface Roughness—The simplest method for assessing surface roughness is to take several measurements of the distance between the top and bottom of the microbasin and average these values. Also count the number of microbasins in a 5-foot distance perpendicular to the slope direction. Shallow, closely spaced microbasins may create more area for seed germination but will also fill up faster with sediments, while microbasins that are deeper and farther apart will take longer to fill up and be more effective for erosion control but may have less surface area for optimum plant establishment from seeds.

Mitigation for Smooth Soil Surfaces

Leave Surface Roughened—Many project engineers have a tendency to "beautify" construction sites at the end of a road project by smoothing soil surfaces. While basic landscape shaping is essential, it is important to keep the soil surface as rough as possible. In many instances, leaving cut slopes "unfinished" or in the "clearing and grubbing" stage provides excellent seed bed diversity and growing environment. The diversity of micro-habitats provides greater climatic and soil environments for seed germination. An exception to this rule is where erosion control matting is used for slope stabilization. For the matting to function best, it needs complete contact with the soil surface. On roughened surfaces matting will "tent" over depressions. On smooth surfaces the correctly installed matting will contact the soil surface, hold seeds in place and stabilize the slope soils.

Surface Imprinting—Imprinting the soil surface to create micro-relief has been shown to be effective in reducing runoff and soil erosion and increasing plant establishment (Section 5.2.2, see Roughen Soil Surfaces).

Tillage—Tilling the surface soil layers will leave the site in a roughened condition (Section 5.2.2). This practice can have other beneficial effects on the soil, such as loosening compacted soils.

Slope Length

Another factor influencing soil erosion and seed transport is the length of slope. As the slope lengthens, so does the potential for transport of sediments and seeds. On very long slopes, the erosive force begins as sheet erosion at the top of the disturbance and often turns into rills and, in extreme cases, gullies at the bottom of the slope (Figure 3-64).

How to Assess Slope Length—Slope length can be measured in the field or from road plans. From road plans, slopes can be grouped into different lengths using the road cross sections (see Chapter 2). In the field, the effects of different slope lengths can be assessed by observing erosional features on existing disturbed areas. New or old disturbances can be used as references for critical slope lengths. Figure 3-64 demonstrates that at some point downslope rills begin to form. The distance that this occurs is the maximum length of slope for this slope angle and soil type before severe erosion takes place. This distance will vary by other factors addressed in this section (e.g., soil cover, climate, slope gradient, surface strength, surface roughness, and infiltration rates).

Mitigating Measures for Long Slopes

Install Barriers—Fiber rolls, straw wattles, downed wood, silt fences, or compost berms or compost socks can be laid on the surface as obstructions or barriers to reduce slope length. To be effective, they must be placed in contact with the soil and perpendicular to the slope gradient. Straw wattles, hay bales, and silt fences must be trenched into the soil.

Create Benches—The creation of slope breaks can reduce slope length. These breaks include benches, steps, or trenches cut into the slope. The reduced gradient at these breaks slows the velocity of overland flow and collects sediments (Figure 3-65).

Figure 3-63 | **Surface roughness creates favorable environment for germination**

Surface roughness consists of microbasins that are favorable to seed germination and early plant establishment.

Photo credit: David Steinfeld

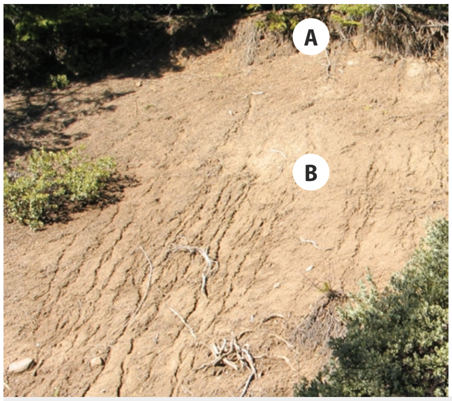


Figure 3-64 | **Surface erosion increase with distance downslope**

On this site, sheet erosion occurs at the top of the slope (A) and turns to rill erosion (B) as runoff collects. Mitigation that shortens slope lengths to less than the distance between A to B will reduce rill erosion.

Photo credit: David Steinfeld

Figure 3-65 | **Structures that shorten slope length**

Structures that shorten the slope length can slow surface runoff, collect sediments and increase soil moisture. Typical treatments include: a) placement of fiber rolls, logs, straw waddles, and compost berms; b) benches, steps, and trenches; c) willow waddles; and d) willow brush layers. Strategic placement of plants can take advantage of increased soil moisture by planting where roots can access the additional moisture. Most species do not respond well to being buried by sediment and should be planted above or below depositional areas (A and B). However, some species, such as willow, root where the stems are buried, and these species can be planted where sediments are expected to be deposited (C and D).

If either practice is applied in a long continuous line, they must be constructed on contour to the slope. If they are not level, water can collect and move along the structure, much like a channel, and eventually spill onto the slope below, creating rills and gullies. (The exception to this is the construction of live pole drains to redirect water off-site for slope stability [Section 5.4.3, see Live Fascines]). When placed properly along the contour, slope distances are shortened and the structures collect sediments and create areas for plant growth. Plants that are grown above barriers or near the bottom edge of benches can take advantage of water and sediments that collect during rainstorms. Native vegetation can be incorporated into many of these designs to take advantage of increased soil moisture and sediment accumulation. The distance that these structures are placed apart from each other should be less than the critical distance where rills are expected.

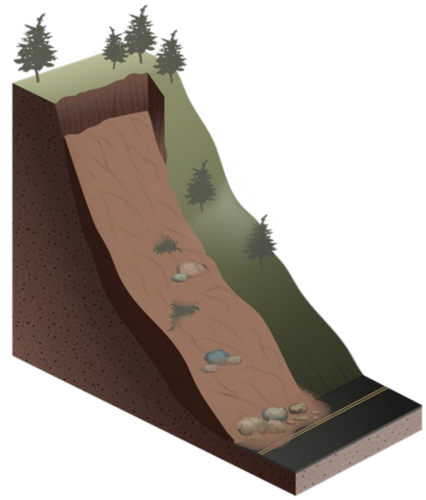
3.8.6 SLOPE STABILITY

This discussion is directed to non-engineers to simplify and make accessible basic slope stability concepts that must be understood in developing revegetation strategies. It is by no means a substitute for professional engineering expertise. Technical references for slope stability are many (including Carson and Kirby 1972; Spangler and Handy 1973; Brunsden and Prior 1984; Denning and others 1994), to which the reader is referred for a comprehensive review of this subject. For a detailed evaluation of the role of vegetation in slope stability, the reader is referred to Gray and Leiser (1982).

Creating stable slopes is essential for establishing healthy plant communities, but the reverse is equally true—establishing native vegetation is critical for stabilizing slopes. The following

Slumps

- Moderate slope gradients
- Circular failure movement
- Cohesive soils
- Deep soils
- Slow moving



Debris slides

- Steep slope gradients
- Planar failure movement
- Noncohesive soils
- Shallow
- Fast-moving

Figure 3-66 | **Slumps and slides**

Common landslides typically associated with road construction.

Modified after Varnes (1978) and Bedrossian (1983)

discussion takes the latter perspective of how to create the most favorable environment for establishing vegetation on potentially unstable slopes and how this approach can be integrated into the overall strategy of slope stabilization. A vegetated slope adds stability to slopes by holding the soil together through a network of root systems and by removing water from the soil, which is the primary driving force behind most landslides.

Slope stability is the resistance of natural or artificial slopes to fail through gravitational forces. The landforms resulting from slope failures are called landslides and they are described by their morphology, movement rates, patterns, and scale. This section will focus on two general types of landslides that are common to road cuts and fills—slumps and debris slides (Figure 3-66). Slumps typically occur on deep soils that are cohesive (e.g., rich in clays). They tend to be deep seated and slow moving. Viewed in profile, the failure occurs in a circular motion, resulting in a series of tilted blocks and circular cracks. Debris slides are shallow, fast-moving landslides that form on non-cohesive soils (e.g., sandy, gravelly). These landslides occur on steep slopes.

Water is the driving force behind most slope stability problems encountered in road projects. It comes as rainstorms, snowmelt, and often as diverted surface water from road drainage. As water increases in a potentially unstable slope, the added weight of the water in the soil plus the increased pressure of water in the pores (pore water pressure) eventually exceeds the strength of the soil and the slope fails (Figure 3-67).

Increased water to a slope is especially a problem where a restrictive layer (e.g., a layer of soil that limits water movement) is close to the soil surface. As water moves through the surface horizon and encounters a restrictive layer, it builds up in the pores of the horizon above it, increasing water pressure. The saturated horizon becomes heavier and eventually the slope fails under the added weight of water and increased pore water pressure.

The faster water moves through soil, the less susceptible a slope is to failure. The measured rate at which water is transmitted through a soil mass is its permeability. When permeability is high, water quickly moves out of the soil pores, reducing the potential for increased pore water pressure and slope weight. When permeability is low, water slowly moves through soil and builds up in the soil pores. On gentle slopes, this is typically not a problem, but as slope gradients increase, gravitational forces acting on the slope raise the potential for slope failure. Slope length is another factor important to water movement because the longer the slope,

Figure 3-67 | **Water pressure and slope stability**

Water pressure is greatest when soils are saturated. Slopes release this pressure through channels created by decomposing roots, animal burrows, and worm holes. When pressures become greater than the strength of the soil, slopes fail. This picture of a decomposed root releasing water pressure was taken 30 minutes before the road cut failed.

Photo credit: David Steinfeld

the greater the buildup of water near the base of the slope. This phenomenon explains why many slope failures occur in the mid to lower portions of fill slopes.

Whether a slope fails or not is ultimately due to the strength of the soil. Soil strength is affected by the amount of clay present in the soil, the level of compaction (the greater soil compaction, the more stable the soil), and the presence of roots (more roots are better). Compaction of soils to increase soil strength usually takes priority in road design over creating optimum soil conditions for root growth. With this practice, not only are there fewer root systems to add slope stability, there is also reduced vegetative cover, which is important for intercepting and removing water from the soil. A road design that integrates vegetation into the stability of the slope can meet both road and revegetation objectives, but it will take a collaborative approach.

This section will discuss each of the following parameters as they relate to increasing slope stability through revegetation treatments:

- Permeability
- Restrictive layers
- Water input
- Slope length
- Slope gradient
- Soil strength

Permeability

The rate at which a volume of water moves through soil material is its permeability (technically referred to as hydraulic conductivity). Soils that have moderate to high permeability rates tend to be more stable than those with low permeability rates. Where permeability is low, water fills the soil pores but does not drain quickly, adding additional weight to the slope and increasing the pore pressure. Both factors reduce the overall strength of slopes and increase the likelihood that slope movement will occur when other conditions are right.

Soils with large interconnecting pores have a higher permeability than soils with smaller pores that are less interconnecting. Soil textures that are well-graded (soils that have only one particle size) typically have a higher permeability than poorly graded soils (soils having a range of particle sizes from clays to small gravels). For example, poorly graded granitic soils have low permeability rates because the different-sized particles are neatly packed together, restricting the pathways for water flow. Well-graded soils, such as pure sands and gravels, have high permeability because pores are large and interconnecting. Alternatively, compacted soils often have low permeability rates because of the reduced or destroyed interconnecting macropores.

How to Assess Permeability—Simple field tests, such as percolation tests, historically utilized in assessing septic leach fields, can be used for determining permeability rates. A small hole is excavated and water is poured to a specified depth. The time to drain the water from the pit is measured in inches per hour.

These tests are run at different soil depths to determine if permeability rates change. Results from percolation tests are subject to significant variability. Nevertheless, they can indicate the relative permeability of different soil types or different soil disturbances.

Engineering laboratory tests for determining permeability include the constant head permeameter for coarse-grained soils. In this test, a soil sample is placed in a cylinder at the same density as the soils in the field. Water is introduced and allowed to saturate the sample. A constant water elevation, or head, is maintained as the water flows through the soil. The volume of water passing through the sample is collected and this provides a direct measurement of the flow rate per unit of time. The test can be repeated at various densities to determine the corresponding permeability. The test can also be repeated for various additions of organic amendments and compaction levels to determine the effects of these treatments on permeability. A soil lab should be consulted for how to collect and submit samples for these tests.

Where testing is not feasible, engineering and soil texts can give ranges for expected permeability based upon the soil gradation and classification. A field assessment can also give some indication of permeability rates. Subsoils or soils lacking organic matter that have a range of soil particle sizes, from clays through small gravels, have a propensity for low permeability rates, especially when they are compacted (Section 3.8.2, see Soil Structure).

Mitigating for Low Permeability

Tillage—Loosening compacted soil through tillage practices (Section 5.2.2) increases permeability by creating large fractures or pathways for water to flow. However, tilled soils often return to near-original permeability as the soils settle over time.

Organic Amendments—Long-fibered organic matter, such as shredded wood, tilled deeply into the soil will increase the infiltration and permeability of the soil because larger, interconnecting pore spaces are created (Section 5.2.5). Several studies evaluating the incorporation of unscreened yard waste suggests that an optimum rate of organic matter additions for increasing infiltration and improving soil structure is approximately 25 percent compost to soil volume (Claassen 2006). In addition, incorporating organic matter can increase slope stability because amended soils are lighter in weight than non-amended soils (mineral soils can weigh 10 to 20 times more than soils amended with 25 percent organic matter). The reduced soil weight lowers the driving forces that create unstable slopes.

Restrictive Layer

A restrictive layer is any soil horizon or stratum (including unfractured bedrock) that has very low permeability. As water flows through a surface horizon with good permeability and encounters a restrictive layer, the rate of downward water movement slows and water builds up in the pores above. The boundary between the permeable surface layer and the harder subsurface material is often a zone of weakness, sometimes referred to as a slip plane. Slope failure occurs when the pores in the soils above the restrictive layer become saturated with water to a point where the pore water pressure and soil weight exceed the soil strength. The depth of slope failure depends on the thickness of the soils above the restrictive layer. On slopes where the restrictive layer is near the surface, slope failure, if it occurs, will be shallow (Figure 3-68). Where the contact is deeper, the soil movement will be more extensive. The types of landslides that occur with restrictive layers are debris slides.

How to Assess Restrictive Layers—Restrictive layers in natural settings can be inferred by the presence of seeps and springs. These features occur most often at the point where a restrictive layer is intercepted or exposed to the surface. These can be intermittent features that are observed in the winter or spring but are dry in the fall or summer. The vegetation around permanent and temporary seeps and springs is typically composed of water-loving species, such as sedges (*Carex* spp.) and rushes (*Juncus* spp.). Figure 3-69 shows how a seep is created when a cut slope intersects a restrictive layer.

On construction sites, restrictive layers can be created by placing a loose soil or compost over highly compacted subsoil. These layers can be identified in the field by determining soil strength using a soil penetrometer or shovel to find compacted or dense soils (Section 3.8.6, see Soil Strength). On roadbed fill slopes or road cut slopes the compaction of the soils can be assumed. This layer is then assessed for the approximate amounts of silt and clay using the field texturing method. Dense or compacted soil layers that are high in silts and clays are likely to be very restrictive to water movement. Field permeability tests can be used to determine the rates of water flow (Section 3.8.6, see Permeability). Often restrictive layers are not observed until after construction when they manifest as intermittent seeps or wet areas in cut and fill

Figure 3-68 | **Restrictive layers can decrease slope stability**

In this photograph, a restrictive layer is very close to the soil surface. During a rain storm, water moved through the shallow soil layer and encountered a restrictive layer. Water then moved downslope, through the soil, building up pressure, until the increased pore pressure and soil weight exceeded the strength of the soil. At this point, the mid to lower slopes failed.

Photo credit: David Steinfeld

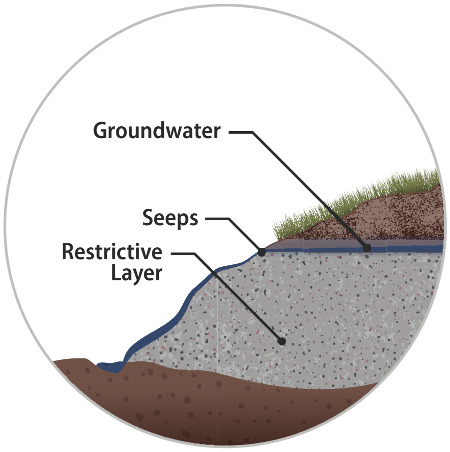


Figure 3-69 | **Restrictive layers and ground water**

Groundwater moves downslope above restrictive soil layers. Seeps are seen in road cuts where the restrictive layer is exposed. Increased soil water that occurs above restrictive layers can decrease slope stability.

slopes. Geotechnical investigation will determine if these features are due to shallow water movement associated with restrictive layers or interception of deeper subsurface water.

Mitigating for Restrictive Layers

Tillage—If restrictive layers are within several feet of the soil surface, site treatments that break up portions of this layer can increase permeability, which will increase stability. Site treatments that accomplish this are bucket tillage, deep ripping, spading, and fill cut (benching and backfilling), which are discussed in Section 5.2.2. The drawback to tillage is that it will reduce soil strength in the short term until roots occupy the soil and increase soil strength. Temporary irrigation systems have been installed on sites where quick establishment of grass cover during summer and fall is essential for slope stabilization prior to winter precipitation (Hogan 2007). Tillage techniques that leave a deep uneven subsurface profile reduce the potential for downslope debris slides.

Organic Amendments—Where possible, the incorporation of organic matter will help keep the restrictive layer from returning to its original soil density and allow more time for roots to establish (Section 5.2.5). As described above, soil strength is reduced until vegetation becomes established, but the negative effects of reduced soil strength are offset by the increased permeability and reduced soil weight of the organic amendments.

Key-In Surface Material Installations—Installation of straw wattles, staked in place on contour, prior to installation of topsoil or compost can hold permeable surface layers in place long enough for plant root systems to knit the layers together. Fully biodegradable wattles should be used.

Live Pole Drains—Live pole drains are constructed to intercept water from seepage areas and remove it through a system of interconnecting willow bundles to more stable areas, such as draws, ditches, or other waterways (Figure 3-70). The interception and flow of water encourages the establishment and growth of willow cuttings along the length of the live pole drain.

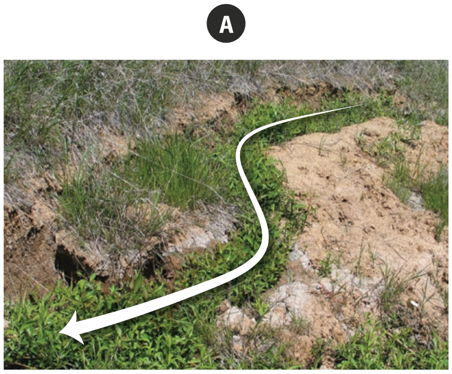
Water Input

Water, which is the driving force behind most landslides, comes through rainfall, groundwater flow, snow melt, or diverted from other areas through road drainage. Landslides often occur after a series of strong winter storms have delivered a high amount of rainfall over a short period of time. Under these conditions, soils have not had sufficient time to drain before the next storms arrive and water in the soil builds up to a very high pressure (Figure 3-67). With additional storms the combination of increased pore water pressure and additional weight of water in the slopes eventually leads to slope failure. Landslides can occur where water from road ditches or other road features drain water onto marginally unstable slopes. Major site factors that affect water input are rainfall duration and intensity, rain-on-snow events, and road drainage.

How to Assess Water Input—See Section 3.8.1 for how to assess water input.

Mitigating for High Water Input

Proper Surface Drainage—Increased water is the driving force behind slumps and debris slides. Designing proper water drainage is probably the most important measure to implement for slope stability (Gedney and Weber 1978). Where road water is inadvertently routed into potentially unstable areas, there is a greater potential for slope failure (Fredricksen and Harr 1981). Road projects that are designed to move storm water away from or out of unstable slopes as quickly as possible through road and slope drainage structures increase slope stability. In some cases, installing a curb at the top of the cut slope will effectively move water away from unstable slopes below. Coordinate with engineers to ensure that surface runoff, during construction of phased projects, is addressed prior to completion of final storm water system.



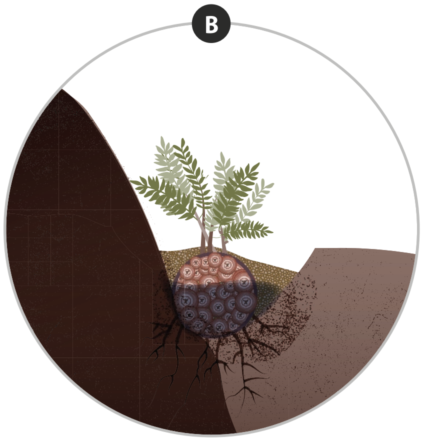


Figure 3-70 | **Live pole drains**

Slumps are characterized by scarps, cracks, and benches. Water collects on benches and in cracks where it is transmitted into the slide mass, creating continued instability. Slopes can be stabilized by removing water through a series of hand-dug surface ditches. Using the cracks as guides for the location of ditches, they are filled in with soil and dug wide enough for a willow fascine (Section 5.4.3, see Live Fascines) to be placed in the bottom (A). Called "live pole drains" (Polster 1997), these structures not only quickly move surface water from the slide to more stable areas, but the willow cuttings in the fascines, encouraged by the presence of high soil moisture, grow into dense vegetation (B) that stabilize the slide through the deep rooting and dewatering.

Photo credit: David Steinfeld

Species Selection—Select species that have adapted to wet soils. These include sedges (*Carex* spp.), rushes (*Juncus* spp.), bulrushes (*Scirpus* spp.), willows (*Salix* spp.), cottonwoods (*Populus* spp.), and cedars (*Thuja* spp. and *Chamaecyparis* spp.). Because each species has a unique way, or strategy, of modifying the moisture regime of a site, planting a mixture of species is a way of ensuring that all strategies are represented on the site. For instance, willows establish quickly and can draw large quantities of moisture from the soil, but only when the willows have leaves. Cedars, on the other hand, are slower to establish, but longer lived. They can withdraw moisture from the soil during the winter, unlike deciduous species. When they are well established, they intercept large amounts of water in the crowns, preventing precipitation from reaching the soil. Trees have a great ability to significantly deplete moisture at considerable depths (Gray and Leiser 1982). Wetland species, such as rushes and sedges, unlike many tree and shrub species, grow well in saturated soils.

Live Pole Drains—The live pole drain (Polster 1997) is a biotechnical engineering technique where continuous willow bundles (Figure 3-70) are placed across a slope, much like an open drain, to redirect water to a more stable area, such as channels and draws. Where small slump failures have occurred during or after construction, live pole drains can be installed to increase slope drainage, add root strength, and remove soil moisture from the slide mass.

Slope Length

Slope length is important for stability because the longer the slope, the more water concentrates in the lower portion of the slope. Increased water increases pore water pressure and soil weights, thereby decreasing the stability of the mid to lower sections of long slopes. This is one reason why slumps are often observed in the mid to lower slope positions of longer fill slopes.

How to Assess Slope Length—Slope length can be obtained from road plans or measured directly in the field using a tape.

Mitigation for Long Slopes

Live Pole Drains—Using live pole drains (discussed in the previous section), shortens the distance water is transmitted through the hill slope by intercepting surface and subsurface water in ditches at frequent slope intervals. Captured water is transmitted downslope through a system of continuous fascines to a stable channel (Figure 3-70).

Create Benches—Another method of reducing slope length can be the creation of a slope break, such as benches, steps, or trenches cut into the slope. The reduced gradient at these breaks slows the velocity of overland flow and collects sediments. However, unless the water is directed off the slope, total water input to the slope is not reduced.

Slope Gradient

As slope gradient increases, the destabilizing gravitational forces acting on the slope become greater. On a level surface, the gravitational force stabilizes the soil mass but as gradients increase, the strength of the soil mass to resist sliding along the failure plane decreases.

How to Assess Slope Gradient—Assessing slope gradient is discussed in Section 3.8.5 (see Slope Gradient).

Mitigating for Steep Slopes

Mitigating measures for steep slopes are discussed in Section 3.8.5 (see Slope Gradient).

Soil Strength

Soil strength (technically referred to as shear strength) is the characteristic of soil particles to resist downslope forces. Physical and biological factors play roles in soil strength. The major physical factors contributing to increased soil strength are reduced porosity (compacted soils), greater range of particle sizes (poorly graded soils), greater angularity of the soil particles, greater surface roughness, and the presence of silts and clays that add cohesive strength (Hall and others 1994).

The biological components of increased soil strength are the matrix of roots that reinforce the surface horizon, roots that anchor an unstable soil mantle to stable subsoils or rock, and stems (e.g., trunks of trees) that add support to the soil immediately uphill (Hall and others 1994) (Figure 3-71). The physical factors, unfortunately, do not always support the biological factors. For example, high porosity soils are of particular interest to the designer because of the role porosity plays in root growth. From an engineering standpoint, however, high porosity soils have lower soil strength because soil particles are not packed closely together and are less interlocking. Balancing the needs of creating a healthy soil for optimum vegetation while still maintaining slope stability until established vegetation adds root strength to the soil is a challenge to engineers and revegetation specialists. A road design that creates soils with high porosity will also decrease soil strength in the short term; however, if this practice increases the biological productivity of the site, the long-term result is a net increase in soil strength (Gray and Leiser 1982). The growth habits of native species can greatly influence slope stability because each species has a unique rooting pattern and root tensile strength. For instance, grass roots are very fibrous and abundant in the surface horizon, adding surface stability when the grass cover is high. Grass and forb roots, however, add very little soil strength at deeper depths because their roots are not as strong and do not penetrate as deeply as tree roots (Gray and Leiser 1982). Alternatively, roots of shrub and tree species are long and deep rooted, with relatively high tensile strength (Gray and Leiser 1982). The main advantage of tree and shrub species is the long vertical roots (taproots) that can cross failure planes and bind the soil strata together (Figure 3-71).

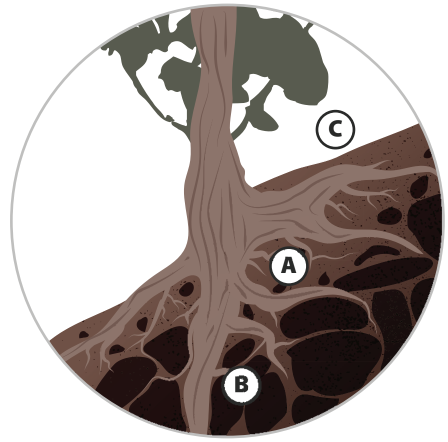


Figure 3-71 | **Plant roots and slope stability**

Plant roots and stems increase slope stability by (A) reinforcing the surface horizon through a matrix of roots, (B) anchoring surface horizons to rock or subsoils, and (C) stems supporting the soil upslope.

How to Assess Soil Strength—The designer will probably not perform engineering tests for soil strength, yet knowing a little about these tests could be important, especially if the designer is making recommendations that soils on potentially unstable sites be deeply tilled or amended with organic matter.

A common method engineers use to estimate soil strength is to correlate soil classification (from sieve analysis and the characteristics of clay particles) with published literature values. Shear vanes or cone penetrometers are good methods to approximate the strength of fine-grained soils in the field, and published research is used to correlate these readings with laboratory shear strength test results.

The triaxial shear test is a more precise laboratory method to determine shear strength of soils. In this test, a long cylinder of the soil is placed in a latex membrane and submerged in a clear plastic cylinder filled with water. A vertical pressure is applied to the cylinder at a slow rate until the soil sample shears. Very sensitive strain gauges measure the soil displacement, applied forces, and any pore water pressures that develop. Various water pressures are applied to the cylinder to simulate the confining pressure of soil depth (Brunsden and Prior 1984). This test can be used to determine the shear strength of soils that have been amended with organic materials.

Mitigating for Low Soil Strength

Biotechnical Engineering Techniques—Many biotechnical slope stabilization techniques use vegetative cuttings from willows or other easy-to-root species to structurally reinforce the soil. As these materials root, they add further stabilization to slopes through interconnecting root systems and soil moisture withdrawal. These practices include stake planting, pole planting, joint planting, brush layers, and branch packing (Section 5.4.3).

Shrub and Tree Seedlings—On drier sites, where willow cuttings are less likely to survive and grow, shrub and tree seedlings can be used. While these species are slower growing, they usually have deeper root systems and persist longer once they are established. Grass and forb species can quickly establish on drier sites, but soil strength is limited to the surface of the soil profile where the roots are most abundant. For this reason, grasses and forbs do not provide as much stability (Figure 3-72). On potentially unstable sites, grasses should be grown between shrub and tree seedlings to add soil strength to the surface soil while tree and shrub species become established. On dry sites, however, grasses must be excluded around seedlings or vegetative cuttings until they have become established. Because of the steep, shallow nature of many of these sites, planting seedlings is not always practical or successful. Hydroseeding or hand sowing, covered by a surface mulch that will protect the surface from erosion for several years while the shrubs become established, should be considered.

Figure 3-72 | **Effects of roots on slope stability**

This debris slide (noted by its shallow, steep appearance) took place two years after construction when the grass and forbs were fully established. Establishing shrub species, rather than grass and forb species, on steep, potentially unstable slopes, would be better for long term stability because shrub species are deeper rooting and have higher root tensile strength.

Photo credit: David Steinfeld

Soil Improvement—Improving soil productivity will increase root densities and enhance slope stability (Hall and others 1994). Mitigating measures that improve water storage, organic matter, and nutrients should, with time, increase slope stability. Some practices, such as soil tillage, reduce soil strength in the short-term. However, once plants have become established more roots occupy the soil and slope stability is increased. Tillage should be integrated with practices that quickly reestablish vegetation to ensure that slope stability is not compromised in the short term. On slopes where root strength is critical for stability in the first year after construction, irrigation could be considered to quickly establish a dense vegetation cover.

Temporary Soil Stabilization—It is important to implement erosion control practices that stabilize the surface of steep slopes while vegetation develops a strong root system and top growth. Where trees are inappropriate because of clear zones and shrubs inappropriate because of sight lines, erosion control products work well to stabilize soils while grasses and forbs establish.

3.9 IDENTIFYING FACTORS THAT AFFECT POLLINATORS

For projects where one of the objectives is to improve pollinator habitat, it is important to identify the core habitat elements supporting local pollinator populations. Similar to identifying limiting factors to plant establishment, as discussed in Section 3.8, the designer evaluates a project area for how well it supports a diversity of pollinators prior to construction and identify those factors important for improving pollinator habitat on roadsides after project construction.

The Pollinator Habitat Assessment Checklist (Table 3.7) is a guide to assessing current and potential habitat conditions based on information collected during the field information planning phase (Section 3.3 and Section 3.6). While the checklist provides habitat characteristics important for most pollinator habitats, the designer may want to modify the checklist to also include the climate, soils, vegetation, and pollinator species of interest specific to the project area and project objectives.

Once the designer has assessed the current condition of the pollinator habitat and identified parameters that are limiting to pollinator populations, a list of mitigating measures can be developed. Mitigating measures are site treatments that will improve pollinator habitat. For example, if breeding habitat is limiting, a mitigating measure is to include butterfly host plants.

There are usually several ways to mitigate each limiting factor and designers can select the measures that most suit their site conditions and objectives discussed in the following section.

3.9.1 NECTAR AND POLLEN SOURCES

Pollinators such as beetles, flies, wasps, moths, butterflies, bees, hummingbirds, and bats all forage for food on flowers. Nectar and pollen are sources of carbohydrates and protein, respectively, for pollinators. The act of pollination is an incidental effect of feeding or gathering food: animals visit flowers seeking sustenance, and in the process transfer pollen grains which allow flowering plants to reproduce.

Flowering plants in roadsides are important sources of nectar and pollen for pollinators that reside within the roadside habitat (e.g., Munguira and Thomas 1992) as well as those that use the roadside as a partial habitat for foraging but reproduce or overwinter elsewhere (e.g., Ouin and others 2004). Adults of bees, butterflies, wasps, hummingbirds, and many species of flies, moths, beetles, and bats feed on nectar to maintain their energy levels. Some adult beetles and flies require the protein that pollen provides in order to reproduce. Female bees actively collect pollen to take back to their nests (Figure 3-73), where they provide for their offspring by leaving a supply of pollen moistened with nectar. The availability of pollen and nectar influences the abundance and diversity of pollinators found on roadsides (Saarinen and others 2005; Hopwood 2008).

Figure 3-73 | **Bees and other pollinators rely on flowering plants as sources of food**

In this picture, a female long horned thistle bee (*Melissodes desponsa*) collects pollen from a tall thistle (*Cirsium altissimum*) and stores it on her hind legs to transfer it back to her nest, where she will leave it for her young to eat.

Photo credit: Jennifer Hopwood/Xerces Society

Attractiveness and Overlapping Bloom Times

It is important to include plants that are known to provide floral resources and attract pollinators. Native plants are more attractive to native pollinators than exotic plants, even when both plant types are present in sites (Hopwood 2008; Williams and others 2011; Morandin and Kremen 2013a). Some species of native plants are particularly attractive to a wide range of pollinators, offering either large quantities of nectar, high quality nectar, or pollen with high protein content. Sourcing plant material locally or within the ecoregion is best for pollinators because the phenology (flowering period) can also differ with the provenance of the plant material (Norcini and others 2001; Houseal and Smith 2000; Gustafson and others 2005) (Section 3.3.3 and Section 3.13.2). Bloom times of non-locally sourced plants have the potential to be out of sync with pollinators. This may be particularly problematic for bee species that are pollen specialists (e.g. *Melissodes desponsa*, a pollen specialist on thistles, Figure 3-73) and are reliant on the pollen from a small subset of plants and time their emergence from overwintering with the bloom time of their host plants.

Additionally, it is important to have flowers available to pollinators throughout the growing season. While pulses of bloom can provide critical resources to pollinators, sustained resources create functional habitat throughout the growing season to best support robust populations and communities. For example, solitary bees have distinct flight seasons that last 4 to 6 weeks. Bees that emerge early in the growing season can begin to forage in February in warmer parts of the U.S., with late-season bees foraging through October. Social bee species have overlapping generations and require forage throughout the growing season.

Gaps in bloom early in the spring or late in the fall are can be easily overlooked during the planning stages, but these are times when nectar and pollen are very important to the health of pollinators such as bumble bees, honey bees, and migrating monarch butterflies. Early-season pollen and nectar sources are important for those species that have flight seasons in the spring and will lead to greater reproduction of those species. Early season forage is also important for pollinators like bumble bees and honey bees that fly all season long but that are in need of floral resources early in the spring after overwintering. Late season flowers provide resources that ensure that queen bumble bees have ample food going into winter hibernation, and that honey bee colonies have enough food stores to last through the winter.

The availability of pollinator-friendly plant species and overlapping bloom times at a site prior to construction can be assessed by recording the plant species that are flowering and their percent cover every 2 to 4 weeks starting at the beginning of the growing season through the fall (February through October in California). These vegetation surveys would be conducted on both the project site and undisturbed reference sites (Section 3.6.1).

It is best to have a minimum of 3 to 5 species of trees, shrubs, or wildflowers blooming during each season (spring, summer, fall). Ideally there would be 5 to 10 species blooming per season, overlapping to ensure availability of resources to the entire pollinator community. Increasing the diversity of flowering plants in seed mixes and planting plans can help to prevent gaps in bloom. If flowering species have been recorded at reference sites during the growing season, these species can be used to develop a list of species with overlapping blooms for the revegetation project. When field surveys have not been conducted, a species list using the ERA tool can be used to generate lists of the recommended workhorse and pollinator-friendly plant species for all EPA Level III ecoregions in the continental United States. The ERA will also denote the bloom periods of the plant species and which general groups of pollinators the plant species will benefit.

Floral Diversity and Cover

Whenever possible, it is best to increase the diversity of wildflowers and blooming shrubs or trees. Pollinator diversity increases with increasing flowering plant diversity (Potts and others 2003). Different pollinators have different floral needs and preferences, so including a diversity

Figure 3-74 | **High plant diversity and floral cover are important for pollinators**

This roadside through the Tonto National Forest in Arizona has high plant diversity and high floral cover, two characteristics that are valuable for pollinators.

Photo credit: Arizona Department of Transportation

of plant species with different flower shapes, sizes, colors, and growth habits helps support the greatest abundance and number of species of pollinators (Ghazoul 2006; Ponisio and others 2015). Additionally, greater flowering species provide greater diversity of pollen and nectar sources for honey bees. Diversity in diet can help support honey bee immune system health (Alaux and others 2010; Di Pasquale and others 2013).

Floral cover is also important; having sparse resources will not sustain pollinator populations whereas high densities of blooms are more attractive and can support higher numbers of pollinators (Herrera 1998). For example, it is best for pollinator habitat to maximize the percentage of wildflowers included in revegetation projects involving herbaceous plants (Figure 3-74). The combination of grasses and wildflowers can effectively resist weed colonization and provide soil stabilization. A planting seed mix that consists of grass species at 50 percent or less of the seed mix volume can prevent the grasses from outcompeting the wildflowers. It is ideal to aim for 45 percent cover of flowering plant vegetation across a growing season. For example, flowering plant cover could be spread out throughout the growing season, with 15 percent cover of vegetation in spring, 15 percent in summer, and 15 percent in autumn.

It can be helpful to emulate the species diversity found on reference sites located in nearby natural plant communities. Diverse plantings that resemble natural communities are the most self-sustaining and long-lasting plantings because they better resist weed invasions and pest outbreaks. A general walk through of the area may be enough to identify flowering species or a more intensive sampling can be conducted using monitoring procedures described in Section 6.4. The Species Presence monitoring procedure (Section 6.3.3) can be used to record floral diversity and the Species Cover monitoring procedure (Section 6.3.2) can be used to record floral cover.

When working at sites with low diversity and floral cover, clumping single species together can benefit pollinators (Frankie and others 2002). For example, planting small clusters of single species of flowering plants to form patches of color when in bloom helps pollinators to spot the plants quickly. This is especially helpful for pollinators searching landscapes for limited resources and also helps pollinators to move quickly and efficiently between flowers to collect the resources they need. In larger plantings, clusters are less important as long as flowering plants are abundant.

Floral cover and diversity increases with site productivity. By improving soil characteristics, floral cover and diversity will increase. On projects where resources are limited, areas important for pollinator habitat can be identified and soil improvement conducted specifically in those areas.

3.9.2 BREEDING HABITAT

Pollinators have diverse habitat needs for breeding, in particular for their egg-laying sites. The habitat needs for insect pollinators are especially varied because insect pollinators select locations in which to lay their eggs based on the needs of their larvae. The main groups of insect pollinators, bees, beetles, flies, moths, butterflies, and wasps, all have four distinct life stages: egg, larva, pupa, and adult. Eating and growing are the primary functions of the larval stage, followed by the dormant pupal stage during which body tissues rearrange and transform into the adult stage. The primary goal of the adult stage is reproduction. The needs of pollinator larvae are often different than the needs of adults. For example, the eggs of some beetles and flies are laid near prey on vegetation or in the leaf litter so that their larvae, which are predatory, have access to the food resources they need. Butterfly and moth larvae (also known as caterpillars) consume vegetation and are found on the leaves and stems of plants, and their eggs are laid on certain species of host plants preferred by their larvae. Bees and predatory wasps construct nests in which to lay their eggs (Section 3.9.3). Roadsides can serve as breeding habitat for all of these and more.

Host Plants

Egg-laying sites for butterflies and moths consist of plants upon which the adult will lay eggs and the larvae will feed after hatching (Figure 3-75). Some butterflies and moths may rely on plants of a single species or genus for host plants. For example, caterpillars of the monarch butterfly feed only on species of milkweed (*Asclepias* spp.) and closely related genera. Some species are even more specialized; caterpillars of the Karner Blue butterfly (*Lycaeides melissa samuelis*) will only survive on lupine (*Lupinus perennis*). Other species may exploit a wide range of plants. The larvae of some swallowtails (*Papilio* spp.) can feed on a range of trees, shrubs, and wildflowers. Given this lifecycle pattern, establishing caterpillar host plants is recognized as a way to sustain butterfly and moth populations (Croxton and others 2005; Feber and others 1996). Roadsides with host plants can support habitat generalist butterflies as well as habitat specialists and migrant species such as the monarch butterfly (e.g., Ries and others 2001; Kasten and others 2016).

There are two main considerations for assessing whether butterflies and moths are using the site for breeding: (1) if host plant species are present within the site and (2) if present, if eggs and/or caterpillars of butterflies and moths are also present at the site. If the goals of the project include supporting particular species of butterflies or moths, it is useful to monitor the presence of the host plants of the target pollinator species. Section 6.4.3 includes a monitoring procedure for host plant abundance and population estimates of a target species (e.g. monarch butterfly) based on counts of eggs and caterpillars.

Many plants used in revegetation projects serve as butterfly and moth host plants, but it may be necessary to include additional species to support particular butterflies or moths. For example, planting milkweeds will contribute to the recovery of the monarch butterfly (Inset 3-5). The ERA tool includes information about the host plant needs of target butterfly and moth species. For additional information, see the HOSTS database of the world's Lepidopteran host plants created by the Natural History Museum, London. The database can be searched by either plant species or Lepidopteran species.

Figure 3-75 | **Caterpillars, butterflies, and moth larvae devour plant material**

This giant silkworm moth (*Antheraea polyphemus*) will feed on a number of host plant species, including maples (*Acer*) and plums (*Prunus*).

Photo credit: MJ Hatfield

Inset 3-5 | **Milkweeds and adjacent landowner concerns**

Increasing milkweed populations in North America is critical to the recovery of the monarch butterfly, but one obstacle to widespread inclusion of milkweeds in new plantings is the perception that milkweeds are in fact weeds. Concerns include:

- the potential for milkweeds to expand from the original planting site and encroach on adjacent land, and
- the chemical compounds present in milkweeds and their toxicity to livestock.

Although milkweed, the common name for plants in the genus *Asclepias*, implies that the plants are indeed weeds, milkweeds are a diverse group of native wildflowers with nearly 100 species in the U.S. that are not listed as noxious weeds at either the State or the federal level in the U.S. Milkweeds may be perceived as weeds because a few species will colonize disturbed areas and tend to reproduce vegetatively (in addition to reproduction by seed), sending up new shoots from roots that spread outward from the parent plant. This clonal reproduction allows their populations to expand over time, and plants may spread out of their original area. Common milkweed (*Asclepias syriaca*) exhibits the highest degree of clonal reproduction, and vegetative growth also occurs to a lesser degree in horsetail milkweed (*A. subverticillata*), narrowleaf milkweed (*A. fascicularis*), plains milkweed (*A. pumila*), prairie milkweed (*A. sullivantii*), showy milkweed (*A. speciosa*), and whorled milkweed (*A. verticillata*) (Borders and Lee-Mader 2014). Despite their vegetative growth, many of these species are unlikely to create an ongoing and unmanageable weed problem for roadside managers or adjacent landowners. However, the issue can also be avoided by selecting from the many milkweed species that do not reproduce clonally.

Another contributing factor to the perception of milkweeds as actual weeds is the presence of cardenolides, steroid plant compounds milkweeds use as a defense against herbivores. The amount of cardenolides present in plant tissue varies with the species of milkweed (it can also fluctuate seasonally) and can make the plants potentially toxic to livestock (Burrows and Tyrl 2013). Farmers and ranchers with livestock are often concerned about the presence and proximity of milkweeds to their stock. However, in properly managed rangeland and pasture, milkweed should pose no risk to livestock. Milkweeds are toxic only if consumed in large quantities, and milkweeds are highly unpalatable (Fulton 1972). Livestock, cattle in particular, will only consume milkweeds in the absence of other forage; a pasture must be barren in order for milkweed to poison a cow. Milkweed poisoning can be prevented by maintaining a sustainable stocking rate and by verifying that sources of hay are milkweed-free (milkweed retains its toxicity when dry and may increase in palatability).

Egg-Laying Sites

The breeding habitat needs are less understood for groups of pollinators beyond butterflies and bees, though what is known suggests that egg-laying sites for beetles, flies, and other pollinators are usually close to food sources for their larvae. If larvae are carnivorous, as is the case for lady beetles, eggs are laid on vegetation near their aphid prey, while syrphid or flower fly species that consume detritus or other decomposing materials as larvae lay their eggs in leaf litter. Egg-laying sites can include moist soil, leaf litter or plant debris, on foliage near prey, or in crevices under bark or rocks (Table 3-11).

Soil cover can potentially serve as a proxy for egg-laying sites for some pollinators. A monitoring procedure for measuring soil cover is presented in Section 6.3.1. Visual scans of vegetation can be used to identify colonies of aphids, whiteflies, or other clusters of plant feeders that serve as egg-laying sites for pollinator species with predatory larval stages (e.g. flower flies).

Table 3-11 | **Egg-laying sites for pollinators**

Pollinator group	Egg-laying sites
Beetles	In crevices, in the soil, on leaves, under plant debris or in leaf litter, on foliage near prey
Bees	In nests (Section 3.9.3)
Butterflies and moths	Host plants
Flies	On foliage among prey, on larvae (for parasitic species), in leaf litter
Wasps	In nests (Section 3.9.3)
Bats	Breeding habitat unknown but bear live young in roosts such as caves, bridges, etc.
Hummingbirds	Eggs in nests, often in forks of branches of trees and shrubs

3.9.3 NESTING HABITAT

Bees and predatory wasps provide for their young by constructing and provisioning nests in which their offspring develop. Bees provision their nests with pollen and nectar as food sources for their young, while predatory wasps supply their young with prey to consume. Some species of bees and predatory wasps nest underground, while others nest in tunnels and in cavities. Nesting is a critical factor affecting the ability of bees to persist within a site (Winfree 2010; Menz and others 2011; Morandin and Kremen 2013b).

Soil as Pollinator Nesting Habitat

Most of North America's native bee species (about 70 percent) nest in the soil. Ground nesting bees provide for their young by excavating nests in the soil. Their offspring develop underground in cells (also known as brood chambers). Ground nesting bees need access to soil surfaces between vegetation to excavate and access their nests (Michener 2007). Some species will nest in a variety of soils while others have very specific requirements for the soil type, moisture, alkalinity, slope, and aspect (Cane 1991).

Many ground-nesting bees prefer to nest in sunny, bare patches of soil (Linsley 1958; Sardiñas and Kremen 2014). Such patches can be found under wildflower plantings where small areas of bare ground are exposed between plants (Figure 3-76A) or around the bases of native bunch grasses that tend to grow in dense bundles. Providing openings in scrub or forest habitat can promote ground-nesting bees (Figure 3-76B). Bunch grasses tend to provide better nesting habitat than sod-forming grass species, and roadsides with native bunch grasses have more nesting opportunities for ground-nesting bees and, consequently, a greater abundance of ground-nesting bees (Hopwood 2008). Bunch grasses also allow establishment of other desirable species and prevents colonization from rhizomatous species. Undisturbed areas of bare ground can facilitate nesting activity (Potts and others 2005; Winfree and others 2009; Williams and others 2010; Roulston and Goodell 2011).

Assessment of patches of bare ground or patchy plant cover can be made through measurements of soil cover. A monitoring procedure for measuring soil cover is presented in Section 6.3.1. Ideally, patches of non-erodible bare ground would be present and cover approximately 5 percent of the project site. If using thick mulch during establishment, it can benefit ground nesting bees and wasps if there are small patches of bare soil left without mulch. Another idea for creating a permanent area of bare soil is to have short sections of cut slopes or banks that

Figure 3-76 | **Ground nesting bee nests**

The entrances of ground nesting bee nests often have small piles of excavated soil around them. Bees can nest in areas of bare ground (A) or amongst vegetation (B).

Photo credits: Eric Lee-Mader/Xerces Society (A) and Matthew Shepherd/Xerces Society (B) are very steep and constantly raveling, preventing plants from establishing. These sections would need to be away from water so that soil would not erode into the stream system.

Stems and Tunnels

A number of above-ground nesting bees nest in hollow stems or excavate pithy stems (e.g., elderberry or cane fruits) (Figure 3-77A). Many of these plants provide resources to other wildlife, such as berries (e.g., Salmonberry). Other native bees nest in tunnels in wood, such as abandoned beetle tunnels in logs, stumps, and snags (Michener 2007) (Figure 3-77B). Where site appropriate, planting native wildflowers with pithy stems, such as cupplant (*Silphium perfoliatum*), ironweeds (*Vernonia* spp.) and sunflowers (*Helianthus* spp.), along with shrubs such as wild rose (*Rosa* spp.), elderberry (*Sambucus* spp.), sumac (*Rhus* spp.), yucca (*Yucca* spp.) or agave (*Agave* spp.), will provide resources for stem-nesting bees.

Figure 3-77 | **Bee nest construction**

Bees can construct nests by excavating pithy stems (A) or in old beetle borer holes (B).

Photo credits: Jennifer Hopwood/Xerces Society

Assessment of potential tunnel nest sites can involve identifying woody plants (species and numbers) that support tunnel-nesting bees that can be planted at the project site. Additionally, because many tunnel nesting species create their nests in tunnels originally built by other insects (e.g., beetles), in old wood, such as snags, or living tree trunks, it can be useful to quantify the amount of dead wood, snags, or wood with holes in it (e.g., fence posts) that already exist at the site or that can be established within the project site.

The best method for increasing nesting habitat for tunnel nesting bees (and predatory wasps with similar nesting habits) is to plant woody vegetation used by bees and to maintain snags or downed wood. A minimum of three species of woody plants or pithy stemmed plants is recommended, though a good rule-of-thumb is to include at least five species. The ERA tool provides information about plants that provide nesting resources for bees. Maintaining or importing dead wood, snags, or wood with holes in it (e.g., fence posts) within the project site will also benefit tunnel nesting bees.

Cavities

Figure 3-78 | **Grass thatch is good nesting habitat**

There isn't much to see from the surface but this grass thatch was home to a healthy colony of eastern bumble bees (*Bombus impatiens*).

Photo credit: Jennifer Hopwood/Xerces Society

Most native bees are solitary and nest either in the ground or in wood or pithy stems. Bumble bees, however, are social and have different nesting requirements. Bumble bees form social annual colonies founded by a single queen in the spring. A bumble bee colony can grow in size through the spring and summer as the bees work cooperatively to raise offspring and find food. At the end of summer, if the colony is healthy, new queens are produced. Queens find mates in the fall, their natal colonies die off, and queens find a place to overwinter, such as in leaf litter or under a shallow layer of soil. Bumble bee colonies require an insulated cavity in which to nest, such as underneath grass clumps (Svennson and others 2000), under the thatch of bunch grasses (Figure 3-78), or under rocks (Hatfield and others 2012). Bunch grasses have a tendency to "lodge" at maturity, meaning they create a gap between the grass and the soil surface that can provide an ideal nesting cavity for bumble bee colonies (Svennson and others 2000; Hatfield and others 2012). Mowing and grazing can have negative impacts on bumble bee colonies (Hatfield and others 2012). If a colony is destroyed via mowing mid-growing season, no queens will be produced, which can lower population levels the following year.

The nest entrances to bumble bee nests can sometimes be located in wood piles. In addition, wild bees may use holes in wood in woodpiles for nest entrances. Wood piles are also attractive to other wildlife, including birds. If non-native woody vegetation is being removed from a project site, leaving some of the wood piled at the edges of the habitat into one or more brush piles can provide nesting locations and also support populations of ground beetles.

Assessment of nesting habitat for bumble bees involves counting the number of different native bunch grass species present, calculating the relative area of the site bunch grasses cover, and noting if downed wood is present at the site.

If native bunch grasses are adapted to the site, it is best to have at least one native perennial bunch grass species present, covering at least 2 percent of site. Ideally there would be at least 2 different species in each project site. If woody vegetation is removed from the site, leave at least 1 wood or brush pile. It is also important to maintain areas of unmown bunch grasses throughout the growing season to support bumble bee nests.

3.9.4 WATER SOURCES

Pollinators utilize water in multiple ways. Some directly consume water, while others use it to construct nests or for evaporative cooling. Pollinators can obtain water from edges of water sources, drops on vegetation, wet soil, puddles, or small pools on rocks.

Water, Mud, Minerals

Although pollinators typically obtain much of the water content they need by consuming nectar, water is also consumed directly on occasion or is collected by pollinators for hydration or evaporative cooling. On warm days it isn't unusual to see bumble bees gathered around the edges of puddles or perched on rocks in streams to sip water. Honey bees will collect water and transport it back to their hive in the heat of the summer to spread the water lightly

Figure 3-79 | **Wasps build their nests from mud**

This female potter wasp is collecting mud in order to build her nest.

Photo credit: Betsy Betros

over their brood and fan them with their wings to reduce the temperatures within the hive via evaporative cooling. Honey bees will also use water to dilute stores of crystalized honey within their hive. Water can also be used by ground nesting bees or wasps that carry it to the soil to moisten hard dry ground to make it easier to dig their nest tunnels.

A number of wild native bees and wasps utilize mud in their nest construction (Figure 3-79). Blue orchard bees (*Osmia lignaria*) collect mud and use it to create nest chambers for their offspring. Blue orchard bees so rely on mud that the females will not nest in areas without a source. Potter wasps (*Hymenoptera*: subfamily *Eumeninae*) also use mud as nest partitions within an existing cavity, as well as free-standing mud structures. Mud-puddling is a behavior to gather liquid nutrients exhibited by butterflies and some other pollinators in which they congregate on wet soil to gather minerals and nutrients needed for their health.

Water sources for pollinators can include culvert outlets, ditches, draws, gullies, and intermittent streams. Water runoff from the edge of the pavement can also create a source of mud for pollinators.

It may not be practical to include a potential water source in every revegetation plan. It also may not be a conservation priority for pollinators. As mobile animals, pollinators can fly to obtain the water or mud they need from surrounding land. However, projects that incorporate topographic enhancements into the roadside design will increase the potential for temporary surface water and mud sources (Section 5.2.8).

3.9.5 SHELTER AND OVERWINTERING

Like other animals, pollinators rely on various places that provide shelter during inclement weather. High winds, rain, cool temperatures, cloudy days, and other weather conditions all force pollinators to seek shelter. Pollinators are a diverse group of animals with a diverse set of needs for shelter and overwintering habitat (Table 3-12). Some rely on vegetation, such as the structure provided by grasses or the cover trees and shrubs provide. Others use rocks or crevices as shelter.

Pollinators also need a place in which to overwinter during the dormant season. Overwintering sites for most species are close at hand. Syrphid fly species and soldier beetles overwinter in roadside soil or litter (Schaffers and others 2012), and butterflies and moths also utilize roadsides as overwintering habitat (Schaffers and others 2012). However, a few species travel long distances to overwinter in warmer locations. Examples of migratory pollinators include monarch butterflies, painted lady butterflies, lesser long-nosed bats, and hummingbirds.

Table 3-12 | **Shelter and overwintering sites for pollinators**

Pollinator group	Egg-laying sites
Beetles	Larvae overwinter in loose soil or leaf litter Adults shelter under rocks, logs, brush
Bees	Adults take shelter in bad weather under leaves on plants; overwintering of most species occurs In nests (Section 3.9.3), but queen bumble bees overwinter under shrubs or in shallow soil and leaf litter.
Butterflies and moths	Shelter in structure of vegetation; Overwinter in a protected site such as a tree, bush, tall grass, or a pile of leaves, sticks, or rocks
Flies	Pupae and adults overwinter in soil or leaf litter
Wasps	In nests (Section 3.9.3)
Nectar-feeding bats	Caves, mines, rock crevices, tree bark, under bridges and within bridge structures
Hummingbirds	Shelter in trees and shrubs; some are resident and some overwinter in southwest U.S., southern Mexico, and Central America

Woody Vegetation and Grasses

Woody vegetation such as trees and shrubs can provide cover during the growing season that can serve as shelter for pollinators, and can also provide niches for overwintering. Some pollinators will overwinter under bark or in the soil just under shallow roots, or in piles of brush. Grasses can provide shelter for a variety of pollinators but notably for butterflies on roadsides (Saarinen and others 2005), and the root systems and grass thatch can also serve as overwintering habitat.

Assessment of shelter and overwintering habitat can involve identifying woody plants and grasses (species and numbers) that can be planted at the project site. It may be useful to calculate the relative area of the site that grasses cover. Refer to the monitoring procedures for soil cover (Section 6.3.1) and species cover (Section 6.3.2) for additional information.

Including a diversity of types of plants in revegetation plans can help to ensure that vegetation structure that can act as shelter and overwintering habitat is present. Trees and shrubs may not be appropriate for every revegetation project; in those situations, including a diversity of grasses both cool and warm season grasses can increase vegetation structure.

3.9.6 LANDSCAPE CONNECTIVITY

With habitat becoming increasingly fragmented (Saunders and others 1991), landscape connectivity is important for the populations of many species, including pollinators (Haddad 1999; Haddad and Baum 1999). Roadsides have the potential to act as corridors, strips of habitat or patches of habitat that serve as stepping stones that connect larger patches of habitat, facilitate movement of organisms between habitat fragments, aid in establishing or maintaining populations, and increase species diversity within isolated areas (Tewksbury and others 2002; Ottewell and others 2009).

Roadsides extend across a variety of landscapes and often contain greater plant diversity than adjacent lands. The linear shape and connectivity of roadsides may help pollinators move through the landscape (Soderstrom and Hedblom 2007), either for daily foraging or for dispersal between larger habitat patches. Evidence suggests that pollinators use roadsides as corridors to facilitate movement through the landscape in search of food or in pursuit of new habitat (Lövei and others 1998; Ries and others 2001; Valtonen and Saarinen 2005; Hopwood and others 2010). Additionally, there is evidence of several pollinator species expanding their ranges along roadsides (Dirig and Cryan 1991; Brunzel and others 2004). Corridors like roadsides and other linear strips of vegetation may provide habitat resilience as changes in climate drive species range contractions or expansions.

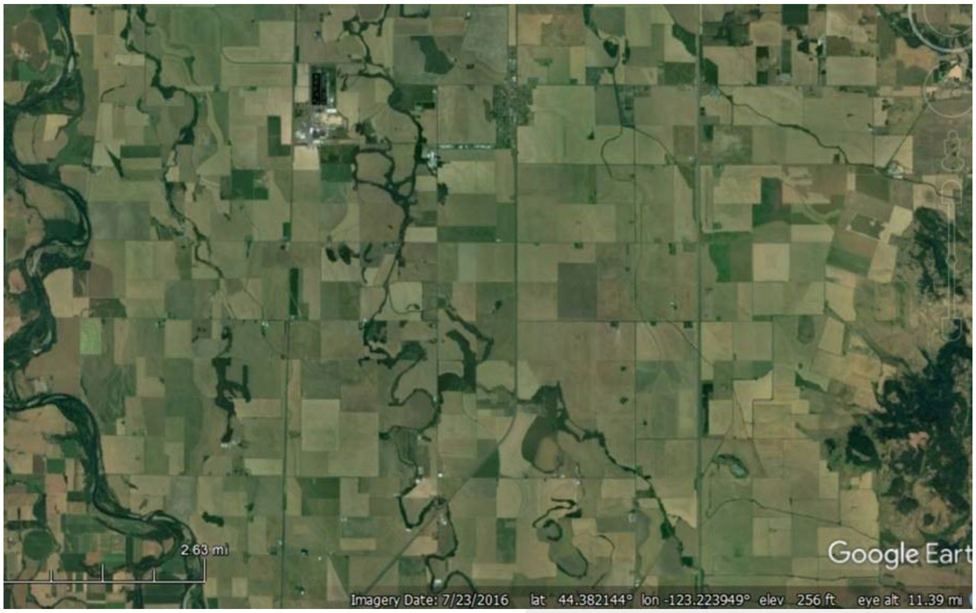


Figure 3-80 | **Roadsides can connect patches of habitat**

Landscapes with isolated or fragmented natural habitats make it difficult for pollinators to move from one natural area to another. The landscape shown in this photograph has poor connectivity between natural areas (dark green riparian and forested areas) because of agricultural land use, however, the high road density creates opportunities to connect isolated natural areas and create migratory pathways by implementing roadside revegetation projects favorable to pollinators.

Image from Google Earth

It is important to consider the landscape context of the revegetation project. Developing a landscape connectivity map of the project area and adjacent lands, using information collected during the vegetation assessment (Section 3.6.1), that locates areas of high, medium, and low pollinator habitat qualities, can be a base for designing a revegetation plan that improves pollinator habitat within a larger landscape connectivity context (Figure 3-80). If resources are limited, it can be helpful to prioritize high floral diversity and cover and other factors that influence pollinators for projects that link or act as stepping stones between existing habitats on private, municipal, state, or federal lands. It is also important to prioritize those projects that can increase the connectivity of existing roadside habitat. If remnant roadside habitat exists, for example, it would be very beneficial if revegetation projects with high plant diversity were installed adjacent to or nearby.

3.9.7 ROAD MORTALITY

Roads can pose specific threats to pollinators. Roads can be a source of mortality for pollinators due to collisions with vehicles (e.g., Munguira and Thomas 1992). Roads may act as barriers to pollinator movement (e.g., Valtonen and Saarinen 2005). The prevalence of invasive and nonnative species on roadsides reduces pollinator abundance and diversity (e.g., Hopwood 2008). Finally, roadside vegetation is exposed to pollution from vehicles, which may impact pollinators (e.g., Jablonski and others 1995).

Vehicle Mortality

Collisions with vehicles are a source of mortality for pollinators that utilize resources in roadsides as well as pollinators traveling through the landscape. Mortality rates can be estimated by counting roadkill (McKenna and others 2001; Baxter-Gilbert and others 2016) but provide incomplete information. Estimates of the population sizes of pollinators using roadsides, in addition to counts of those killed by vehicles, provides a mortality rate that includes context for the proportion of the population impacted. Mortality rates of butterflies using roadside vegetation range from 0.6 percent to 7 percent of the population (Munguira and Thomas

1992) or 6.8 percent of the butterflies found on the roadside (Skorka and others 2013). Of the butterflies observed crossing roads, 2.8 percent were hit by vehicles (Ries and others 2001).

Rates of mortality due to collisions with vehicles are influenced by a number of factors. Some species of pollinators are more vulnerable to collisions than others due to their behavior or biology; species that are strong fliers, for example, appear to have lower rates of mortality than those that are not (Munguira and Thomas 1992; Ries and others 2001; Skorka and others 2013). Volume of traffic may influence rates of mortality (Skorka and others 2013); however, several studies have found that traffic volume does not consistently influence observed mortality (McKenna and others 2001; Saarinen and others 2005). The width of road or overall density of roads in the landscape may also influence butterfly response to roads. Wider roads may increase mortality rates (Skorka and others 2013) and some butterflies have decreased movement within a dense network of roads (Valtonen and Saarinen 2005).

Vegetation quality can also influence pollinator mortality: roadsides with more species of plants had fewer butterflies killed by traffic (Skórka and others 2013) (Figure 3-81). The frequency of mowing is also linked to a higher proportion of butterflies killed on roads; butterflies that had to disperse to find new habitat after roadsides were mowed may have had a greater likelihood of collisions with vehicles (Skórka and others 2013).

If quality roadside habitat is present, it may reduce the amount of pollinators killed by vehicles by providing pollinators with necessary habitat and less need to disperse elsewhere. It is important to consider increasing plant diversity of the roadside vegetation and reducing mowing beyond the clear zone (the strip of low growing or routinely mowed vegetation, or vegetation-free area, directly adjacent to the pavement) in order to reduce mortality rates due to vehicles. In areas with high traffic density, it may be helpful to increase the width of the clear zone, which is not typically used by pollinators as habitat, to increase the distance between pollinators foraging in the habitat and vehicles on the roadway. When developing the landscape connectivity map, it may also be helpful to prioritize locations for high quality revegetation projects with goals of supporting pollinators, focusing first on sites that are not in areas of high road density.

Figure 3-81 | **Roadsides with high plant diversity have fewer butterflies killed by vehicles**

Research indicates that fewer butterflies are killed by vehicles when roadside vegetation has high plant diversity and floral cover.

Photo credit: Maria Urice/Iowa Living Roadway Trust Fund

Invasive Species

Many invasive and noxious plants can be present in roadsides (Tyser and Worley 1992; Gelbard and Belnap 2003) due to favorable conditions for plant introductions and invasions (Hansen and Clevenger 2005; Von der Lippe and Kowarik 2007). Nonnative plants can decrease the quality of roadside habitat for pollinators (Hopwood 2008; Valtonen and others 2006). Nonnative plants compete with native plants for resources as well as alter habitat composition, and some cause significant reductions in the abundance and diversity of pollinators and other herbivorous insects (Samways and others 1996; Kearns and others 1998; Spira 2001; Memmott and Wasser 2002; Zuefle and others 2008; Burghardt and others 2009; Tallamy and Shropshire 2009; Wu and others 2009; Hanula and Horn 2011; Fiedler and others 2012). There is also evidence that native pollinator insects prefer native plants (Burghardt and others 2009; Wu and others 2009; Williams and others 2011; Morandin and Kremen 2013a), even though many native insects will feed on nonnative plants when few natives are available (Zuefle and others 2008; Burghardt and others 2009; Wu and others 2009; Williams and others 2011).

To reduce invasive species and nonnative plants, it can be helpful to control weeds before and during construction (Section 3.11.5), as well as during the establishment phase following revegetation (Section 3.11.6) and maintaining a weed-resistant roadside following construction (Section 3.11.4). Salvage topsoil whenever possible, and source the imported project mulch, compost, and other inputs carefully, specifying testing certificates and/or certified weed free products where possible, in order to avoid introducing and spreading weed seeds. Additionally, purchasing seeds for the revegetation project within seed transfer zones can help to curb the spread of weed seed contamination of seed mixes.

Roadside Contamination

Routine vehicle use and maintenance of roads contribute to roadside contamination by depositing pollutants, including vehicle exhaust and de-icing materials. Roadside soils and vegetation can be contaminated with heavy metals such as lead, iron, zinc, copper, cadmium, nickel, and others deposited from tire rubber, brake dust and gasoline and diesel combustion products (Gjessing and others 1984; Oberts 1986; Araratyan and Zakharyan 1988). Vehicle-derived contamination is proportional to traffic levels (Leharne and others 1992). In general, plant and soil contamination is greatest adjacent to the road and decreases with distance from the road (Quarles and others 1974; Dale and Freedman 1982; Jablonski and others 1995; Swaileh and others 2004). Contamination tends to decline within 20 meters but can still be present at high levels up to 200 meters from the road (Spellerberg 1998; Trombulak and Frissell 2000). Pollen and nectar contamination is also greatest nearest to the road (Jablonski and others 1995).

Heavy metals can be harmful to pollinators directly (Nieminen et. al 2001; Moroń and others 2010; Perugini and others 2011) or indirectly by weakening vegetation (Mulder and others 2005). However, few studies have explicitly examined the impacts to pollinators of heavy metal exposure in roadsides. Ozone, nitrates, and other exhaust gases may also have an impact on roadside vegetation and pollinators. Ozone and nitrates can inhibit floral scent, which reduces a pollinator's ability to detect flowers and in turn may reduce reproductive output of both pollinators and plants (McFrederick and others 2008). Dry deposition of particles with nitrogen derived from fuel combustion can create a strip of "fertilized" soil along roadsides, particularly in more arid regions (Gade 2013).

De-icing salts used on roads alter roadside soil chemistry by increasing sodium levels in plant tissues significantly (Snell-Rood and others 2014) and can damage plants (Bogemans and others 1989), with probable indirect impacts on pollinators (Section 3.11.9, see Deicing for Winter Safety). Varying levels of sodium in butterfly host plants can affect development of caterpillars in both positive and negative ways. Sodium is an important micronutrient for butterflies and moderate levels of sodium can increase flight muscle and brain size of adults (Snell-Rood and other 2014). More data about the impacts of salts, heavy metals, and exhaust on pollinators is needed. Until that data is available, increasing the width of the clear zone, particularly in areas with high traffic and frequent use of road salts, may help reduce pollinator exposure to these contaminants.

3.9.8 VEGETATION MANAGEMENT

The management of roadside vegetation can have a significant impact on pollinators. Mowing vegetation beyond the clear zone multiple times a growing season, for example, can cause direct mortality to pollinators in the egg or larval stages that cannot avoid the mower (Humbert and others 2010) (Figure 3-82), can deprive pollinators of sources of pollen and nectar, as well as host plants for caterpillars (Johst and others 2006) (Figure 3-83), and can destroy bumble bee colonies (Hatfield and others 2012). However, the timing and frequency of mowing can be adjusted to reduce the impacts to pollinators (e.g. Halbritter and others

Figure 3-82 | **Mowing pattern can facilitate pollinator habitat**

Cutting the clear zone with well-defined edge looks groomed and provides safe run-off zone.

Photo credit: Magnus Bernhardt/ODOT

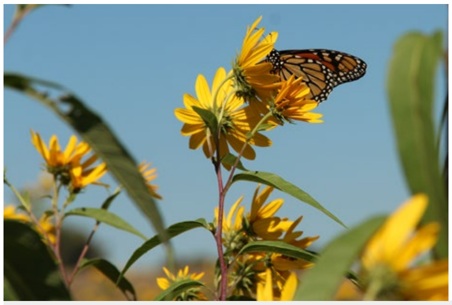


Figure 3-83 | **Mowing can affect food sources**

If mowing occurs too frequently, plants will not be able to flower and pollinators will have fewer sources of food.

Photo credit: Jennifer Hopwood/Xerces Society

2015). When designing revegetation plans, it is important to consult with the site's maintenance department. Maintenance departments have processes and practices in place for reasons that are not obvious to habitat designers, such as the timing of mowing. Discussions with maintenance departments may result in a willingness to alter maintenance practices that can facilitate pollinator habitat, but that determination cannot be made without the designer opening communication with roadside maintenance.

If maintenance practices cannot be adjusted in ways that support pollinators, there are other opportunities for pollinator habitat on land managed by DOTs that are not roadside rights of way. These areas include DOT "back 40" lots, stockpile lots, maintenance yards, under used DOT office land, special management areas, bicycle paths, scenic viewpoints or historic or geologic points of interest or roadside rest areas. Maintenance is often glad to put forthright uses to these underutilized areas. These areas also offer opportunities for collaboration with citizen groups because they are less exposed to the hazards of traffic and DOTs may be more willing to allow volunteer groups to install or manage pollinator gardens in these areas.

If one of the goals of the project is to support pollinators, it is important that the vegetation can be managed such that pollinators benefit. For additional information about vegetation management and strategies that can support pollinators, see Chapter 7.

3.10 INVENTORYING OF SITE RESOURCES

Most project sites contain resources that can be used to meet revegetation objectives. Identifying these potential resources early in the planning process is essential so that they are not inadvertently wasted. The more that local resources are used, the more cost-effective, efficient, and effective the revegetation efforts may be. Physical resources to inventory include topsoil, duff, litter, parent materials, woody materials, logs, plant materials (seeds, seedlings, and cuttings), large rocks, and water (seeps, springs, creeks). Intangibles should also be considered, such as community cooperation and the local knowledge base.

3.10.1 TOPSOIL

One of the most important site resources for revegetation is topsoil. If considered early in the planning process, topsoil can be salvaged and reapplied to disturbed sites after construction. This is one of the best ways of increasing productivity on a disturbed site.

Topsoil is inventoried early in the planning process to evaluate topsoil quality and quantity, costs, and the feasibility of removal and storage. Topsoil recovery is an expensive operation requiring knowledge of basic soil attributes. For this reason, it is a good idea to conduct a soil survey or assessment of those locations that will be disturbed. An example of soil and site information commonly collected for topsoil recovery is shown in Table 3-13. The road in this example is planned through undisturbed forested lands. Soils data is collected every 50 meters (at road stations) due to the high variability of the soils in this area. Where soils are very uniform, distances between plots can be increased. Soil texture, rock fragments, and depth of the topsoil are measured in the field. At selected intervals, or on different soil types, a sample is collected for lab analysis.

During topsoil survey, other site attributes that could affect the quality of topsoil should be noted, especially the locations of all noxious weeds. These weeds can be treated or removed prior to topsoil salvage or the weed-infested areas can be avoided to prevent the spread these weeds across the project area.

The outcome of the topsoil survey is a short report and map in the revegetation plan showing the areas and depth to salvage topsoil. The report should discuss the fertility of the topsoil, how it should be stored, and whether the duff and litter are removed and stored separately. Areas should also be identified where topsoil should not be collected, such as areas of noxious weeds or high rock. The volume of topsoil can be calculated based on soil depth and area of the road prism.

Table 3-13 | **Example of a form for collecting topsoil information**

	Plot number				
	C1	**C2**	**C3**	**C4**	**C5**
Location	1 + 300	1 + 350	1 + 400	1 + 450	1 + 500
Site Condition	Undisturbed	Undisturbed	Undisturbed	Undisturbed	Undisturbed
% Slope	30	45	35	45	40
Aspect	N	N	NE	S	S
Topsoil depth	12″	14″	14″	6″	6″
Topsoil texture	Loam	Loam	Loam	Loam	Loam
Topsoil % rock	30	25	20	40	45
Subsoil texture	Sandy loam	Sandy loam	Sandy loam	Clay loam	Clay loam
Subsoil % rock	40	35	45	45	35
Total soil depth	> 60″	> 60″	> 60″	> 40″	>40″
% Soil cover	100	100	100	100	100
Soil surface cover	Litter, duff	Litter, duff	Litter, duff	Litter, duff	Litter, duff
Depth of cover	1″	1″	2″	0.25″	0.25″
Parent material	Granite	Granite	Granite	Basalt	Basalt
Fracturing	Massive with some fracturing	Massive with some fracturing	Highly fractured	Highly fractured	Highly fractured
Sample depth	0-14″	0-14″	0-14″	0-14″	0-14″

3.10.2 DUFF AND LITTER

Duff and litter are the dead plant materials that have accumulated on the surface of the soil. The level of decomposition differentiates litter from duff. Litter is the layer of recently fallen, undercomposed leaves, needles, and branches; duff (which occurs immediately below the litter layer) is litter that is decomposed beyond recognition. The duff layer is a dark, light-weight organic layer. It is a large reserve of nutrients and carbon, and has a high water-hold capacity. Litter and duff layers protect the soil from erosion by absorbing the energy of rainfall impact and reducing overland flow. Combined, the litter and duff layers can be very thick, ranging from 1 to 4 inches depending on the productivity and climate of the site.

Litter layers typically have viable seeds originating from the overstory vegetation. Under the right conditions, these seeds will germinate. If collected, stored and reapplied correctly, this natural seed bank can be used as a seed source. Litter and duff layers can also contain mycorrhizal inoculum.

Litter and duff layers can be assessed concurrently with topsoil surveys by measuring their depths using a ruler. Refer to Section 5.2.3 (see Litter and Duff), for a discussion of methods for collection and application.

3.10.3 SUBSOIL AND PARENT MATERIAL

Certain subsoils and parent materials can be salvaged during road construction and used to produce manufactured topsoil (Section 5.2.4, see Manufactured Topsoil). Textures low in rock content, including sandy loams, silt loams, loam, and sandy clay loams, are often good materials for manufactured soils. These are often found in areas where the parent materials are derived from alluvial or windblown deposits. They include river sands, pumice, volcanic sands, and loess.

3.10.4 WOODY MATERIAL

Woody material consists of live and dead plant materials that are cleared in the early stages of road construction. This material includes tree boles, root wads, bark, and branches. During clearing and grubbing, these materials are often concentrated in piles and burned. All of these materials can be ground up as shredded wood and used as surface mulches (Figure 3-84) (Section 5.2.3, see Shredded Wood) or soil amendments (Section 5.2.5). Large wood can be used for biotechnical engineering structures, obstacles for erosion control, or placed upright or on the ground for pollinator habitat and site productivity. Substituting shredded wood derived from these materials for composts and soil amendments can lower overall project costs.

Figure 3-84 | **Creating shredded wood for mulch**

Woody material from road clearing can be ground up into shredded wood and used as a mulch or soil amendment.

Photo credit: David Steinfeld

Suitable plant materials are often destroyed during road construction. These consist of seeds (Section 5.3.1), plants (Section 5.3.3), and cuttings (Section 5.3.2). If these materials are collected from the construction site prior to disturbance and stored correctly, they can be used, instead of propagated or purchased plant materials, to revegetate the project. Surveys of the project site prior to construction will indicate the location and abundance of appropriate plant materials.

3.11 DEVELOPING A VEGETATION MANAGEMENT STRATEGY DURING PROJECT DESIGN

3.11.1 INTRODUCTION

During the planning phase, it is important to consider how vegetation will be maintained after the road project is completed. The effects of road surface and roadside vegetation management can have unexpected and often, unwanted effects on the long-term outcome of the revegetation project. Developing a written maintenance strategy can assure that there will be a rational documented approach to the management of roadside vegetation long after the project is completed and can be used to gain acceptance of the strategy from the maintenance department.

The intent of a maintenance strategy is to consider how the results of a revegetation project will affect the management and maintenance of the roadside and to incorporate this understanding into the revegetation plan. The strategy also anticipates and mitigates for those biotic and abiotic factors that may affect the development of native plant communities and pollinator habitats. Ideally, the planning team or designer meets with local roadside maintenance personnel to discuss their current and future anticipated maintenance procedures in order to learn what problems can be expected in reestablishing roadsides with native plants and how these problems could be addressed. This is a time when maintenance personnel can raise concerns and then work collaboratively with the design team to develop solutions. The planning phase is a good opportunity to develop a plan that maintenance personnel will understand and support.

The intended audience for this section is the designer and design team because they will integrate road maintenance and operations into how to achieve the long-term revegetation objectives during the planning process. Chapter 7 also covers vegetation management but from a maintenance perspective and the intended audience for that chapter is maintenance and operations staff. Chapter 7 focuses on approaches to road surface and roadside maintenance that will meet revegetation objectives after the revegetation project is completed.

A vegetation maintenance strategy may cover some, or all of the following:

- Protection of areas currently free of invasive species
- An outline of an integrated vegetation management approach to weed control
- How existing weeds may be controlled prior and during construction
- How a weed-resistant road environment will be created
- How roadside vegetation maintenance objectives will be achieved after construction
- How the vegetation maintenance strategy is handed off to maintenance personnel
- How roadside disturbances will be treated during the maintenance phase

3.11.2 INTEGRATING ROAD MAINTENANCE OBJECTIVES INTO THE REVEGETATION PLAN

For a successful project, it is important that road surface and roadside maintenance objectives align with treatments and species outlined in the revegetation plan. Many states have developed IRVM (Integrated Roadside Vegetation Management) Plans that outline roadside maintenance objectives. When available, it is strongly recommended that the designer refer to these individual plans while developing the revegetation plan. The IRVM plan is “an approach to right-of-way maintenance that combines an array of management techniques with sound ecological principles to establish and maintain safe, healthy and functional roadsides” (Brant and others 2015). It applies many of the Integrated Pest Management concepts developed for agriculture, horticulture, and forestry to roadside vegetation management. The IRVM elements include prevention, monitoring, action thresholds, pest treatments, and evaluation (NRVMA 1997). Most of these plans are available on the internet or by contacting the state Department of Transportation (DOT) or the local maintenance agency.

A vegetation management strategy considers how road maintenance objectives are integrated into plant species selection, planting patterns, vegetation control, invasive species control, and site treatments. Typical road objectives are stated below, along with their possible effects on roadside vegetation. In the development of the vegetation management strategy, consider how each objective will affect vegetation and, in turn, how vegetation treatments and design will affect roadside objectives.

- **Maintain line of sight**—It is important to not plant masses of tall grasses, shrubs or trees in areas where line of sight is important. If they are existing to remain on a site that is being revegetated, they may need to be maintained or removed and replaced with appropriate smaller plant material so as not to reduce line of sight. Designing for safety is further discussed in Section 3.11.7.
- **Maintain clear zones**—The FHWA (2017) defines the clear zone as "an unobstructed, traversable roadside area designed to enable driver to stop safely or regain control of a vehicle that has accidentally left the roadway … and an effective strategy for prevention and mitigation of roadway departure crashes." The publication further states that "trees are the single most commonly struck objects in serious roadside collisions. Therefore, it is important to integrate the selection of appropriate plant species with safety objectives in mind." The integration of habitat features such as brush piles or dead wood should be placed well beyond the clear zone.
- **Maintain road surface**—Encroaching vegetation can reduce the longevity of road surfaces. Selecting plant species that are least likely to do this can preserve the longevity of roads.
- **Reduce fire hazards**—One of the reasons for maintaining low growing roadside vegetation is to reduce the starting of fires by motorists and the spread of wildfires. In planning, choosing plants that are more fire resistant and encouraging plants that stay green in the summer (e.g. native perennials) by creating good optimum growing environment (e.g. good soil conditions). Mowing, herbicides, grazing, and fire are also measures that may affect pollinator habitat and need to be planned accordingly (Section 7.3).
- **Maintain stable roadside**—Cuts, fills, and drainage facilities need to be maintained so that they are stable. When they are not, they create road hazards and degrade water quality. Unstable material will need to be removed and replaced. The removal area and replacement material will need to be reviewed and revegetated. Areas that fail will also need to be repaired and revegetated. It is important that the maintenance provider have the native-sourced seeds or plants for the waste or disturbed areas (Section 7.4.2)
- **Maintain or increase water quality**—Maintaining water flow off pavements, down ditches, and into natural waterways is important for road maintenance but may affect water quality or plant growth. Cleaning out ditches affects plants and cut slopes. Poor flow of water off pavements can cause rill and gullies on fill slopes affecting plants. Poorly designed culvert placement can cause downcutting of natural drainage channels.
- **Reduce or eliminate invasive species**—Controlling invasive species may also negatively affect non-target plants and pollinator species and need to be considered when developing treatments. (Section 7.3).
- **Maintain safe road surfaces during winter months**—Winter roadway surface treatments vary throughout the country. Gravels used in mountainous, heavy snowpack areas, coarse sand used in smaller urban areas, and the more prevalent deicing chemicals

can be the most devastating treatments on roadside vegetation. Sweeping gravels off pavement during melt periods buries roadside plants. Reusing gravels from along roadsides can spread weeds. Blowing snows can create drifts that melt later in the year and may call for different plant species in those areas to withstand that condition. Sand accumulations in swales and drainage structures can create clogs, ponding, and spreading sand bars which can smother groundcover over time. Deicing with salts and other chemicals can kill or reduce growth on certain plant species. This is further discussed in Section 3.11.9 (see Deicing for Winter Safety).

- **Reduce impacts of wildlife to motor safety**—The selection of plant species and where they are planted along roadsides can affect how wildlife moves through a road corridor and their potential hazards to motorists. Planning for wildlife is an important consideration when selecting plant species and planting patterns. Providing desirable browse or a refuge of thick vegetation on both sides of an identified animal crossing can draw wildlife to the safe crossing location. Existing vegetation near known unsafe animal crossing locations may be controlled through removal, thinning, and mowing to reduce cover and forage opportunities, and to increase visibility in an attempt to reduce animal-vehicle collisions. Vegetation types, patterns, and maintenance can encourage the movement of wildlife to crossings. Wildlife fencing that direct animals to grade separated crossings are very successful in reducing wildlife-vehicle collisions (WVC). The fencing should be planned with wildlife biologists who are familiar with wildlife passage patterns.
- **Protecting utilities**—Encroaching vegetation can overgrow and hide utility structures, which may lead to accidental damage during maintenance procedures, may affect maintenance access, and may cause maintenance review to be missed. Utility service may also be damaged and disrupted by accumulation of heavy vines, wind-blown branches, and by falling trees or branches. It is important to that species that may interfere with utility access and protection are not planted near these structures.

The vegetation management strategy will ideally span the entire length of the project, into the operation and maintenance phase (Chapter 7). In the early stages of planning, weed sources are identified and treatments to control or eliminate often begin prior to construction (Section 3.11.6). Areas of functioning plant communities, relative free of invasive species are identified and plans for protection are developed (Section 3.11.3). During planning, road maintenance objectives are integrated into the revegetation treatments. As the project moves into construction, treatments to create a weed-resistant environment (Section 3.11.4) and measures to reduce the introduction of weed sources are implemented (Section 3.11.5). Once construction is completed, the project is handed off to the agency responsible for road maintenance. At this point, the responsible agency implements their vegetation maintenance plan which dovetails with the revegetation plan objectives (Chapter 7).

3.11.3 PROTECTING HEALTHY PLANT COMMUNITIES

Mature forests, prairies, and wetlands are often high quality, healthy, and diverse landscapes supportive of a wide range of native plant, pollinator, and wildlife communities. These healthy plant communities are typically more resistant to invasive plant and animal species, and contain flora and fauna capable of supporting high level predators, particularly in larger areas. For the purposes of this report, landscapes of healthy plant communities capable of providing quality habitat for large animals, are referred to as 'refugia.'

Many of the larger blocks of refugia habitat have been preserved by local, State, and National parks, but remnants remain on undeveloped public and private land across the country that are essential for the preservation of native flora and fauna. Migrating animals and those that require large ranges depend on refugia and safe connections between refugia areas.

Revegetated roadsides can offer safe connections for wildlife to under and over-crossings and to other areas of refugia.

Despite best efforts to prevent impacts to environmental assets during the planning and construction of roadway expansions, development of roadway systems often causes disturbances to refugia. Introduction of road rights-of-way near or through these natural areas often results in a slow degradation of the landscape and wildlife population through the removal of habitat, altering or cutting off of wildlife corridors, and introduction of construction and traffic noise, pollution, deicing chemicals, and invasive plant and animal species.

Roadside revegetation treatments can be designed to provide a measure of protection for uninfested areas through buffering of on-going pollutions and disturbances and by preventing encroachment of invasive plants and annual weeds. Further protections of uninfested areas can be achieved through the processes listed below and described in more detail in following subsections:

- 3.11.4 Creating a Weed-Resistant Roadside Environment
- 3.11.5 Keeping Weed Sources from Entering the Project
- 3.11.6 Controlling Unwanted Vegetation
- 3.11.7 Designing for Safety and Utility Protection
- 3.11.8 Designing to Isolate Wildlife from Vehicles
- 3.11.9 Designing for Disturbances

3.11.4 CREATING A WEED-RESISTANT ROADSIDE ENVIRONMENT

The foundation of long-term weed control is to create a growing environment that encourages the development of a healthy native plant community resistant to the introduction and spread of weeds. For most weeds to become established, there must first be an opening, or space, in the native plant community for plants to grow. These conditions occur in disturbed areas associated with recent construction, landslides, bladed ditches, gullies, waste areas and other areas where native plants and soil have been removed or disrupted. Secondly, the disturbed environment must be favorable for weeds to take hold and thrive. This requires that the soils and climate be optimal for the environmental needs of the weed species. Third, the weed species must have an advantage over native species. If a weed is more resilient or robust in its growth habits in both adjacent lands and disturbed sites, then it is more likely to become established.

Some mitigating measures that can be taken to limit the environment where weeds can gain a foothold are:

- **Minimize ground disturbance**—Most weed seeds need bare soil to germinate and become established. Reducing the footprint of the project results in less area being disturbed and exposed to possible weed invasion. Avoid ill-timed blading, mowing, dredging, and other ground-disturbing activities (Harper-Lore and others 2013).
- **Develop optimum environments for quick native plant recovery**—Establishing a healthy native plant community after construction greatly reduces the possibility for weed invasion. Optimum native plant establishment is dependent on the site's soils and climate. Site factors restricting the downward root growth of native perennial plant roots (e.g., compacted soil) give the advantage to weed species. For example, a site with loose, reapplied topsoil is much more likely to support a native plant community than a compacted site lacking topsoil and organic matter. Unlike perennial plants, the roots of most annual weed species occur in the surface layer (Jackson and others 1988; Claassen and others 1995) and do not require deeper soils to survive and grow. Annual species therefore have an advantage over perennials on compacted or shallow soils.

Developing site treatments that create an optimum environment for native perennial plant recovery will limit the establishment and spread of weeds (Sheley 2005).

- **Develop a weed-resistant seed mix**—Where appropriate, apply a seed mix that resists weed establishment. Using a seed mix composed of a diversity of species can reduce the potential for weed establishment by creating a plant community that fills niches that otherwise would have been occupied by weeds. Sowing native seeds at high rates can also flood bare soil with the seeds of desirable species, reducing the germination sites where weed species can become established. The objective of this strategy is to fill the openings first with desirable species to crowd out unwanted species (Section 5.4.1).
- **Establish desirable non-native plants if establishment of natives is not feasible**—Due to surrounding site limitations, project parameters, timelines, or other circumstances, using locally adapted native plant materials may not always be possible. For example, if the project is surrounded largely by contiguous populations of cultivars, using locally adapted plant materials may not be worth the effort. If the surrounding area is primarily native species, careful selection of cultivars is important to consider. Many cultivars, both native and introduced, have the potential to cross with their locally adapted native equivalent genera (Section 3.13.2).
- **Avoid applying nitrogen fertilizers in the first year**—Many annual weeds out-compete native plants on soils that are high in nitrogen because they are more adapted to utilizing nitrogen during early plant establishment. High rates of nitrogen fertilizers can encourage the growth of weedy annuals at the expense of the establishment and growth of native perennials (McLendon and Redente 1992; Claassen and Marler 1998), whereas perennial grasses have a competitive advantage at lower nitrogen levels (Welker and others 1991). Application rates of up to 108 lb/ac N (121 kg/ha N) have been shown to promote the establishment of introduced grasses over less competitive native grasses (DePuit and Coenenberg 1979). High rates of nitrogen fertilizers can also affect revegetation efforts by decreasing species richness and increasing the presence of non-native species (Munshower 1994; Wedin and Tilman 1996). When nitrogen fertilizer is applied at seeding, root systems of native perennials establish in the upper portion of the soil. The decrease in deep roots gives the annual weed species a competitive growth advantage (Claassen and others 1995). Limiting the amount of nitrogen fertilizer used the first year (during vegetation establishment) will help force the roots of perennials deeper into the soil where there is more moisture. The deeper root system increases the competitive advantage of the native perennials over the annual weeds. This strategy, however, does not preclude the need for fertilization. One option is not to apply fertilizer until a year after sowing when the native plants have become established (Section 5.2.1), though this may not be possible due to construction schedules and budget constraints.
- **Apply mulch**—Mulch can be applied to the surface of a disturbed soil to create a poor germination environment for weed seeds (Section 5.2.3). The mulch should have high void spaces (typical of long-fiber mulch materials) and low water-holding capacity, which is an unfavorable environment for seed germination. The deeper the mulch, the less weeds will become established. Depending on the weed species, 2 to 4 inches of mulch are required to effectively control the establishment of many weed species (Pellett and Heleba 1995; Ozores-Hampton 1998; Ozores-Hampton and others 2002; Penny and Neal 2003).
- **Apply high C:N materials to high nitrogen sites**—If soils are high in nitrogen, applying a high C:N material (e.g., wood products, coir mulch, or pine straw) to the surface of the soil, or mixed into the soil, is another strategy to reduce the amount of available nitrogen for annual weed growth (REAP 1991; St John 1999). Over time, the organic material will break down and release nitrogen for uptake by perennials.

- **Retain shade**—Most weeds require full or partial sunlight to thrive (Penny and Neal 2003). To reduce the vigor of undesirable plants, retain as much shade as possible.

3.11.5 KEEPING WEED SOURCES FROM ENTERING THE PROJECT

Weed species are often brought onto the site from outside sources such as construction equipment, mowing equipment, cars and trucks, shoes and socks, and in materials used on the project such as gravel and rock. All too often, weeds arrive during the revegetation efforts in contaminated mulches, topsoil, hydroseeding equipment, and uncertified seed sources. Making the effort to prevent the introduction of weed propagules onto the project is always the preferred strategy because it is easier and more economical to prevent the introduction than to control or eliminate weeds once they have become established. There are many possible entry points for weeds:

- **Vehicles and equipment**—Weeds seeds and plant parts can arrive during construction on vehicles and equipment. Portable wash stations are often set up at staging areas and/or designated site entrance/exit points to thoroughly clean tires, wheel wells, and chassis of vehicles and equipment to reduce the possibility that weed seeds are brought in from other projects or areas or transferred within a project area.
- **Erosion control seeding**—Rye grasses are non-native and commonly used for temporary or permanent erosion control seeding. Seeds of these species are also found in material used for wattles. These grasses persist in the landscape and are difficult to eradicate once introduced. Unless these species are required by jurisdiction on the project, other species, such as native grasses used in conjunction with sterile hybrid grass seeds would satisfy erosion control needs and offer greater benefits to the environment. Erosion control matting works well to block the establishment of weeds while preventing erosion and facilitating the growth native plants.
- **Hydroseeding tanks, range drills, and other seed delivery systems**—Seed delivery systems, such as hydroseeding tanks and range drills, brought in from other projects, can contain plant species that are not wanted on the project. A thorough cleaning and inspection of this equipment are essential to eliminate the potential introduction of unwanted seeds. It is recommended that hydroseeding tanks are washed out and range drills air-blown before this equipment is brought on the project site.
- **Seed sources**—Commercial grass and forb seed sources, whether native or non-native, can contain weed seeds that were harvested along with the native seeds. The quantity of this material is dependent on the weed control practices and seed cleaning technology implemented by the seed producer. A good means of eliminating the possibility of contamination of native seeds with weed seeds, is to ask for seed tests of the seed being considered for purchasing. The purity seed test identifies the contaminants in a seed lot, including weed seeds, other plant seeds, and inert material. It is important to ask for tests that determine the presence of state-listed noxious weeds and other crop species (check state and federal lists to determine if any local weed species should be added to the testing list). Testing is conducted through certified seed labs per the standards of the Association of Official Seed Analysts. The seed should be cleaned and retested or reject the seed lot.
- **Mulches**—Buy mulch that is free of weed seeds. Hay and straw mulches are of special concern (Figure 3-85). Some states certify hay or straw as "weed-free" which means that the material is free of noxious weeds but not necessarily free of all seeds. Some straw comes from the stubble left after a seed harvest of native and non-native grasses, which often includes unharvested seeds. These seeds are viable and will establish into plants when the straw is applied. A site visit or discussion with the vendor prior to purchase is a good way to assess if there are seeds of unwanted species in the material.

Figure 3-85 | **Hay often contains weed seeds**

Hay bales often contain seeds from unwanted species that will germinate once the hay is spread. Some states have certified "weed-free" programs, however, "weed-free" does not mean the hay will be seedless.

Photo credit: David Steinfeld

- **Compost sources**—Compost sources are not always free of weeds, especially if the materials were not composted properly. Compost must reach lethal temperatures and remain there long enough for plant seeds to be rendered nonviable. Fresh, moist compost piles, where temperatures are maintained between 140 to 160 degrees F for at least several days, will kill most pathogens and weed seeds (Epstein 1997; Daugovish and others 2006). When obtaining compost, make sure that the supplier complies with standards that meet the time-temperature requirements to ensure destruction of weed seeds. Visiting the mulch sources or testing mulch for weed seeds may also be appropriate prior to purchase (Section 5.2.5).
- **Gravel, sand, and rock sources**—Prior to acquiring road building materials such as sand, gravel, and rock, determine if this material comes from a source that is free of undesirable weeds. A plant survey of the source area will identify whether the material is suitable.
- **Haul routes and waste areas**—Haul routes and waste areas can have weeds that may be transported around the project on vehicles and equipment. It is recommended that these areas be treated prior to construction or avoided during construction to reduce this risk.
- **Salvaged and purchased topsoil**—During the survey for salvaging topsoil, areas of weed populations are also typically identified (Section 5.2.4). To reduce the possibility that these weed populations are spread when topsoil is salvaged and reapplied, weed populations are avoided during topsoil excavation. Salvaged topsoil is stored in a manner that limits weeds from becoming established. For topsoil that is being considered for purchase, prior inspection of the piles will assure that the soil is free of weeds (Figure 3-86).
- **Sand, gravel, rock, or topsoil storage**—Inspect areas where topsoil, gravel, rock, sand, or other materials to be used on the construction project will be stockpiled. If there are weeds growing nearby, it is very likely that seeds will end up on these piles, especially if the piles are to be stored for over a year. Remove these populations prior to stockpiling materials and require stockpiles to be maintained free of weeds.

Figure 3-86 | **Quality topsoil is low in weed seeds**

Know the origin and quality of the topsoil. Topsoil sources contain seeds of the species that grew on them prior to salvage. In this picture, the topsoil pile on the right (B) was salvaged from a nearby pasture and the pile on the left (A) from an undisturbed native forest site. The pasture topsoil pile revegetated quickly (within 3 months after stockpiling) because of the abundance of non-native seeds in the soil. The forest topsoil revegetated slower because there were less seeds. Application of the pasture topsoil (B) resulted in a site dominated by introduced pasture plant species.

Photo credit: David Steinfeld

- **Hedgerows and windbreaks**—Planting windbreaks with non-native species, such as autumn olive, privet, honeysuckle, buckthorn, and multiflora rose, introduces fast-growing, highly competitive species (Harper-Lore and others 2013). Use of native species is preferable.
- **Livestock grazing**—Cattle can bring weed seeds from offsite where they have been grazing. Until native vegetation has become established, it is important to keep livestock out of the area.

3.11.6 CONTROLLING UNWANTED VEGETATION

Stratifying the Project by Weed Status

Locating weed populations early in the planning phase will help in developing a successful vegetation management strategy. During the initial vegetation assessment (Section 3.6.1) and topsoil surveys (Section 3.10.1), weed populations are typically identified and mapped to produce a weed status map.

The weed status map is typically composed of these 4 mapping units:

- **State-listed noxious weeds**—Areas where state-listed weeds are present and regulations require their control.
- **Species of concern**—Areas where species of concern are present. These are plants that are known to occur within the area, are not regulated for treatment by the State or County, but cause concern due to their population density, life strategies that provide them with a competitive advantage over desired native plants, dense growth in waterways, affinity for habitats specific to those required by desired specialist plant species, toxicity or ability to cause injury to livestock, etc. If the resources are available, the implementation of a new project can often provide a great opportunity to treat these species.
- **Weed-free, non-functioning plant communities**—These are areas where there is no state listed noxious weeds or species of concern present, but the plant communities are composed of exotic species, monocultures, poor pollinator species, or have depauperate plant communities with a large proportion of bare ground.
- **Weed-free, functioning plant communities**—Areas where a suite of native plant species is present, soils are intact, and there are minimal noxious weeds or species of concern present. These are optimum habitats for pollinators and larger areas may be wildlife refugia as well (Section 3.11.3).

Understanding the Life History

Understanding the life history and ecology of the regulated noxious weeds and species of concern of the project area is important in developing a weed control strategy. There are several resources to learn about specific noxious weeds or invasive species. The USDA PLANTS database describes each weed species and has PDF documents called Plant Guides that detail the life history of the weed and how it can be controlled. Another source of information is the Invasive Species Assessment Protocol (I-Rank) website and covers many of the nonnative plants in the United States. This website describes some of the important characteristics of the weed species and ranks each on its threat to native plant communities and its difficulty to control. Because these websites are frequently updated, it is important to check the most current lists. Local County Weed Boards and county and State road maintenance staff are also good sources of weed information, as they track and treat specific weed species, often within the project area.

The important information to have about each weed species in the project area includes:

- Life form
- How it reproduces (i.e. vegetatively, by seed, both)
- Viability and longevity of propagule
- Reproductive period
- Mechanism and distance of propagule dispersal (i.e., wind, animal/bird/insect, explosive seed capsules)
- Life/growth strategy
- Life cycle
- Limiting factors to establishment
- Importance to pollinators
- Treatment options

Based on the ecological requirements and life history information, weeds can be grouped into two treatment groups: (1) species that are treated prior to, and during, construction (Section 3.11.6, see Weed Control during Pre-Construction and Construction Activities) and (2) species that are treated after construction (3.11.6, see Post-Construction Weed Control and Vegetation Management).

Weed Control during Pre-Construction and Construction Activities

Construction activities often occur during the time that seeds are ripening or beginning to disperse, which increases the potential that unwanted seeds will be scattered throughout the project area. To effectively treat some state or county listed weeds and species of concern, it is often optimal to treat prior to, and during, construction. These species include:

Species with wide seed dispersal—These are species that spread seeds long distances, which can be achieved by a number of methods. Some plants have structures that forcibly eject seeds when disturbed or at maturity employ ballistic dispersal (e.g., brooms [*Cytisis* spp.), bittercress (*Cardamine* spp.), jewelweeds (*Impatiens* spp.]). Ballistic seed dispersal can often provide propagation advantage to shorter plant species.

Additional seed dispersal mechanisms that allow transport are gravity and wind dispersal (Figure 3-87). In general, the taller the plant, the further its seeds are dispersed. Plants that utilize wind dispersal frequently have appendages on their seeds (more often this would be fruits) to aid movement via wind. Yellow salsify (*Tragopogon dubius*) is an example in the aster family that employs wind dispersal, while the elm (*Ulmus pumila*) is a well-known weedy tree species in many areas that utilizes gravity and wind dispersal.

Bird and insect assisted dispersal is another strategy that facilitates movement of plant propagules across considerable distances. Seeds or fruits may stick to the feet or body of an animal and be transported as they walk or fly. Seeds can also stick to the feet of humans, including restoration designers and implementers. Animals can consume the seeds of plants, depositing them at new locations once the seeds pass through their digestive systems. Animals and insects often actively move seeds or vegetative material from one location to another to utilize them as an immediate or stored source of food or nesting material. Humans move the seeds of many of these species when walking and driving as well.

Any non-native plant species that disperse their propagules substantial distances from their source are ones for which pre-construction treatment should be considered.

Vine species—Species that form vines [e.g., English ivy (*Hedera helix*) and kudzu (*Pueraria montana var. lobata)*] are of concern when they are attached to trees that might be transported from one location within the project to another. If the trees are felled and skidded for removal

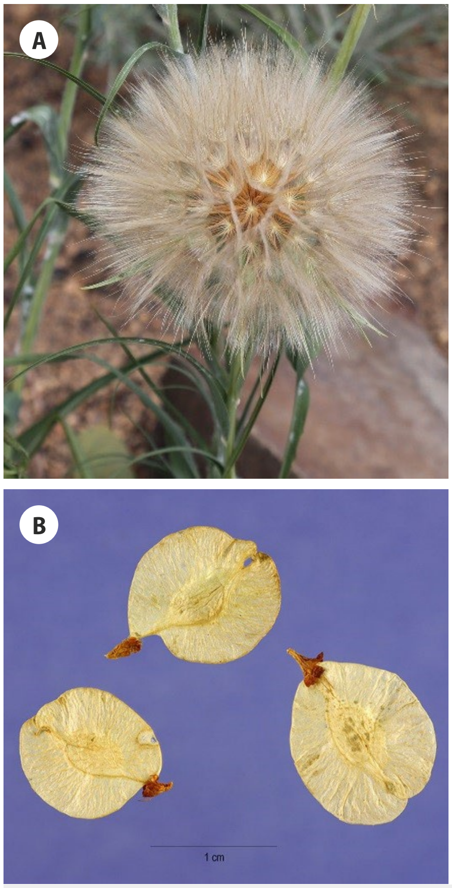


Figure 3-87 | **Examples of plant seeds adapted for wind or gravity dispersal**

Yellow salsify (*Tragopogon dubius*) (A) is just one example of many plants within the Aster family that develop white, hairy pappus to facilitate airborne flight of seeds on the wind. The Siberian elm tree (*Ulmus pumila*) (B) develops a papery membrane around its seeds to assist their dispersal by gravity and wind.

Photo credits: (A) Jane Shelby Richardson, (B) Steve Hurst from the project site, or for use for wildlife habitat, stream restoration, erosion control, or other practices on site, pretreatment of the vines is essential. Unless the vining plants are effectively killed prior to felling, the movement of the tree will spread seeds and vegetative parts of the vine across the construction area. This often necessitates treatment for at least one season prior to construction.

Species that propagate vegetatively—Many species spread vegetatively from portions of roots, stems, or both [e.g., Himalayan blackberry (*Rubus armeniacus*)]. If there is no control prior to construction, whole plants or fragments can be moved during soil excavation, clearing and grubbing activities, and movement of equipment with the result that the species will establish in disturbed areas. Because of the potential spread and tenacity of some species, the objective is to eliminate the risk of spread by the end of construction. Possible treatments include:

Applying herbicides—All state, local, and labeling laws must be followed when using herbicides. In addition, site specific stakeholders might have policies or regulations for herbicide use and their consultation can be very helpful. Herbicides affect plant species through a number of mechanisms such as disruption of cell division, regulation of growth, stopping photosynthesis, and many others. When possible, attacking the weed species through more than one mechanism will prove most effective. Most species that are considered weeds tend to spread readily and respond more vigorously following ground disturbance than many native species. Due to these factors, systemic herbicides are often desirable. The herbicide(s) used will be determined by regulations, the target treatment species, phenology of target species, tolerance for collateral damage to desired species, season of year, deadline for treatment, and more.

Applying herbicides and mastication—A strategy that has proven effective for monocultures of aggressive weedy species, such as Himalayan blackberry in the northwest, is to treat the plants with a combination spray of herbicide, followed by mastication or mowing, and then retreatment with herbicides. The herbicides used combine mechanisms of action as described above and are allowed to translocate for three to six weeks, depending on conditions and herbicides utilized. Once the herbicides travel through the plants' tissues, the above ground shoots are mowed to approximately two to four inches high. The shoots are then allowed to grow until sufficient leaves are developed so that another treatment of herbicide can be conducted. By doing this the plant has been attacked from a number of pathways: 1) multiple mechanisms of action through the herbicides used; 2) reduction of the photosynthetic material; 3) reduction of the seed source; and 4) eventual starvation of root tissue.

Scraping and removing—In cases when herbicide use is not desired or allowed, or when there is not sufficient time to conduct treatments, removal of the non-native weed species can be employed. The undesired plants can be scraped from the site during the clearing and grubbing process and buried at an agreed upon location or hauled off site to an approved facility. If an on-site spoils or waste area is to be used, it is important to include language in the special contract requirements to address the specific needs for containment. This often includes the prevention of further mixing or movement of soil once the weeds are placed, and installation of a "cap" of clean fill dirt on top of the weedy species.

Hand removal—If weed infestations are relatively isolated, have patchy distribution, or are in small populations they can often be removed by hand.

Post-Construction Weed Control and Vegetation Management

Most unwanted vegetation can be treated after construction through revegetation contracts, however, long-term vegetation management is typically conducted by road maintenance personnel within a statewide Integrated Vegetation Management (IVM) plan or an Integrated Roadside Vegetation Management (IRVM) plan. Treatments, when they are selected through a decision-making process, include mowing, applying herbicides, mechanical removal, hand-pulling, grazing, fire, and biological control. A discussion of post-construction vegetation management is presented in Chapter 7.

For areas that have been identified as weed-free, functioning plant communities (Section 3.11.6, see Stratifying the Project by Weed Status), it will be important to maintain these areas in a sustainable manner. An approach to maintaining these areas is outlined in Section 7.2. Although hand removal can be labor intensive it is a great opportunity to involve community volunteers once construction activities have been completed.

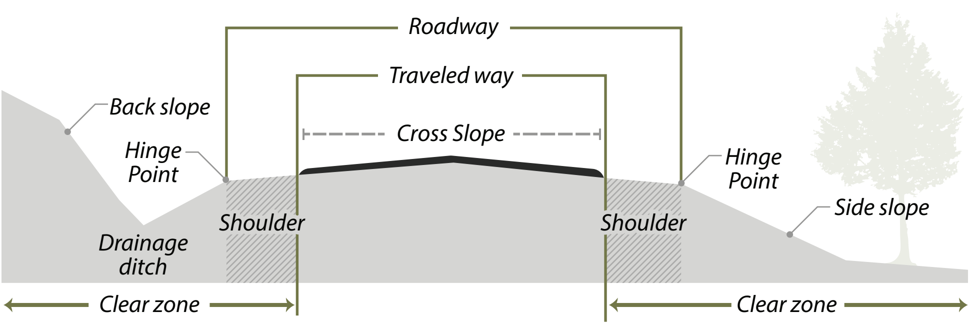
For weed-free, non-functioning plant communities, it is important to decide whether to enhance the current plant community or accept the existing conditions and conduct no additional work. If enhancement is desired, contract components can be included to augment existing native plants to increase competition or to reset community succession, treat surrounding non-native plants, treat the soil to better support native plants, alter the light regimen to better support natives, and improve water drainage.

3.11.7 DESIGNING FOR SAFETY AND UTILITY PROTECTION

Planting treatments along roadsides are limited by National Highway System (NHS) design standards and road development best practices guidelines provided by the American Association of State Highway and Transportation Officials (AASHTO) which are adopted by its member State departments of transportation (DOTs). Designers can find guidance on roadside revegetation treatments in key AASHTO guidelines that include the Roadside Design Guide, A Policy on Geometric Design of Highways and Streets (Green Book), Guidelines for Geometric Design of Very Low-Volume Local Roads, and A Guide to Achieving Flexibility in Highway Design. The design guidelines prescribe minimum highway/rural roadside clear zones and urban streetscape horizontal clearances or operational offset distances recommended for motorist safety. The zone distances from edge of travel lane or edge of roadway pavement are determined based on traffic volume, road speed, vertical alignment, and roadside slope conditions. Clear Zones are defined as unobstructed, traversable roadside area that allows

Figure 3-88 | **Roadway clear zone illustration**

Trees, utility poles, fence posts, and other utility structures are examples of potential immovable objects that the guidelines recommend eliminating from clear zones or protecting with energy absorbing guardrails. Many DOTs recommend protecting existing trees and utility structures instead of removals where possible, based on cost-benefit data. Grasses and forb groundcover in the clear zones can provide a durable and forgiving surface for hazard-free motorist vehicle recovery use, as well as a low groundcover that provides open view of approaching large wildlife or traffic stopped around a curve.

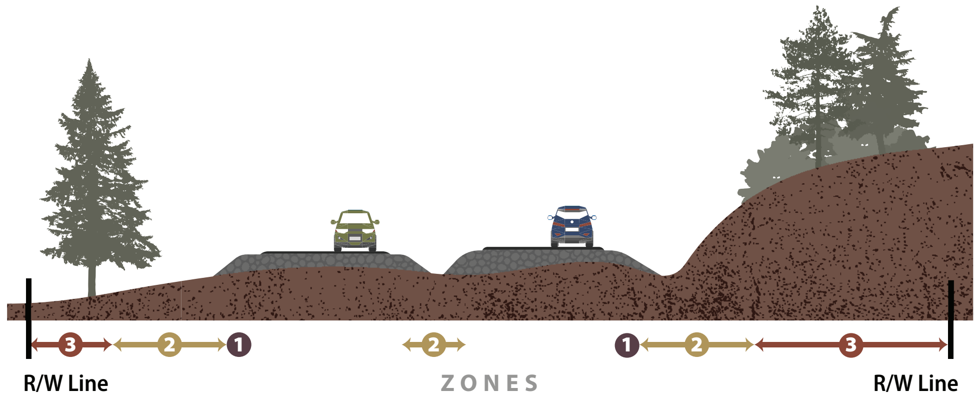


Hinge Point—Point where the slope rate changes

Clear Zone—A traversable area that starts at the edge of the traffic lane, includes the shoulder, and extends laterally to sufficient distance to allow a driver to stop or return to the road before encountering a hazard or overturning.

a driver to stop safely, or regain control of a vehicle that has left the roadway (Figure 3-88) (FHWA 2008(B)).

Vegetation Treatment Zones (VTZ) are designations used by many DOTs to describe the vegetation coverage and maintenance requirements at certain distances off of the edge of roadway. VTZs typically correspond to highway clear zone distances. The VTZ dimensions, vegetation, and maintenance treatments vary by State and roadside conditions, but generally, DOTs have adopted a 3-zone treatment approach (Figure 3-89), (FHWA 2008(B). Zone 1 generally extends from the edge of pavement to the drainage ditch along the roadway and is composed of low native grasses that are regularly mowed. Some DOTs mow this area less frequently and some choose to spray it with herbicide to eliminate plant growth entirely. Zone 2 extends across the drainage ditch and a few feet beyond, and is composed of grasses, forbs and low shrubs. Maintenance of zone 2 is focused on maintaining drainage and removal of tree species. Zone 3 extends from Zone 2 out to the edge of right-of-way and may be covered with grasses, forbs, shrubs and trees outside of prescribed safety distances. This area is generally not mowed and may contain large shrub and tree species outside of the clear zone. Maintenance for all zones consists of removal and control of invasive plant species and removal of tree species within safety distances.



ZONE 1
Vegetation Free Zone

Width as necessary to meet operational needs

- Provide for surface drainage
- Prevent pavement breakup by plants
- Provide for visibility and maintenanceof roadside hardware

ZONE 2
Operational Zone

From Zone 1 to meet operational needs

- Maintain a hazard free vehicle recovery area
- Provide sight distance for passing and stopping
- Provide sight distance at intersections
- Maintain hydraulic capacity of ditches

ZONE 3
Transition Zone

From Zone 2 to R/W Line

- Blend and/or screen adjacent surroundings
- Control weeds
- Remove danger trees
- Manage trees to reduce shading in areas prone to roadway icing

Figure 3-89 | **Vegetation treatment zones**

Clearance for "Line of Sight" and Safety—Trees and shrubs are often thinned or removed in areas where roadway or roadside line-of-sight is impeded. Good communication with the government agency responsible for maintaining the road during the planning phase will help identify those areas not suitable for shrub and tree species. Native grasses, forbs, and low growing shrubs (3 feet tall or less) can provide durable groundcover for these areas and not affect line-of-sight or motorist safety.

Trees Management Location—Trees that reach 4 inch diameter at breast height (DBH) are typically considered immovable objects that can cause heavy damage, injuries, and loss of life in a vehicle crash. According to a study in 2005, more accidents occur between 0 and 12 feet from the travel lane with significantly less between 12 to 30 feet (Mok, Landphair, Naderi, 2006). Tree masses close to the roadway can provide cover for large mammals and can contribute to WVCs. DOTs typically will not allow tree species in clear zones, unless they are protected with guardrail. Best practices for WVC reduction includes full tree and shrub removals or strategic thinning out tree and shrub masses close to the roadway in order to remove desirable cover for ungulates and to open views for motorists to see potential wildlife hazards.

Protection of Utilities—Planting of large trees under power lines can lead to damage of utility lines during wind and ice events and can make line maintenance access difficult and dangerous. Coordination of the roadside revegetation plan with the utility agencies of jurisdiction can identify utility easements, planting requirements, utility maintenance access needs, and additional utility accommodations.

3.11.8 DESIGNING TO ISOLATE WILDLIFE FROM VEHICLES

According to a 2008 U.S. Department of Transportation study, "there are an estimated one to two million collisions between cars and large animals every year in the United States"…"commonly or typically…with deer (mule deer and white-tailed deer combined)…near forested cover and drainages." (U.S. DOT, 2008). The collisions often kill the wildlife and can cause high damage expenses, injuries, and even loss of life for the driver. New roadway corridors inevitably intersect wildlife crossings. The analysis of the local wildlife population, their traffic patterns, proximity of their habitat fragments, and any data on area wildlife-vehicle collisions (WVCs) in the pre-budget planning stage can inform the designers on the roadway design features to consider in order to reduce the probability of future WVCs along the corridor. It is important to keep animals out of roadway corridors but to also plan for their safe crossing above or below the roadway (Figure 3-90). Preservation and enhancement of wildlife corridors under or over roadways can be an effective method for reducing WVCs. Natural wildlife corridors often occur along creeks, rivers, and along drainage swales, features that can be preserved through the use of natural bottom culverts or clear span roadway bridge structures. Design of wildlife crossings to accommodate the needs, preferences, and tendencies of the animals that may use the crossings can maximize the likelihood of use and increase safety for all involved.

The design considerations vary with each project location. The FHWA has produced two best practices manuals for designers of roadway corridors and wildlife crossings entitled, *Wildlife Vehicle Collision Reduction Study* (Huijser, 2008) and the *Wildlife Crossing Structure Handbook Design and Evaluation in North America* (Clevenger/Huijser, 2011). Each contain recommendations based on specific studies of wildlife interactions with various wildlife crossing structures, treatments, and conditions.

Wildlife crossing design for motorist safety will typically focus on accommodations for the largest most prevalent animals in the area, often deer. Designing for a variety of wildlife considerations may require greater culvert or bridge clearance height and span length at each crossing, small tunnels for critter crossings, high-water crossings inside culverts (Figure 3-91), hundreds to thousands of feet of tall wildlife exclusion fencing or wildlife friendly/game fence that allows one-way animal pass through/pass back from the roadway (Huijser, Kociolek, McGowen, Cramer, and Venner, 2015), specific plant material to attract and guide animals to the crossing, or a combination of these measures. As the crossings directly impact the budget for the roadway project, and impact the safety of the public who will use the roadway, it is recommended that their evaluation and planning begin at the early planning stages of a new roadway alignment or bridge/culvert replacement project and that the revegetation expert be involved throughout the process.

Suitable habitat on both sides of the road is a necessary condition for all wildlife to cross, and areas with the highest quality habitat will often have the highest rates of crossing (Barnum 2003). Distance to cover is another factor that affects wildlife crossing use. Small animals prefer plentiful and consistent cover before and, if possible, through an undercrossing. Deer and elk tend to prefer crossing in open areas away from forest cover, especially during the winter (Clevenger and Waltho 2005; Barnum, Rinehart, and Elbroch 2007). Other animals prefer a more balanced composition of cover and open space while most carnivores prefer a dense forest cover.

Roadside revegetation design provides the opportunity to support safe wildlife crossings by creating a roadside planting and maintenance plan that will reduce animal browsing within the ROW, and provide planted conditions that will attract wildlife to the crossing points. Open views to vegetation beyond the undercrossing will encourage animal movement through the crossing to the other side, and continue on to wildlife corridors or refugia beyond. Ungulates, or hoofed mammals, especially deer, are browsers that prefer fresh new growth. Spring growth and new growth after cutting and mowing maintenance will attract ungulates and encourage them to linger and graze. Increasing mowing maintenance at wildlife undercrossings may

Figure 3-90 | **Mule deer using an underpass**

Deer are frequently involved in WVCs. Early planning and thoughtful design of undercrossings and overpasses can encourage wildlife use and enhance safety for wildlife and motorists.

Figure 3-91 | **Culvert with high-water ledge for small mammal crossing**

Maintaining safe access to habitat, including during high water periods can enhance safety for wildlife and motorists and also keep the food chain functioning.

Photo credit: Unknown

increase more regrowth periods that can draw browsers to the crossing locations. Reducing the quantity of roadside mowing events away from undercrossings and strategically timing mowing operations to late fall or very early spring, can reduce the number of mass new growth events that draw ungulates to browse along the ROW.

Study results for vegetation control effect on WVCs indicate that flatter ROW side-slopes and lower vegetation along the roadway can improve driver safety and discourage use by large wildlife. Low plant material is less desirable for use as cover by ungulates, and opens up view-sheds so drivers can potentially see animals in the right-of-way (ROW) and allow time to react and slow down to avoid wildlife-vehicle collisions. Plant material 3 feet tall or lower, not counting seed head stalks that may rise taller late in the year is generally considered low. Elimination of large trees from roadway clear zones can remove desirable wildlife cover from the ROW and immovable tree trunks that can damage vehicles and injure motorists that leave the roadway.

Wildlife over-crossings are still rare in the United States but are preferred by ungulates and other species more than under-crossings. Ungulates and other species will use under-crossings if they appear open and free from predator hiding places. They generally prefer level open space leading up to the crossing, a generous tall and wide bridge span or box culvert, natural low vegetation or soil walking surface, and clear views to open space on the other side.

Easy access to wildlife crossing locations can increase their use. If an existing ROW fence exists beyond the wildlife crossing area, it is recommended that portions of fence be removed if possible. In the case of cattle or other livestock use outside of the ROW, a section of fencing may be replaced with a gate that remains open when the field is not occupied. Additionally, wildlife friendly adjustments may be made to the top and bottom strands of barbed wire, such as adjusting the wire spacing and/or replacing with smooth wire on the top and bottom to protect wildlife that jumps over or crawls under the fence.

High-use crossing locations and those with narrow rights-of-way may need the addition of protective traffic barrier and guardrail and/or lengths of tall animal fencing to help encourage animals back down to the under-crossing. Resources that provide wildlife control methods to consider for specific site conditions include Best Management Practices for Wildlife Corridors (Beier, 2008), Wildlife Vehicle Collision Reduction Study (Huijser, 2008), the Wildlife Crossing Structure Handbook Design and Evaluation in North America (Clevenger/Huijser, 2011), Construction Guidelines for Wildlife Fencing and Associated Escape and Lateral Access Control Measures (Huijser, et al., 2015), and Implementing Measures to Reduce Highway Impacts on Habitat Fragmentation (Louis Berger Group, 2011).

Experts recommend that wildlife crossings remain open and clear overnight, during the construction process if possible. These areas should be completed and planted as early as possible in order to reduce animal stress and to keep them from learning new less desirable places to cross the roadway. Supplemental hay and salt licks may also be used to encourage continued crossing use during construction; supplemental feeding may then taper off over a few months after construction.

Plant selection for wildlife crossing locations can be approached as seeded roadside pollinator habitat development supplemented with low native forbs and grasses that are preferred by wildlife for food and browse.

3.11.9 DESIGNING FOR DISTURBANCES

Disturbances that affect roadside vegetation often occur after plants have become established. While some of these disturbances are unforeseen, others can be expected. The designer may want to consider what disturbances can be expected and how they may be mitigated within the design of the roadsides and revegetation plan.

Deicing for Winter Safety

Approximately 70 percent of the roads in the US are in snow regions (FHWA 2012) which may require deicing practices to make them safe and passable during winter periods. Most deicing materials contain chloride-based salts which, when applied road surfaces, lowers the freezing point and melts snow and ice. Solid salt (NaCl) is the most common product used, following by calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), potassium acetate (KAc) and calcium magnesium acetate (CMA) flakes for bridges (AASHTO 2013). The suggested rate of NaCl is 100 to 300 pounds per lane-mile (Salt Institute 2008).

Potential Impacts to soils and vegetation—Deicing materials can pose a risk to soil properties and plant growth. Salt concentrations in roadside soils correlate positively with salt application rates (Jones and others 1992) and high levels of sodium disperse soil organic and inorganic particles, reducing soil permeability and increases runoff (AASHTO 2013a). The negative effects on plant growth, however, are often associated with road spray on plant foliage rather than presence of salts in the soil. Roads that are treated with deicing materials does not preclude that plants on adjacent roadsides will be affected. The effects of road salts on soils and plant depend on the:

- **Sensitivity of plant species to salt**—At very high salt levels in the soil, germination of native plant species can be reduced (Harrington and Meikle 1992, Fulbright 1988) or delayed (Ungar 1992) though there is considerable variability between native species. In general, shrubs and grasses tolerate salt concentrations better than trees (Sucoff 1975, Bryson and Barker 2002). And sensitivity among tree species ranges from sensitive to tolerant. In the Lake Tahoe Basin, for example, two and three needle pines (e.g. Jeffrey, ponderosa, and lodgepole pines) show salt damage more frequently than white and red fir (University of Nevada 2009).
- **Amount of salt applied annually**—The amount of salt damage is related to the total amount of salt applied during the winter. The higher the quantities of salt applied, the greater the effects to soil and plant quality. The University of Nevada (2009) found that the proportion of trees affected by salt damage coincided with the annual quantity of salts applied to the road surface.
- **Distance from the road**—The highest amount of salts occurs closest to the road and diminishes moving away from the road surface. Ninety percent of salt deposition from road spray often occurs within 65 feet of the roadside (Blomqqvist and others 1999) and it is in this zone where foliar damage such as needle necrosis, twig dieback and bud kill on trees happens.
- **Type of salt**—The type of deicer may affect plant species differently. Trahan and Peterson (2008) found that $MgCl_2$ was more damaging when directly applied to tree foliage than NaCl. Calcium magnesium acetate was found to be less toxic on certain grass species than sodium based salts (Robidoux and Delisle 2001) and may even improve soil properties by increasing permeability and providing calcium and magnesium for soil fertility (Fritzsche 1992).
- **Precipitation**—In areas of high precipitation, salts will become diluted and move through the soil profile, reducing the potential negative effects to seed germination and plant growth. In areas of very low precipitation however, salts and sodium will remain at the soil surface and accumulate.
- **Soil type**—Soils with low pH values may benefit from some addition of road deicers. By raising soil pH, certain nutrients become more available (Section 3.8.4). Soils already high in sodium could become even more toxic to plant growth with NaCl additions.

Assessing potential impacts of deicing practices —During the planning phase, it may be important to assess the level of impact deicing practices have on native plant establishment and growth after construction. The type and amount of deicing material used on the highway project can be obtained from maintenance and operations records. If the quantities are considered high (Figure 3-47), then it may be beneficial to conduct a field survey of soils and vegetation along a stretch of road in or similar to the project area. The survey area can be stratified into zones parallel to the road alignment because the effects of salts on vegetation composition and health grade from most affected to least affected, moving away from the road. Specific monitoring procedures that may be helpful include Soil Cover (Section 6.3.1), Species Cover (Section 6.3.2), and Species Presence (Section 6.3.3), using a Rectilinear Sampling Area design (Section 6.3.6, see Rectilinear Areas), because the narrow width of each sampling area is not conducive to using transects.

Comparing the differences in each zone may show the effects of deicing practices on vegetation. If there are no differences between each zone, then it can be assumed that deicing practices have no effect. If there are differences, then those differences are taken into consideration when developing seed mixes or soil improvement practices. It may be important to determine if these differences are due to deicing practices or due to other factors, such as mowing, surface contaminants, soils, air pollution, drought, or tree diseases or pests. One method to make this determination is to collect soil samples in each zone and measure soil conductivity using a pH meter (Section 6.3.1). If conductivity readings recorded in the zone next to the road are higher compared to the zone furthest away it would indicate that deicing practices maybe responsible. Refer to Figure 3-47 for interpreting conductivity values that affect plant growth.

Mitigating for deicing practices—If road deicing salts are determined to be detrimental to plant growth, the designer may want to select a species mix that has a higher tolerance for soluble salts. Selecting the tolerant plant species can be determined from information collected during the vegetation assessment (Section 3.6.1). Desirable species growing in the deicing zone are good species to consider in species mixes. The ERA tool may also give some guidance on those species most adapted to high salt environments.

Gravelling for Winter Safety

In areas where gravels are frequently applied to road surfaces during snow or icy conditions, there can be a buildup of gravels on the road shoulders. Vegetation that has been established in these areas is often completely covered with gravel after snow melt. In addition, road maintenance often excavates these gravels to reuse and in the process, removes established

Figure 3-92 | **Graveling road surfaces can lead to burying roadside vegetation**

Gravel applied to road surfaces in winter for traction is swept or blown to the side, burying vegetation (A). Some species, such as *Lupinus* spp. (B), have adapted to these conditions and do well. Species such as pinemat manzanita (*Arctostaphylos nevadensis*) also do well when covered by gravel because the plant will produce roots from buried stems.

Photo credits: David Steinfeld

plants growing in this zone. The designer will want to design revegetation treatments in these areas according to the expected disturbance. In areas where gravels are not salvaged, the designer may want to select plant species that survive and grow well in this unique growing environment. Some species respond favorably to being covered by gravels. These include species such as manzanita and willows that root from their stems when covered by soil or gravel. Tap-rooted species, such as lupines, can take advantage of such conditions because they can access moisture deep in the gravel deposits (Figure 3-92). A vegetation assessment (Section 3.6.1) of the road shoulders of the project area will identify species that have adapted to these conditions. In areas where gravels are annually removed, the designer will want to identify the width of this disturbance and remove the area from the revegetation plan.

Annual roadside maintenance

Ditches at the base of steep cut slopes are depositional areas for rock and soil that have moved down from the slopes above. This material fills ditches, disrupting the flow of water and creating potential road drainage problems during storms. Blading is the removal of material that has filled in the ditchline and is a normal maintenance procedure for erosive cut slopes. This operation not only removes plants that were established in the ditchline, but also destabilizes the surface slopes immediately above the ditch which can affect the revegetation of the entire slope. Designing cut slopes so that they are stable is one method of reducing the need to blade ditches. This includes reducing slope gradients near the ditches and establishing a good vegetative cover that resists slope movement.

Recreational Activities

The road corridor is sometimes used for recreational purposes that can disturb established vegetation. This recreation is not usually sanctioned or intended, but it exists in certain areas nonetheless. Recreational disturbances include off-road vehicle travel, mountain bike use, trails to recreational sites, parking, and Christmas tree cutting.

It is important for the design team to identify the public's demand for recreational activities and to determine how these activities might affect short- and long-term vegetation goals. For example, abandoned roads that have been revegetated are often desirable places for off-road vehicles because they are open and flat. Roads bordering recreation destinations, such as favorite fishing spots, may have demands for access trails or scenic views that the public does not want blocked by tall vegetation. Public scoping often identifies these needs. There are several approaches to mitigating the effects of recreational impacts, most of which are forms of awareness, protection, and exclusion. Intruders can be excluded physically with barriers, such as ditches, fences, down trees, and large rocks outside of the clear zone. Before these measures are put in place, communication should be tried first. For example, a sign explaining native revegetation efforts may help make potential users aware that they should take their activities elsewhere. Local residents are often great sources for ideas on how to approach these problems; off-road vehicle clubs are another. Educating the public on the purpose for the revegetation treatments can go a long way toward protection. Short paragraphs in the local newspapers or on the FHWA website for each project may help. Using local contractors to implement the revegetation work and engaging local residents brings ownership to the project. In addition to exclusion measures, designers should consider desire paths to accommodate foot traffic that is bound to occur. Incorporating and planning for such access can reduce the impact to the surrounding established vegetation and keep traffic confined as much as possible.

Livestock

Damage to revegetation projects can be high in areas that are intensively grazed by cows or sheep. In areas with large livestock populations, planted tree seedlings can be injured by rubbing and trampling. Newly establishing native grass and forb cover can be harmed through grazing and by the high-pressure hoof marks tearing up the new roots and surface soil, leaving the site exposed to non-native annual species.

Restricting the entry of livestock for several years after planting or sowing, or until native grasses and forbs have established, is the best prevention measure. This is typically accomplished by fencing the entire area being revegetated. Fencing is most effective when it is installed prior to establishing native vegetation. For this reason, having the fence installed as part of the road contract will ensure that livestock is controlled prior to revegetation work. Working with the local USDA Forest Service or USDI Bureau of Land Management range conservationist will be necessary to ensure that damage by livestock is kept to a minimum.

3.11.10 DESIGNING FOR CARBON SEQUESTRATION

Carbon sequestration is an important environmental and public health benefit that is a result of revegetating disturbed landscapes with native plants. It is often overlooked as a revegetation objective and as part of a vegetation management strategy. The "carbon sequestration capacity" is a quantifiable volume of carbon that can be estimated for existing roadside revegetation and compared to the proposed revegetation plan. Knowing the values in the planning stage can help the design team as they make decisions about design, implementation, and maintenance throughout the project development. Selection of plant material and the ongoing vegetation maintenance procedures have a dramatic effect on the carbon sequestration capacity of a revegetation project.

Carbon sequestration is a process in which CO_2 is transferred from the atmosphere into plants through photosynthesis and stored in long-term carbon pools. These pools consist of above-ground biomass (e.g. live trees, shrubs, grasses, and standing dead trees, branches, litter, and duff) and below-grown biomass (e.g. soil organic matter, roots, organisms). Roadside management practices that maintain or increase these carbon pools may reduce atmospheric concentrations of CO_2 and mitigate the effects of climate change (Proudfoot 2015). With the large land base of the US in roadsides, the current and potential capacity to capture CO_2 is considerable (Ament 2014). For example, roadsides along US highways and federal lands (10.5 percent of all public roads) currently capture nearly 2 percent of the total US transportation carbon emission (Lavelle 2014). Another way that atmospheric carbon can be reduced is by decreasing or changing roadside maintenance operations that generate greenhouse gas emissions such as mowing and mechanized pesticide applications. In combination, practices that reduce carbon emission and increase carbon pools can reduce atmospheric carbon while reducing maintenance costs (Proudfoot 2015).

Minimizing Soil Disturbance

Soils contain large amounts of carbon fixed in soil organic matter. When soils are disturbed, CO_2 is released through the oxidation of organic matter. One of the best strategies for maintaining carbon in soils is to minimize soil disturbances. In planning road construction projects, this is accomplished by minimizing the footprint of the project. Another strategy is to create and maintain a resilient plant community that resists disturbances associated with soil erosion and landslides. When disturbances do occur, immediate action assures the quick recovery of native plants and carbon sequestration processes (Section 7.4.1).

Revegetating with Trees and Shrubs

Establishing and maintaining trees and shrubs along roadsides can be a cost-effective means of capturing carbon (Brown 2010). Compared to other vegetation, trees sequester larger amounts of carbon for longer periods of time (an average of 120 years, FHWA 2010). Trees also shade ground surfaces, reducing the amount of heat generated from roadsides. Shrubs have less capacity to store carbon than trees but greater capacity than grasslands (Ament 2014).

There is an opportunity to use vegetative plantings to create or replace wind breaks, shelterbelts, and snow fences (see Inset 3-3). Using trees and shrubs for these purposes will not only reduce blowing and drifting snow, but can increase wildlife diversity, pollinator habitat, and capture carbon. Using a thick vegetative barrier composed of shrub species near the roadway may also have the added benefit of slowing out-of-control vehicles from roadsides impacts (Ament 2014).

It is important that trees and shrubs are planted in areas that meet road safety and maintenance objectives. When choosing tree and shrub species to plant, species that live longer and are larger at maturity have a greater capacity to store carbon than shorter lived, smaller plants (Proudfoot 2015). In addition, increasing the complexity of a forested site, by planting a multilayer of trees, shrubs, grasses and forbs, has the potential of increasing carbon sequestration (Ament 2014).

Revegetate with Perennial Grass, Forb, and Wetland Species

Perennial grasses store more carbon in the soil than annual grasses (Cox and others 2006) and can sequester carbon for up to 50 years (FHWA 2010). In addition, perennial grasses have greater ground cover than annual grasses which protect soils from surface erosion, water loss, and nutrient loss (Glover 2005), important for optimizing carbon capture. Wetland species capture more carbon than grasses and forbs because of the higher productivity of wetland sites. For this reason, wetland swales are preferable to dry swales (Bouchard 2013).

Create and Maintain a Good Growing Environment

Revegetation planning that promotes healthy functioning plant communities is good for carbon capture and maintenance (Ament 2014). Restoring soils with organic amendments, tillage, mulch, and nutrients will increase the rooting depth and productivity of roadsides to store more carbon. Other practices that maximize slope stability and minimize surface runoff reduce the potential that soils are disturbed which maintains soil carbon. Where road sections are being abandoned or recontoured, restoring the soils and reestablishing perennial vegetation, such as shrubs and trees, have the potential to capture and store carbon while increasing pollinator habitat.

Utilize Site Resources

Land clearing during road construction often creates woody material that is placed in piles and burned. This material can be processed and placed on constructed roadsides as a soil amendment or mulch. Unprocessed woody material, such as logs, can be used as wildlife structures in areas where they meet maintenance objectives. Depending on site factors, processed and unprocessed materials can last from years to decades, temporarily storing carbon before they decompose. How salvaged topsoil is removed and stored may also make a difference in how much soil carbon is oxidized during road construction. Removing topsoil when it is dry and keeping it dry during storage reduces the potential for oxidation of organic matter.

Changing Mowing and Pesticide Practices

Changes in mowing and pesticide practices can directly reduce carbon emissions and increase carbon storage (Dunn 2013). A review of maintenance practices, when developing a vegetation maintenance strategy (Section 3.11) and an Integrated Vegetation Management plan (Chapter 7), can highlight areas where changes can be made. In addition to decreasing carbon emissions, changes to practices can also lower maintenance costs because of reduction in fuel and wages, and can be beneficial to pollinators (Section 7.3.2). Maintenance practices that can be adapted to reduce emissions and increase carbon capture include:

- **Mowing times**—Shifting mowing times from active growing periods (when mowing disrupts the flow of carbon to the soil) to times of the year when plants are more dormant (early spring, fall, and winter), will increase carbon capture (Dunn 2013).

- **Frequency of application**—Cutting back on the frequency of mowing or pesticide applications reduces carbon emissions.
- **Height of mowing equipment**—Raising mowing equipment several inches higher can save fuel costs and reduce the effects of carbon flow to the soil.
- **Treatment widths**—Reducing the widths of mowing and pesticide applications reduces travel time, amount of pesticide used, and carbon emissions.

Reducing Road Salts

On road systems where applications of deicing salts are detrimental to roadside vegetation (Section 3.11.9, see Deicing for Winter Safety), minimizing the quantity of salt applied or the frequency of application, can reduce the effects on plant productivity and carbon sequestration (Ament 2014). These changes will also result in less carbon emission.

Highway Carbon Sequestration Estimators

Numerous highway carbon sequestration estimators can help calculate the quantity of carbon being captured on a roadside and estimate the potential volume of carbon offsets. These tools do not necessarily provide estimates required for full project development and should be used only to provide a sense of scale (Proudfoot 2015). One such program is the Highway Carbon Sequestration Estimator. This tool is intended to help DOTs assess the return on investments for carbon sequestration practices based on state-specific considerations (FHWA 2010).

3.12 SELECTING SITE IMPROVEMENT TREATMENTS

In this stage of planning, the treatments that will improve the site for plant growth (e.g. topsoil, compost) are selected. The selection of treatments begins with identifying the factors that limit plant growth. As the designer identifies limitations specific to the project site, a list of possible treatments that will mitigate or reduce the effects of the limiting factor is developed. Specific treatments to mitigate each limiting factor are presented in Section 3.8. The case study presented in Inset 3-6 shows how a list of mitigating measures can be developed for specific limiting factors.

In narrowing down the possible treatments that will encourage plant success, the designer considers all possible resources on the project site that can be used in lieu of purchasing and transporting materials from offsite sources (Section 3.10). For example, in reviewing the plans of a road reconstruction project, it is found that a portion of the road is being realigned through a wooded area. For this section, the designer lists the potential site resources to include topsoil, large wood, tree branches and foliage, duff and litter. These resources can be used in a variety of ways to improve growing conditions and pollinator habitat.

At this point, the vegetation management strategy is revisited to ensure that the mitigating measures being considered in this process are compatible with road maintenance objectives (Section 3.11.2) or if they could present problems for long-term maintenance and if so, what modifications to the treatments can be made. The final selection of treatments is based on many factors, including project funding, project objectives, experience of the designer or contractor, and availability of resources and equipment. A Limiting Factor and Site Resource tables are available in this Planning workbook.

3.13 SELECTING PLANT SPECIES FOR PROPAGATION

Selecting plant species to propagate and install on a project requires an understanding of the revegetation objectives (Section 3.2), identifying the limitations of the site to support the species being considered (Section 3.8), identifying the factors that affect pollinator (Section 3.9), and determining if the plant species integrate into the vegetation management strategy

Inset 3-6 | **Case Study—Defining limiting factors and selecting mitigating measures**

Site Inventory—During the planning stage of a revegetation project in central Oregon, the soils assessment (**Section 3.6.2**) highlighted several limiting factors that would negatively affect plant growth.

Limiting Factors—From the list of limiting factors outlined in Figure 3-11, factors affecting plant growth at this site were narrowed down to low precipitation, low water storage, high water loss, and low nutrients.

Mitigating Measures—For each of these factors, a list of possible mitigating measures (described for each limiting factor in **Section 3.8**) was developed.

Site Resources—A review of the site resources was made at this point to determine if there were any resources on the site that could be used in developing mitigating measures (**Section 3.10**). It was found that there were several areas where weed-free, high quality topsoil could be salvaged and reapplied. In addition, the project would produce a large amount of slash from cleared shrubs and trees that could be processed into shredded wood and used as a mulch. Other resources available were a local municipal waste treatment plant had Class A biosolids available for application in lieu of bringing in fertilizer, loam borrow from a source of pumice deposit, and an excavator that would be available for subsoiling.

Maintenance—The potential effects of these treatments on long-term maintenance was then considered (**Section 3.11**). It was determined that deep tillage was not compatible with safety in Zones 1 and 2 but would be done in Zone 3, otherwise there were no foreseen maintenance problems.

Treatment Selection—It was decided to salvage topsoil; however, the amount of topsoil would not cover all the project needs. It was determined that a manufactured topsoil would be created by using shredded wood processed the slash from road right-of-way clearing, loam borrow from excavated pumice, and biosolids from the local municipal waste treatment plant. To increase infiltration and rooting depth, it was decided that once the topsoil and manufactured topsoil was applied that it would be subsoiled only in subsoil Zone 3 but not in Zones 1 and 2. At planting, lupine would be included in the seed mix for additional nitrogen and inoculum would be applied to the seed mix. Because there would be additional shredded wood, it would be blown over the seed as a mulch.

Critical plant factors	Parameters	Limiting	Possible mitigating measures
Water input	Precipitation	✓	Irrigate, water harvesting
	Interception		
	Infiltration	✓	Tillage, organic matter, mulch, avoid compaction
Water storage and accessibility	Soil texture	✓	Organic matter
	Rock fragments		
	Soil structure	✓	Tillage, organic matter, avoid compaction
	Rooting depth	✓	Tillage, topsoil, planting islands/pockets
	Mycorrhizal fungi	✓	Topsoil, inoculums
Water loss	Wind		
	Aspect		
	Competing vegetation		
	Soil cover	✓	Mulch
Water input	Precipitation	✓	Irrigate, water harvesting
	Interception		
	Infiltration	✓	Tillage, organic matter, mulch, avoid compaction

Critical plant factors	Parameters	Limiting	Possible mitigating measures
Water storage and accessibility	Soil texture	✓	Organic matter
	Rock fragments		
	Soil structure	✓	Tillage, organic matter, avoid compaction
	Rooting depth	✓	Tillage, topsoil, planting islands/pockets
	Mycorrhizal fungi	✓	Topsoil, inoculums
Water loss	Wind		
	Aspect		
	Competing vegetation		
	Soil cover	✓	Mulch
Critical plant factors	Parameters	Limiting	Possible mitigating measures
Nutrient cycling	Topsoil	✓	Topsoil, planting islands
	Site organic matter	✓	Shredded wood, compost, litter, wood
	Nitrogen and carbon	✓	Topsoil, compost, N-fixing plants, fertilizers
	Nutrients	✓	Topsoil, compost, fertilizers, biosolids
	pH and salts		
Surface stability	Rainfall		
	Wind		
	Freeze/Thaw	✓	Tillage, mulch
	Soil cover		
	Surface strength		
	Infiltration		
	Slope gradient		
	Surface roughness		
	Slope length		
Slope stability	Permeability		
	Restrictive layer		
	Water input		
	Slope length		
	Slope gradient		
	Soil strength		

(Section 3.11). This section covers how to use the comprehensive species list and seed zones and transfer guidelines to develop a potential plant species list.

3.13.1 DEVELOPING A POTENTIAL PLANT SPECIES LIST

From the comprehensive species spreadsheet developed in Section 3.6.1, each species is evaluated for its potential to be used on the project. This is accomplished by sorting the spreadsheet using some or all of the following criteria:

- **Nativity**—If the revegetation objectives call for using native plants, then species on the comprehensive species list are first sorted by whether it is native or not.
- **Pollinator-friendly**—Based on the pollinator habitat assessment (Section 3.6.3, see Habitat Assessment), a list of pollinator plant species to enhance site quality for pollinators can be developed from the ERA tool and the reference site plant species inventory.
- **Workhorse species**—The next sort is by workhorse species. Workhorse species is a term used to describe locally adapted native plants that: (1) have broad ecological amplitude, (2) high abundance, and (3) are relatively easy to propagate. A list of workhorse species for ecoregions (Level III) can be obtained using the ERA tool. Because these lists are still in development, some species may need to be evaluated for potential as a workhorse species based on the project objectives and needs. To determine if a species (not listed as a workhorse in ERA) is a potential workhorse species, sort the comprehensive species list by amplitude and abundance columns. Those species that have high amplitude and abundance are good candidates for workhorse species status. From these species, evaluate how easy they are to propagate. This includes the availability of the starter plant materials, how easy the species is to propagate in the nursery or seed production fields, how well the seeds store, the survival of the plant materials once they are installed on the project, and expense.
- **Availability of starter plant materials**—Seeds, plants, and cuttings often have to be collected in the wild and supplied to the nursery or seed producer for plant production, seed increase, or stooling beds. Species that are difficult to obtain or collect are not good candidates for workhorse species status (Section 5.3.1 through Section 5.3.3).
- **Nursery and seed production**—Species that are difficult to propagate in the nursery, stooling beds, or seed production fields do not make good workhorse species (Section 5.3.4 through Section 5.3.6). Because new techniques in propagating native species is constantly improving, talking to nursery managers or seed growers, in addition to referring to documented plant production protocols available on the internet, is important in maintaining a current workhorse species list.
- **Longevity**—Seeds that have a poor shelf life under seed standard storage practices (seed germination that drops significantly after one year in storage) are often not good candidates (Section 5.3.4).
- **Field establishment**—The ease that a plant material will establish on a project site will determine if a species is a workhorse species (Section 5.3.3 and Section 5.5). Some species do not perform well because breaking seed dormancy and obtaining good germination may be difficult. Other species, planted as seedlings, experience unusually high transplant shock that significantly reduces plant survival.
- **Expense**—The total costs for establishing native plants on the project site is the easiest measure of whether a species is a good candidate for workhorse species status.
- **Working groups**—A working group is a mix of workhorse species developed for a specific ecological function or management objective. One of the best ways to develop working groups is to sort the comprehensive species list by ecological setting and succession. This will assemble species into groups that naturally occur together. From these

groups, working groups are developed based on project objectives, such as pollinator habitat enhancement, weed control, visual enhancement, conservation management, and erosion control (Figure 3-93). The development of these working groups is often the basis for a project's seed mixes and planting mixes for each revegetation unit.

- **Specialist species**—Species that are important for achieving project objectives yet do not meet the workhorse species criteria for seed propagation are called specialist species (Figure 3-94). These species may still be propagated; however, because there may be very little information about seed propagation, they may take more time and higher costs to develop. Projects that contain special microclimates or soils may require a unique mix of specialist species (e.g., a wetland working group), while other projects may require a specific species to meet a project objective (e.g., milkweed as host plant for monarch butterfly). If only a small quantity of specialist species is needed, then methods other than seed propagation should be considered. These include collecting plant materials in the wild or growing seedlings in the nursery.

Once the spreadsheet is complete, the species and stocktypes to propagate can be selected.

3.13.2 ENSURE LOCAL ADAPTATION AND MAINTAIN GENETIC DIVERSITY

Seed Zones and Transfer Guidelines

Figure 3-94 | **Example of a specialist species**

Aspen does not meet "workhorse" criteria because it is challenging to propagate (starter material is difficult to obtain and plants require special protection from browsing after outplanting). However, aspen is very important for ecological reasons, and therefore can be propagated as a specialist species for specific projects.

Photo credit: Chris Jensen USFS

Figure 3-93 | **Steep roadcuts require an erosion control working group**

Steep roadcuts on the North Umpqua Highway in Oregon required an erosion control working group that hold the slopes together and keep them from sloughing and eroding into road ditches. An erosion control working group composed of Roemer's fescue (*Festuca roemerii*), blue wildrye (*Elymus glaucus*), and California brome (*Bromus carinatus*) was applied with high rates of hydromulch and tackifier to the cut slopes. One year after application, cut slopes had a high cover of these native grass species that significantly reduced sloughing and erosion.

Photo credit: David Steinfeld

Table 3-14 | **Selecting species to propagate**

The comprehensive species list developed in Table 3-6 can be used to determine the species that are most appropriate to use on the project. In this example, non-native species were removed from the list, leaving only native species. Then potential workhorse species were determined by their amplitude, abundance, and ease of propagation. A species such as *Achillea millefolium*, for instance, is considered a workhorse species because it fits all criteria—high abundance, high amplitude, and easy to propagate. Whether this species is used for this project depends on whether it is a member of a particular working group that meets a specific project objective. Because *Achillea millefolium* fits into the "visuals" working group, which is an important road objective, this species is selected for propagation. *Agastache urticifolia* is also showy and has a high amplitude and abundance. However, very little is known about the propagation of this species. While this species has the potential of being a workhorse species, it will be grown as a trial in small quantities. *Allium fibrillum* and *Allium macrum* are specialist species that occur together in a unique meadow habitat. Because this road project provides an opportunity to enhance meadow habitat, these two species are placed in a "conservation" working group. They are considered specialists because they have low abundance, low amplitude, and little is known about their propagation, yet they are an important component of the working group. These species will be selected for use on the project; however, because little is known about seed propagation, seeds will be sent to a nursery for plant or bulb propagation.

Achillea millefolium	**common yarrow**	High	High	Early	All	Seeds	Easy	Yes	Visuals		Yes
Agastache urticifolia	**horsemint**	High	High	Early	All	Seeds	Unknown	No	Visuals		Trials
Agoseris aurantiaca	**orange agoseris**	High	Mod	Early	All	Seeds	Unknown	No			
Agoseris glauca	**pale agoseris**	High	Mod	Early	All	Seeds	Unknown	No			
Agoseris grandiflora	**bigflower agoseris**	High	Mod	Early	All	Seeds	Unknown	No			
Abies grandis	**grand fir**	High	High	Late	All	Plants	Easy	Yes			Yes
Abies lasiocarpa	**subalpine fir**	High	Mod	Late	Cool	Plants	Difficult	No			
Allium acuminatum	**tapertip onion**	Low	Low	Early	Wet	Bulbs	Difficult	No			
Allium fibriatum	**fringed onion**	Low	Low	Early	Warm/Dry	Bulbs	Difficult	No	Conservation	Yes	Yes
Allium macrum	**rock onion**	Low	Low	Early	Wet	Bulbs	Difficult	No	Conservation	Yes	Yes
Allium madidum	**swamp onion**	Low	Mod	Early	Wet	Bulbs	Difficult	No			

It is important to know the original collection source and genetic background of target plant materials to ensure better long-term adaptation to local conditions and protect plant-pollinator relationships and the genetic resources of local plant communities. Seed transfer guidelines (how far plant material can be transferred from point of origin to the project with minimal risk of maladaptation) were initially developed for commercially important forest tree species. This was the outcome of years of research that revealed that failures in tree planting establishment were sometimes the result of moving seeds too far from their source of origin. More recently, research has been completed or is under way to develop seed zones and transfer guidelines for grasses, forbs, and shrub species commonly used in revegetation activities, particularly in the western U.S. (e.g., Table 1 in Bower and others 2014; St. Clair and others 2013; Johnson and others 2013; Horning 2010).

Seed sources that originate within the specific seed zone where a planting site is located are likely to be well adapted, with improved survival, reproductive success, and resiliency in harsh sites and changing climate conditions. Genetic research indicates there is no fixed number determining the geographic distance that plants might be successfully moved (e.g., within a 50-mile radius). Rather, "local" is best defined in terms of the environment (local climate and soils) rather than absolute distance. Many factors contribute to the environmental conditions to which a plant species must adapt, including rainfall, aridity, maximum and minimum temperatures, aspect, soil drainage, and pH. The scale of adaptation also varies greatly among species. Some species (genetic generalists) can tolerate broader movement across environmental gradients than others (genetic specialists) and still be well adapted to local conditions and regions (Rehfeldt 1994; Johnson and others 2010). Thus, plant movement guidelines derived from empirical genetic studies are specific to the individual species and geographic area where the research was conducted.

In addition to improving the success of revegetation projects, seed zones can create efficiencies and economies of scale in commercial markets and seed banking programs and partnerships (Erickson 2008). This will reduce the cost of native plant material production and use, as well as increase the availability of genetically appropriate plant materials. Despite the numerous benefits, genetic guidelines for plant material movement are lacking for many native grass, forb, and shrub species used in roadside revegetation and pollinator habitat enhancement activities. In these cases, generalized provisional seed zones (Figure 3-95) (Bower and others 2014) may be useful in guiding seed movement and sourcing plant materials. The generalized guidelines are based on climate data (winter minimum temperatures and aridity) and boundaries of the Environmental Protection Agency (EPA) Level III ecoregions (Section 3.3.3, see Ecoregions and Seed Zones) to delineate areas that are similar climatically yet differ ecologically. These provisional seed zones can be considered a starting point for guidelines for seed transfer and should be used in conjunction with appropriate species-specific information as well as local knowledge of microsite differences. Inset 3-7 and Inset 3-8 provide further details on the provisional seed zones, as well as other information and tools to assist designers in choosing appropriate plant materials for revegetation and pollinator plantings. Provisional seed zones have been incorporated into the ERA online tool discussed in Section 3.3.3 (see Ecoregional Revegetation Application (ERA)) as an independent map layer.

Genetic Variation

Another important issue in selecting native plant materials is maintaining genetic variation in the populations established in revegetation work. This is especially important to ensure resiliency in the context of a rapidly changing climate. Plant populations must be genetically variable to be able to adapt and respond to changing stresses and climates. Collection and propagation procedures, as well as agronomic and nursery production methodologies, need to conserve sufficient genetic diversity to enhance revegetation success and buffer against environmental stresses and changes in both the short and long term (Section 5.3.1 and Section 5.3.4). In addition, a sufficient number of unrelated seed parents must be included to ensure that

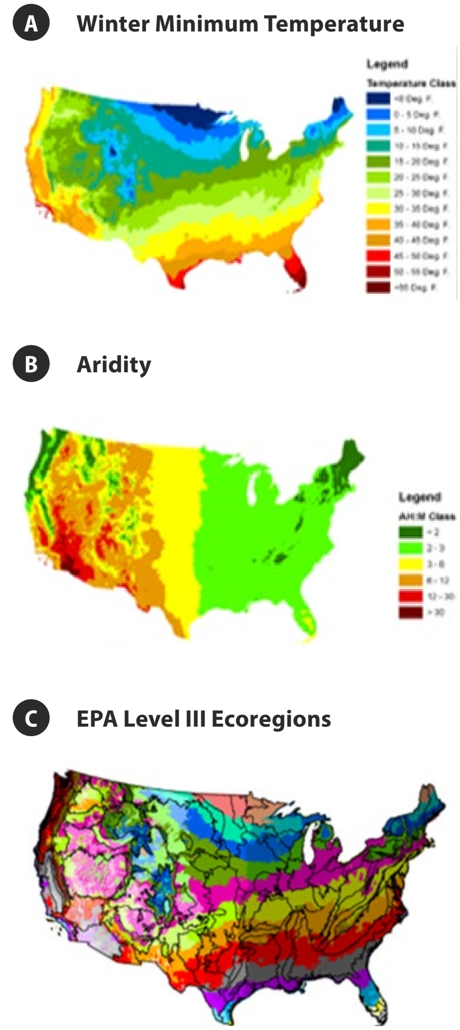


Figure 3-95 | **Provisional seed zones**

Provisional seed zones for native plants are unique climatically delineated areas (A and B) nested within EPA Level III Ecoregion boundaries (C). The provisional zones can be used to guide seed sourcing decisions when species-specific genetic information is lacking (Bowers and others 2014).

Inset 3-7 | **Locally adapted plant materials**

Choosing the right plant materials for a project is fundamental to revegetation success, both in the short and long term. With inappropriate seed mixes, projects may fail outright (e.g., low germination or high seedling mortality) or lead to more cryptic problems in the future, such as poor regeneration potential, phenological asynchrony with dependent pollinators, genetic degradation of surrounding plant communities, and loss of resiliency and adaptive capacity in responding to new stresses (e.g., invasive plant species or climate change).

A large number of studies have shown that locally derived and genetically diverse plant sources are likely to be best adapted to prevailing climatic and environmental conditions (Hufford and Mazer 2003; Savolainen and others 2007; Johnson and others 2010). This means that in addition to matching species assemblages to a project site, designers must also understand and consider the seed source origin and genetic diversity of available plant materials to be successful (McKay and others 2005; Crémieux and others 2010; Mijnsbruggea and others 2010; Schröder and Prasse 2013). Moreover, federal and state agencies are increasingly suggesting or requiring the use of locally adapted and regionally appropriate native plant materials in revegetation work based on site characteristics and ecological setting (see Appendix 1 in Johnson and others 2010).

Because restoration with native plants is still relatively new in the United States, the supporting research, infrastructure, and plant material development programs are in the early stages of development. Genetic guidelines for determining what is local are often lacking for many native species of interest (Erickson 2008; Johnson and others 2010). As a consequence, native plants of inappropriate or unknown origin are being sold and planted, including some that may originate well outside of the area targeted for planting.

Provisional Seed Zones

Seed zones help identify where plant materials originated and how far they can be moved. Empirical seed zones for individual species are developed through field trials in which a large number of seed sources from a wide range of source environments are evaluated for important adaptive traits, such as growth rate and vegetative and reproductive phenology. By relating measured traits to climate or other environmental variables, researchers are able to create maps and delineate areas (seed zones) that are relatively homogenous with respect to adaptive genetic variation. The seed zones represent areas within which seed and plant materials can be transferred with little risk of maladaptation or other adverse consequences (Campbell 1986; Sorensen 1992; Rehfeldt 1994; Erickson 2004; St. Clair and others 2005).

Generalized or "provisional" seed zones (Bower and others 2014) have been developed for the continental United States using minimum temperature and aridity variables in combination with EPA Level III Ecoregions (Omernik 1987). The resulting map (Figure 3-95) captures much of the variation existing in adaptive seed zones (Bower and others 2014; Kramer and others 2015). Therefore, the combined generalized or "provisional" seed zone and ecoregion mapping approach is a good starting place for species and geographic areas where empirical seed zones are unavailable.

In creating the provisional seed zones, temperature minimum values were grouped into 13 discrete classes that reflect the temperature bands used in the USDA plant hardiness zone map (USDA Agricultural Resource Service 2012). The hardiness map is familiar to designers and land managers and has been widely used for decades. An annual heat:moisture index (AH:M) was used as a measure of aridity to distinguish areas that are warm and wet (low-moderate aridity), cold and wet (low aridity), warm and dry (high aridity), and cold and dry (moderate-high aridity). Index values were divided into six discrete classes, with higher values indicating more arid environments. Intersection of the minimum winter temperature with the AH:M layer created unique climatically delineated (temperature-aridity) zones. In the final map, EPA Level III Ecoregions were overlaid on climate zones to identify areas that differ ecologically although they may be similar climatically (Figure 3-95).

The provisional seed zones, along with empirical seed zones for some native plants, are available online in the **Seed Zone Mapper application**. Provisional seed zones have also been incorporated into the **ERA online tool**, discussed in **Section 3.3.3 (see Ecoregional Revegetation Application (ERA))**, as an independent map layer.

inbreeding does not become a problem in the future. Both issues come down to numbers—the more plants that contribute to the new population, the more genetic variation will be captured and the lower the likelihood that relatives will mate (less inbreeding). These criteria should be considered by managers, whether they are buying plant materials or collecting their own. When procuring seed on the commercial market, designers should consult with seed producers and distributors and other reputable sources, including government websites and published literature, to determine the most appropriate available plant materials for a project area. Factors to consider include seed source origins relative to the project site, plant development methodologies, and certification class. In many states, the newer native species releases are certified as "Source Identified, Pre-Varietal Releases", which originate from natural stands, seed production areas, seed fields, or orchards where no selection or genetic manipulation of the parent population has been conducted. The Association of Official Seed Certifying Agencies (AOSCA) has published certification standards and guidelines for the certification of Pre-Varietal Germplasm releases, however not all state certifying agencies have adopted these plant release types within their respective state laws and regulations.

Failing to consider genetic variation when selecting plant materials could have significant consequences on the viability and sustainability of revegetation efforts. Yet it is easy to imagine how variability can be eroded. If plants are propagated from a very small and inadequate sampling of the population, genetic variation of the propagated plants will be greatly reduced.

Inset 3-8 | **What to do if there are no locally adapted native seed sources available**

Adapted from Erickson and others 2003; Aubry and others 2005

The volume of seeds needed for a revegetation project may not always be available in sufficient quantities, particularly when plans have changed or the revegetation specialist has not been involved until the latter stages of the project. In these instances, three choices are available to the revegetation specialist:

- wait several years until the appropriate seeds are available;
- use introduced species that are non-persistent, non-invasive, or sterile, or
- use non-native cultivars or non-local native cultivars.

Defer Seeding

If the appropriate species or seed sources are not available, then consider not seeding until the appropriate seeds become available. In the interim, soil cover for erosion control should be considered.

Introduced Species

When appropriate seed sources are unavailable, sterile hybrids or annual/biennial/perennial introduced plant species that are non-persistent and non-invasive may be considered. Preferred non-native species are those that will not aggressively compete with the naturally occurring native plant community, invade plant communities outside the project area, persist in the ecosystem over the long term, or exchange genetic material with local native plant species. Some of these species include sterile hybrids, such as Regreen (a wheat x wheatgrass sterile hybrid) and annuals such as common oat (*Avena sativa*) and common wheat (*Triticum aestivum*). Exotic species that have not already been introduced into the area, or that have been found to be aggressive and/or persistent, should be avoided. Non-native species that were commonly used in the past and that should be avoided include Kentucky bluegrass (*Poa pratensis*), smooth brome (*Bromus inermis*), crested wheatgrass (*Agropyron cristatum*), orchardgrass (*Dactylis glomerata*), yellow and white sweetclover (*Melilotus officinalis and M. albus*), alsike clover (*Trifolium hybridum*), and alfalfa (*Medicago sativa*), among others. These species are generally no longer recommended due to their highly aggressive nature, resulting in widespread displacement of native species and plant communities that are low in diversity and poor pollinator habitat.

Non-Local Native Species

Native species that do not occur naturally in the local ecosystem, or native plant material that does not originate from genetically local sources, may be considered. These types of plant materials may include commercial cultivars. A cultivar is "a distinct, often intentionally bred subset of a species that will behave uniformly and predictably when grown in an environment to which it is adapted" (Aubry and others 2005). These cultivars are generally not preferable for wildland use due to concerns over adaptability, genetic diversity level, and the potential for genetic contamination, or "swamping," of local native gene pools, including those of threatened, endangered, and sensitive plants (Millar and Libby 1989; Knapp and Rice 1994; Linhart 1995; Montalvo and others 1997; Lesica and Allendorf 1999; Hufford and Mazer 2003). Because commercial cultivars are typically selected for agronomic traits, such as high fecundity, vegetative vigor, and competitive ability, their use may also adversely impact resident plant populations through direct competition and displacement. Cultivars bred for traits such as showiness may have little value to pollinators due to low pollen and nectar production. Plant-pollinator relationships could be disrupted if the growth and reproductive cycle of non-locally sourced plants is different or out of sync with pollinator needs (Norcini and others 2001; Houseal and Smith 2000; Gustafson and others 2005). This is especially a concern with specialist pollinators that are reliant on the nectar and pollen from a small subset of plant species and synchronize their annual emergence to the flowering time of their host plants. Cultivars of native species (and introduced look-alikes such as sheep fescue [Festuca ovina]) can also be problematic if they are difficult to distinguish from native germplasm. This could severely complicate efforts to collect and propagate local material and waste valuable economic resources.

Because of these numerous concerns, cultivars should be used sparingly or not at all, with project objectives clearly understood. Consult with the seed producer or distributor before buying seeds and ask for the most appropriate cultivar for the project area, where the source for the cultivar was collected (geographic location and elevation), and how many collections were made. The seeds should be certified with a certification tag attached to each seed bag. Tests for seed germination, purity, noxious weeds, and seeds per pound should be obtained.

Reproductive strategies vary widely among species. No single collection and propagation protocol will ensure the genetic integrity of all types of plants used in revegetation. However, the issue of genetic variation cannot be ignored. The following should be considered when purchasing or collecting native plant materials:

- **Number of related individuals**—Identifying which plants in a population are likely to be related can be difficult without expensive genetic analyses, but there are ways to minimize the collection of related individuals. In general, avoid collecting plants growing very close to each other to minimize the risk of collecting siblings or even clones of the same plant (Vekemans and Hardy 2004; Rhodes and others 2014). It is recommended to collect plants growing throughout the whole site to ensure that the full diversity of the site is captured, especially plants growing along the edges of each population.
- **Number of parents**—Collecting seed or cuttings from a minimum of 50 unrelated parent plants will help ensure that most of the genetic variation in a population is captured. Additional plant material would be needed if contribution by parents (of seeds or cuttings) is unequal. For dioecious species, attention to male-female ratios is essential to ensure adequate representation of both sexes.
- **Source sites (stands)**—To represent the population of a seed zone well, seeds or cuttings should be collected from multiple sites within the zone. A similar number of parents should be sampled from each site. Seek out larger communities to help meet parent selection criteria.
- **Individual parents within a selected source**—Individual maternal parents (seed plants) should be well separated from each other yet not isolated from other plants of the same species. This will allow cross pollination by numerous paternal parents, adding to diversity. A similar amount of seeds should be collected from each parent. Collecting from plants throughout the entire site will also promote sampling the full range of diversity that is present.

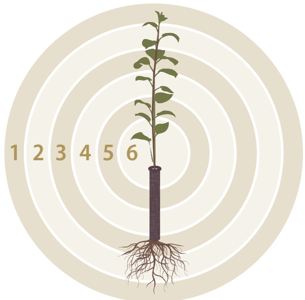
Section 5.3 provides additional guidance on ensuring genetic diversity when collecting seed and cuttings. Guidelines have also been developed to help designers work with seed producers and nurseries that follow practices for maintaining high genetic variability throughout the native plant material production process (e.g., Basey and others 2015).

3.14 SELECT PLANT ESTABLISHMENT METHODS

After compiling a list of species and genetic sources to use for revegetation, the next steps are to determine the optimal propagation methods for each species and to identify the most appropriate plant material sources for a particular site or revegetation objective.

A useful tool for selecting the plant materials best suited to the project is the Target Plant Concept (Landis 2009). The Target Plant Concept (Figure 3-96) is an integrated sequential process for evaluating plant material requirements within the context of project objectives and site characteristics that may influence the suitability of seed sources or stocktypes, as well as the timing and optimal method of out-planting. The concept is based on the premise that there is no such thing as an "ideal" all-purpose seed mix, genetic source, or stocktype that will always work in any situation. Instead, the fitness of the plant material is determined by its appropriateness to the site in which it will be out-planted. Because every site is unique, seed mix and sourcing decisions should be tailored to each site or project to the extent possible. Otherwise, time and investments in site preparation, plant propagation, and outplanting may be wasted.

At this phase in the overall planning process, two of the steps in the Target Plant Concept have previously been covered: the objectives for establishing vegetation (Section 3.2) and the factors that possibly play the largest role in limiting plant survival and growth on each revegetation unit (Section 3.8).



1. Objectives of Outplanting Project
2. Type of Plant Material
3. Genetic Considerations
4. Limiting Factors on Outplanting Site
5. Timing of Outplanting Window
6. Outplanting Tools and Techniques

Figure 3-96 | **The Target Plant Concept**

The Target Plant Concept identifies six requirements for establishing native plants.

Adapted from Landis 2009

The remaining target plant requirements to consider are as follows:

- What type of plant material should be used (seeds, cuttings, containerized or bareroot seedlings, or salvaged plants)?
- What methods will be used to install plant materials and what post-installation plant care is appropriate?
- What is the proper season for outplanting or seeding (the outplanting or seeding window)?

Once species have been selected and genetically appropriate sources of plant materials have been identified, the next step is to determine the most appropriate plant materials for the project. Revegetating with native plants commonly involves multiple methods to reestablish vegetation on the project site. The following are possible considerations:

- Maximizing natural regeneration/recovery
- Salvage existing plants
- Direct seeding
- Outplanting nursery stock

3.14.1 SELECTING PLANT MATERIALS

In areas with relatively good soil stability that are bordered by healthy populations of viable native species, the existing seed bank and natural regeneration processes are key parts of re-establishing native vegetation on road sites. Minimizing the road footprint and damage from road construction are important aspects of any type of planning but are especially key if revegetation tactics involve supporting natural regeneration over more intensive revegetation interventions. In these cases, as long as topsoil is saved, the disturbance from road construction might serve to scarify the native seed bank. Often the option of maximizing natural regeneration is not sufficient to fully revegetate a roadside environment; nevertheless, it should always be considered as a possibility. Salvaging and reapplying duff and litter layers to disturbed surfaces can aid in maximizing natural regeneration. The revegetation plan should acknowledge aspects of the revegetation process that are expected to develop naturally (Clewell and others, 2005).

However, if native seed regeneration is not sufficient to revegetate the site, additional plant materials will need to be obtained and established. Plant materials may include the following:

- Seeds
- Cuttings
- Plants

Determining which plant material to select for revegetation depends on the type of species being grown. For example, conifer trees have been shown to establish better and faster from plants than from seed or cuttings. Alternatively, grasses can be established from plants, but growing grass plants and planting them is very expensive compared to using seeds. Some species, however, do not produce reliable crops of seeds and therefore other plant materials, such as cuttings, will have to be used. Table 3-15 and Table 3-16 compare the advantages and disadvantages of different establishment methods and stocktypes. Various implementation guides provided in Chapter 5 describe in more detail the process for obtaining plant materials.

Seeds

Seeds are collected in the wild from native stands of grasses, forbs, shrubs, trees, and wetland plants. This plant material is used for seeding projects, such as hydroseeding of cut and fill slopes or other large areas of bare soil. Seeds of grass and forb species are best used for direct sowing, whereas seeds of shrubs and tree species are best used to grow nursery plants. If large amounts of grass or forb seeds are required for a project, seed collections can be increased through seed increase contracts. It can take up to three years to obtain enough seeds for a revegetation project—one year to collect the wild seeds and one to two years for seed increase. One of the advantages of direct seeding is that it can be an inexpensive method of reestablishing plants for a large area. Guides to collecting wild seeds, increasing seeds, and salvaging topsoil, duff, and litter are provided in Chapter 5.

Cuttings

Cuttings are taken from stems, roots, or other plant parts and directly planted on the project site or grown into rooted cuttings at a nursery for later outplanting. Only a few species, such as willow (*Salix* spp.) and cottonwood (*Populus* spp.), can be easily established from direct sticking of cuttings on a project site. Other species, such as quaking aspen (*Populus tremuloides*), can be established from cuttings in a controlled nursery environment but not in the field. Propagating plants from cuttings of most species is not possible under most growing conditions. Cuttings are collected in the wild in the winter and either stored or immediately planted on the project site. If large quantities of cuttings are required, they can be propagated by growing them in stooling beds for several years at a nursery or other growing facility. Guides to working with cuttings are presented in Section 5.3.2 and Section 5.3.5.

Plants

Trees and shrubs are typically established using nursery stock rather than by direct seeding for several reasons. First, obtaining seeds from most tree and shrub species is expensive; in many years, they can be difficult to find or collect. Second, shrub and tree seeds germinate and grow into seedlings at a slower rate than grass and forb species, giving them a disadvantage on the sites where grasses and forbs are present. Starting shrubs and conifers from large plants instead of seeds gives them a competitive advantage over grasses and forbs because roots are often longer and better developed, allowing access to deeper soil moisture. Grass and forb species are seldom established from nursery-grown plants because of the high cost. Exceptions are when grass or forb seeds are rare or difficult to collect or increase (often referred to as “recalcitrant” species); if species are difficult to establish from seeds on disturbed sites; or when the project requires restoring threatened or sensitive species that are typically not considered workhorse species.

Plants are typically grown in a nursery or agricultural setting. However, for some projects, plants are salvaged from the construction site or adjacent areas. Sometimes salvaged plants are simply relocated quickly from one area to another. At other times, they may be transplanted into a nursery and replanted at a later time. Plants that are grown in a nursery require a lead time of one to two years from the time of ordering to availability. A variety of stocktypes are available from nurseries, including small to very large plants—plants in containers or those without soil around the roots (bareroot)—and plants grown in greenhouse environments or field-grown plants (Table 3-15). Selecting a stocktype will depend on the needs of the project, as there are multiple options for propagation and establishment, as well as many stocktypes to choose from.

Table 3-15 | **Comparison of plant material types for revegetation planning**

Type	Advantages	Disadvantages
Balled-in-burlap The plant is grown in the field, dug up with its roots and surrounding soil, and wrapped in a protective material such as burlap.	Well-developed root systems increase chances of survival on site	Expensive
	Provide shade and earlier establishment of upper canopy on site	Large and heavy to transport
Bare-root The plant is sold without any soil around its roots.	Less expensive	Requires care not to let root systems dry out before planting.
	Easier to transport to site; lightweight to carry around for planting	Difficult to establish in dry sites or sites with warm, sunny spring seasons.
	Roots have not been restricted by containers	
Container The plant is sold in a container of potting media or soil with drainage holes. Sizes and shapes or containers range from very small to very large.	Well-established root systems with intact soil	Native soil not used in nursery; transplant shock may occur when roots try to move into native soil
	Provide "instant" plants on site	Can be expensive
	Available in a variety of sizes; many are available year-round	Can be difficult to transport to and around site if large numbers are used
	Can be planted all year long	Can be difficult to provide irrigation until established; may actually require more maintenance than plug
Liners/Plugs A small plant, rooted cutting, or seedling that is ready for transplanting. They are often used for herbaceous plants and grasses.	Well-established root systems with intact soil.	Same as above
	Easy to transplant; plant material pops out of containers easily	Smaller plants may take longer to establish; require more initial maintenance
Cuttings A piece of branch, root, or leaf that is separated from a host plant and used to create a new plant. These may be placed in a rooting medium or stuck directly into the ground for planting.	Inexpensive to produce; cutting may easily be taken on site or from nearby site	No established root systems
	Etasy and light to transport; known to work well in rocky areas or areas difficult to access	Timing of taking cuttings and planting them is important; varies among species and limited to dormant periods
Salvage Native plants that are removed from a site (to a nursery, storage area, or directly to another field location) before ground disturbance at that site occurs. (Can also refer to salvaged cuttings or seed sources.)	Can use plant material that would otherwise be destroyed	Different native plants respond differently to being dug up; some loss could be expected
	Plant material could be local to site	Requires fairly intensive measures to protect plants and ensure they have adequate irrigation
	Relatively inexpensive	
	Small or young salvage plants often adapt more readily to transplant than do mature specimens	

Adapted from Dorner 2002

Potential disease and insect issues

Diseases can affect all native plant species used in revegetation, but assessing and mitigating for individual diseases is at times overlooked during revegetation projects. If a disease occurs, many times it is the result of trying to establish plant species in the wrong environment. For instance, species adapted to dry environments may be susceptible to certain diseases if planted in wet soils where a different set of root and other pathogens are present. While pathogens might be present on a site, this does not necessarily mean that plants will be affected. Much like humans, plants are always surrounded by a variety of pathogens, but it is not until they experience stress that they become more susceptible to diseases.

Planting appropriate species matched to sites where they have adapted to, using genetically appropriate stock, purchasing high quality plant materials from nurseries with good disease and insect management practices, improving the soil, and mitigating for climate extremes all play an essential role in creating healthy plants capable of resisting diseases or insect pests. If diseases are found on seedlings after planting, they may have previously become infected at the nursery. Appropriate sanitation procedures and practices a nursery might employ to help mitigate the risk of diseases include using only clean containers and potting media, starting with disease-free stock, and using only clean (non-recycled water). For more information on nursery practices that help prevent the spread of diseases or insect pests, the designer can find example guidelines in the Native Revegetation Resource Library. There have been some cases when diseases originating in the nursery can spread to native plant populations with devastating effects. The recent spread of *Phytophthora ramorum* (the water mold pathogen that causes Sudden Oak Death, aka SOD) in California, Oregon and elsewhere serves as a dramatic example of the problems faced when pathogens are released into the landscape (www.calphytos.org). Avoiding the purchase of damaged and infested stock and purchasing from growers that use best management practices can greatly reduce the risk of spreading diseases or insects.

A variety of insects can damage newly planted seedlings, as discussed briefly in this section. Because this is a specialized field, the designer is advised to consult technical or academic experts if insect problems are extensive on a revegetation project. Insect damage is grouped into four classes (Helgerson and others 1992), based on where insect feeding occurs:

- **Sap-suckers**—foliage
- **Root beetles**—root system
- **Terminal feeders**—terminal shoots
- **Secondary bark beetles**—stems

It may be difficult during the planning stages to determine if insects will be a limiting factor. However, designers can consult with entomologists to determine which insects might be known species of concern. Damage to seedlings by insects may be often overlooked because the injury usually occurs before the seedling shows visible signs of stress. By this time, the insect is no longer present, leaving only signs of previous activity. When dead or dying seedlings are discovered, it is important to systematically evaluate the seedling from the root system to the terminal bud for the presence of insects, insect damage, and diseases (discussed in the following section). If insects are found, individuals should be collected for later identification. Designers can place insects in small glass or plastic containers until they can be examined by an entomologist. It is important to look under the leaves for aphids and scrape the entire seedling with a sharp knife to observe boring and tunneling. Damage caused by insects and diseases can occur under the bark of the stems and roots themselves. A hand lens is helpful when evaluating damage. The following discusses some of the most prominent insects that damage conifer seedlings. Non-conifer species will have their own unique associated pests. Nevertheless, classifying the insect into one of the four classes is a start in making a diagnosis.

For the Designer
Consult pathologists at extension offices, universities, or other agencies for expert input on disease issues.

For the Designer
To prevent disease spread to native populations, designers should only work with nurseries that have practices to ensure only disease-free nursery stock is out-planted.

For the Designer
Designers should consult entomologists at extension offices, universities, or other agencies for expert input on insect issues.

- **Sap-Suckers**—Sap-suckers include the Cooley spruce gall adelgid (*Adelges cooleyi*) and the giant conifer aphids (*Cinara* spp.) that feed on succulent foliage of tree seedlings. While these can cause shoot deformity and foliage loss, aphids will normally not kill seedlings. The appearance of aphid ants (which cultivate aphid populations) on the leaves are indications that aphids are present.
- **Root Beetles**—The root bark beetles (*Hylastes* spp.) and root-collar weevil (*Steremnius carinatus*) girdle the roots and stems of conifer seedlings and will weaken or kill newly planted seedlings. The damage can be mistaken for herbivory by small mammals, but the lack of teeth marks and the below-ground location of the damage are indications that the damage is caused by root beetles.
- **Terminal Feeders**—The larvae of this group of insects feed on the terminal shoots of young conifers, killing much of the new growth. Continued annual attack by these insects can severely stunt conifer seedlings. The major insects include white pine weevil (*Pissodes strobi* [Peck]), ponderosa pine tip moth (*Rhyacionia zozana*), western pine shoot borer (*Eucosma sonomana*), and the cone worm (*Dioryctria* spp.).
- **Secondary Bark Beetles**—The Douglas-fir engraver beetle (*Scolytus unispinosus*) attacks the stems of stressed seedlings, creating galleries under the bark that weaken or kill Douglas-fir seedlings.

Some examples of ways to mitigate for insects include:

- **Plant a Variety of Species**—Insects are often host-specific, meaning they attack only one species. For this reason, a preventative measure is to plant a variety of species. If an insect infestation occurs, it may not affect all the seedlings planted.
- **Plant Healthy Stock**—Insects often attack weakened seedlings or seedlings that are stressed. Planting only healthy and vigorous seedlings, appropriate to the site, reduces the potential damage by insects.
- **Create a Healthy Soil Environment**—Seedlings grown on poor sites, or on sites outside of the species' environmental ranges, will be stressed and become susceptible to insect damage. Planting seedlings on optimal growing sites will produce healthy seedlings resistant to insect damage. Judicious use of fertilizers (that is, avoid over-fertilization) is also important for pest prevention. For example, sucking insects often attack plants that have been over-fertilized with nitrogen.
- **Install Bud Caps**—Some terminal feeders can be controlled through the use of bud caps that are placed over the terminal in the spring prior to shoot growth (Goheen 2005). Bud caps are materials made out of paper or fine cloth that temporarily cover the terminal and prevent adult insects from laying eggs on the bud.

For any stocktype, various desired characteristics should be defined, including age, size, likelihood of survival on the site, ability to compete with other vegetation and/or tolerate animal effects, and methods that will be necessary to out-plant and maintain the stocktype. For bareroot stocktypes, size, age, and potential survival rates should be considered. For cuttings, consider if the project requires containerized cuttings (with a root system in a container), heeled or bareroot cuttings (with roots but no container), or simply cuttings to stick directly in the ground on the project site. For cuttings, length, caliper, and conditions of storage are also important factors. For container plants, no standard terminology exists for describing the different types of container plants available (Landis and others 1992). They are usually described by their container type, referring to the volume and usually the shape of the container. Size and age of the plant are also described. When ordering container plants, consider age, caliper, height, and root size and depth, as well as any other special characteristics that might help the plant survive on the project site (Table 3-15).

Salvaging plants from the project area can be an important component of protecting native plant diversity on the project site. Sometimes salvaged plants are simply relocated instantly from one area to another. Other times, they may be transplanted or moved to a nursery area, cared for, and then re-planted at an appropriate time. As much native soil as possible is included when digging the salvaged plants, as this soil not only supports the health of the plants but also contains the native seedbank and root fragments of it and adjacent plants. “Salvage” may also involve harvesting cuttings or seeds from plants that are going to be removed during the road construction process.

Depending on the species, genetics, site limiting factors, and specific project objectives, some concept of the appropriate “target” stocktypes will already be defined. For example, some plants respond well to certain propagation methods; some will be salvaged (“wildings”) from the site; and some are obvious candidates for direct seedling applications in order to facilitate fast regeneration. The needs and characteristics of a particular species will help determine if direct seeding, nursery propagation, or other methods are the more appropriate strategy. Many options can be considered, some of which are summarized in Table 3-16.

Table 3-16 | **Comparison of different plant establishment methods**

Characteristic	Wild	Cuttings	Seeds	Nursery plants
Efficient use of seeds and cuttings	N/A	No	No	Yes
Cost of establishment	High	Moderate	Low	Moderate
Ability to establish difficult species	Yes	No	No	Yes
Option of using specific genotypes	No	No	Yes	Yes
Precise scheduling of plant establishment	Yes	Yes	No	Yes
Control of stand composition and density	Yes	Yes	No	Yes
Matching stocktypes to site conditions	No	No	No	Yes
Depletion of adjacent plant stands	Yes	Yes	No	No

Scheduling

Timing is a key factor for obtaining plant materials because many native plants or seeds are not widely available from nurseries and seed companies. Even if a species is available, the odds are that it is not from a local source that is genetically adapted to the project site. Therefore, it is essential to identify plant material needs early. It usually takes a lead time of two to four years to administer seed collection, seed increase, and seedling propagation contracts. Sometimes three years may be required to achieve sufficient quantities of seeds. Plants (seedlings, cuttings, and so on) ordered from nurseries take a great deal of advanced planning for both seed collection and for plant propagation. Failure to realize the lead time necessary for seed collection and propagation of appropriate native plant materials is one of the most common mistakes made in revegetation projects (Figure 3-97).

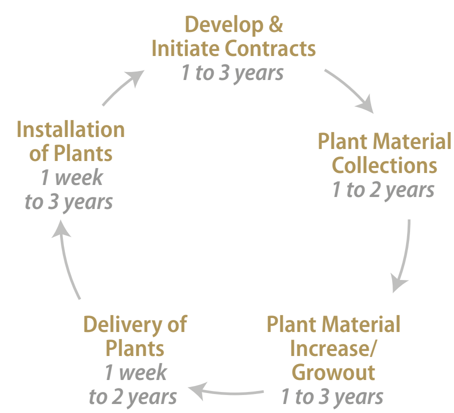


Figure 3-97 | **Early planning for plant material procurement**

Early planning for plant material procurement is essential. Depending on plant species, stocktype, and quantity desired it can take up to three years or more to obtain suffient plant material. Due to the biology of plants, a missed window of collection may result in a full year’s delay. Outplanting may occur across multiple growing seasons, requiring several delivery and installation events spanning a timeframe of years.

Select Installation and Maintenance Methods

Many methods are available for installing plant materials on a project site. Seeds can be applied through hydroseeding equipment, disked or drilled into the soil surface, broadcast sown, imprinted, and/or covered with a variety of types of mulch. A variety of techniques are also available for installing cuttings and plants, including an expandable stinger, waterjet stinger, pot planter, auger, and a shovel. These methods are discussed in Chapter 5.

After plant materials, have been installed, care is required until they are well-established. This includes protection from browsing animals, high temperatures, winds, competing vegetation, and drought. Measures that can mitigate for browsing animals include installing netting and tree shelters, over-planting to compensate for expected browse, as well as applying animal repellents. If netting or tree shelters are used, it is important to account for their removal in the implementation budget and contract. Seedlings can be protected from high temperatures and wind with shade cards, tree shelters, and large obstacles, such as logs. Competing vegetation is controlled through weeding, mulch, or herbicides. In extremely dry conditions, soil moisture can be supplemented by using irrigation systems.

3.14.2 DETERMINE OUTPLANTING WINDOWS

In addition to ensuring enough lead time to successfully carry out native revegetation goals, the optimum seasons for planting must be determined. There are advantages and disadvantages to carrying out operations at any time of the year, and determining the timeframe should be based on the species, plant material, and site factors.

The optimum time of year to outplant for greatest plant survival is called the outplanting window. It is determined by graphing the annual precipitation, temperatures, and snow accumulation of a site. This information can be obtained from climate stations, as described in Phase One. Outplanting windows are also defined by the species, stocktype, and outplanting methods. For example, two different species of bunch grass might have very different survival rates depending on when they were outplanted. Figure 3-98 shows survival rates for bluebunch wheatgrass (*Pseudoroegneria spicata*), that survived better when planted in fall, and spreading needlegrass (*Achnatherum richardsonii*), that survived better when planted in spring.

Several factors are important for determining outplanting windows, including soil temperatures in late winter and early spring, precipitation during spring and early summer, soil temperatures in fall, precipitation in fall, and snow cover. Three examples of identifying outplanting windows are provided in Figure 3-99, Figure 3-100, and Figure 3-102. Applying the following set of guidelines to the climate data will help clarify the optimum times to plant.

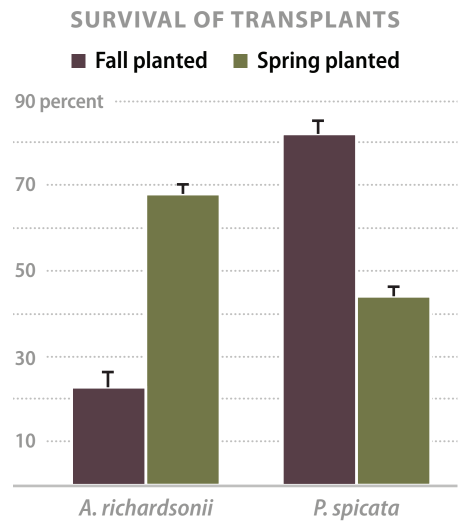


Figure 3-98 | **Survivorship can vary between spring and fall plantings**

Outplanting must be timed properly for best results given site conditions and species requirements

Reproduced from Page and Bork 2005

Soil Temperatures in Late Winter and Spring

Seedlings must develop new roots soon after they are planted to become established and survive the hot (and in many regions, dry) summer of the first growing season. For most species, new root growth occurs when soil temperatures exceed 42° F. Waiting for soil temperatures to warm to 42°F in the spring before outplanting, however, will shorten the period when soil moisture is available to the seedling. For this reason, a common restoration strategy is to outplant seedlings as soon after the last threat of a deep frost in the winter has passed, even if the soil temperatures are below 42° F.

Precipitation in Spring and Summer

Much of the western United States experiences dry summers, with winters receiving most of the precipitation. Under this regime, soils lose their moisture in the summer and recharge from storms that occur in the fall and winter. Plants have adapted to this climate by growing new roots and leaves during spring, when soil moisture is high, and becoming dormant in summer, when soil moisture is depleted.

The most critical factor for seedlings that are outplanted in the spring is the length of time available for the seedling to develop new roots before soil moisture is depleted. Sites with little or no precipitation in the spring or summer will dry out faster than sites with high spring and summer precipitation. A guideline is that an average monthly precipitation of less than 1.5 inches will do little to recharge a dry soil during late spring through fall. Figure 3-99, Figure 3-100, and Figure 3-101 show spring outplanting windows for three very different project sites. On low elevation sites west of the Cascade Mountains, the planting window can be fall and spring (Figure 3-99), whereas high elevation sites might have a planting window only in late spring (Figure 3-101).

Figure 3-99 | **Case study—Low elevation, Western Cascade site**

The project site is located near Tiller, Oregon, where winters are wet and relatively mild, and summers are dry and hot. North slopes support Douglas-fir, incense cedar, and madrone. South slopes support ponderosa pine, oaks, and grasses. During summer, strong drying winds blow up the valley in the afternoon. Weather station records, from a U.S. Regional Climate Station located several miles away, show daily maximum summer temperatures in July and August averaging 84° F.

The site has two planting windows. The spring planting window starts after the risk of the last winter cold front in mid-February has passed and ends two months before monthly precipitation dips below 1.5 inches. The fall planting window begins as soon as the first fall rains wet the soil profile and ends one month prior to soil temperatures dropping below 42° F.

Long dry summers, coupled with high temperatures and strong winds, create challenges to establishing seedlings. Outplanting in the fall or in mid to late winter is essential in order to develop new roots. Removing grass and other vegetation from around the seedling and applying a mulch fabric in March increases soil moisture. In places, tree shelters and shade cards placed around seedlings can protect them from the drying effects of the afternoon wind.

Hydroseeding in October with mulch and tackifier will keep seeds in place long enough to germinate in November. Complete seedling establishment will occur by the following April.

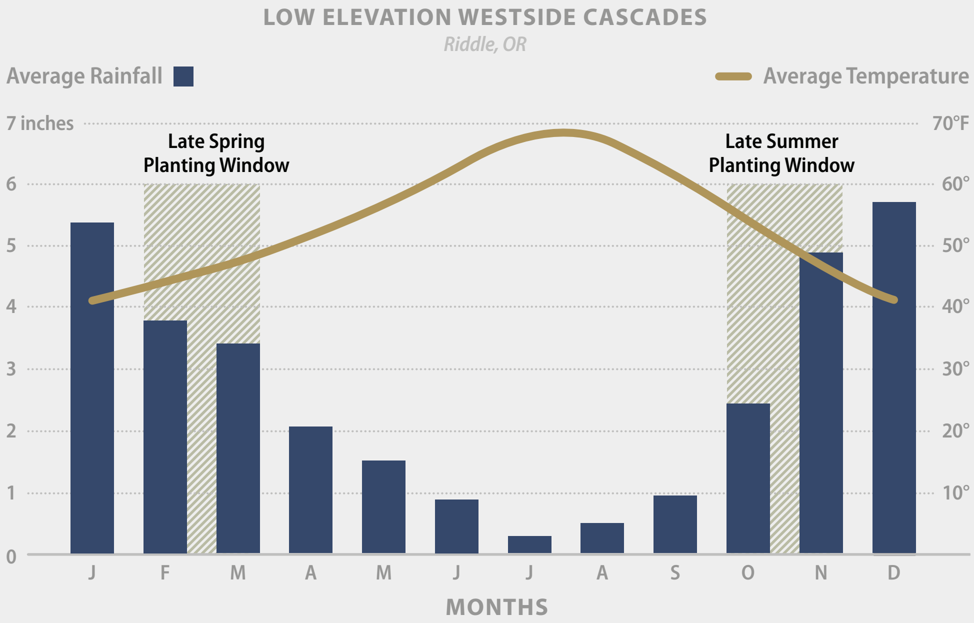


Figure 3-100 | **Case study—Cool, arid site**

The climate at this project site is typified by dry, mild summers and cold winters with a snow pack extending from late fall to late winter. (Climate data was from a weather station located near the town of Chiloquin, Oregon.) Ponderosa pine, quaking aspen, and bitterbrush are the dominant vegetation on the site. The planting window begins immediately after snowmelt. Precipitation drops off significantly in April and May. Planting must be completed no later than the first week of April when monthly precipitation drops below 1.5 inches. Note that soil temperatures during the recommended planting windows are cooler than 42° F. Nevertheless, it is more important to plant early on arid sites than wait until soil temperatures warm. Rainstorms in the fall do not deliver enough moisture to recharge the soil before mean fall temperatures drop below 42° F. Early planting can take place in the fall if seedlings are irrigated at the time of planting. Seedlings on south slopes should be mulched to conserve soil moisture, while seedlings on cooler north aspects would benefit from, but may not require, mulch.

Grass and forb seeding in September and October is essential because most seeds from this area require a stratification period. Seeds will not germinate in the fall because of the lack of continuous fall moisture and low temperatures. Germination occurs immediately after snowmelt in the spring. Seed germination can be poor because the soil surface dries out quickly due to low humidity, high solar radiation, and low precipitation. Mulching the seedbed with ground wood fiber or straw will maintain high humidity around germinating seeds. Spring seeding can be successful if seeds are soaked for several days prior to seeding and if seeding is done as soon as snows have melted.

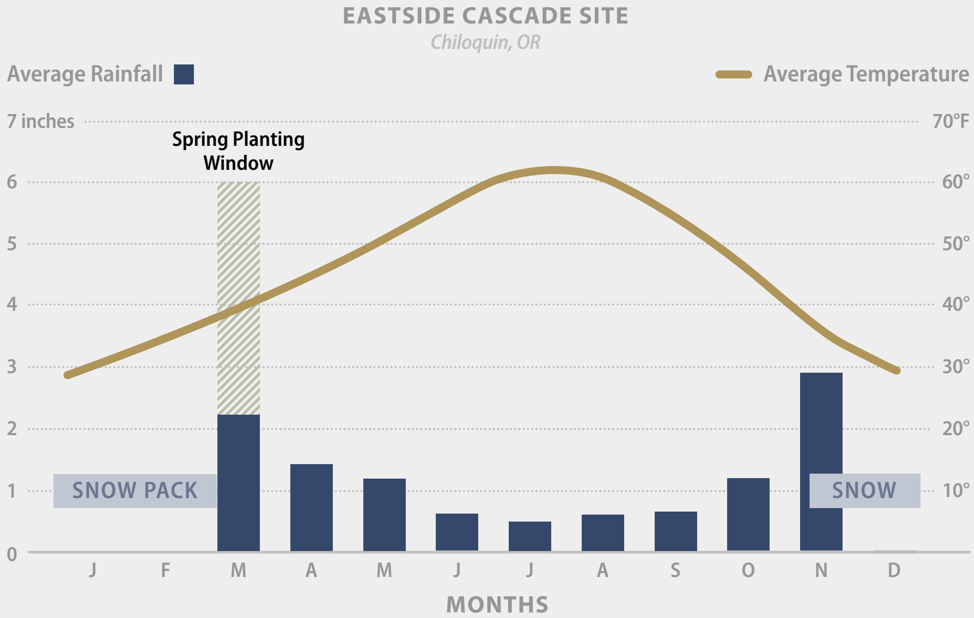
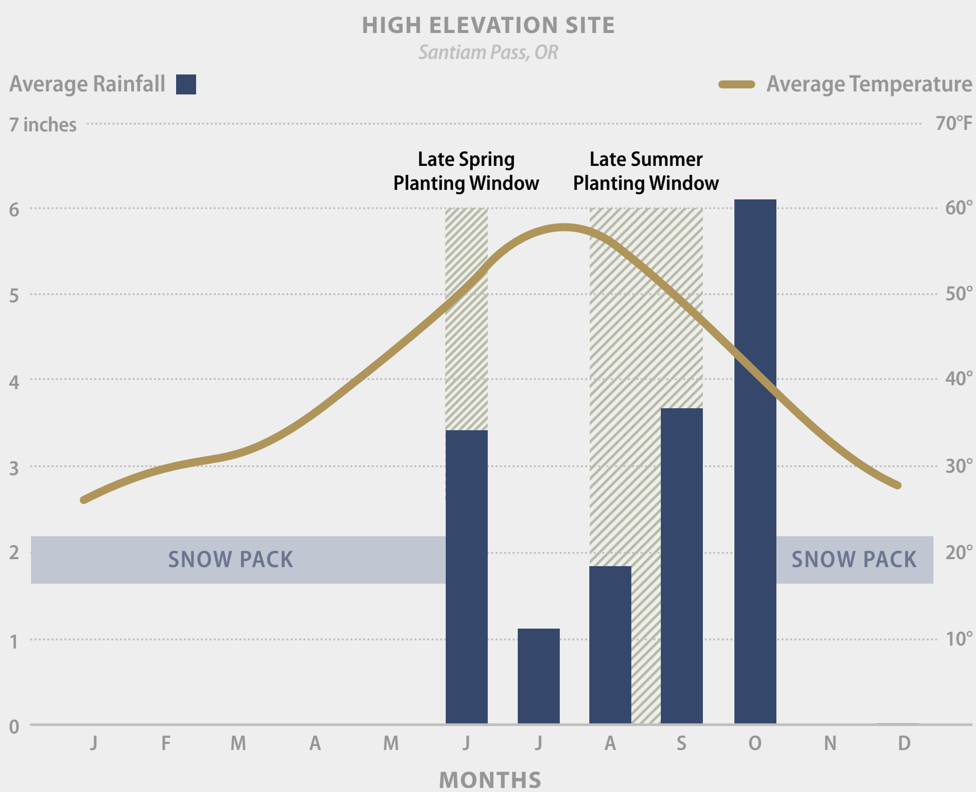


Figure 3-101 | **Case study— High elevation site**

This site is located in the high Cascade Mountains at 4,800 feet elevation. Mixed stands of mountain hemlock and noble fir occupy the site. Snowpack begins in November and is present on the site until May. Seedlings must be planted as soon as the snow leaves the site. Thunderstorms will typically wet the soil by late summer, opening a second planting window sometimes as early as late August. Competing vegetation must be controlled around container seedlings planted at this time to maintain high soil moisture for the remainder of the fall. Scalping vegetation immediately after planting and applying a mulch will help maintain high soil moisture. As temperatures begin to drop in late summer, evaporative demands on the planted seedlings are reduced. Planting must be completed by late September to ensure that seedlings will have some time to develop new roots. North aspects will have cooler soil temperatures and should be planted sooner than south aspects.

Weather station data indicate average minimum air temperatures are cold during the growing season. Applying tree shelters around seedlings will increase daily air temperatures, creating a more favorable environment for seedling growth. North aspect seedling plantings might benefit more from tree shelters than south aspect plantings.

Sowing can take place in the late spring, immediately after snowmelt, and again in the fall. Late spring sowing will be significantly enhanced by applying mulch over the seedbed and/or pre-germinating seed prior to sowing. Seeds of species that do not require stratification should germinate within a month after sowing in late spring. Species requiring stratification should be sown in the fall.



Soil Temperatures in Fall

If outplanting is planned for late summer or early fall, it is important that soils have high moisture and temperatures are warm enough to encourage new roots to grow into the soil before winter arrives. On cold sites where seedlings are not protected by snow, the upper portions of the soil profile will typically freeze (e.g., frost heave) and can dislodge seeds or seedlings exposing roots to desiccation. Fall outplanted seedlings that have not established new roots below the frost line risk desiccation by wind or sun exposure in winter because little to no water is available to the seedling. For greatest success, soil temperatures should remain above 42° F for at least one month after seedlings are planted in the fall for root development and seedling establishment prior to winter. Figure 3-101 shows a late summer planting window on a high elevation site where precipitation is high in September and soil temperatures are above 42° F.

Soil temperatures are significantly warmer on south aspects, which means that outplanting windows on south exposures are often temporally broad and extend further into the fall than planting sites on north aspects, given soil moisture is adequate for root growth. Weather stations do not report soil temperatures. However, they can be extrapolated from average monthly air temperatures with a certain degree of reliability. Placing recording thermometers in the soil before construction will give more exact soil temperatures.

Precipitation in Fall

When outplanting seedlings in the fall, high soil moisture is essential for seedling survival and growth. Fall soil moisture can be very low, and the only means of recharging a dry soil is through rainstorms or irrigation. Two or more inches of rain over a period of at least several days are often required to moisten most dry soils. Many sites in the western United States, however, seldom have rainstorm events great enough to moisten the top 12 inches of soil before cold soil temperatures occur. Fall planting on these sites has a low potential for seedling survival. On sites with sufficient fall precipitation, planting windows are open as soon as a rainstorm event wets the surface 12 inches of soil.

Snow Cover

Seedlings should not be planted through snow, so outplanting windows are open before snow accumulation and after snowmelt. Be aware, however, that cold water from melting snow keeps soil temperatures low. Soil temperatures should be monitored during or following snowmelt.

Determine Sowing Windows

The outplanting windows for seed sowing may be different than those for planting nursery stock. Optimum planting times for seeds are called "sowing windows." Sowing windows change by site environment, sowing methods, and seed needs. Seeds will germinate and develop into healthy, viable plants when: seed stratification requirements are met and seeds are in a warm, moist environment during germination. Seed stratification requires a cold, moist period, ranging from a few weeks to several months, during which time the seeds are conditioned for germination. This usually occurs naturally in the western United States during early to mid-spring, but it can be induced artificially in seed coolers.

After seed stratification requirements, have been met, a moist, warm period must follow in which seeds and soil do not appreciably dry down. Drying during this time can prevent germination and kill new germinants. In the western United States, these conditions are best met by sowing seeds in late summer to early fall. On warm, moist sites (Figure 3-99), seeds that require a very short stratification period will germinate in early fall and begin to establish ground cover before winter rains occur. Fall-sown seeds requiring stratification will have moisture and temperature requirements met during winter. On drier sites (Figure 3-100), fall-sown seeds will not germinate due to lack of precipitation.

If fall sowing is not possible, sowing can take place in late winter or early spring. Sowing at this time generally results in less vigorous stands of grass and forb seedlings because there is a shorter period of favorable conditions for seeds to germinate and seedlings to become established. Another drawback of spring sowing is that some species will not receive the required cold, moist period to break seed dormancy and germinate. Once germination has occurred, several months of periodic precipitation with average air temperatures exceeding 40° F are required for successful establishment of ground cover.

Spring sowing can be enhanced in several ways. A mulch applied over the seeds will help maintain higher seed moisture levels and keep soil moisture in the soil for a longer period. Seeds requiring stratification can be artificially stratified for spring sowing to achieve earlier germination. Care must be taken that the seeds do not mold or begin to germinate during this period, or dry down for sowing. The effect of hydromulch equipment on germinating native species seeds is unknown at this time; seeds may be damaged if sown using this method.

3.15 **DEVELOP A REVEGETATION PLAN**

The last step in the planning process is to write a revegetation plan which is the blue print for successfully implementing a revegetation project. It contains project objectives, site treatments details, plant species that will be used, and planting methods. This document is referred to during project implementation by contractors, contract inspectors, and road project engineers, as to what will be done and the reasoning behind the action. Managers refer to it for roles and responsibilities, timelines, and budgets and it is often shared with maintenance and operations personnel in case there are special maintenance requirements for that section of road. Because revegetation projects often exceed five years, from start to finish, planning personnel may not be available during or after implementation for consultation or perspective and the revegetation plan may be all the construction engineer, road builder, revegetation contractor, and monitoring personnel may have as background for the project.

Developing a revegetation plan has the added benefit of forcing the designer and the teams the designer works with to think more clearly about the project. In the process of developing a revegetation plan, for instance, subjects that may not have been fully addressed during meetings, are discussed at greater depth resulting in better decisions. Another important aspect of this document is that when a draft plan is sent around to managers, maintenance personnel, engineers, and other teams for review, the comments that are returned to the designer are considered and appropriate changes made to the document. There may be several drafts that are made to a revegetation plan and each draft documents the thinking that went into the plan. Not only does this process record decisions, it creates ownership and understanding of the project by others. It is not uncommon for the best ideas to come from organizing and writing a revegetation plan. So, the revegetation plan is more than a report, it encapsulates the process for how a revegetation project was developed.

There is no size or set format for a revegetation plan but there are elements that may be common to all. These include a summary of the:

- Revegetation objectives and desired future conditions (DFC targets)
- Vegetation, soils, and climate of disturbed and undisturbed sites
- Revegetation unit map and unit description
- limiting factors & site resources
- Site improvement treatments
- Contract specifications
- Species & plant materials table

- Seed sources
- Planting and seeding plans
- Monitoring
- Schedule
- Budget
- Roles and responsibilities
- Maintenance strategy

Chapter 4 gives an example of a revegetation plan that is specific to developing pollinator habitat. Other examples of revegetation plans can be viewed on the Native Revegetation Resource Library by typing “revegplan” into the search field.

4— Revegetation Plan Example

PREFACE

FHWA's Historic Columbia River Highway State Trail project has a representative revegetation plan for the planning stage.

Photo credit: Matt Horning, USFS

The following sample Revegetation Plan (the Plan) was written for a Federal Highway Administration WFLHD project that is currently in the planning stage. The Plan highlights actions to be taken by the USDA Forest Service Region 6 Restoration Services Team in association with WFLHD. The Plan was previously submitted to WFLHD and will be used in the permitting process by the Contractor and Contracting Officer's Representative during the implementation phase and will be referred to during the monitoring phase. Revegetation Plans are unique to each project. This sample plan is provided here as a stand-alone document in the larger manual and is meant only as a reference from which to develop a project-specific Revegetation Plan.

This Plan is unique to the Restoration Services Team in that it is the first to intentionally include elements in the planning, implementation, and monitoring phases with the specific goal of increasing plant-pollinator interactions. Areas that would support pollinator insects with moderate effort and alteration were identified as distinct revegetation units during the planning phase. Plant species lists were developed during the planning phase to include plants known to increase nectar availability and to provide nesting, breeding, and refuge benefits. Plant materials for these species were collected for seed increase and grow-out. Minor grading to create depressions for water retention, large woody debris placement to create microhabitats, and out-planting will occur during the implementation phase in an effort to increase pollinator habitat. Pollinator abundance and diversity information will be collected during the monitoring phase to better understand practices that increased pollinator use within the project area and to identify opportunities for improving these approaches on future projects.

Restoration Services Team- R6 USDA Forest Service
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HISTORIC COLUMBIA RIVER HIGHWAY STATE TRAIL: SEGMENTS A-C FINAL REVEGETATION PLAN

June 2016

Prepared for:
Federal Highway Administration
Western Federal Lands Highway Division
610 East Fifth Street, Vancouver, WA 98661

TABLE OF CONTENTS

Prepared by

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Submitted June 8, 2016

BACKGROUND

Background

The Historic Columbia River Highway (HCRH), originally constructed between 1913 and 1922, took full advantage of the unparalleled beauty of the Columbia River Gorge. The highway dazzled tourists and locals alike as it meandered near breathtaking waterfalls, panoramic vistas, and spell binding geomorphology. Many of these scenic features such as nearly thirty named waterfalls, including Multnomah Falls and Hole-in-the-Walls, and the Crown Point Vista House still delight travelers today. The construction of Interstate 84 during the late 1940s and early 1950s disrupted the HCRH, leaving much of it in fragmented segments.

Directive was given to the State of Oregon in 1986 via the Columbia River Gorge National Scenic Area Act, to reconnect the fragments of the historic highway. Further direction was provided by the Oregon Legislature in 1987 to the Oregon Department of Transportation (ODOT) to facilitate the development of the Historic Columbia River Highway State Trail (hereafter HCRHST) by preserving and enhancing existing HCRH segments. Since then, multiple partner agencies including the Federal Highway Administration-Western Federal Lands Highway Division (WFLHD), ODOT, Oregon Parks and Recreation Department (OPRD), the U.S. Forest Service (USFS), the State Historic Preservation Office, and private entities have collaborated to reconnect the HCRH fragments. Sixty-two of 73 miles are currently open along the HCRHST, in the form of drivable motor vehicle roads and foot or bicycle paths. There are approximately eleven miles remaining of the original HCRH for which plans are in place to reconnect and incorporate into the HCRHST.

This document specifically addresses revegetation efforts planned by the U.S. Forest Service Region 6 Restoration Services Team (RST) within Segments A through C of the HCRHST. These segments cover from approximately one half mile west of the Wyeth Campground (west end of Segment A) to Lindsey Creek at the eastern end of Segment C, slightly less than ten miles west of the town of Hood River, Oregon (Figure 1). The combined length of Segments A-C is 3.08 miles and spans from station 499+89.18 at the west, to station 151+73.53 to the east.

Plans for Segments A-C call for developing a parking lot and trailhead on the west end, a mitigation area of approximately 5 acres, and new interpretive resting spots along the trail. Revegetation efforts will be closely coordinated with Walker Macy, a Portland Landscape Design firm.

BACKGROUND

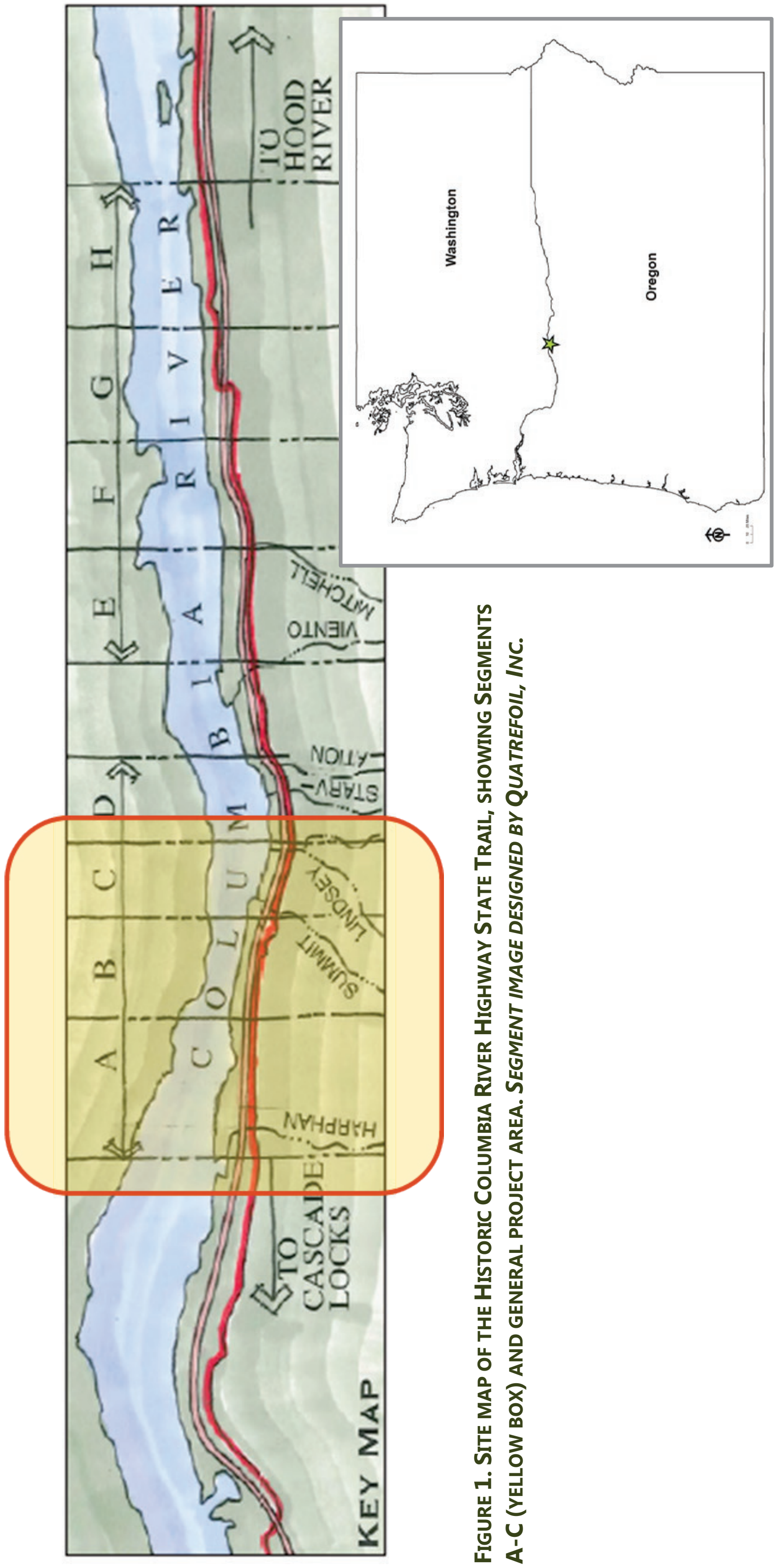

Figure 1. Site map of the Historic Columbia River Highway State Trail, showing Segments A-C (yellow box) and general project area. ***Segment image designed by Quatrefoil, Inc.***

Page 4

Historic Columbia River Highway State Trail, Segments A-C Final Revegetation Plan

BACKGROUND

Past Use

The project area of the HCRHST has a long history of human utilization. Evidence including remnants of poured concrete foundations, door stoops, invasive plants, imported fill material, trails and roads are found throughout the project area. In addition, creek channels have been re-routed and straightened, culverts have been installed, and surface water flow patterns have been altered significantly. Many of the hardscaped artifacts will be preserved in place, while non-native vegetation will be eliminated.

Soils

Native soils in the majority of the project area are of the Wyeth Series. This soil type is well drained and consists of very cobbly loam, having formed from basalt colluvium. The project area experiences rapid runoff and moderate permeability.

Climate

The elevation is about 120 feet above mean sea level. The area is influenced by winds from the Columbia River Gorge (Fig. 2) and on average, the greatest precipitation occurs during the month of December with six inches (Fig. 3). The average growing season in nearby Hood River, Oregon occurs from approximately late April through mid- to late October, with about 183 frost free days. The maximum average temperatures are around 83°F in July, with the lowest minimums being around 30°F in December. Annual average humidity is highest in December at 84%, and lowest in July at 51% (2004-2014).

BACKGROUND

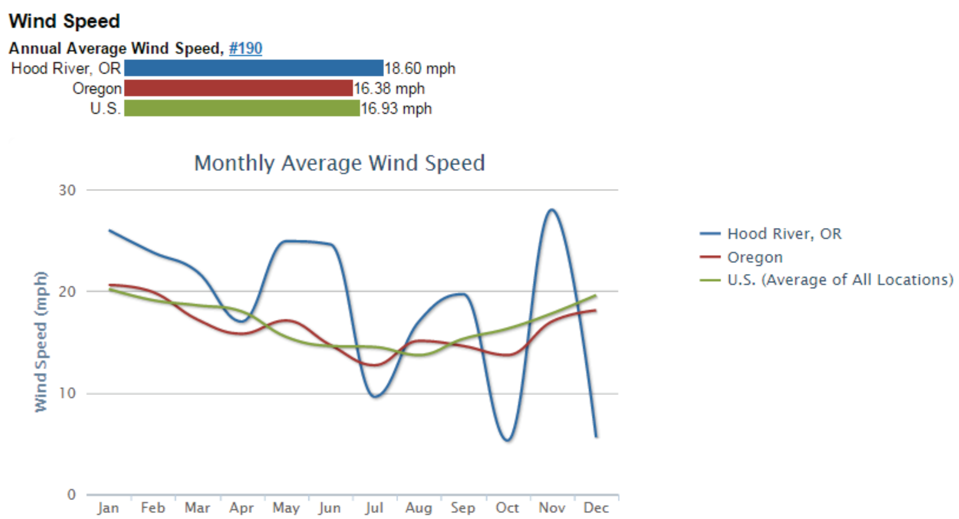

FIGURE 2. AVERAGE MONTHLY WIND SPEEDS IN HOOD RIVER, OREGON. DATA ARE AVERAGED FROM 1980-2010.
SOURCE: USA.COM HISTORIC WEATHER DATA

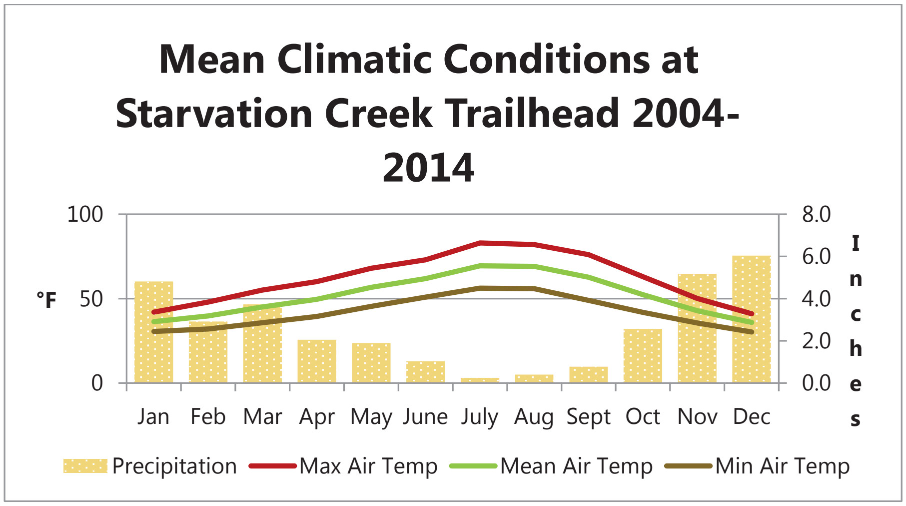

FIGURE 3. THE AVERAGED MAXIMUM, MINIMUM, MEAN AIR TEMPERATURE AS WELL AS PRECIPITATION AT STARVATION CREEK TRAILHEAD. DATA ARE AVERAGED ACROSS 2004-2014. NOTE THE TWO DIFFERENT AXES.
SOURCE: PRISM TIME SERIES DATA FOR LATITUDE 45.7055N/LONGITUDE -121.5855W

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BACKGROUND

Trail Construction

The trail is planned to be 12 feet wide, with two foot shoulders on either side. In some areas of constriction the trail width will be reduced to 10 feet. One exception is the planned pedestrian viaduct near Summit Creek that will be 14 feet wide. Grades will be limited to approximately five percent and when able, the trail surface will be sloped to the north. There will also be an additional five foot construction allowance on either side of the trail for temporary work access. In addition to the trail itself, plans call for a new trailhead with parking lot at the western terminus, a new motorist/pedestrian bridge over Gorton Creek, a pollinator meadow and mitigation area, a pedestrian viaduct near Summit Creek, and two new interpretive idle spots along the trail. Revegetation efforts will be proportional to the need for restoration and public visibility of each location.

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Strategy

Locally sourced, genetically adapted plant materials will be utilized for this project. The canopy within segments A-C is quite varied; ranging from open meadow to partial forest canopy to dense woods. The mitigation site near the historic Wyeth trailhead is a mostly open area, surrounded by trees. However, there is a large infestation of invasive weeds (namely Himalayan blackberry (*Rubus armeniacus*) and Scotch broom (*Cytisus scoparius*)) that occupy greater than 40% cover. Once the Himalayan blackberry and Scotch broom are treated there will be very little to no canopy cover over the majority of the almost five acre site. This location is well suited to be left as an open meadow and as such has been designated as an area where we will focus revegetation efforts on creating a pollinator-supporting habitat (see Mitigation Site #2 discussion below). This emphasis on pollinator habitat for this area specifically addresses action items in the National Pollinator Strategy and the National Native Seed Strategy, in addition to other FHWA/WFLHD and Forest Service strategies.

Appendix 1 shows the suite of species that are planned for revegetation efforts. The plant species suite represents native plants that are present at the project site, at adjacent reference sites, or for which there are documented records of them having once been native and present but which have been out competed by introduced species. The suite is broad and not all species will be utilized at all sites. The most common container size used will be D27s. These containers are 2.5 inches wide by 7 inches long, and have a capacity of 27 cubic inches. This size pot accommodates a wide range of shrub and tree species and has proven reliable under similar out-planting conditions. Grass and forb seed will either be hydroseeded or hand broadcasted.

The planting goal of RST is to: 1) create good line-of-sight and facilitate public safety (as designed in Walker Macy planting plans); 2) create a natural appearance that is consistent with the surrounding environs; and 3) create habitat to support pollinators. RST will draw on the planting notes and design of Walker Macy (Appendix 2) but will incorporate multiple native species of the designated height classes into each planting area and blur the boundaries of the planting areas to create a random and natural appearing pollinator-friendly habitat.

Plant Species of Special Interest

There are no known threatened, endangered, or sensitive plants within the area to be directly affected by this project (Robin Dobson, *pers. comm.*). RST is aware of only one observation of

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a sensitive plant species within the project vicinity, which occurs in a plant buffer of Segment B near station 105+50 (CH2M Hill 2014). This occurrence of long-bearded hawkweed (*Hieracium longiberbe*) is not expected to be affected. Although there are no known plants of concern within the area to be directly affected there are additional areas of potential habitat for long bearded hawkweed and Columbia kittentails (*Synthyris missurica* ssp. *stellata*). If RST Restoration Specialists observe a species of concern they will salvage plants and care for them ex situ at Dorena Genetic Resource Center, a USFS plant center in Cottage Grove, Oregon, or adjacent to the affected area in similar habitat (on or near the project site). The plants would then be resituated in their original location, or the nearest suitable location if the original is no longer available, once the potential for disturbance has passed.

Wyeth Trailhead and Parking Lot

The planned parking lot at the Wyeth Trailhead incorporates a number of planting locations that encompass approximately one acre in area, including a drainage catch basin in the center and nine to twelve distinct planting pockets integrated into the outer curb. This area, more so than any other along the project, is designed with an eye toward more traditional landscape and horticultural practices. RST will work closely with Walker Macy to maintain public safety and line-of-sight while creating multi-seasonal interest.

RST will conduct weed control throughout the area prior to planting, especially near the entrance. There is currently a robust population of Scotch broom growing along Wyeth Road and continuing beyond the ownership boundary to the west. Although it would be ideal to treat the larger surrounding area (approximately four acres) to reduce future Scotch broom re-establishment, funding for this work is not currently available. Therefore, only the area referenced on the project plan sheets will receive treatment; less than one tenth of an acre. Once treated, the open area on the west side of the trailhead entrance will be planted with species that support pollinator-plant interactions (Table 1a). Efforts will be made to maintain visuals of the trailhead sign and entrance while blocking the view of the new vault toilet facility from the traveling public on Wyeth Road.

Contracting responsibility will be coordinated between WFLHD and RST. WFLHD will place 18" of weed-free topsoil or borrow material into all planting areas other than the planting pockets. The RST contactor will be responsible for providing weed-free topsoil to be combined with compost for use in the planting pockets and the two large planting beds on either side of the parking lot entrance. WFLHD will remove the non-native black locust trees currently on site.

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Table 1b depicts tree and shrub species to be incorporated into the parking lot landscape plan. Native trees will be installed in the curb planting pockets and will be approximately 1-2″ caliper and 4-6′ tall.

TABLE 1A. PLANTS TO POTENTIALLY BE USED IN REVEGETATION EFFORTS NEAR THE ENTRANCE TO THE WYETH TRAILHEAD PARKING LOT. 'XX' DENOTES SEEDING RATHER THAN TRANSPLANTING TO BE UTILIZED. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
narrow-leaf milkweed	*Asclepias fascicularis*	A	S, RL10	4"
showy milkweed	*Asclepias speciosa*	A	S, RL10	4"
aster	*Aster spp.*	A	S	XX
mountain brome	*Bromus carinatus*	A	S	XX
Howell's reedgrass	*Calamagrostis howellii*	A	S	XX
Pacific dogwood	*Cornus nuttallii*	B	#1	15'
blue wildrye	*Elymus glaucus* ssp. *glaucus*	A	S	XX
smooth alumroot	*Heuchera glabra*	A	S	4"
lupine	*Lupinus latifolius.*	A	S	4"
creeping Oregon grape	*Mahonia repens*	A	D27	4'
Sandberg's bluegrass	*Poa secunda*	A	S	XX
self heal	*Prunella vulgaris*	A	S	XX
checkermallow	*Sidalcea spp.*	A	RL10	XX
goldenrod	*Solidago canadensis*	A	S	XX
fringecups	*Tellima grandiflora*	A	RL10	4"
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
Pacific dogwood	*Cornus nuttallii*	B	#1	15'
oceanspray	*Holodiscus discolor*	B	D40	8'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
Douglas fir	*Pseudotsuga menziesii*	B	D27, B&B	15'
red flowering currant	*Ribes sanguineum*	B	#1, #5	4'
baldhip rose	*Rosa gymnocarpa*	B	D27, B&B	4'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'
western red cedar	*Thuja plicata*	B	#1, B&B	15'

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TABLE 1B. PLANTS TO BE USED IN THE WYETH TRAILHEAD PARKING LOT, INCLUDING THE DRAINAGE BASIN. 'XX' DENOTES SEEDING RATHER THAN TRANSPLANTING TO BE UTILIZED. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
narrow-leaf milkweed	*Asclepias fascicularis*	A	S, RL10	4"
showy milkweed	*Asclepias speciosa*	A	S, RL10	4"
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
fringecups	*Tellima grandiflora*	A	RL10	4”
grand fir	*Abies grandis*	B	#1, B&B	15’
vine maple	*Acer circinatum*	B	#1, #5	8’
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8’
redosier dogwood	*Cornus sericea* spp. *sericea*	B	D27, D40	8’
Oregon ash	*Fraxinus latifolia*	B	#1, #5	15’
oceanspray	*Holodiscus discolor*	B	D40	8’
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4’
osoberry	*Oemleria cerasiformis*	B	#1, #5	8’
ninebark	*Physocarpus capitatus*	B	#1, #5	8’
Douglas fir	*Pseudotsuga menziesii*	B	D-27, B&B	15’
red flowering currant	*Ribes sanguineum*	B	#1, #5	4’
thimbleberry	*Rubus parviflorus*	B	D27, D40	4’
elderberry	*Sambucus nigra*	B	D27	8’
common snowberry	*Symphoricarpos albus*	B	D27, D40	4’
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'
western red cedar	*Thuja plicata*	B	#1, B&B	15'

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Wyeth Campground Entrance and Gorton Creek Bridge

The trail will cross the existing entrance to the Wyeth Campground and continue toward the east over the newly constructed Gorton Creek Bridge. WFLHD will install a water filling station near the Wyeth Campground entrance, adjacent to the grassy campground overflow area. They will also install a split-railed fence, positioned about halfway between the edge of the planting area and the edge of the trail along the length of the overflow area. At the request of the USFS (Columbia River Gorge National Scenic Area), RST will treat the planting area between the grassy overflow area and the trail with a mix of low growing shrubs, forbs, and clumping grasses. These will be planted sparsely and randomly in order to assimilate the surrounding environment, yet densely enough to provide visual and physical separation between the overflow area and the trail.

RST will install riparian plantings in disturbed ground at and near the new Gorton Creek Bridge. In an effort to maintain adequate water flow yet prevent backup, WFLHD has determined no live staking will occur in the rip-rapped areas. All other construction related areas near the creek will be planted. Table 2 below depicts the suite of species that is available for use in these areas.

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TABLE 2. THE SUITE OF SPECIES AVAILABLE FOR PLANTING AT THE WYETH CAMPGROUND AND GORTON CREEK. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
narrow-leaf milkweed	*Asclepias fascicularis*	A	S, RL10	4"
showy milkweed	*Asclepias speciosa*	A	S, RL10	4"
mountain brome	*Bromus carinatus*	A	S	XX
Howell's reedgrass	*Calamagrostis howellii*	A	S	XX
blue wildrye	*Elymus glaucus* ssp. *glaucus*	A	S	XX
lupine	*Lupinus latifolius*	A	S	4"
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
Sandberg's bluegrass	*Poa secunda*	A	S	XX
licorice fern	*Polypodium glycyrrhiza*	A	Short 4	2'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
goldenrod	*Solidago canadensis*	A	S	XX
fringecups	*Tellima grandiflora*	A	RL10	4"
vine maple	*Acer circinatum*	B	#1, #5	8'
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
redosier dogwood	*Cornus sericea* spp. *sericea*	B	D27, D40	8'
Oregon ash	*Fraxinus latifolia*	B	#1, #5	15'
oceanspray	*Holodiscus discolor*	B	D40	8'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
osoberry	*Oemleria cerasiformis*	B	#1, #5	8'
Douglas fir	*Pseudotsuga menziesii*	B	D27, B&B	15'
thimbleberry	*Rubus parviflorus*	B	D27, D40	4'
elderberry	*Sambucus nigra*	B	D27	8'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'

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Mitigation Site #2

The open area of approximately five acres, less than half a mile east of the Wyeth Trailhead and parking lot, is designated as a mitigation site. Restoration of this area will not only serve as mitigation for impacts incurred as a result of the project, but will also address Section 3 of the 2014 Presidential Memorandum "Creating a Federal Strategy to Promote the Health of Honey Bees and Other Pollinators" which provides directive to increase and improve pollinator habitat. Plant species that provide feeding, nesting, resting, and rearing (e.g., host plant) benefits to pollinating insects will be utilized to support and encourage plant-pollinator interactions. To this end, attention will be paid not only to nectar producing plants but also to plant architecture, the creation of micro-habitats and climates through the use of large and small woody material, depressions to retain moisture, areas of vegetative refuge, patches of bare ground (necessary for some ground nesting pollinator species), as well as other pollinator sustaining habitat characteristics.

Given the location of this project, two pollinator species of conservation concern will be supported explicitly. First, the imperiled western bumble bee (*Bombus occidentalis*) will be supported in this important part of its remaining range by providing a large and diverse resource of nectaring plants. Second, and more specifically, we will create breeding habitat to support the imperiled Monarch butterfly (*Danaus plexippus*). Milkweed is the only known plant genus to serve as host plant for the Monarchs in the lower 48 states. We will incorporate two species of milkweed (*Asclepias fascicularis* and *A. speciosa*) in the plantings at Mitigation Site #2, upon which Monarchs may lay their eggs. Critically, the local area which includes other nearby locations in the Columbia River Gorge, is a known Monarch migration and breeding area with observations of Monarchs close to the project area.

Mitigation Site #2 includes a pump house, a wellhead, and remnants of old buildings including steps, foundations, etc. These artifacts will remain in place, as is. There are also a number of old roads, the majority of which are gravel/crushed aggregate. WFLHD will remove the material from the old road prisms, spread shredded woody material over the entire mitigation site (4-6" deep), and incorporate the material to a depth of at least 18" by either ripping or using an excavator bucket.

Aesthetic augmentation will include the creation of an earthen berm by WFLHD to screen the pump house, and RST will select and install appropriate vegetation to enhance this screening. Topographic sculpting will create terrain variation to mimic existing conditions found elsewhere on the project site. Plants will be installed in the pollinator meadow in random

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groupings with some individual plants interspersed throughout, or broadcast seeded to create a natural appearing end meadow-woodland complex.

Because of the very different light and canopy regimes at the edge of the existing forest that surrounds the meadow, a different suite of species will be utilized in this area than those in the open habitat. There is a desire among the partners involved with this project to leave the area of Mitigation Site #2 somewhat open and create a meadow-like habitat to support the previously discussed pollinator initiatives. As such, plant species installed at this site will include more forbs, low shrubs, and native grasses than trees. It is expected that without regular maintenance the natural seed rain from the surrounding trees will eventually convert the open area into a treed area over time. This will not be facilitated through active revegetation efforts by RST, however.

The species suite to be utilized in pollinator meadow of Mitigation Site #2 will include some or all of the plants in Table 3a below. The mix used for the forested ecotone is reflected in Table 3b.

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TABLE 3A. POTENTIAL PLANTS TO BE USED IN REVEGETATION EFFORTS TO ENHANCE POLLINATOR-PLANT INTERACTIONS AT THE OPEN HABITAT OF MITIGATION SITE #2. 'XX' DENOTES SEEDING RATHER THAN TRANSPLANTING TO BE UTILIZED. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
narrow-leaf milkweed	*Asclepias fascicularis*	A	S, RL10	4"
showy milkweed	*Asclepias speciosa*	A	S, RL10	4"
Aster	*Aster spp.*	A	S	XX
mountain brome	*Bromus carinatus*	A	S	XX
Howell's reedgrass	*Calamagrostis howellii*	A	S	XX
Pacific dogwood	*Cornus nuttallii*	B	#1	15'
blue wildrye	*Elymus glaucus* ssp. *glaucus*	A	S	XX
smooth alumroot	*Heuchera glabra*	A	S	4"
Lupine	*Lupinus latifolius*	A	S	4"
creeping Oregon grape	*Mahonia repens*	A	D27	4'
Sandberg's bluegrass	*Poa secunda*	A	S	XX
self heal	*Prunella vulgaris*	A	S	XX
checkermallow	*Sidalcea spp.*	A	RL10	XX
goldenrod	*Solidago canadensis*	A	S	XX
fringecups	*Tellima grandiflora*	A	RL10	4"
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
Pacific dogwood	*Cornus nuttallii*	B	#1	15'
oceanspray	*Holodiscus discolor*	B	D40	8'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
Douglas fir	*Pseudotsuga menziesii*	B	D27, B&B	15'
red flowering currant	*Ribes sanguineum*	B	#1, #5	4'
baldhip rose	*Rosa gymnocarpa*	B	D27, B&B	4'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'
western red cedar	*Thuja plicata*	B	#1, B&B	15'

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TABLE 3B. PLANTS TO BE UTILIZED AT THE ECOTONE BETWEEN THE EXISTING FORESTED AREA AND THE NEWLY CREATED POLLINATOR MEADOW AT MITIGATION SITE #2. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
licorice fern	*Polypodium glycyrrhiza*	A	Short 4	2'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
grand fir	*Abies grandis*	B	#1, B&B	15'
vine maple	*Acer circinatum*	B	#1, #5	8'
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
Pacific dogwood	*Cornus nuttallii*	B	#1	15'
Oregon ash	*Fraxinus latifolia*	B	#1, #5	15'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
osoberry	*Oemleria cerasiformis*	B	#1, #5	8'
western white pine	*Pinus monticola*	B	D27	15'
Douglas fir	*Pseudotsuga menziesii*	B	D27, B&B	15'
red flowering currant	*Ribes sanguineum*	B	#1, #5	4'
thimbleberry	*Rubus parviflorus*	B	D27, D40	4'
elderberry	*Sambucus nigra*	B	D27	8'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'

Stepped, Plantable MSE Wall

There is a stepped, plantable mechanically stabilized earth (MSE) wall to be constructed from approximately ST 44+05 to ST 63+88. The height of this wall will vary from about 10-30 feet tall and it is planned to be 1,983 linear feet long. WFLHD will place topsoil along the entire base of the wall, burying the first two to three steps and creating a 3:1 slope (H:V). RST will place weed-free topsoil mixed with compost (1:1) over the remaining exposed wall to provide a continuous slope and effectively eliminating the appearance of steps. Shrubs and small trees will be randomly planted at the toe of the slope to provide vegetative screening, as well as sparsely planted along the newly created slope. RST will hydroseed the entire area with hydromulch, grass and forb seed, and tackifier. Irrigation will be an option item should the RST specialist determine it necessary for the survival of the plants. See Table 4 for the suite of potential restoration plants to be used on the plantable MSE wall.

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TABLE 4. PLANT SUITE THAT MIGHT BE UTILIZED FOR VEGETATING THE STEPPED, PLANTABLE MSE WALL. 'XX' DENOTES SEEDING RATHER THAN TRANSPLANTING TO BE UTILIZED. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
mountain brome	*Bromus carinatus*	A	S	XX
blue wildrye	*Elymus glaucus* ssp. *glaucus*	A	S	XX
smooth alumroot	*Heuchera glabra*	A	RL10	4"
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
Sandberg's bluegrass	*Poa secunda*	A	S	XX
licorice fern	*Polypodium glycyrrhiza*	A	Short 4	2'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
fringecups	*Tellima grandiflora*	A	RL10	4"
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
osoberry	*Oemleria cerasiformis*	B	#1, #5	8'
Douglas fir	*Pseudotsuga menziesii*	B	D27, B&B	15'
red flowering currant	*Ribes sanguineum*	B	#1, #5	4'
thimbleberry	*Rubus parviflorus*	B	D27, D40	4'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'

Summit Creek Viaduct

The extensive pedestrian viaduct planned near Summit Creek will present specific challenges to revegetation efforts. The viaduct will cover approximately 0.16 acres and will prevent precipitation and direct sunlight from reaching the surface of the ground below the viaduct deck. Currently there are micro-habitats that have a variety of vegetation growing at the toe slope of rock walls. Soil accumulates at the junction of the rock wall and ground, and precipitation drips down the face of the rock; both contribute to the ability to support plant life. Revegetation efforts will take advantage of similar micro-habitats under the viaduct, utilize shade tolerant plant species, and incorporate organic matter into the soil to aid in

REVEGETATION PLAN

moisture retention. The primary contractor will place topsoil conserved from the project at the viaduct footings to bring the soil up to existing native soil depths and provide planting medium. Please refer to Table 5 for candidate species for planting near the Summit Creek Viaduct.

TABLE 5. PLANTS POTENTIALLY TO BE USED IN REVEGETATION EFFORTS AT THE SUMMIT CREEK VIADUCT. 'XX' DENOTES SEEDING RATHER THAN TRANSPLANTING TO BE UTILIZED. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
smooth alumroot	*Heuchera glabra*	A	RL10	4"
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
licorice fern	*Polypodium glycyrrhiza*	A	Short 4	2'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
fringecups	*Tellima grandiflora*	A	RL10	4"
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
redosier dogwood	*Cornus sericea spp. sericea*	B	D27, D40	8'
oceanspray	*Holodiscus discolor*	B	D40	8'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
osoberry	*Oemleria cerasiformis*	B	#1, #5	8'
baldhip rose	*Rosa gymnocarpa*	B	D27, D40	4'
thimbleberry	*Rubus parviflorus*	B	D27, D40	4'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'

HCRHST Embankments (Cuts and Fills) and Planned Idle Spots

In coordination with WFLHD, RST will provide the primary contractor with a native grass and forb seed mix to use on exposed trail embankments during and post construction as a part of erosion control measures. RST will install native plants (Table 6) throughout the construction limits once construction activity ceases. Due to the effort to create a natural appearing setting, native shrubs and forbs will be planted in groupings, spread at varying intervals, and in a mix of species. Some areas, such as near Shell Rock Mountain and the new idle spots might not require any plant installation other than seed for erosion control efforts. The planting plans

REVEGETATION PLAN

from Walker Macy will be referenced to maintain line-of-site and safety, utilizing shorter plants directly adjacent to the trail and creating a natural appearing visual experience.

Slopes of greater than average length or slope (1:2) will receive a mulch application of weed-free compost or shredded woody material, applied to a depth of 1-2 inches, and a final grass seed application. The addition of mulch and final seeding will assist to preserve slope integrity, decrease weed recruitment and establishment, and facilitate moisture retention. Practices that increase soil compaction are best avoided and it is ideal that slopes be left in a roughened condition (i.e., use a toothed rock bucket rather than smoothing bucket, avoid back blading, etc.).

TABLE 6. POTENTIAL PLANT SPECIES TO BE UTILIZED ON CUT/FILL SLOPES AND PLANNED IDLE SPOTS OF HISTORIC COLUMBIA RIVER HIGHWAY STATE TRAIL. 'XX' DENOTES SEEDING RATHER THAN TRANSPLANTING TO BE UTILIZED. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
mountain brome	*Bromus carinatus*	A	S	XX
Howell's reedgrass	*Calamagrostis howellii*	A	S	XX
blue wildrye	*Elymus glaucus* ssp. *glaucus*	A	S	XX
lupine	*Lupinus latifolius*	A	S	4"
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
Sandberg's bluegrass	*Poa secunda*	A	S	XX
licorice fern	*Polypodium glycyrrhiza*	A	Short 4	2'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
self heal	*Prunella vulgaris*	A	S	XX
fringecups	*Tellima grandiflora*	A	RL10	4"
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
baldhip rose	*Rosa gymnocarpa*	B	D27, D40	4'
thimbleberry	*Rubus parviflorus*	B	D27, D40	4'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'

REVEGETATION PLAN

Staging Area(s)

The potential suite of plant species for restoration of staging areas is diverse. The staging area(s) can encompass a variety of environments with differing light regimes, infiltration rates, and habitats. Other than weed control, most revegetation efforts will be delayed until after staging equipment and material are removed by WFLHD. Table 7 shows the species that may be used in revegetation efforts of staging areas.

Table 7. Proposed revegetation species for Staging Area(s) utilized. 'XX' denotes seeding rather than transplanting to be utilized. Stock type definitions are as follow: 'S' Seed; 'RL10' 10 cubic inch container volume; 'D27' 27 cubic inch container volume; 'D40' 40 cubic inch container volume; '#1' one gallon container; '#5' five gallon container; 'B&B' balled and burlapped.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
mountain brome	*Bromus carinatus*	A	S	XX
Howell's reedgrass	*Calamagrostis howellii*	A	S	XX
blue wildrye	*Elymus glaucus* ssp. *glaucus*	A	S	XX
lupine	*Lupinus latifolius*	A	S	4"
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
Sandberg's bluegrass	*Poa secunda*	A	S	XX
licorice fern	*Polypodium glycyrrhiza*	A	Short 4	2'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
goldenrod	*Solidago canadensis*	A	S	XX
fringecups	*Tellima grandiflora*	A	RL10	4"
grand fir	*Abies grandis*	B	#1, B&B	15'
vine maple	*Acer circinatum*	B	#1, #5	8'
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
Pacific dogwood	*Cornus nuttallii*	B	#1	15'
redosier dogwood	*Cornus sericea* spp. *sericea*	B	D27, D40	8'
Oregon ash	*Fraxinus latifolia*	B	#1, #5	15'
oceanspray	*Holodiscus discolor*	B	D40	8'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
osoberry	*Oemleria cerasiformis*	B	#1, #5	8'
Douglas fir	*Pseudotsuga menziesii*	B	D27, B&B	15'
red flowering currant	*Ribes sanguineum*	B	#1, #5	4'
thimbleberry	*Rubus parviflorus*	B	D27, D40	4'
elderberry	*Sambucus nigra*	B	D27	8'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'
western red cedar	*Thuja plicata*	B	#1, B&B	15'

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NON-NATIVE PLANT CONTROL

Non-Native Plant Control

Weed Control Plan

All Oregon Noxious Class 'A' and 'B' weeds will be treated within the construction limits (Appendix Three). The one exception to this is herb Robert (*Geranium robertianum*) which will not be targeted for treatment, as determined during site visits with WFLHD, ODOT, CH2M, CRGNSA, and RST. Of the targeted Class A and B species the following Class B species have been noted within Segments A-C: Canada thistle (*Cirsium arvense*), English ivy, Himalayan blackberry, Scotch broom, perennial peavine (*Lathyrus latifolius*), and St. Johnswort (*Hypericum perforatum*). Although not listed by the State, periwinkle (*Vinca minor*) will also be targeted for control, as will other species that appear to impede restoration efforts. Table 8 provides an estimated schedule of non-native plant treatment.

Only approved herbicides and surfactants will be used and all aquatic setbacks adhered to. Personnel from partnering agencies including the Mt. Hood National Forest, Columbia River Gorge National Scenic Area, Oregon Parks and Recreation Department, and Oregon Department of Transportation will be consulted regarding permissible herbicides and surfactants.

Himalayan blackberry

Himalayan blackberry will be sprayed with glyphosate or triclopyr + surfactant from a backpack sprayer or an ATV. In the area of Mitigation Site #2 the plants will then mowed no sooner than 3 weeks after the first spray treatment, allowed to re-sprout, and chemically treated again. The area with the greatest concentration of Himalayan blackberry is Mitigation Site #2, but the plants do occur throughout the segments. RST will chemically treat these populations where they occur, but most likely will not utilize mowing.

Scotch Broom

Scotch broom populations are most robust at the Wyeth Trailhead/parking lot and at Mitigation Site #2. There are plants scattered throughout other areas of segments A-C, as well as along Wyeth Road near the proposed Wyeth Trailhead and parking lot. Treatments should include these plants that are in close proximity along Wyeth Road to prevent immediate recolonization of Wyeth parking lot. Plants less than three feet in length will receive herbicide treatment and left in place; those greater than three feet in length will be wrenched out, including as much root as is possible, and removed from the project site.

Additional weeds

In addition to the above, periwinkle has been observed scattered throughout segments A-C. Populations of these plants will be treated at the same time as the others previously discussed. Periwinkle will be sprayed with either glyphosate or triclopyr.

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MONITORING PLAN

Monitoring Plan

The agreed upon parameters to evaluate native plant revegetative success for this project are percent cover and plant stem density (Table 8). Because of this, monitoring will be conducted at 1/100th acre plots distributed randomly throughout the project area. In an effort to ascertain unbiased data the plots will not be fixed and will occur in different locations from year to year. A minimum of ten (10) plots will be analyzed within the boundaries of Mitigation Site #2 and ten (10) additional plots will be randomly distributed throughout the project area. Native species cover and stem density will be recorded within each plot, as well as other variables.

Noxious weed success criteria is total percent cover. Prior to construction RST will conduct ocular estimation of non-native plant cover within Mitigation Site #2 and repeat annually. Percent cover of each non-native species will be noted within each plot described above; at Mitigation Site #2 as well as throughout the project area. Refer to Table 9 for an estimated monitoring timeline and Table 10 for overall costs associated with this project.

In addition to native and non-native plants, monitoring protocol for pollinating insects will be conducted at the newly created pollinator meadow of Mitigation Site #2. Of particular interest are native bees and Monarch butterflies. The streamlined bee monitoring procedure developed by the Xerces Society will be utilized twice per year after plant establishment. During the surveys all pollinators observed will be noted including wasps, flies, honey bees, native bees, Monarch butterflies, other butterflies, moths, ants, etc.

SUCCESS CRITERIA

Success Criteria

TABLE 8. CRITERIA UPON WHICH NATIVE AND NON-NATIVE PLANT SUCCESS WILL BE MEASURED.

Item	Benchmark	Timeframe	Notes
Noxious weed control	≤ 20% cover	By year 3	Oregon Noxious Weed List A and B
Noxious weed control	≤ 10% cover	By year 5	Oregon Noxious Weed List A and B
Planting density	≥ 400 woody stems per acre	By year 5	
Native plant percent cover	≥ 20% cover	By year 1	
Native plant percent cover	≥ 40% cover	By year 3	
Native plant percent cover	≥ 80% cover	By year 5	
Native plant diversity	≥ 5 woody species comprise ≥ 5% total cover	By year 5	
If performance standards not met	Use of adaptive management practices	As early as detected	May include replanting, reseeding, noxious weed removal, improvement of soil quality, irrigation, mulch.

APPROXIMATE TIMELINE & BUDGET

Approximate Timeline & Budget

TABLE 9. THE FOLLOWING TABLE DEPICTS THE ESTIMATED TIMELINE OF REVEGETATION EFFORTS PLANNED BY RST WITHIN SEGMENTS A-C OF THE HISTORIC COLUMBIA RIVER HIGHWAY STATE TRAIL.

Task	2016				2017				2018				2019				2020				2021			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Weed treatment																								
Collect plant propagules																								
Grow-out plant propagules																								
Install plants (as ready)																								
Monitor non-native plants																								
Monitor native plants																								
Monitor pollinator species																								

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APPENDIX ONE

Appendix One- Plant Species Suite

POTENTIAL SUITE OF PLANT SPECIES TO BE USED IN REVEGETATION EFFORTS OF SEGMENTS A-C OF HCRHST. STOCK TYPE DEFINITIONS ARE AS FOLLOW: 'S' SEED; 'RL10' 10 CUBIC INCH CONTAINER VOLUME; 'D27' 27 CUBIC INCH CONTAINER VOLUME; 'D40' 40 CUBIC INCH CONTAINER VOLUME; '#1' ONE GALLON CONTAINER; '#5' FIVE GALLON CONTAINER; 'B&B' BALLED AND BURLAPPED.

Common	Botanical	Zone	Stock Type	Spacing (on center)
common yarrow	*Achillea millefolium* var. *occidentalis*	A	S	XX
pearly everlasting	*Anaphalis margaritacea*	A	S	XX
narrow-leaf milkweed	*Asclepias fascicularis*	A	S, RL10	4"
showy milkweed	*Asclepias speciosa*	A	S, RL10	4"
Aster	*Aster spp.*	A	S	XX
mountain brome	*Bromus carinatus*	A	S	XX
Howell's reedgrass	*Calamagrostis howellii*	A	S	XX
blue wildrye	*Elymus glaucus* ssp. *glaucus*	A	S	XX
smooth alumroot	*Heuchera glabra*	A	RL10	4"
Lupine	*Lupinus latifolius*	A	S	4"
creeping Oregon grape	*Mahonia repens*	A	D27, D40	4'
Sandberg's bluegrass	*Poa secunda*	A	S	XX
licorice fern	*Polypodium glycyrrhiza*	A	Short 4	2'
western sword fern	*Polystichum munitum*	A	Short 4, #1	4'
self heal	*Prunella vulgaris*	A	S	XX
checkermallow	*Sidalcea spp.*	A	S	XX
goldenrod	*Solidago canadensis*	A	S	XX
fringecups	*Tellima grandiflora*	A	RL10	4"
grand fir	*Abies grandis*	B	#1, B&B	15'
vine maple	*Acer circinatum*	B	#1, #5	8'
western serviceberry	*Amelanchier alnifolia*	B	#1, #5	8'
Pacific dogwood	*Cornus nuttallii*	B	#1	15'
redosier dogwood	*Cornus sericea spp. sericea*	B	D27, D40	8'
Oregon ash	*Fraxinus latifolia*	B	#1, #5	15'
oceanspray	*Holodiscus discolor*	B	D40	8'
Oregon grape	*Mahonia aquifolium*	B	D27, D40	4'
osoberry	*Oemleria cerasiformis*	B	#1, #5	8'
ninebark	*Physocarpus capitatus*	B	#1, #5	8'
western white pine	*Pinus monticola*	B	D27	15'
Douglas fir	*Pseudotsuga menziesii*	B	D27, B&B	15'
red flowering currant	*Ribes sanguineum*	B	#1, #5	4'
baldhip rose	*Rosa gymnocarpa*	B	D27, D40	4'
thimbleberry	*Rubus parviflorus*	B	D27, D40	4'
elderberry	*Sambucus nigra*	B	D27	8'
common snowberry	*Symphoricarpos albus*	B	D27, D40	4'
trailing snowberry	*Symphoricarpos mollis*	B	D27, D40	4'
western red cedar	*Thuja plicata*	B	#1, B&B	15'

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APPENDIX TWO

Appendix Two- Walker Macy Planting Plans

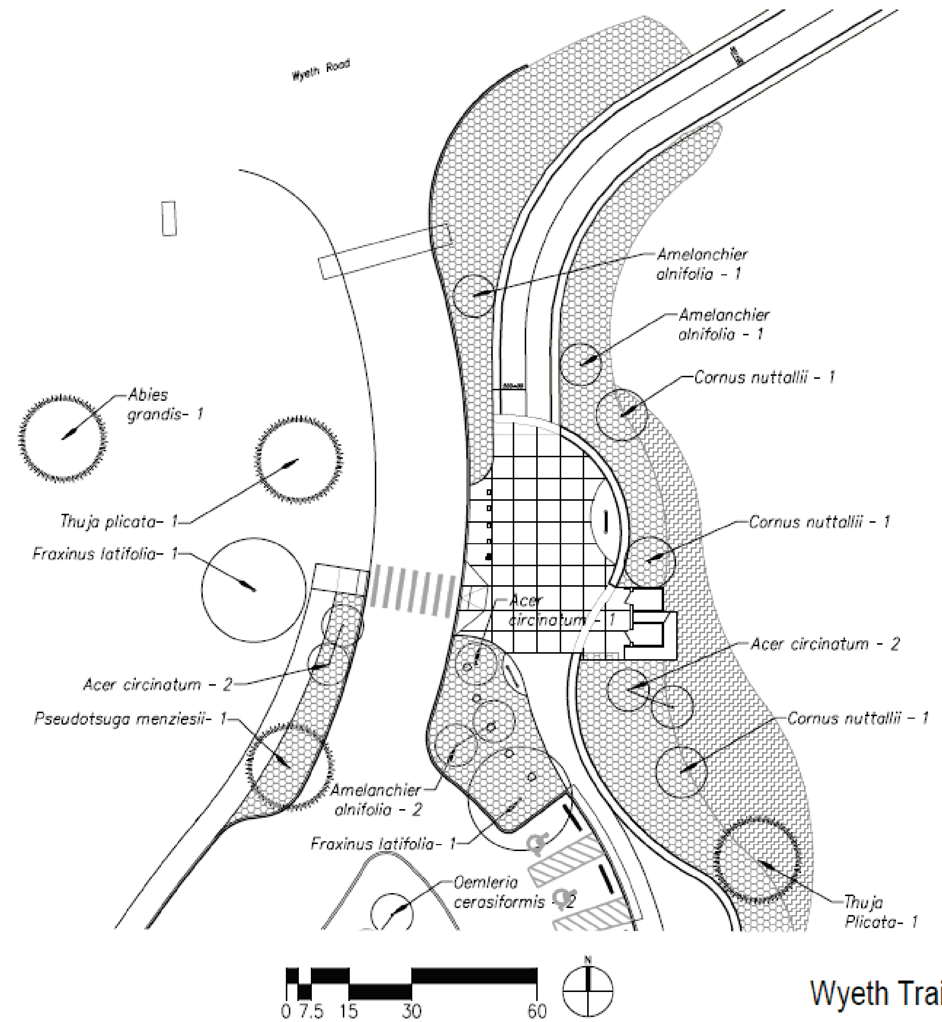
PLANT SCHEDULE

	BOTANICAL NAME	COMMON NAME	SIZE/CONDITION	SPACING	COMMENTS
	TREES EVERGREEN				
	Abies grandis	grand fir	5–6 ft.	15 ft. O.C.	Min. 3 ea. per cluster or as shown
	Pseudotsuga menziesii	Douglas fir	5–6 ft.	15 ft. O.C.	Min. 4 ea. per cluster or as shown
	Thuja plicata	Western red cedar	5–6 ft.	20 ft. O.C.	Min. 3 ea. per cluster or as shown
	TREES DECIDUOUS				
	Acer circinatum	vine maple	5–6 ft.	6 ft. O.C.	Min. 3 ea. per cluster or as shown; Multi trunk
	Amelanchier alnifolia	Western serviceberry	3–4 ft.	6 ft. O.C.	Min. 3 ea. per cluster or as shown; Multi trunk
	Cornus nuttallii	Pacific dogwood	5–6 ft.	12 ft. O.C.	Min. 3 ea. per cluster or as shown;
	Oemleria cerasiformis	osoberry	3–4 ft.	6 ft. O.C.	Min. 3 ea. per cluster or as shown; Multi trunk
	Fraxinus latifolia	Oregon ash	1" Cal.	15 ft. O.C.	Min. 3 ea. per cluster or as shown
	SHRUBS				
	Cornus sericea spp. sericea	redosier dogwood	#2	4 ft. O.C.	As shown
	Physocarpus capitatus	ninebark	4–5 ft.	6 ft. O.C.	As shown
	Rubus parviflorus	thimbleberry	#2	30" O.C	As shown
	Sambucus nigra	elderberry	#2	8 ft O.C	As shown
	Symphoricarpos albus	common snowberry	#2	30" O.C.	As shown
	mixture of forbs				Min. 5 ea. per species cluster
	SHRUBS ZONE A				
	Mahonia repens	creeping Oregon grape	#2	24" O.C.	Min. 12 ea. per cluster
	Polystichum munitum	Western sword fern	#2	30" O.C.	Min. 9 ea. per cluster
	Symphoricarpos mollis	creeping snowberry	#1	30" O.C.	Min. 5 ea. per cluster
	mixture of forbs				Min. 5 ea. per species cluster
	SHRUBS ZONE B				
	Mahonia repens	creeping Oregon grape	#2	36" O.C.	Min. 7 ea. per cluster
	Rosa gymnocarpa	baldhip rose	#1	36" O.C.	Min. 5 ea. per cluster
	Polystichum munitum	Western sword fern	#2	30" O.C.	Min. 5 ea. per cluster
	Rubus parviflorus	thimbleberry	#1	30" O.C.	Min. 5 ea. per cluster
	Symphorocarpus mollis	creeping snowberry	#1	36" O.C.	Min. 5 ea. per cluster
	Ribes sanguineum	red flowering currant	#2	48" O.C.	Min. 3 ea. per cluster
	Physocarpus capitatus	ninebark	#2	48" O.C.	Min. 3 ea. per cluster
	Holodiscus discolor	oceanspray	#2	60" O.C.	Min. 1 ea. per cluster
	mixture of forbs				Min. 5 ea. per species cluster

PLANTING NOTES

1. Plant Zone B plants no less than 10 feet from the outside edge of pedestrian trails.
2. Shrubs to be planted within limit of disturbance or as shown.
3. In exposed clearings, plant clusters of deciduous trees in quantities and spacing as shown on plant legend.
4. Maintain clear line of sight from new trailheads to primary pedestrian trails whenever possible.
5. Shrubs and trees are to be planted no closer than ½ of their on–center spacing from outside edge of pedestrian trail or trailhead.

APPENDIX TWO



Wyeth Trailhead

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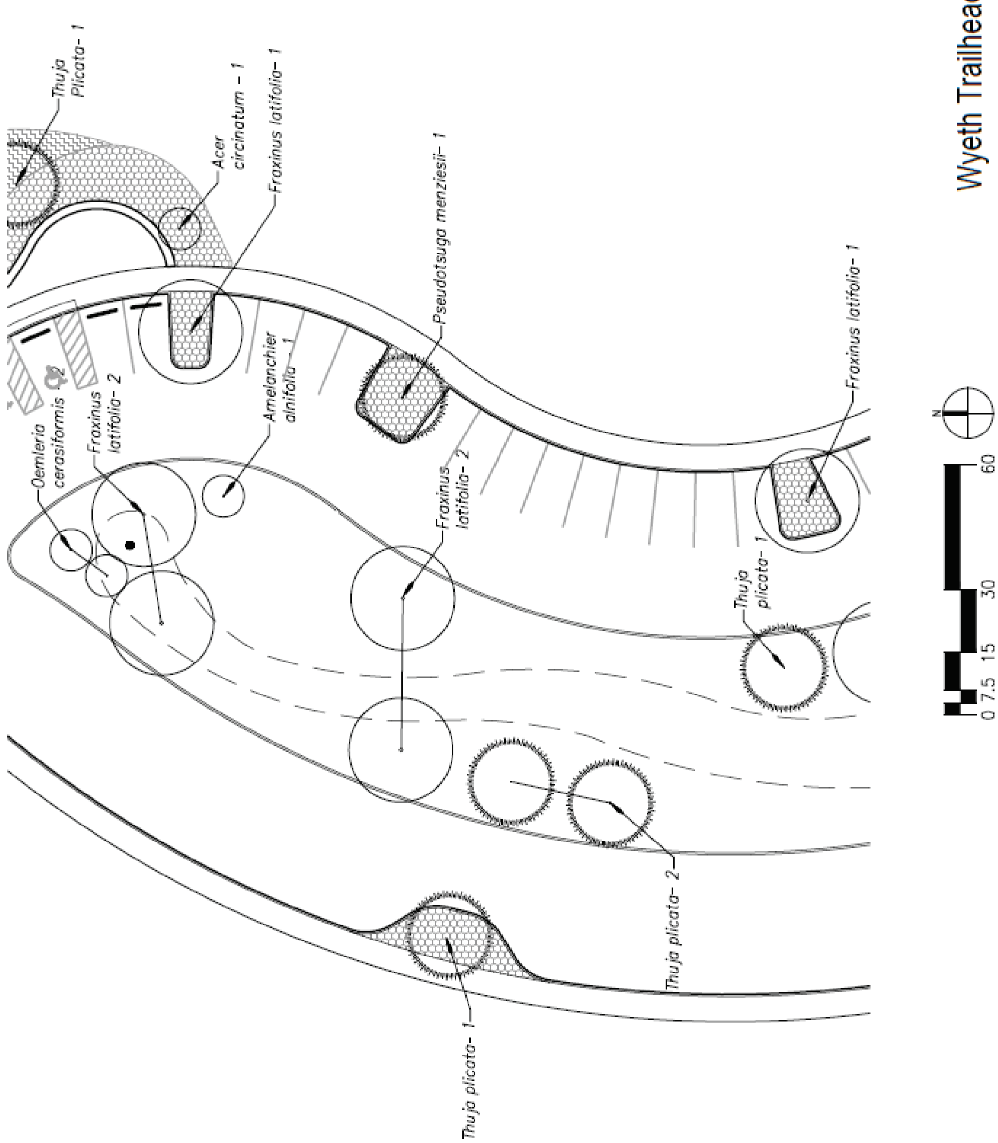

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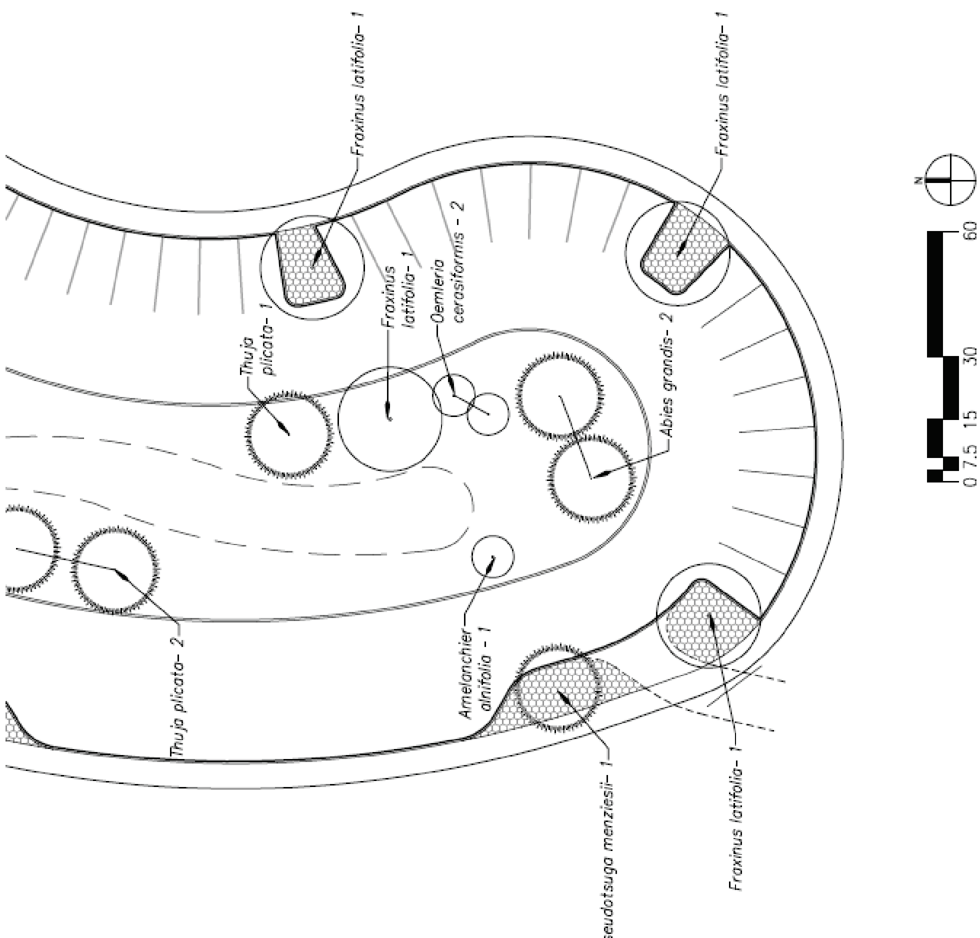

Wyeth Trailhead

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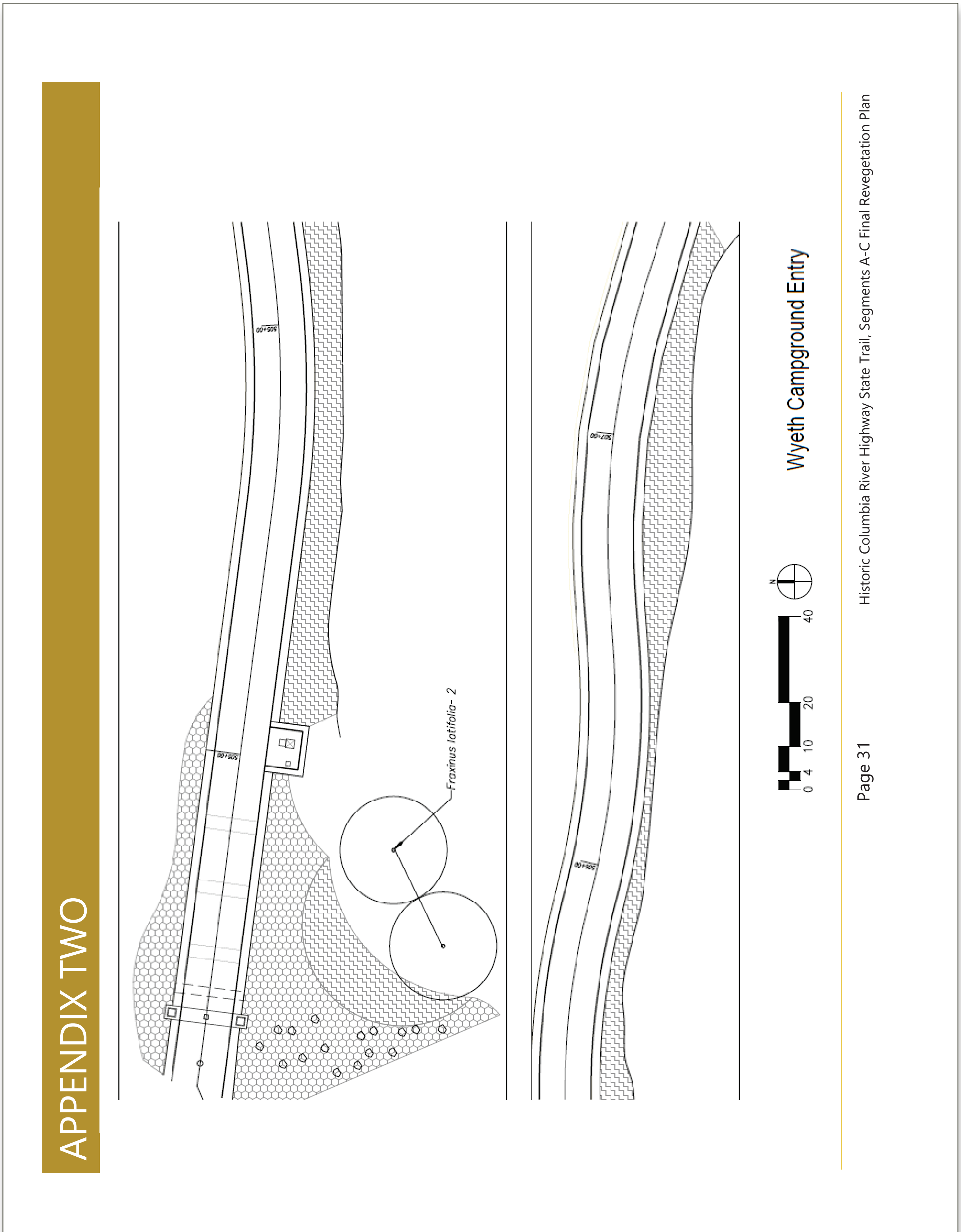
APPENDIX TWO
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Wyeth Campground Entry
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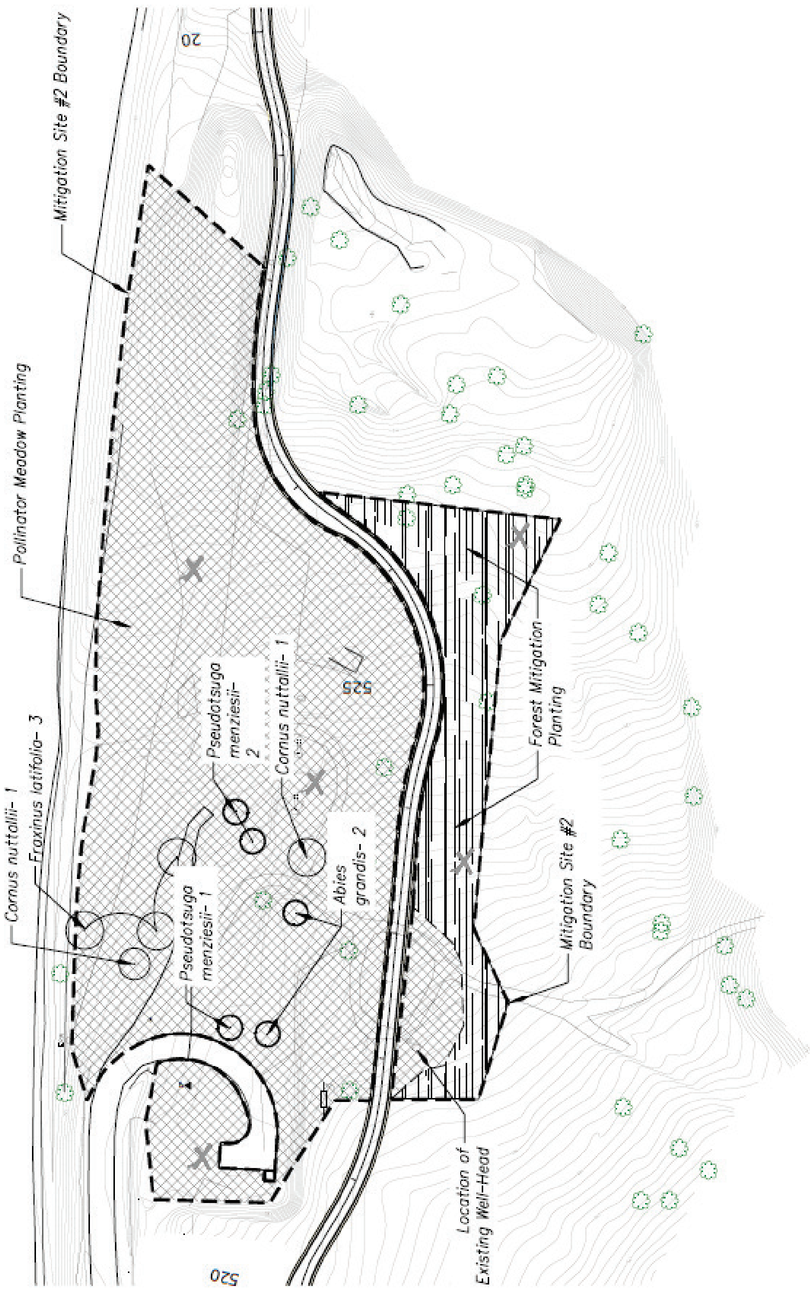

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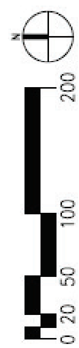

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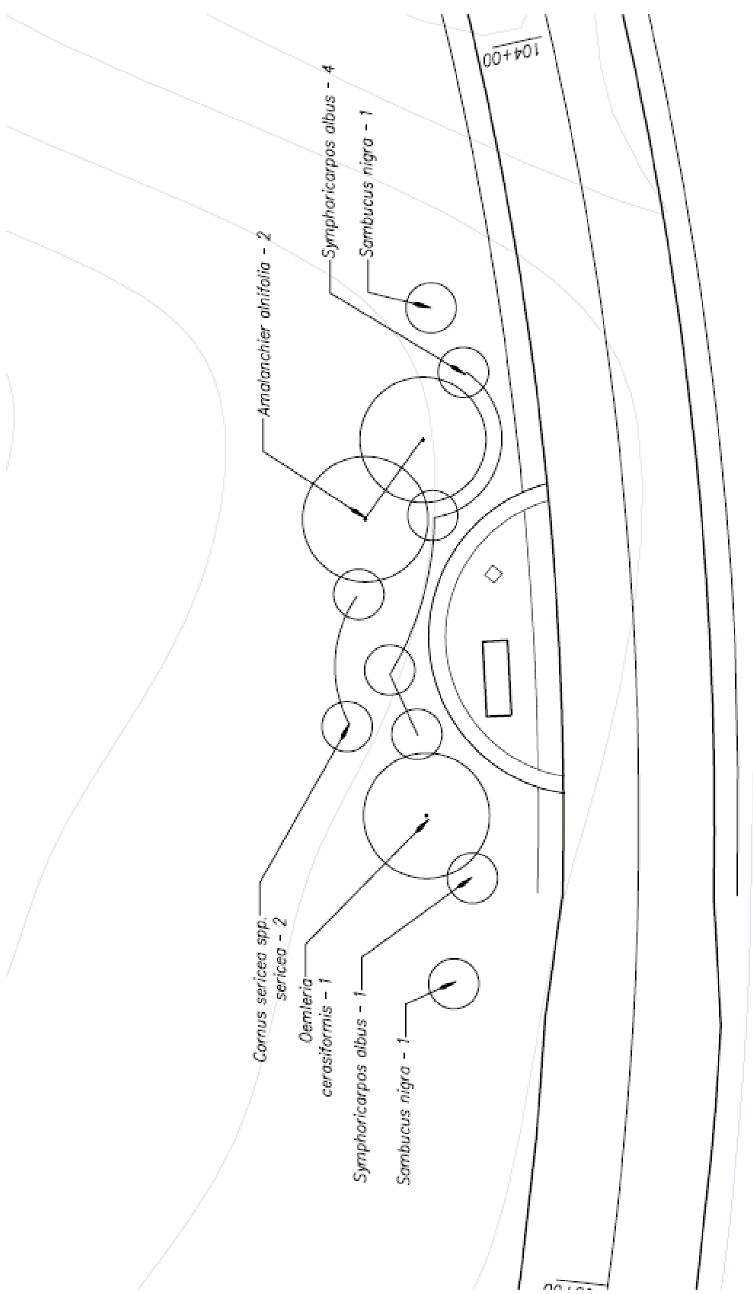

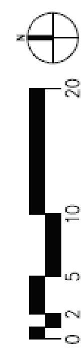

Pull-off Near Memorial Plaque

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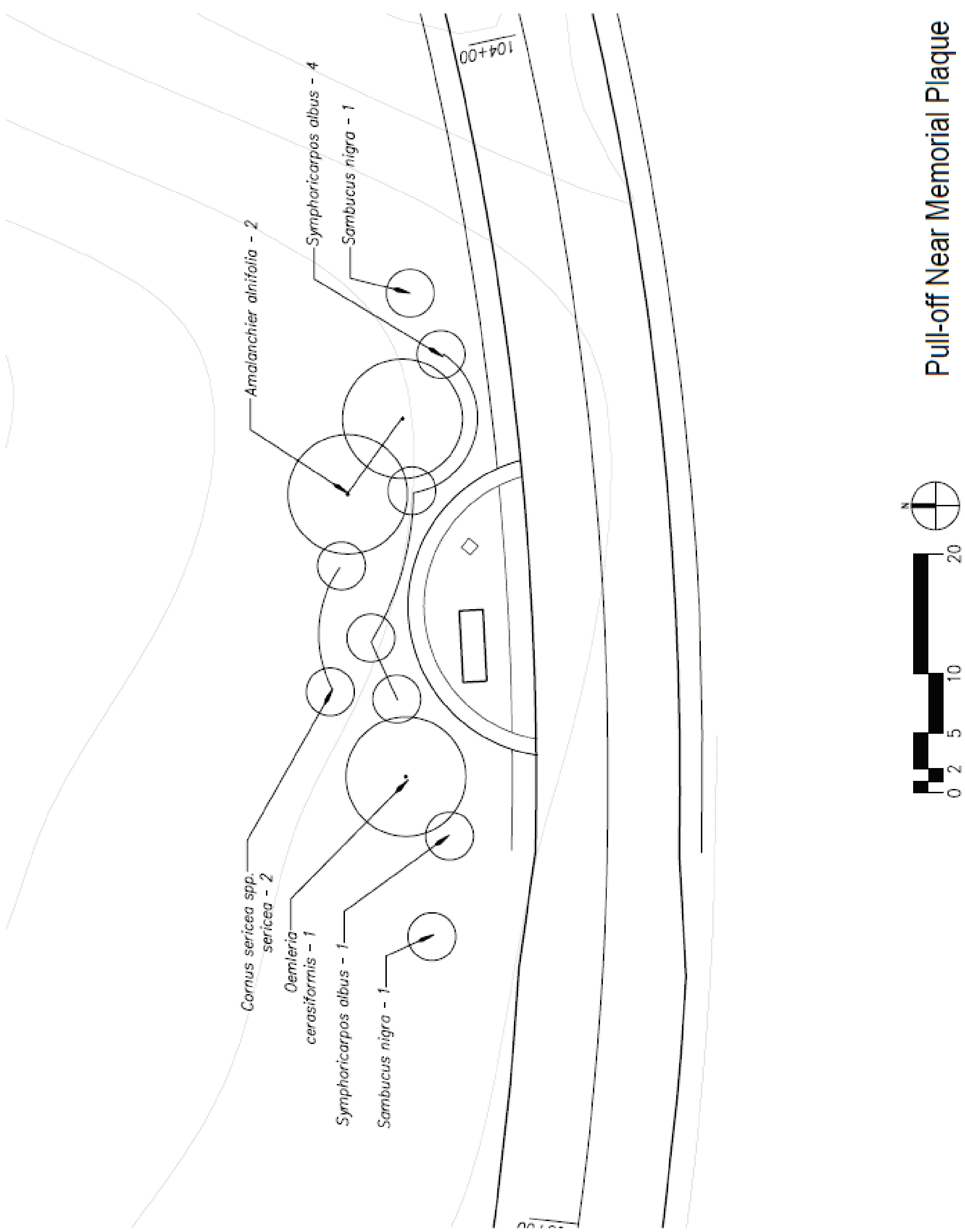

Pull-off Near Memorial Plaque

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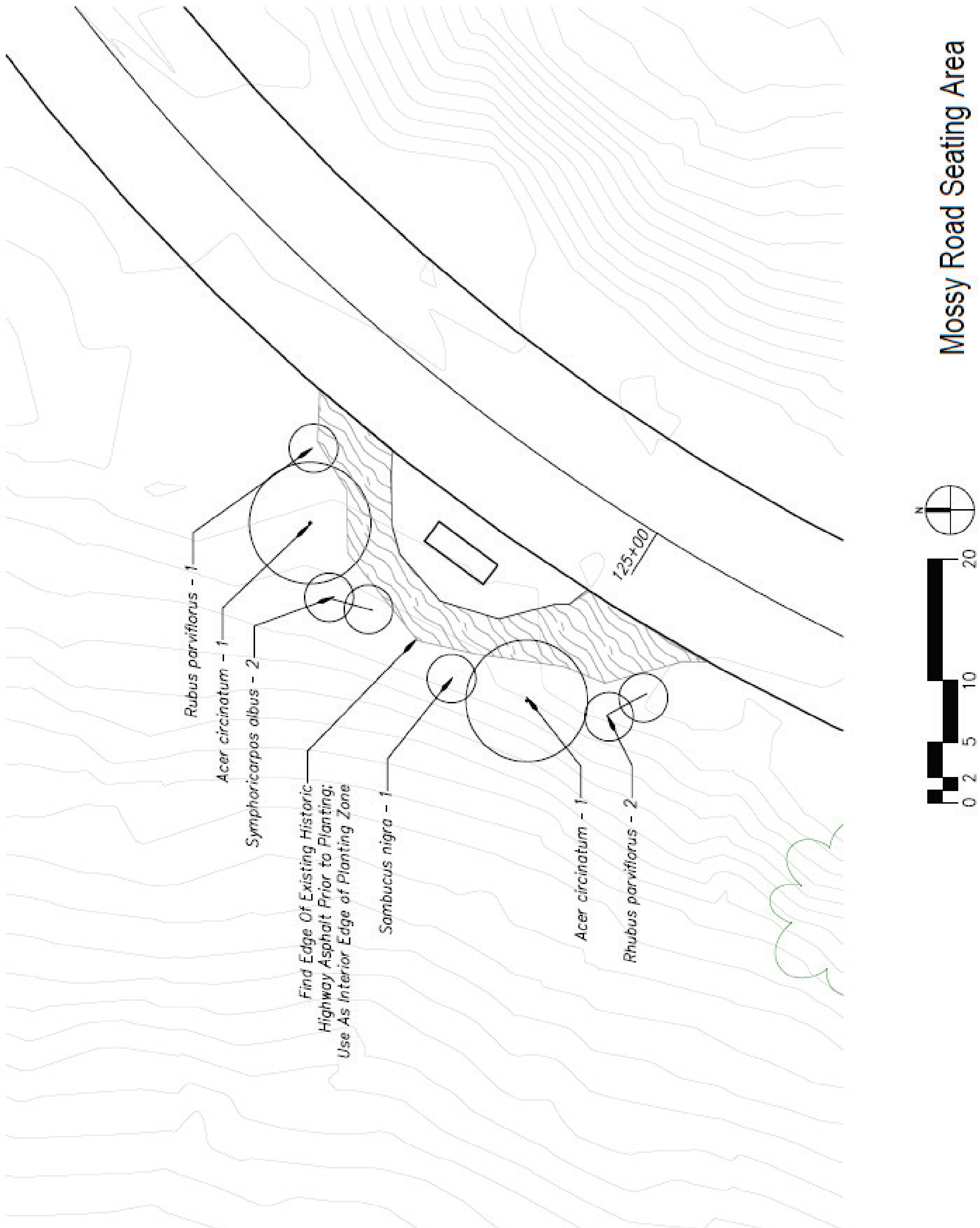

Mossy Road Seating Area

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APPENDIX THREE

Appendix Three- Oregon Noxious Weed List

Table I: A Listed weeds

Common name	Scientific name
African rue (T)	*Peganum harmala*
Cape-ivy	*Delairea odorata*
Camelthorn	*Alhagi pseudalhagi*
Coltsfoot	*Tussilago farfara*
Cordgrass	
Common (T)	*Spartina anglica*
Dense-flowered (T)	*Spartina densiflora*
Saltmeadow (T)	*Spartina patens*
Smooth (T)	*Spartina alterniflora*
Common frogbit	*Hydrocharis morsus-ranae*
European water chestnut	*Trapa natans*
Flowering rush (T)	*Butomus umbellatus*
Garden yellow loosestrife	*Lysimachia vulgaris*
Giant hogweed (T)	*Heracleum mantegazzianum*
Goatgrass	
Barbed (T)	*Aegilops triuncialis*
Ovate	*Aegilops ovata*
Goatsrue (T)	*Galega officinalis*
Hawkweed	
King-devil	*Pilosella piloselloides (Hieracium)*
Mouse-ear (T)	*Pilosella pilosella (Hieracium)*
Orange (T)	*Pilosella aurantiacum (Hieracium)*
Yellow (T)	*Pilosella floribundum (Hieracium)*
Hoary alyssum (T)	*Berteroa incana*
Hydrilla	*Hydrilla verticillata*
Japanese dodder	*Cuscuta japonica*
Kudzu (T)	*Pueraria lobata*
Matgrass (T)	*Nardus stricta*
Oblong spurge (T)	*Euphorbia oblongata*
Paterson's curse (T)	*Echium plantagineum*
Purple nutsedge	*Cyperus rotundus*
Ravennagrass	*Saccharum ravennae*
Silverleaf nightshade	*Solanum elaeagnifolium*
West Indian spongeplant	*Limnobium laevigatum*
Squarrose knapweed (T)	*Centaurea virgata*
Starthistle	
Iberian (T)	*Centaurea iberica*
Purple (T)	*Centaurea calcitrapa*
Syrian bean-caper	*Zygophyllum fabago*
Thistle	
Plumeless (T)	*Carduus acanthoides*
Smooth distaff	*Carthamus baeticus*
Taurian (T)	*Onopordum tauricum*
Woolly distaff (T)	*Carthamus lanatus*
Water soldiers	*Stratiotes aloides*
White bryonia	*Bryonia alba*
Yellow floating heart (T)	*Nymphoides peltata*
Yellowtuft (T)	*Alyssum murale, A. corsicum*

* Indicates weeds targeted for biocontrol (T) T designated species

APPENDIX THREE

Table II: B listed weeds

Common name	Scientific name
Armenian (Himalayan) blackberry	*Rubus armeniacus (R. procerus, R. discolor)*
Biddy-biddy	*Acaena novae-zelandiae*
Broom	
French*	*Genista monspessulana*
Portuguese (T)	*Cytisus striatus*
Scotch*	*Cytisus scoparius*
Spanish	*Spartium junceum*
Buffalobur	*Solanum rostratum*
Butterfly bush	*Buddleja davidii (B. variabilis)*
Common bugloss (T)	*Anchusa officinalis*
Common crupina	*Crupina vulgaris*
Common reed	*Phragmities australis*
Creeping yellow cress	*Rorippa sylvestris*
Cutleaf teasel	*Dipsacus laciniatus*
Dodder	*Cuscuta* spp.
Dyer's woad	*Isatis tinctoria*
English ivy	*Hedera helix (H. hibernica)*
Eurasian watermilfoil	*Myriophyllum spicatum*
False brome	*Brachypodium sylvaticum*
Field bindweed* (T)	*Convolvulus arvensis*
Garlic mustard (T)	*Alliaria petiolata*
Geranium	
Herb Robert	*Geranium robertianum*
Shiny leaf geranium	*Geranium lucidum*
Gorse* (T)	*Ulex europaeus*
Halogeton	*Halogeton glomeratus*
Houndstongue	*Cynoglossum officinale*
Indigo bush	*Amorpha fruticosa*
Johnsongrass	*Sorghum halepense*
Jointed goatgrass	*Aegilops cylindrica*
Jubata grass	*Cortaderia jubata*
Knapweeds	
Diffuse*	*Centaurea diffusa*
Meadow*	*Centaurea pratensis*
Russian*	*Acroptilon repens*
Spotted* (T)	*Centaurea stoebe (C. maculosa)*
Knotweeds	
Giant	*Fallopia sachalinensis (Polygonum)*
Himalayan	*Polygonum polystachyum*
Japanese	*Fallopia japonica (Polygonum)*
Kochia	*Kochia scoparia*
Lesser celandine	*Ranunculus ficaria*
Meadow hawkweed (T)	*Pilosella caespitosum (Hieracium)*
Mediterranean sage	*Salvia aethiopis*
Medusahead rye	*Taeniatherum caput-medusae*

* Indicates weeds targeted for biocontrol (T) T designated species

APPENDIX THREE

Continuation of B listed weeds	
Old man's beard	*Clematis vitalba*
Parrot feather	*Myriophyllum aquaticum*
Perennial peavine	*Lathyrus latifolius*
Perennial pepperweed (T)	*Lepidium latifolium*
Pheasant's eye	*Adonis aestivalis*
Poison hemlock	*Conium maculatum*
Policeman's helmet	*Impatiens glandulifera*
Puncturevine*	*Tribulus terrestris*
Purple loosestrife*	*Lythrum salicaria*
Ragweed	*Ambrosia artemisiifolia*
Ribbongrass (T)	*Phalaris arundinacea var. Picta*
Rush skeletonweed* (T)	*Chondrilla juncea*
Saltcedar* (T)	*Tamarix ramosissima*
Small broomrape	*Orabanche minor*
South American waterweed	*Egeria densa (Elodea)*
Spanish heath	*Erica lusitanica*
Spikeweed	*Hemizonia pungens*
Spiny cocklebur	*Xanthium spinosum*
Spurge laurel	*Daphne laureola*
Spurge	
Leafy* (T)	*Euphorbia esula*
Myrtle	*Euphorbia myrsinites*
St. Johnswort*	*Hypericum perforatum*
Sulfur cinquefoil	*Potentilla recta*
Swainsonpea	*Sphaerophysa salsula*
Tansy ragwort* (T)	*Senecio jacobaea (Jacobaea vulgaris)*
Thistles	
Bull*	*Cirsium vulgare*
Canada*	*Cirsium arvense*
Italian	*Carduus pycnocephalus*
Milk*	*Silybum marianum*
Musk*	*Carduus nutans*
Scotch	*Onopordum acanthium*
Slender-flowered*	*Carduus tenuiflorus*
Toadflax	
Dalmatian* (T)	*Linaria dalmatica*
Yellow*	*Linaria vulgaris*
Tree of heaven	*Ailanthus altissima*
Velvetleaf	*Abutilon theophrasti*
Water primrose, floating primrose-willow, large-flower primrose willow (T)	*Ludwigia peploides, L. hexapetala, L. grandiflora*
Whitetop	
Hairy	*Lepidium pubescens*
Lens-podded	*Lepidium chalepensis*
Whitetop (hoary cress)	*Lepidium draba*

* Indicates weeds targeted for biocontrol (T) T designated species

Continuation of B listed weeds	
Yellow archangel	*Lamiastrum galeobdolon*
Yellow flag iris	*Iris pseudacorus*
Yellow nutsedge	*Cyperus esculentus*
Yellow starthistle*	*Centaurea solstitialis*

* Indicates weeds targeted for biocontrol (T) T designated species

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REFERENCES

References

The following resources were not cited directly, but were referenced in the development of this document.

Bennett, Max. 2007. Managing Himalayan blackberry in western Oregon riparian areas. Oregon State University Extension Service, Oregon State University. Corvallis, Oregon.

Bergerson, Terry. 2012. Visitor survey of day-use visitors at Starvation Creek State Park. Oregon Parks and Recreation Department.

Biggerstaff, Matthew and Christopher Beck. 2007. Effects of method of English ivy removal and seed addition on regeneration of vegetation in a southeastern Piedmont forest. The American Midland Naturalist 158: 206-220.

Binelli, Eliana K., Gholz, Henry L., and Mary L. Duryea. 2000. Chapter 4: Plant succession and disturbances in the urban forest ecosystem. *In*: Restoring the urban forest ecosystem. The School of Forest Resources and Conservation, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida.

CH2MHill, Inc. 2014. Wetlands/Waters delineation report, Historic Columbia River Highway State Trail Segments A-D. Columbia River Gorge National Scenic Area Task Order No. T-13-001, Modification 004, Task 3.8 Multi-Discipline IDIQ Contract No. DTFH70-10-D-00020.

CH2MHill, Inc. 2014. Mitigation Plan: OR DOT CRGNSA 100(1) Historic Columbia River Highway State Trail (Segments A-D) Columbia River Gorge National Scenic Area Task Order No. T-13-001, Modification 006, Task 3.9 Multi-Discipline IDIQ Contract No. DTFH70-10-D-00020.

CH2MHill, Inc. 2015. Draft Design Acceptance Package, Historic Columbia River Highway State Trail: Gorton Creek to Lindsey Creek (Segments A-C). Prepared for Western Federal Lands Highway Division and Oregon Department of Transportation.

Dlugosch, Katrina M. 2005. Understory community changes associated with English ivy invasions in Seattle's urban parks. Northwest Science 79(1): 52-59.

Dobson, Robin. 2015. *Personal communication*. Email to author, April 20, 2015.

Flory, Luke S. and Keith Clay. 2009. Invasive plant removal method determines native plant community responses. Journal of Applied Ecology 46: 434-442.

REFERENCES

Green, George L. 1981. Soil survey of Hood River County area, Oregon. United States Department of Agriculture, Soil Conservation Service, in cooperation with the Oregon Agricultural Experiment Station.

Hood River County Chamber of Commerce. Hood River County, About Hood River. Hoodriver.org

Hopwood, Jennifer, Black, Scott, and Scott Fleury. 2016. Pollinators and roadsides: Best management practices for managers and decision makers. Prepared for the Federal Highway Administration.

Invasive plant species assessment working group. Invasive plant species fact sheet: Periwinkle *Vinca minor*. www.invasivespecies.IN.gov

King County Noxious Weed Control Program. 2014. Himalyan blackberry best management Practices.

Michigan Department of Natural Resources. 2012. Invasive species- Best control practices: black locust (*Robinia pseudoacacia*).

Oregon Plant Atlas, Oregon Flora Project. Oregon State University. www.oregflora.org/atlas.php

Pollinator Health Task Force. 2015. National strategy to promote the health of honey bees and other pollinators. The White House.

Quatrefoil, Inc. 2010. The Historic Columbia River Highway State Trail plan- Wyeth to Hood River.

Steinfeld, David E., Riley, Scott A., Wilkinson, Kim M., Landis, Tom D., Riley, Lee E.. 2007. Roadside revegetation: An integrated approach to establishing native plants. Federal Highway Administration, Western Federal Lands Highway Division report number FHWA-WFL/TD-07-005.

United States Department of Agriculture, Forest Service. 2009. Gifford Pinchot National Forest south zone invasive plant treatment 2009 implementation plan.

United States Department of the Interior, Bureau of Land Management. National seed strategy for rehabilitation and restoration. http://www.blm.gov/ut/st/en/prog/more/CPNPP/0/seedstrategy.html

REFERENCES

Ward, K., Cariveau, E., May, M., Roswell, M., Vaughan, N., Williams, R., Winfree, R., Isaacs, and K. Gill. 2014. Streamlined bee monitoring protocol for assessing pollinator habitat. Portland, OR: The Xerces Society for Invertebrate Conservation.

Wisconsin Department of Natural Resources. 2004. Black locust (*Robinia pseudoacacia*).

5— Implementation

5.1 INTRODUCTION

A successful revegetation project requires not only good planning but effective implementation of the plan. The Initiation Phase of this report (Chapter 2) described the organizations, decision processes, and technical concepts involved in beginning a roadside revegetation project. The Planning Phase chapter (Chapter 3) outlined the steps in the revegetation planning process resulting in a revegetation plan. This chapter details how the revegetation plan is translated into action at the project site.

The shift from the planning phase to the implementation phase involves a change in approach, and often, personnel. The planning process tends to be orderly and systematic, with the design team able to take an idealized bird's-eye perspective of how the project might best proceed. In contrast, implementation requires flexibility and adaptability in order to fulfill the objectives of the plan while working with the sometimes-unpredictable nature of construction.

The tasks necessary to successfully implement a revegetation plan are:

- Developing contracts
- Developing an implementation schedule
- Maintaining a materials inventory
- Reviewing plans and coordinating with project engineer
- Assisting in implementing contracts

This chapter provides an overview of the implementation process, providing details on the key factors to consider, including soil and site treatments, obtaining plant materials, installing plant materials, and caring for plants after they have been installed.

5.1.1 DEVELOPING CONTRACTS

Revegetation tasks can be performed in-house, by agency personnel, or through contracts, either performed within the scope of road construction contracts or as separate revegetation contracts. The FHWA and most state DOT agencies have developed revegetation contract specifications within their standard specifications for construction of roads and bridges. These specifications are designed, in most cases, to be included directly into a road construction contract or revegetation contract. As a designer, it is important that the language in the contract specification accurately describes both the work to be done and the desired outcome, from a revegetation standpoint. Because every revegetation project is different in scope and environmental setting, it is essential that these factors are conveyed in the specification.

Contract specifications detail the *how*, not the *why*. To understand the background for a specification for revegetation, it may be useful to review the implementation guides presented in this chapter that pertain to the specific task or topic. With this information, a special provision or supplemental specification based on standard DOT or other agency specifications can be developed to respond to the specifics of the project and environmental surroundings. It may also be helpful to review contract specification examples developed by other agencies. Some revegetation specifications for the FHWA and several state DOT's can be found in the Native Revegetation Resource Library by selecting "Contract Specifications" under the Report Type search filter.

To evaluate the implementation of contracts, quality assurance standards are defined in the contract specifications. The contractor typically provides monitoring and inspection of these standards to ensure that tasks are carried out as contracted. For example, a hydroseeding contract may have a specification to apply 30 pounds of seeds, 1,000 pounds of wood fiber mulch, and 50 pounds of tackifier per acre. Quality control for this task might be to count the pounds of seeds, wood fiber, and tackifier going into the hydroseeder tank and measure the

For the Designer
Special Provisions or Supplemental Specifications require agency review and approval and the process may take several months. Identification, development, and submittal of these specifications early in the project will reduce delay of final project review approvals for bidding.

area to which the mix is applied. This assessment determines if that the rate of materials applied is within quality standards and, if not, alerts the contractor to make appropriate corrections. The written results of these assessments become "as-built" records which can be used by the designer when developing the monitoring report (Section 6.2).

Accurately calculating the contract area is essential in developing contracts. Table 5-1 is an example of how cross sections can be used to determine the contract area. When cross sections are not available, the contract area can be determined from the plan map. In this method, the area is measured and adjustments are made for slope gradient (Table 5-2). A third method is to physically measure the distances in the field.

Table 5-1 | **Calculating project area from road plans and cross sections**

In this example, cross sections are available for each station. The length of each cross section is measured and recorded in a spreadsheet. The slope length is multiplied by the distance between stations to calculate the area for that station. When all stations areas are calculated, the total contract area is summarized.

Station	Slope length (m)	Distance between stations (m)	Area (m^2)
20+1000	3	20	60
20+1020	4	20	80
20+1040	6	20	120
20+1060	7	20	140
20+1080	6	20	120
20+1100	4	20	80
20+1120	2	20	40
		Total	**640**
		Acres	**0.16**

Table 5-2 | **Area computations adjusted for slope gradient**

When cross sections are not available, the plan map can be used to calculate area. On steeper terrain, the area may need to be adjusted by slope gradient based on the following factors.

Slope (V:H)	Increase factor	Percent of increase
1:1	1.41	41%
1:1.5	1.20	20%
1:2	1.12	12%
1:2.5	1.08	8%
1:3	1.05	5%
1:4	1.03	3%
1:5	1.02	2%

The contract specifies the work to be done by the contractor or agency personnel, with clear definitions of roles and schedules.

In general, a contract outlines the following:

- Supplies/services to be provided
- Scope of work (size, schedule, etc.)
- Project location
- Contractor obligations
- Revegetation specialist obligations
- Delivery details (who, how, when, including timelines and deadlines)
- Quality standards
- Contractor quality assurance plan (to be provided by contractor)
- Revegetation specialist quality assurance plan (to be provided by designer who will be inspecting the contractor's work)
- Price (including bid, unit prices, additive or deductive alternate items)
- Payment method (submission of invoices, approval of work)
- Contractor's designated representative (more efficient to only coordinate with one person)
- Safety plan
- Other terms and conditions (e.g., what to do in the event of changes)

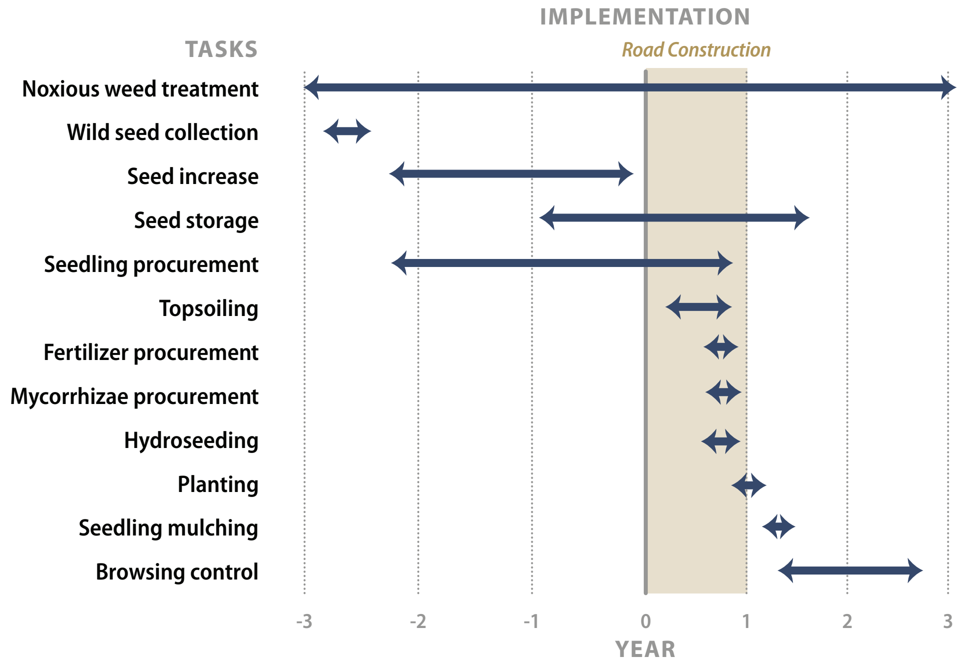


Figure 5-1 | **Example implementation schedule**

In this implementation schedule overlapping tasks, some requiring different contractors, are displayed.

5.1.2 MAINTAINING SCHEDULES AND MATERIALS INVENTORY

Revegetation contracts can begin up to three years before road construction. For example, it is not uncommon for a seed or plant procurement contract to begin during the planning stage of a road project and span into road construction. In addition, procuring plant materials and implementing mitigating treatments often involve separate schedules with different contractors. To keep these details straight, developing an implementation schedule can be helpful. Timelines are often developed during the planning stages and included in the revegetation plan and these become the basis of an implementation schedule.

Most schedules have interdependent and time-linked tasks. In Figure 5-1, for example, the hydroseeding contract is dependent on the success of the seed increase contract. Before that, the seed increase contract requires wildland seeds to be collected by agency personnel or contractors. The success of the hydroseeding contract rests on the successful execution of two tasks that begin years before the actual seeding.

When creating schedules, it is important to incorporate additional time needed to issue contracts. This is especially crucial when ordering plant materials, which will require several years for production.

Material quantities for revegetation tasks change through the life of a road project. For example, a nursery may have succeeded in growing more seedlings for certain species, while producing less of others (due to poor germination, frosts, insects, disease, or other events). For plant material contracts, it is important to stay in touch with the growers to determine if there are any changes to the inventories, and make adjustments to the inventory as needed. Other material quantities that can change are topsoil and shredded wood for mulch.

5.1.3 COORDINATING WITH CONSTRUCTION ENGINEER

For some road projects, one engineer will oversee the project from inception through its completion. For more complex projects however, the design engineer may hand off the project to a construction engineer member of the project team or from the DOT or agency client to implement. The design engineer, in this case, ensures that tasks outlined in the revegetation plan are designed into the construction documents: plans, specifications, contracts, schedules, materials lists, and coordinated with erosion control plans. The construction engineer implements the road plan with guidance from the design team. Complex revegetation designs, such as vegetated retaining walls, planting pockets, and other biotechnical engineering structures, may require more involvement from the design team.

Before construction begins, a meeting is often scheduled with the construction engineer, road building contractor, and revegetation design team to discuss the revegetation plan. This meeting covers revegetation objectives and outlines the revegetation tasks that need to be coordinated with road construction activities. The construction engineer is made aware of the revegetation treatments and how they are to be implemented. After the initial meeting, the revegetation designer may keep in contact with the construction engineer to help implement the contract specifications. Timely field visits by the designer will help overcome difficulties in integrating revegetation treatments into construction design and schedule.

5.1.4 IMPLEMENTATION GUIDES

Implementation guides are presented in this chapter as background for developing contracts or procedures for revegetation tasks.

The following implementation guides are grouped into four subject areas:

- Section 5.2 Soil and Site Treatments
- Section 5.3 Obtaining Plant Materials
- Section 5.4 Installing Plant Materials
- Section 5.5 Post-Installation Care of Plant Materials

The eight guides in Section 5.2 explain how to improve site and soil conditions prior to the installation of plant materials. These guides cover the mitigating measures most often referenced in Section 3.8.

Section 5.3 includes six implementation guides that pertain to collecting and propagating plant materials. These guides describe how to take the species lists developed in Section 3.13, and obtain the desired species in the wild as seed, cuttings, or seedlings. These guides also cover how to increase gathered wild collections at nurseries to ensure that the revegetation project has sufficient quantities of plant materials.

Once plant materials are obtained from the wild or from nurseries, they are installed on the project site. The four guides in Section 5.4 cover the techniques for sowing seed, installing cuttings, and planting seedlings. They also cover how to determine the quality of the plant materials and how to care for them during storage and transportation.

Section 5.5 outlines those practices that occur after the installation of plant materials. These practices help ensure that plants will become established. Practices include protecting seedlings from animal browsing, installing shade cards, irrigating, and installing tree shelters.

Other sources for implementation guides can be found in the Native Revegetation Resource Library by selecting “Implementation Guides” under the Report Type search filter.

5.2 **SOIL AND SITE TREATMENTS**

Most post-construction sites are in poor condition for plant growth and will require implementing a set of mitigation measures if good revegetation is expected. The following set of implementation guides cover the common mitigating measures for improving site conditions after construction.

- **Fertilizers**—Covers how to determine fertilizer quantity, type, and application method.
- **Tillage**—Describes the common practices of tilling the soil to improve water infiltration and root growing environment.
- **Mulches**—Seed germination, seedling survival, and surface erosion can be improved through the application of mulches.
- **Topsoil**—Outlines the removal, storage, and application of topsoil to reconstruct soils on highly disturbed sites. For sites where topsoil is not available or in short supply, organic matter can be applied to improve post-construction soils.
- **Organic Matter**—Discusses the types of organic matter, how to determine rates, and how it is applied. On some sites where the topsoil has been removed, pH levels may need to be raised to improve plant growth.
- **Lime Amendments**—Details materials, application methods, and how to determine liming rates.
- **Beneficial Microorganisms**—Many sites devoid of topsoil will require the introduction of mycorrhizae or nitrogen fixing plants. This section covers how to obtain and apply the appropriate sources of these important biological organisms.
- **Topographic Enhancements**—Revegetation projects can be enhanced by integrating plants into bioengineering structures, water capture features, or planting islands or pockets.

5.2.1 FERTILIZERS

Introduction

Fertilizers are used to bring soil nutrients up to levels essential for establishing and maintaining a desired plant community. When applied within a soil fertility strategy, fertilizer can be a good tool for revegetation but it should not be assumed that fertilizers are needed for every project. In recent years, the use of fertilizers on roadsides for native plant establishment has come under greater public scrutiny and more restrictive water quality laws. Many roads are adjacent to streams, lakes, or residential areas that can be affected by runoff or leaching of inappropriately applied fertilizers. In some instances, fertilizers may not be recommended for establishing native vegetation (see Idaho Roadside Vegetation Management Handbook) because of the potential of encouraging invasive species over native plants. It is important for the designer to learn how to develop fertilizer prescriptions that integrate short- and long-term site fertility goals with water quality and native plant establishment objectives.

It is important to base a soil fertility strategy on the nutrient levels of found in the reference soils when considering the application of topsoil, mulch, compost, wood waste, biosolids, and/or the planting of nitrogen-fixing species. In addition, using commercial fertilizer with other methods of raising nutrient levels, can result in a greater long-term nutrient management of the revegetation project (Section 3.8.4).

This section guides the designer through the steps necessary of developing a fertilizer prescription which is the instructions for ordering and applying fertilizers. They include:

- Determine nutrient thresholds and deficits

For the Designer
Base fertilizer recommendations on soil tests and native plant needs.

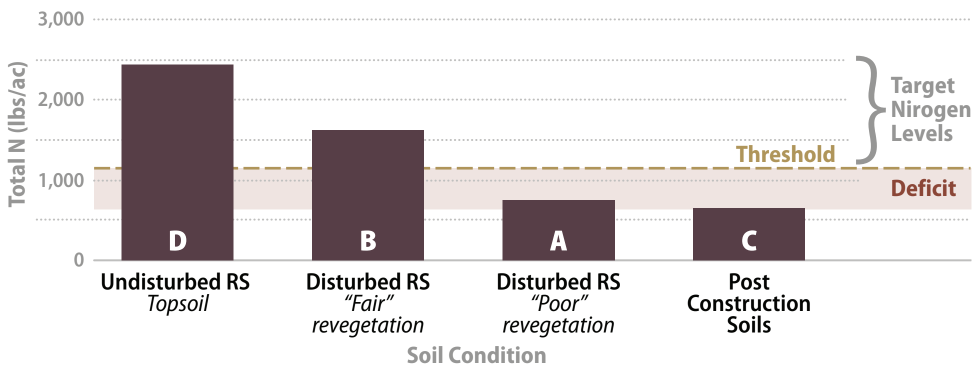
- Delineate areas to be fertilized
- Select fertilizer analysis
- Select fertilizer release rates
- Determine application rates
- Determine timing and frequency
- Select application method

Develop Nutrient Thresholds and Determine Deficits

All sites have a minimum, or threshold, level of nutrients that needs to be met for each plant community to become functioning and self-sustaining (Section 3.8.4). Threshold values can be determined by comparing soil tests from several disturbed and undisturbed reference sites (Section 3.5). Finding disturbed reference sites that range from poor success to good success provides a good understanding of nutrient levels and plant response. Based on nutrient values from good and poor revegetation sites, a target nitrogen range can be established between these values. Figure 5-2 provides an example of how a nitrogen threshold value was obtained by evaluating the total soil nitrogen levels from two disturbed reference sites, one considered "fair" revegetation and one considered "poor." The threshold was set between these two nitrogen levels. Threshold levels represent the minimum level of nutrients needed for a site. In this example, the target nitrogen range for establishing and maintaining the original plant community would be between the minimum nitrogen levels and the nitrogen levels found in the undisturbed reference sites.

Figure 5-2 | **Threshold values of nitrogen**

Threshold values are determined from reference sites. In this example, the threshold was established at 1,100 lb/ac, which was between the total N of a disturbed reference site with "poor" revegetation (A) and one with "fair" revegetation (B). Total N in post-construction soils was 650 lb/ac (C), making these soils deficient by 450 lb/ac. The undisturbed topsoil of reference sites showed a total N of 2,430 lb/ac (D), which sets the target nitrogen range between 1,100 and 2,430 lb/ac.



To determine whether nutrients are deficient, soil samples are collected from the post-construction sites and tested (Inset 3-2). The nutrient values obtained from these tests are compared against the target ranges to determine if a deficiency exists. By comparing post-construction nutrient values against threshold values, the nutrient deficit can be estimated for each nutrient. Figure 5-3 shows an example of how nitrogen deficits are calculated based on post-construction soil tests. In this example, total soil nitrogen is determined from soil tests. Because soil testing facilities report nutrients in a variety of rates, it is important to convert the rates to percentages then to pounds per acre. Values reported as gr/l, ppm, mg/kg, and ug/g are converted to

A	**Total soil nitrogen (N)**	0.025%	From soil test of post construction soils (gr/l, ppm, mg/kg, ug/g divide by 10,000 for %)
B	**Thickness of soil layer**	0.5 feet	The thickness of soil represented in A
C	**Soil bulk density**	1.4 gr/cc	Unless known, use 1.5 for compacted subsoils, 1.3 for undisturbed soils, 0.9 for light soils such as pumice
D	**Fine soil fraction**	70%	100% minus the rock fragment content – from estimates made from sieved soil prior to sending to lab
E	**N in soil layer** *A * B * C * D * 270 =*	331 lbs/ac	Calculated amount of total nitrogen in soil layer. To convert to kg/ha: *E * 1.12*
F	**Minimum or threshold N levels**	1,100 lbs/ac	Determined from reference sites (see Figure 5-2)
G	**N deficit** *F - E =*	769 lbs/ac	Minimum amount of N to apply to bring up the threshold

Figure 5-3 | **Determining nitrogen needs from soil tests**

Determining the amount of nitrogen (N) needed to bring soils up to a nitrogen threshold can be calculated from equations shown in this spreadsheet.

percentages by multiplying by 10,000. Converting nutrient percentage to lb/ac of the nutrient is done by multiplying percent of nutrient, soil layer thickness, soil bulk density, and fine soil fraction together with a constant (Line E). The result is the pounds of nutrient in an acre of soil on the post-construction site. To determine if the nutrient is deficit, the pounds of nutrients per acre is subtracted from the threshold level (Line F). This value (Line G) represents the nitrogen deficiency and becomes the basis for determining fertilizer prescriptions.

The availability of many nutrients is regulated by soil pH. As discussed in Section 3.8.4, many nutrients are tied up in low pH and high pH soils. Calcium and magnesium are less available at low pH; phosphorus, iron, manganese, boron, zinc, and copper become unavailable in high pH soils. It is important to compare the pH of post-construction soils with reference site soils to determine if the pH is substantially different between the two. If the pH of post-construction soils is different, then taking measures to bring the pH closer to pre-disturbance values is important when developing a nutrient strategy (Section 5.2.6).

Delineate Areas to be Fertilized

Because the post-construction site may differ in soil types and disturbance levels, it is important to delineated areas where fertilizer prescriptions may differ. These differences are usually based on post-construction soil type changes, topsoil salvage, organic amendment additions, or the species and plant material being grown. Areas adjacent to, or that feed into, live water are often delineated and treated with lower rates of fertilizer. Note: If seedlings of shrubs and trees are being planted, spot fertilization may be a more appropriate method than fertilizing the entire area (Inset 5-1).

Select Fertilizer Analysis

A variety of commercially available fertilizers can be used for fertilizing disturbed sites associated with road construction. The composition, or makeup, of the fertilizer is called the fertilizer analysis. Each container of fertilizer will have a label with a stated "guaranteed analysis" that indicates the percentage of each nutrient contained in the fertilizer (Figure 5-4). The label is the guide for determining which fertilizers to select and how much to apply. Table 5-3 and Table 5-4 provide analysis values for many common fertilizers. Labels can also be obtained from the manufacturer or fertilizer representatives.

Inset 5-1 | **Spot-fertilizing seedlings**

Fertilizing shrub or tree seedlings is done by placing fertilizer in each seedling hole or on the soil surface after each seedling has been planted. This practice has some risks because fertilizers release salts that can damage roots. Studies have shown that placing fertilizers or liming materials in the planting hole or on the soil surface around seedlings at the time of planting can significantly decrease seedling survival, especially on droughty sites (Nursery Technical Cooperative 2004; Jacobs and others 2004; Walker 2002).

These practices may reduce the likelihood of seedling damage:

- Assess the need for fertilizer (do not apply if nutrient levels are adequate)
- Use slow release fertilizers with low salt indexes
- Use low rates of fertilizer if applying at the time of planting
- If applying in seedling hole at planting, use low fertilizer rates and place fertilizer to the side at least 3 inches away from the root system (see figure)
- Preferably broadcast fertilizers on the soil surface after seedlings are well established

When slow-release fertilizers are spread around well-established seedlings (several years after planting), seedlings often respond favorably, especially on highly disturbed sites. Walker (2005) found that slow-release fertilizers applied around the seedlings three years after they were planted increased stem diameter and shoot volume by 143 percent and 104 percent, respectively, over the control when they were measured five years later. In this study, rates of .05 grams of nitrogen per seedling showed the greatest response (at 8 percent nitrogen analysis, this would be over a half pound of bulk slow-release fertilizer per plant).

21-5-20

All Purpose Fertilizer

Guaranteed Minimum Fertilizer

Total nitrogen (N)	**21.00%**
Ammonium nitrogen	6.50%
Nitrate nitrogen	12.40%
Urea nitrogen	2.10%
Available phosphate ($P_2 0_5$)	**5.00%**
Soluble potash (K_2O)	**20.00%**
Boron (B)	**0.02%**
Copper (Cu)	**0.01%**
Iron (Fe)	**0.10%**
Water soluble manganese (Mn)	**0.05%**
Molybdenum (Mo)	**0.01%**
Water soluble zinc (Zn)	**0.07%**

Figure 5-4 | **Example of a fertilizer label for an "all purpose" fertilizer**

The three numbers (21-5-20) represent the percentage of nitrogen, phosphorus, and potassium respectively (21%N, 5% P_2O_5, and 20% K_2O). The label may also contain percentages of other nutrients in the fertilizer. Multiplying these percentages (divided by 100) by the pounds of bulk fertilizer applied per acre will give the quantity of each nutrient applied per acre. In this analysis, applying 500 pounds of fertilizer to an acre would deliver 105 lbs N, 25 lbs P_2O_5, 100 lb K_2O, 0.01 lbs B, 0.005 lbs Cu, etc.

Fertilizer labels report nutrients as a percentage. The example label for a 50 pound bag of fertilizer in Figure 5-4 shows 21 percent nitrogen (N), which indicates that 10.5 pounds of material in the bag is made up of nitrogen (*50 * 21 / 100 = 10.5*). The bag also contains 0.02 percent boron (B), which indicates that there is 0.01 pounds of boron in the bag. Calculating the amount of phosphorous and potassium is different because the convention for reporting these nutrients is P_2O_5 and K_2O instead of elemental P and K. To convert P_2O_5 to P, the analysis for P is divided by 2.29. The percentage of P in the bag in Figure 5-4 is actually 2.2 percent, not 5 percent (*5.0% / 2.29 = 2.2*). K_2O is divided by 1.21 to obtain 1.6 percent K.

Fertilizers are selected based on whether they contain the nutrients that are deficient on the project site (Section 5.2.1, Develop Nutrient Thresholds and Determine Deficits). For example, if nitrogen, phosphorus, and boron are deficient, only fertilizers that contain these nutrients are considered. Most fertilizers contain more than one nutrient. For example, ammonium sulfate contains nitrogen and sulfur; and triple superphosphate contains phosphorus, sulfur, and calcium. Organic fertilizers contain a range of macro and micronutrients. Fertilizers containing more than one nutrient are used if the nutrients contained in these fertilizers are deficient in post-construction soils. Table 5-2 and Table 5-3 show the combination of nutrients that are available in some commercially available fertilizers.

Table 5-3 | **Analysis of common fertilizers**

		Available nutrients (typical percentages)													
		N	**P_2O_5**	**P**	**K_2O**	**K**	**S**	**Ca**	**Cu**	**Fe**	**Mn**	**Zn**	**B**	**Mo**	**Mg**
Phosphorus	Mono-ammonium phosphate	11	48	21			24								
	Ammonium phosphate	82													
	Diammonium phosphate	17	47	21				21							
	Single superphosphate	19					12	20							
	Triple superphosphate		45	20			1	13							
	Phosphoric acid		53	23											
	Dicalcium phosphate														
	Soluble potassium phosphate														
	Superphosphoric acid		80	35											
Potassium	Potassium chloride				61	50									
	Potassium nitrate	13			45	37									
	Potassium sulphate				51	42	18								
Micro-nutrients	EDTA								10	10	10	10			
	HEEDTA								6	7	7	9			
	NTA									8					
	DTPA									10					
	EDDHA									6					
	Granular borax												11.3		
	Copper sulfate								25						
	Ferrous sulfate									20					
	Sodium molybdate													40	
	Zinc sulfate											36			
	Zinc chelate											4			
Ca & Mg	Dolomitic limestone							21							11
	Magnesium sulfate														43
	Gypsum							23							
	Epsom salt (Epsogrow brand)						13								10

Table 5-4 | **Estimated nitrogen release rates for commercially available fertilizers**

Nutrient release rates are obtained from lab testing but how they release on-site will vary from site to site, depending on temperature, moisture, and whether the fertilizer was placed on the surface or incorporated into the soil. If slow-release fertilizers are broadcast on the soil surface, release rates are slower than if incorporated into the soil where the conditions are better for break down. Arid sites have slower rates of release than sites with high moisture; cold sites take longer to release nutrients than warm sites. First-year nitrogen release rates for fertilizers are identified with an asterisk were adapted from Claassen and Hogan (1998).

Note: Non-asterisk fertilizers were based on best guess estimates.

	Available Nutrients			
Source	**N %**	**1st year N release (%)**	**% P_2O_5**	**% K_2O**
Ammonium nitrate	34	99 to 100	0	0
Ammonium phosphate*	10	99 to 100	34	0
Ammonium sulfate	21	99 to 100	0	0
Anhydrous ammonia	82	99 to 100	0	0
Biosol® *	7	50 to 70	2	3
Calcium nitrate	15.5	99 to 100	0	0
Diammonium phosphate	18	99 to 100	46	0
Fertil-Fibers® *	6	50 to 70	4	1
Gro-Power® *	5	95 to 99	3	1
IBDU	29	95 to 99	3	10
Osmocote 18-6-12® *	18	95 to 99	16	12
Polyon PCU 40® *	30	99 to 100	0	0
Potassium nitrate	13	99 to 100	0	45
Ringer® *	5	50 to 70	10	5
Sustane® *	5	50 to 70	2	4
Urea	46	99 to 100	0	0

In selecting a fertilizer, the macronutrients (nitrogen, potassium, and phosphorus) that are deficient on a site are considered first because they are the most important for long-term site recovery. If these nutrients are not deficient, chances are that the remaining nutrients are not deficient either. On most highly disturbed sites, nitrogen is most likely to be deficient. This nutrient should be considered first when approaching fertilizer selection. Table 5-3 lists common nitrogen fertilizers with typical label analysis. It is common to apply more than one fertilizer to meet the various nutrient requirements of the soil. Nutrients other than nitrogen can be supplied by fertilizers shown in Table 5-3.

Biosolids—Biosolids are a nutrient-rich organic material produced from wastewater treatment sewage sludge that are high enough in macronutrients to be considered a fertilizer (Figure 5-5).

Organic matter	45-70%
Nitrogen	3-8%
Phosphorous (P2O5)	3-8%
Potassium (K2O)	<1%
Sulfur (S)	0.6-1.3%
Calcium (Ca)	1-4%
Magnesium	<1%

Figure 5-5 | **Range of organic matter and nutrients in biosolids**

Biosolids are rich in nutrients and organic matter, often meeting the requirements to be classified as a fertilizer. This table shows the usual range of organic matter and nutrients by dry weight of material (from Sullivan and others 2007). Biosolids also provide micronutrients, including copper, boron, molybdenum, zinc, and iron.

When applied to agricultural, forestry, reclamation, and landscaping sites it is a source of nutrients and organic matter. Biosolids improve roadside soils by increasing water-holding capacity, improving soil structure and infiltration, providing slow-release nutrients, and increasing soil biological activity (Sullivan and others 2007). Biosolids are sold as packaged fertilizers from commercial sources or directly in bulk from wastewater treatment centers.

The U.S. Environmental Protection Agency's Part 503 rule, along with State and possibly local regulations, provides comprehensive requirements for the application of biosolids (EPA 1994). Biosolids fall into two classes:

- **Class A Biosolids**—These are materials that meet rigid requirements which include no detectable levels of pathogens, strict vector requirements, and low metals contents. The applicator has only to apply for permits, though in some cases, site approval may be required if trace elements exceed Exceptional Quality (EQ) limits or if they are not sufficiently stabilized (Sullivan and others 2007).
- **Class B Biosolids**—These are materials that have been treated but still contain detectable levels of pathogens. Setbacks and public access restrictions are required to protect public health. Site approvals and permits are required for Class B Biosolids application.

Nitrogen is an important component of biosolids because this nutrient is limiting on most roadsides. Biosolids are basically composed of two forms of nitrogen:

- **Ammonium-nitrogen**—This form of nitrogen is readily available for plant uptake. If biosolids are surface applied, a portion of ammonium-N is lost as gas. Sprinkler irrigating or tilling biosolids into the soil immediately after application can reduce the amount of nitrogen that is lost (Sullivan and others 2007).
- **Organic-nitrogen**—Nitrogen in this form is bound to organic matter which must be digested by soil microorganisms to be released. This process, called N mineralization, takes time. When first applied however, nitrogen release rates are rapid, but level off over the years, to supply a relatively consistent annual supply of nitrogen.

Biosolids are high in other macro nutrients including phosphorus, calcium, magnesium, and sulfur (Figure 5-5). Phosphorus however, is very low and may need to be added depending on the nutrient status of the roadside soils and the biosolids being applied. Phosphorus is present in biosolids at significant quantities yet the availability is around half of a commercial fertilizer because of the predominance of inorganic phosphorus (EPA 1995). Micronutrients, such as boron (B), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn) are present in varying amounts but may not be at the ratios found in a well-balanced commercial fertilizer and micronutrient fertilizers may need to be supplemented (EPA 1995).

Some biosolids are stabilized with alkaline materials which can raise the pH of roadside soils. Where soil pH is low, this can be an advantage, and biosolids can be used as a replacement for agricultural limestone (Sullivan and others 2007). However, on high pH soils, the addition of alkaline-stabilized biosolids can be detrimental to plant establishment and plant growth. For these reason, the pH of the roadside soils is important when considering applying an alkaline-stabilized biosolids.

Biosolids are typically applied on roadsides at higher rates than agricultural lands to improve soils and provide nutrients and organic matter capable of supporting native vegetation (EPA 1994). Rates range from 3 to 200 tons/acre but average around 50 tons (EPA 1995). biosolids are relatively light weight and can be half the weight by volume of soil. A 50 tons/acre application rate of biosolids is approximately 0.5-inch thick layer biosolids applied to the surface of a soil. Baxter and Stephan (2011) found that biosolids placed one inch deep on an abandoned timber haul road in Oregon and disked into the soil, was successful in obtaining a high cover of native grass species. On highway right-of-way plots in Rhode Island, Brown and Gorres (2011) found significant improvement of vegetative cover with a 2.0-inch application rate of biosolids compared to a 2.0-inch application of compost. The differences in plant response to compost and biosolids was due to the C:N ratios (biosolids – 7, compost – 64). In this study, biosolids had four times as much total N as the compost. Fava (2015) however, found that at a 1.0 inch application rate, vegetative cover did not differ from the control plots. The differences in findings of these studies point out the importance of knowing the composition of the biosolids and how they respond to the site they are being applied to. Administrative trials, where different rates of biosolids are applied in combination with compost or shredded wood, can will help develop appropriate rates and soil amendments to use to improve the roadside soils.

Select Fertilizer Release Rates

Fertilizers are grouped by how quickly they break down and release nutrients to the soil. They are either fast-release or slow-release. Release rates are important because they determine the rates at which nutrients become available to plants during the year. If nutrients are released during periods when vegetation cannot use them, some will be lost from the site through soil leaching. This is not only a waste of fertilizer but can be source of ground-water pollution.

Fast-Release Fertilizers—Fast-release fertilizers are highly soluble fertilizer salts that dissolve rapidly and move quickly into the soil during rainstorms or snowmelt. The fertilizer label gives an indication of how quickly nutrients are released. Terms such as "soluble," "available," or "water soluble" indicate that these nutrients are released relatively quickly. "Ammonium" and "nitrate" forms of nitrogen are also indications of fast-release fertilizers. The fertilizer label shown in Figure 5-4 indicates that the fertilizer contains a fast-release fertilizer and most of the nitrogen would be relatively mobile and available to plant growth within the first growing season. Ammonium nitrate, ammonium sulfate, potassium nitrate, and urea are several examples of fast-release fertilizers.

"Water soluble" or "available" nutrients do not always remain available or soluble after they are applied to the soil. Available forms of phosphorus, for example, react in the soil to form less soluble compounds; potassium gets bound up in soils with moderate to high proportions of clay; and many of the micronutrients (e.g., zinc, copper, and manganese) become unavailable when applied to soils with low pH (Section 3.8.4, see pH). Unless soils are sandy or rocky, it can be assumed that many of the nutrients stated as "available," except for nitrogen and sulfur, will become somewhat immobile once they are applied. Over time, however, these nutrients will become available for plant uptake.

The advantages of fast-release fertilizers are they are relatively inexpensive, easy to handle, immediately available to the plant (especially nitrogen), and can be applied through a range of fertilizer-spreading equipment. Disadvantages are that some nutrients, such as nitrogen, will leach through the soil profile if they are not first taken up by plants or captured by soil microorganisms in the breakdown of carbon. Nitrates from fast-release fertilizers have been found to leach through sandy soils to depths that are four times the rate of rainfall (Dancer 1975). For example, for sites with annual rainfall of 12 inches, nitrate could move to a depth of 4 feet if it is not taken up by plants or soil organisms. At this depth, nitrogen would be out of range of most establishing root systems.

Because fast-release fertilizers are salts, they have a potential to burn foliage and roots, especially when fertilizers are applied at high concentrations or when applied during dry weather . High concentrations of fast-release fertilizers can also affect germination rates (Figure 5-6) because of the high soluble salt levels (Brooks and Blaser 1964; Carr and Ballard 1979). Salt damage

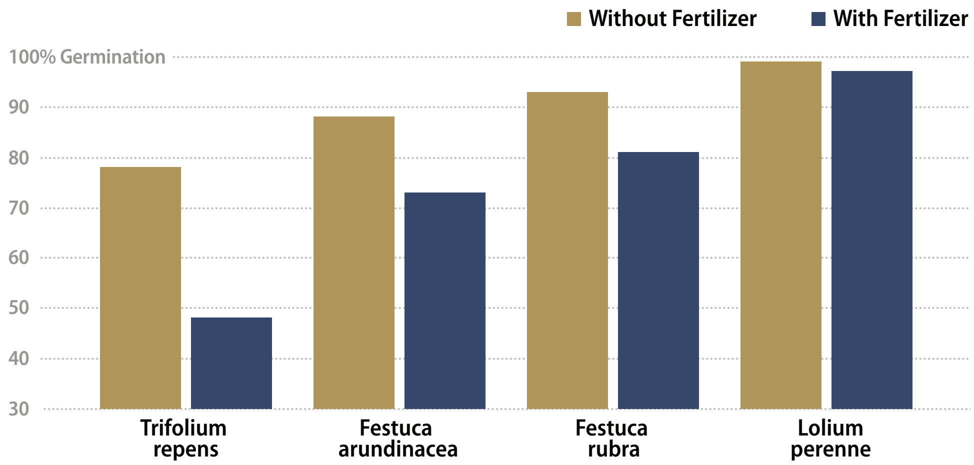


Figure 5-6 | **Reduced seed germination after exposure to fertilizer**

Germination for some species can be reduced following exposure to a 10-30-10 fertilizer solution at a rate of 750 pounds of fertilizer per 1,000 gallon hydroseeder (after Carr and Ballard 1979).

can be reduced by mixing fast-release fertilizers at lower concentrations or by applying them during rainy weather.

Slow-Release Fertilizers—These fertilizers are designed to release nutrients at a much slower rate. To be labeled slow-release fertilizer, some states require a specific amount of nitrogen to be in a slow-release form. Forms of nitrogen shown on the label as "slowly available" or "water-insoluble" are good indicators that a fertilizer is in a slow-release form. The advantages of using slow-release fertilizers are as follows:

- Nutrients are supplied at a time when plants are potentially growing
- Less frequent applications
- Less potential for leaching into ground water
- Less potential to cause salt injury

The disadvantages are that many slow-release fertilizers are bulky, cost more to purchase and apply, and are limited by the type of fertilizer application equipment that can be used. Nevertheless, slow-release fertilizers have greater applicability for revegetating disturbed sites than fast-release fertilizers.

Organic slow-release fertilizers—These fertilizers come in either organic or inorganic forms. Organic fertilizers include animal manures (e.g. chicken, steer, and cow), bone meal, fish emulsion, composted sewage sludge (biosolids), and yard waste. Unprocessed organic fertilizers are hard to apply to roadside projects because they are bulky and high in moisture content. Commercially available organic fertilizers, such as Fertil-Fiber™ and Biosol®, have been processed to remove most of the water, which makes them easier to apply with most fertilizer-spreading equipment. For a good discussion on organic fertilizers, see Landis (2011).

The agents responsible for release of nutrients from organic fertilizers are decomposing soil bacteria. When soil bacteria are active, the release of nutrients is high; when dormant, the rate is low. The release of nutrients is therefore a function of moisture and temperature, which governs the rate of bacterial growth. Warm temperatures and high moisture, conditions conducive to plant growth, are also favorable for the breakdown of organic fertilizers. Because of this, the release of nutrients from the decomposition of organic fertilizers often coincides with the period when plants are growing (spring and fall) and the need for nutrients is greatest. The nutrient-release mechanism of slow-release organic fertilizers reduces the risk that highly mobile nutrients, such as nitrogen, will be released in the winter when plants are incapable of absorbing them and the potential for leaching is greatest.

Inorganic forms of slow-release fertilizers were developed for the horticulture and landscape industries where they have become an effective method of fertilizing nursery plants. These are expensive forms of fertilizer and have not been tested on roadside revegetation conditions. Nevertheless, they should not be overlooked in their potential applicability for some native revegetation projects.

Inorganic slow-release fertilizers—These fertilizers include ureaform, nitroform, isobutylidene diurea (IBDU), sulfur-coated urea, and polymer-coated nitrogen, phosphorus, and potassium. These fertilizers have varying mechanisms for nutrient release. Fertilizer granules coated with materials that release nutrients only during warm, moist conditions ensure that nutrients are available during the period when plants are most likely to be growing. These coatings include sulfur (e.g., sulfur-coated urea) and polymers. Each fertilizer has its own formulated nutrient release rate, which varies from 3 months to 18 months. Release rates are available from the manufacturers for most inorganic, slow-release fertilizers. However, it should be noted that these rates were developed for 70° F soil temperatures (Rose 2002), which are higher than soil temperatures in the western United States during the spring and fall when roots and foliage are growing. If roadside soils are colder than 70° F, nutrient release will take longer than what the manufacturer states.

Determine Fertilizer Application Rates

Fertilizer rates are determined for each deficient nutrient, as shown in Figure 5-7. The calculation in this example was done to eliminate a nitrogen deficit of 769 lb/ac. Using a slow-release fertilizer with 8 percent nitrogen, the amount of bulk fertilizer necessary to bring nitrogen levels to minimum targets is 9,613 lb/ac (*769 * 100 / 8 = 9,613*), which is a high rate of fertilizer to apply. With a release rate of approximately 40 percent the first year, 308 lbs N/ac would be available, far more than the establishing plant community could absorb. Alternatively, using a fast-release fertilizer with higher nitrogen analysis, such as ammonium nitrate (33 percent N), would reduce the amount of bulk fertilizer to 2,330 lbs/ac (*769 * 100 / 33 = 2,330*). While there would be less weight with this more concentrated fertilizer, this is considered a dangerously high application rate because all of the nitrogen would be released in the first year resulting in a much greater potential that high amounts of nitrates are leached through the soil into the ground water and a higher risk that elevated salt levels would be toxic to plant growth. This example illustrates the difficulty in developing fertilizer prescriptions to meet long-term nutrient targets. How does the designer develop a fertilizer strategy to meet short-term and long-term plant needs without over- or under-fertilizing?

A	Nitrogen (N) deficit	769 lbs/ac	Calculated from example in Figure 5-3
B	N in fertilizer	8%	From fertilizer label
C	Total bulk fertilizer needed *A * (100 / B) =*	9,613 lbs/ac	To eliminate deficit
D	Estimated first year N release rate of fertilizer	40%	From Table 5-4 or obtain from manufacturers
E	Available N first year in fertilizer from first year application *B * C * D / 10,000 =*	308 lbs/ac	N available to plants and soil
F	Short-term N target (first year)	50 lbs/ac	Depends on C:N ratio, plant cover, and age
G	Excess nitrogen *E - F =*	258 lbs/ac	Wasted N could leach from soils into water
H	Adjusted rates of fertilizer to add *(F * 100 / D) * (100 / B) =*	1,563 lbs/ac	To assure that N released first year is not wasted
I	Remaining N deficit *A - (H * B / 100) =*	644 lbs/ac	Additional N needed as later applications of fertilizer

Figure 5-7 | **Example of calculating fertilizer application rates to reduce nitrogen**

This spreadsheet shows how a slow-release fertilizer would have to be applied at high quantities to reduce the nitrogen deficit. The problem with these high rates is that approximately 40 percent of the nitrogen (Line D) would be released the first year which is more than an establishing plant community could use, resulting in nitrogen leaching (Line G). Fertilizer rates can be lowered to meet just the first-year nitrogen needs (Line F) but not the long-term nitrogen needs of the site (Line I).

The approach presented in this section is based on meeting short-term nutrient needs of the establishing plant community while building a long-term nutrient capital. For example, applying fertilizer at the time of seeding requires very low rates of available nitrogen to meet the first-year needs of the establishing vegetation. Any extra fertilizer has the potential of being wasted. As the vegetation develops over the next few years, the ability of the plant community to take up more available nutrients increases. A strategy of applying low amounts of fertilizer the first year, followed up with higher rates in later years would supply the levels of nutrients needed for a developing plant communities without wasting fertilizers. This practice, however, is seldom employed in roadside revegetation projects. In fact, the typical fertilizer practice does just the opposite—high rates of fertilizers are applied with the seeds to a site that has no vegetation that could utilize the available nutrients. There is no return to the site in later years to assess whether additional applications of fertilizers might be essential for vegetation maintenance or growth. The approach advocated in this section is applying the appropriate mix of fertilizers to meet the annual needs of the vegetation while building long-term nutrient capital until the plant community is self-sustaining. This approach may require fertilizer application over a period of several years.

Because nitrogen is the key nutrient in establishing plant communities, this approach requires setting short-term and long-term nitrogen requirements of the plant community being established. Calculating long-term nitrogen target is addressed in Section 5.2.1 (see Develop Nutrient Thresholds and Determine Deficits). Short-term targets are more difficult to set because they change over time. They are governed by the following:

- Soil type
- Carbon-to-Nitrogen ratio (C:N ratio)
- Climate
- Amount of vegetative cover
- Type of vegetation
- Age of vegetation

Some general guides can be helpful in setting short-term nutrient targets for available nitrogen. Applying fertilizer at the time of sowing, for example, requires very low rates of available nitrogen because vegetation is not there to utilize it. Rates range from no fertilizer to up to 25 lb/ac of N when applying fertilizer with seeds. During plant establishment, available N can range from 25 to 50 lb/ac (Munshower 1994: Claassen and Hogan 1998). After plant establishment, rates can be increased to account for increased plant utilization above this amount. These suggested rates are adjusted upward on sites where high C:N soil amendments, such as shredded wood or straw, have been incorporated into the soil to compensate for nitrogen tie-up. Calculating precise rates of supplemental nitrogen for incorporated organic amendments is very difficult. In nursery settings, rates of over 100 pounds of supplemental nitrogen have been recommended for incorporated straw, sawdust, and other high C:N materials (Rose and others 1995). However, applying supplemental rates on highly disturbed sites should be done with caution, utilizing trials where possible to determine more precise fertilizer rates. Periodic soil analysis can provide the designer with a better understanding of the soil nitrogen status. To keep testing costs low, only available nitrogen and total nitrogen need to be tested (Section 3.8.4, see How to Assess Soil Nitrogen and Carbon).

In determining how much fertilizer to apply, it is important to estimate how much nitrogen will be available the first and second years. Manufacturers have this information for most inorganic slow-release fertilizers. Claassen and Hogan (1998) have also performed tests on some slow-release organic fertilizers (Table 5-4). Release rate determinations are performed in the laboratory but the actual release rates will vary in the field by soil type and climate. In the example described in Figure 5-7, the first-year release rate of nitrogen from the slow-release organic fertilizer was estimated at 40 percent. This was a guess based on the manufacturer's estimates of 55 percent release, but because it was being applied to a semi-arid site where decomposition of the fertilizer would be slow, the rate was dropped to 40 percent (Line D). If 40 percent of the nitrogen became available the first year, 60 percent would remain for the following years (Line E). At this release rate, 308 lb/ac of nitrogen would become available the first year after application (Line F). While this is an extremely high rate, consider the application of ammonium nitrate at 100 percent first year release, which would supply 769 lb/ac (Line A) of immediately available nitrogen. Recalculating fertilizer rates using a more realistic rate of 50 lb/ac available nitrogen needed the first year after application (Line F), bulk fertilizer application rates would be 1,563 lb/ac (Line H). At this new rate, the site would have sufficient first- and second-year supplies of nitrogen but lack adequate nitrogen the following years. The remaining deficit to meet long-term nitrogen targets would be approximately 644 lb/ac, which should be supplied through later applications of fertilizer or other carriers of nitrogen (topsoil, compost, biosolids, wood waste, mulch, and nitrogen-fixing plants). In this example, nutrient strategy would be built upon treatments that would increase long-term nitrogen capital.

The process of calculating fertilizer application rates in Figure 5-7 can be used for other deficient nutrients, however, understanding the availability of these nutrients is problematic. Many nutrients become fixed in the soils and their availability is dependent on highly variable factors such as soil texture, pH, and placement in the soil. It is a reasonable assumption that unless the soils are sandy or very rocky, that all nutrients, aside from nitrate or ammonium forms of nitrogen, are relatively unavailable the first year after application. With time, however, they will slowly become available.

Determine Timing and Frequency

The primary reason to fertilize is to supply nutrients during periods when plants can take them up for growth. The demand for nutrients changes throughout the year depending on the physiological state of each plant. In nursery settings, fertilizers are adjusted throughout the year at rates and formulations that correspond to the requirements of the plant. While that capability is not possible in roadside environments, fertilizers can be used more wisely by applying an understanding of how the assortment of fertilizers function in meeting the nutrient requirements of plant communities. At least two plant growth phases are important in the timing of fertilizer application: (1) seed germination and plant establishment and (2) post-plant establishment.

Seed Germination and Plant Establishment Phase—Traditionally, fast-release fertilizers have often been applied at high rates in the fall in the northern United States during the seed-sowing operation. This practice is a quick and easy way to apply fertilizers. However, the timing can result in ineffective and wasteful use of fertilizers (Figure 5-8B) (Dancer 1975). In addition, application of fast-release fertilizers at this time can potentially pollute water

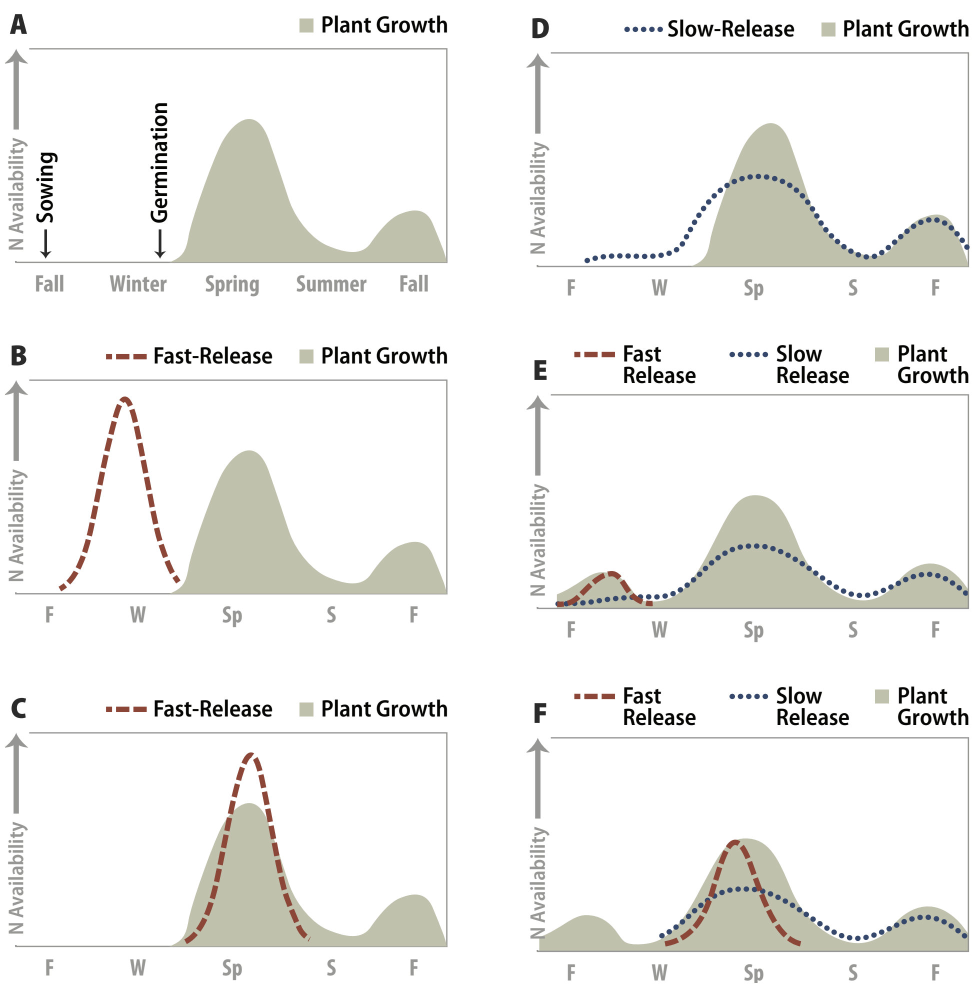


Figure 5-8 | **Strategies for applying slow and fast release fertilizers**

Fertilizers should be applied during seasons and at rates and formulations that release nutrients when native plants can efficiently draw them from the soil. The following are strategies for applying slow and fast release fertilizers.

(A) When seeding occurs in the fall, seeds typically do not germinate until the following spring, at which time there is rapid growth. During the summer, growth rates slow. Growth rates accelerate again in the fall.

(B) When fast-release fertilizers (dashed line) are applied in the fall during seeding, fertilizers move into the soil with fall rains. However, there is no vegetation to take up the nutrients. Mobile nutrients, such as nitrogen, are leached and unavailable in the spring when the establishing plants require them.

(C) Fast-release fertilizer applied in the spring after plants are established is more effective because plants are rapidly growing and can take up nutrients. There are fewer storms in the spring to leach nutrients from the soil.

(D) Slow-release fertilizers (dotted line) release nutrients at a much slower rate. When they are applied in the fall, most of the nutrients should still be available in the following spring.

(E) Once vegetation has become established, plant growth will take place in the fall. Fertilizers applied at this time will be taken up by growing vegetation. Since slow-release fertilizers might not be immediately available, small amounts of fast-release fertilizers can be added to give immediate release nutrients.

(F) Slow- and fast-release fertilizers can be applied in the early spring before rapid root and vegetative growth. Fast-release fertilizers can supplement slow-release fertilizers by supplying immediately available nutrients.

Note: These examples are based on a Mediterranean climate and assumes that seeds germinate in the spring, not in the fall or winter.

sources. Slow-release fertilizers are more appropriate for seed sowing in the fall because much of the fertilizer, but not all, is expected to release nutrients the spring, not in the fall or winter (Figure 5-8D).

Perennial grasses and forbs do not require high levels of nitrogen for germination and early establishment (Reeder and Sabey 1987). In fact, an elevated level of available nitrogen can be a problem because it encourages the rapid establishment and growth of annual weed species over slower-growing perennial grass and forbs (McLendon and Redente 1992; Claassen and Marler 1998). It is important to calculate fertilizer quantities based on the plant requirements over time (Section 5.2.1, see Determine Fertilizer Application Rates).

One strategy is to apply little or no fertilizer during sowing and wait until seeds have germinated and grown into small seedlings before fertilizers are applied (Figure 5-8C). This strategy ensures that nutrients are available when the seedlings actually need them, not before. Fertilizers applied as slow-release form are preferred because they have less potential for causing salt damage when applied over emerging seedlings. Another strategy is to wait until the following fall (Figure 5-8E) or spring (Figure 5-8F) of the second year to fertilize.

Post-Establishment—Once vegetation is established (one or two years after sowing), fertilizers may be applied at higher rates with the assurance that nutrients will be taken up by the plants. It is important that the application rates are based on nutrient levels of the soil and the needs of the native plant species. On fertile soils, there may be no need to fertilize, whereas on soils without topsoil or low in organic matter, a post-establishment fertilizer application may be needed.

Slow- and fast-release fertilizers can be combined to provide short- and long-term nutrient requirements (Figure 5-8E and F). Spring applications of fast-release fertilizers are more effective than fall application because of the higher nutrient requirements of growing plants during that period (Figure 5-8F). In addition, spring applications may pose less risk of damaging vegetation through fertilizer salts on sites where precipitation in the spring is frequent enough to wash fertilizers from the foliage. The conductivity of a fertilizer solution being applied over existing vegetation can be measured with a conductivity meter to avoid salt damage (Section 3.8.4, see Salts). If rates exceed 3,500 mS/cm, then diluting the solution or applying the fertilizer during rainy weather is advised. Fertilizer rates can also be adjusted based on the salt tolerance of a plant species (see ERA).

Select Fertilizer Application Method

Because nutrients have varying degrees of mobility (nitrogen is highly mobile; phosphorus and many micronutrients are relatively immobile), how fertilizers are applied will determine how accessible nutrients are to the root systems of establishing vegetation. If nutrients are highly mobile, the easiest and least expensive method is broadcasting fertilizer to the soil surface to allow rainfall or snowmelt to release and move nutrients into the soil. A more difficult, yet more effective application method for immobile nutrients is to incorporate, or mix, fertilizers into the soil so fertilizer granules are uniformly distributed and accessible by root systems.

Broadcast Fertilizer Application—For fertilizers with highly mobile nutrients, such as nitrogen and sulfur, broadcast application on the soil surface is an appropriate practice. Broadcast fertilizer application is less effective, however, for immobile nutrients. These nutrients often become immobilized at the soil surface and are very slow to move into the rooting zone where they can be accessed. Depending on soil characteristics, such as pH and clay content, some immobile nutrients will take years to move only a few inches from the point of fertilizer placement.

A variety of dry fertilizer spreaders are available, from hand-operated to tractor-mounted. Most equipment is limited to moderate slope gradients (less than 1V:2H). With all forms of spreaders, they should be calibrated before they are used to ensure that the correct rates are being applied.

Hydroseeding equipment can be used to apply fertilizer in the same operation with seeds, tackifiers, and hydromulch (Section 5.4.2). This equipment can also be used solely to apply fertilizers, especially after vegetation has become established. A great advantage to using hydroseeding equipment is that it can uniformly spread fertilizers on steep slopes and a variety of topographies. In addition, a combination of fertilizers can be easily mixed in the hydroseeder tank and applied uniformly at relatively even proportions. This is especially useful for applying small quantities of fertilizer, such as micronutrients, which are difficult to spread evenly over large areas.

Fertilizer Incorporation—It is important that nutrients that are deficient and have low mobility be incorporated into the soil prior to sowing or planting. Incorporation is possible on gentle slopes but becomes very difficult with increasing slope gradients because of equipment limitations or slope stability. On sites where fertilizers containing immobile nutrients cannot be incorporated, an alternative is to create roughened soil surfaces (Section 5.2.2) prior to fertilizer application. Broadcast fertilizers will accumulate in the depressions of the surface. As soil gradually moves into the depressions over time through erosion (water, wind, or surface ravel), the broadcast fertilizers will become covered with soil. When this happens, immobile nutrients are accessible by roots and nutrient uptake is possible. Surface roughening also reduces the potential for fertilizers to move off-slope through erosion.

Some agricultural spreaders, called fertilizer banders or injectors, are designed to place fertilizer, or other soil amendments including mycorrhizae, at varying depths in the soil. Usually this equipment has a ripping shank or tine that loosens the soil, followed by a tube that drops the fertilizer, and coulters or rollers that close the furrow. As the bander is pulled through the soil, a line, or band, of fertilizer is created. Sowing and banding are often combined in one piece of equipment and applied at the same time. Fertilizer banders were developed for agricultural use and are limited by rock content and slope gradients, however, there are injectors that have been developed for wildland conditions (St. John 1995).

The most common approach to incorporating fertilizer is accomplished in two operations, broadcasting fertilizer on the soil surface and tilling it into the soil. In this approach, hydroseeders and broadcast fertilizer spreaders are used to apply fertilizers evenly over the soil, then the fertilizer is incorporated using tillage equipment outlined in Section 5.2.2.

5.2.2 TILLAGE

Introduction

Tillage is defined in this section as any mechanical action applied to the soil for the purposes of long-term control of soil erosion, reestablishment of native plant communities, and improve soil function. Most tillage equipment was developed for agricultural soils and has limited applicability for steep, rocky sites typically encountered in revegetation. This section describes the agricultural equipment that can be used for revegetating roadsides, as well as equipment specifically developed for extreme site conditions.

Among the reasons to use tillage in a revegetation project is to shatter compacted soils, incorporate soil amendments, and roughen soil surfaces. These objectives often overlap. For example, incorporating organic matter also loosens compacted soils and roughens soil surfaces. Identifying the objectives for the project will lead to selecting and effectively using the appropriate equipment to achieve the desired soil conditions (Table 5-5).

Shatter Compacted Soils

One of the primary purposes for tilling is to loosen compacted soils. When performed correctly, tillage can increase porosity in the rooting zone, increase infiltration rates, and increase surface roughness. For revegetation work associated with road construction and road obliteration,

Table 5-5 | **Types of tillage and equipment**

The appropriate tillage equipment for the project depends on project objectives.

	Shattering	Incorporating	Imprinting
Objectives	**Rippers and subsoilers**	**Disks, plows, excavator attachments**	**Dixon imprinter, excavator attachments, trackwalking**
Loosen compacted soil	Good	Good	Poor
Incorporate amendments	Poor	Good	Poor
Roughen surface	Good	Good	Good

tillage to break up deep compaction is important for reestablishing plant communities. Shattering compaction at depths of at least 2 feet is essential for the healthy growth of most perennial plant species. Without this measure, it may take decades for deep compaction to recover its original bulk density (Wert and Thomas 1981; Froehlich and others 1983). In a review of tillage projects on rangeland soils, Gifford (1975) found that deep tillage greatly reduced runoff, while shallow tillage had little effect. Still, tillage alone may not return a soil to its original bulk density or hydrologic function, nor will the effects of tillage last indefinitely, especially in non-cohesive soils (Figure 5-9) (Onstad and others 1984). Many factors affect the return to bulk densities and infiltration rates typical of undisturbed reference sites. These include the type of tillage equipment used, tillage depth, soil moisture during tillage, soil texture, presence of topsoil, and organic matter content.

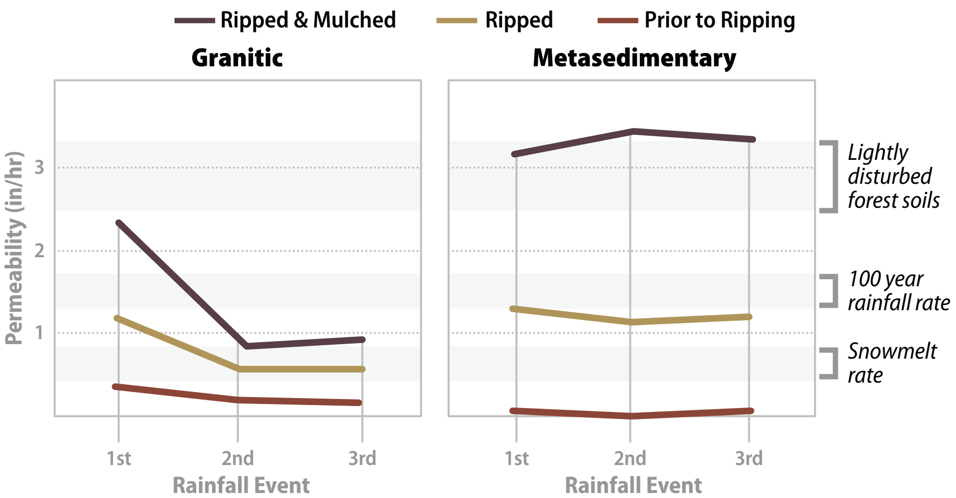


Figure 5-9 | **Benefits of ripping and mulching vary by soil type**

Short-term benefits of ripping (using a winged subsoiler) and mulching road surfaces vary by soil type, as shown in rainfall simulation tests on sites in northern Idaho. Granitic soils responded to ripping and mulching with increased permeability during the first storm, but permeability rates returned to near pre-treatments rates with successive rainfall events. Metamorphic soils reacted positively to both treatments and maintained high permeability rates after three rainfall events. Mulching improved permeability in both soil types. In fact, for metamorphic soils, the combination of ripping and mulching increased permeability to rates that were typical of lightly disturbed forest soils (adapted from Luce 1997).

There are two fundamentally different equipment designs for reducing compaction. One design lifts and drops soil in place, shattering compacted soil in the process. This type of equipment includes rock rippers, subsoilers, and "winged" subsoilers. The second design churns and mixes the soil. Equipment that falls into this category includes disk harrows, plows, spaders, and attachments to excavators. This type of equipment can also incorporate soil amendments, such as organic matter or fertilizers, in the same operation, as described in Section 5.2.2 (see Incorporate Soil Amendments).

The terms "subsoiling" and "ripping" are used interchangeably to describe soil-shattering operations. Soil shattering involves pulling one tooth, or a set of teeth, at various depths through the soil to break up compaction created by equipment traffic. The rock ripper is a common tool found on most construction sites. When used to break up compaction, one or two large ripper tines are typically pulled behind a large bulldozer at 1 to 3-foot soil depths. While this equipment will break up compaction in portions of the soil where the ripper tines have been dragged, it does not effectively fracture the compacted soil between the ripper tine paths (Andrus and Froehlich 1983). The effectiveness of rippers can be increased by multiple passes through the soil or by adding tines to the toolbar. Even on small machines, up to five tines can be added to increase soil shatter.

Rippers have also been adapted to increase soil lift between tine paths by welding wide metal wings to the bottom of each tine. These wings are angled upwards so the soil between the tines has greater lift, and therefore greater shatter when the soil drops behind the wing. When two or more tines are placed together on a toolbar, they work in tandem to more effectively break up compaction. The resulting equipment is called a "winged" subsoiler (Figure 5-10). Andrus and Froehlich (1983) found that the winged subsoiler was a far more effective tool for breaking up compaction. This equipment fractured over 80 percent of the compaction in several operational tests, as compared to 18 to 43 percent for rock rippers and 38 percent for brush rakes. However, winged subsoilers are not practical in all soils, especially those with high rock fragments, buried wood, or slopes greater than 3H:1V gradients.

Achieving good shatter at deeper soil depths requires that tillage equipment be adjusted for site-specific soil conditions, especially soil texture, soil moisture, and large rock content. Tines will slice through the soil, causing very little soil shatter, if soils are too moist during ripping. Subsoiling when soils are extremely dry can bring up large blocks of soils, especially when the soils are high in clays (cohesive soils).

It is important the winged subsoiler and rock ripper be adjusted to meet the soil conditions of the site. Making the proper adjustments can lead to greater shatter and more efficient use of tractor equipment. These adjustments include the following:

- Tine depth
- Tine spacing
- Number of tines
- Wing width and angle (for winged subsoiler)

For optimum shatter, the depth of the tines is adjusted based on the soil properties and moisture conditions. The tines are adjusted to be above a "critical depth," the point below which soils will not shatter effectively (Figure 5-11B). The critical depth changes for soil type and tine configuration. Soils high in clays with high soil moisture have shallower critical depths (Andrus and Froehlich 1983).

The closer the spacing of tines, the greater the shattering. The more tines that are placed on a toolbar, the more area of soil that can be shattered. However, where large rocks, slash, and roots are present, closely spaced tines will drag these materials out of the ground. Three to five tines are typically used for most soil types. Wing size, angle, and shape of the tines all play a role in breaking up compaction (refer to Inset 5-2 for specifications for winged subsoiler).

Typical settings for rock ripper and winged subsoiler equipment configurations are shown in Table 5-6. These are suggested settings and should not be applied without first monitoring the results of the equipment on the project soils. The most direct method for monitoring soil shatter is to measure the depth to the compacted soil with a soil penetrometer or shovel (Section 3.8.2, see Soil Structure). Immediately after a pass is made with the tillage equipment, the shovel or penetrometer is pushed into the soil and the depth to resistance (the compacted layer) is recorded. Measurements are taken every 6 inches across a small transect perpendicular to the direction of the tractor and spanning the width of the tillage disturbance. Plotting the depths

Figure 5-10 | **Winged subsoiler**

Soil shattering becomes more effective when wings are mounted on subsoil tines. This equipment is called a winged subsoiler.

Photo credit: Brent Roath

Inset 5-2 | **Contract specifications for a winged subsoiler**

A winged subsoiler consists of a self-drafting, winged subsoiler on a dolly mount, sized for use with a D-7 tractor. The unit consists of three-winged ripper tines capable of extending 12 to 34 inches below the draw bar. Wings shall be at least 20 inches wide with a 2-inch lift of the wings from horizontal. Tines shall have an individual tripping mechanism that automatically resets; tine spacing must be adjustable, and individual tines must be removable. Various wing patterns must be available and easily interchangeable. Implement must be capable of achieving maximum fracture of compacted soils (minimum 24 inches) in one pass (adapted from Wenatchee National Forest contract specifications).

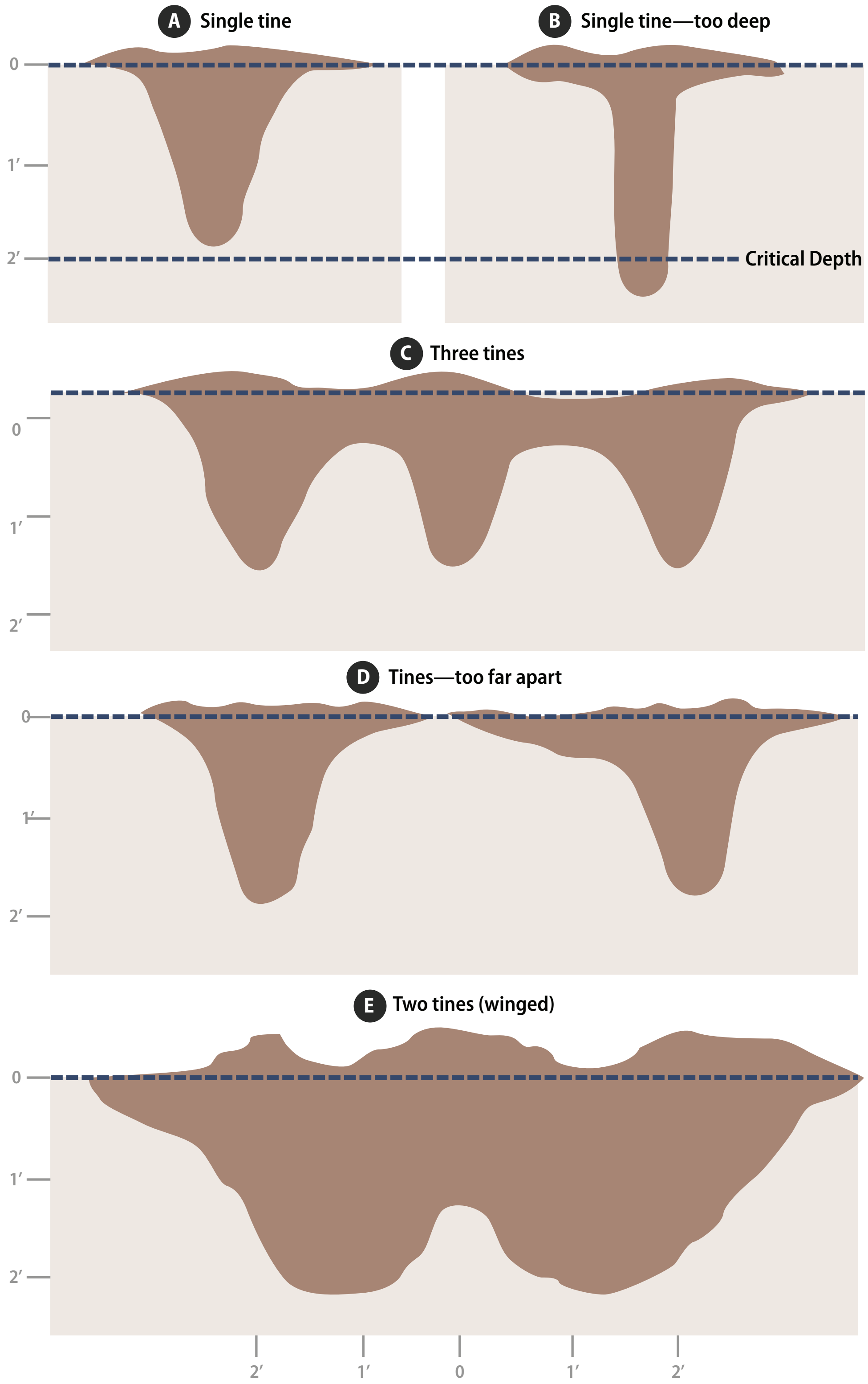


Figure 5-11 | **Subsoiler tine and wing configurations determine effectiveness**

The effectiveness of subsoiling or ripping equipment to shatter compacted soil is a function of tine depth, number of tines, distance between tines, and wing configuration. Pulling a single tine (A) above a critical depth does some soil shattering as compared to a single tine ripping deeper than a critical depth (B). Placing three or more tines together (C) can be more effective than one tine, but tines spaced too far apart will not effectively shatter the soil (D). Attaching wings to the tines is very effective in shattering compaction between the tines (E) (modified after Andrus and Froehlich 1983).

Table 5-6 | **Recommended design features for some tillage equipment**

Modified after Andrus and Froehlich 1983; Froehlich and Miles 1984

Item	Implement feature	Recommended design
Disk harrow	Disk diameter	40-50 in.
	Number of disks	6-12
	Average disk weight	>1,800 lbs
	Disk arrangement	Offset gangs, independent disks
	Max slope (cross slope travel)	<5:1 H:V
	Max slope (down slope travel)	5:1 H:V
Brush blade	Tine spacing	22-26 in.
	Tine depth	<20 in.
	Max slope (cross slope travel)	<5:1 H:V
	Max slope (down slope travel)	3:1 H:V
Rock rippers	Tine spacing	24-30 in. (one pass) 40-48 in. (two passes)
	Ripping depth	20-24 in.
	Number of tines	5 (one pass) 3 (two passes)
	Max slope (cross slope travel)	<5:1 H:V
	Max slope (down slope travel)	2.5:1 H:V
Wings of subsoilers	Ripping depth	18-22 in.
	Number of tines	3-4
	Tine spacing	30-40 in.
	Wing width	12-24 in.
	Wing angle	10-60°
	Max slope (cross slope travel)	<5:1 H:V
	Max slope (down slope travel)	2.5:1 H:V

to compaction on graph paper provides a cross-section of the shattering pattern (Figure 5-11 is an example of plotting soil shatter). If the shattering pattern is inadequate, adjustments can be made to the tine depth, tine spacing, and angle of the wing. If these adjustments fail to increase soil shatter, a second and perhaps third pass by the ripper or winged subsoiler can be considered. Successive passes made at 45 to 90 degrees angles from the first pass achieves the greatest benefit. Most soil-shattering equipment is attached to the tractor toolbar and is limited to slope gradients of 3H:1V or less. Subsoilers and rippers are best used for projects that consist of gentle terrain or obliterated road sections.

The excavator is good piece of equipment on steeper slopes where its arm can reach 35 feet up and down slope and decompact targeted areas of compacted soil. In this operation, the bucket of the excavator is placed several feet into the soil, lifted and dropped in place (Figure 5-12). Special attachments, such as the "subsoiling grapple rake" have been developed for the excavator that can decompact, incorporate, and remove rock and slash in the same operation (Archuleta and Baxter 2008).

Figure 5-12 | **Excavators decompact and incorporate soil amendments**

The excavator incorporates and decompacts soils by lifting the soil and dropping in place.

Photo credit: David Steinfeld

A general rule for tillage is to operate equipment on the contour to reduce the potential of water concentrating in the paths of the furrows and creating soil erosion and slope stability problems. This is especially important on steeper slopes where the potential for soil erosion and slope instability are greater. If several passes are made, it is important to make the last pass on the contour.

It is also important to consider that when cuts and fills are tilled, soil strength is reduced and the soils are less resistant to concentrated water. Improper road or slope drainage may result in rills and gullies on tilled soils, a situation that is less likely to occur when soils are compact. Therefore, on slopes that have been tilled, it is important that road water is directed away from fill slopes at least until vegetation has stabilized the slopes. It is important to discuss any tillage operation on slopes adjacent to roadways with the design engineer to ensure that slope stability and road objectives are not compromised.

Incorporate Soil Amendments

Tilling is used to incorporate fertilizers, organic matter, lime, and other amendments that are placed on the soil surface and evenly distributed in the soil. Tilling with these objectives requires equipment that mixes soil, such as plows, tillers, disks, chisels, and soil spaders. These types of equipment are tractor-drawn and limited to gentle slope gradients (5H:1V or greater) and soils low in rock fragments. They are not designed to break up deep compaction. Under most disturbed soil conditions, the best that can be expected from this equipment is tillage to a depth of 8 inches.

The excavator is also another tool for incorporating soil amendments. It has the advantage over tractor based equipment in that it can incorporate soil amendments several feet into the soil. It can also be used to move topsoil or organic matter to concentrated locations to create mounds or planting islands (Section 5.2.8). When islands are created for deep-rooted species, such as shrubs and trees, soil amendments are applied to the surface of the soil and incorporated several feet deep. Care must be taken on sites where natural soil horizons or soil layers have been placed (e.g. topsoil, liter, and duff) to prevent mixing these layers together.

Rippers and subsoilers are less effective in incorporating materials such as fertilizers or organic matter into the soil. Nevertheless, spreading mulch on the soil surface prior to ripping or subsoiling usually incorporates enough organic matter into the soil surface to enhance infiltration rates (Luce 1997). In the same manner, fertilizers applied to the soil surface, especially those containing immobile nutrients, will be mixed into the top several inches of soil and made available to surface roots.

Roughen Soil Surfaces

Tilling is often done to roughen the soil surface for erosion control and to create a more optimum seedbed (Section 3.8.5, see Surface Roughness). The micro-topography of a roughened surface consists of discontinuous ridges and valleys where the valleys become the catch basins for seeds and surface runoff. Seeds have greater opportunities to germinate and become established in the micro-valleys because of increased moisture, higher humidity, protection from the wind, and shelter from the sun. Surface roughening is a side benefit of the incorporating and shattering operations described in Section 5.2.2 (see Shatter Compacted Soils) and Section 5.2.2 (see Incorporate Soil Amendments).

Roughening is also accomplished by either scarifying or imprinting operations. Scarification is the shallow loosening of the soil surface using brush blades, harrows, chains, disks, and chisels. It does not loosen compacted soils below the surface. Because it only loosens the soil surface several inches, the benefits for revegetation are only seen during seed germination and early seedling establishment. Once root systems hit a compacted layer, which is typically present several inches below the surface, growth is curtailed.

Imprinting is a form of surface tillage that leaves the soil with a pattern of ridges and valleys. The equipment applies a downward compressive force to a metal mold, leaving an impression on the soil surface. Specialized imprinters have been developed for rangeland restoration. For example, the "Dixon" imprinter was developed to restore perennial grasses for rangelands in Arizona and other arid states. It consists of a roller with large angular metal "teeth" that is pulled behind a tractor. The imprinter creates a pattern of V-shaped troughs, 4 to 7 inches deep, encompassing approximately 1 ft^2 area (Dixon and Carr 2001a, 2001b). This equipment also has a set of ripping shanks attached to the tractor that shatters deeper compaction before imprinting.

Figure 5-13 | **Trackwalking compacts soils**

Trackwalking creates imprints on the soil surface, but will also compact surface and subsurface soils.

Photo credit: David Steinfeld

A common practice of imprinting is trackwalking (Figure 5-13). In this operation, a tractor is "walked" up and down cut and fill slopes, leaving a pattern of tractor cleat imprints on the soil surface, parallel to the slope contour, no deeper than several inches. These imprints are substantially shallower than those created by the Dixon imprinter, with less longevity. Because heavy equipment is used, trackwalking can compact soils. Compaction is not often considered when selecting trackwalking practices because soils of most roadside construction sites are already very compacted and trackwalking is unlikely to significantly increase compaction. This is one reason why trackwalking has been considered beneficial for erosion control and revegetation because it can create a somewhat better "short-term" growing environment and reduce surface erosion and sedimentation on very poor sites.

If the last operation on a construction site is to subsoil or rip soils 1.5 to 2 feet deep and leave the soil in a decompacted condition prior to revegetation, trackwalking would be more detrimental than beneficial on most soils in the long-term. The weight of the tractor used to create imprints would compact the tilled soil leaving the surface smoother (less rough) than if left alone. As noted before (Section 3.8.2, see Soil Structure), compaction reduces infiltration and increases runoff; therefore, trackwalking has the potential to increase in soil erosion. Rainfall simulation tests can be run on sites near the construction project that have been trackwalked and compared with those that have been left in an uncompacted state to determine the effects on runoff and soil erosion (Hogan and others 2007).

Figure 5-14 | **Soil imprinting with modified excavator bucket**

An alternative form of imprinting road cuts and fills that does not compact soils is welding angle iron onto the bucket of an excavator. As the excavator pulls top-soil into place and contours the slope, it presses the face of the bucket into the soil surface to form surface imprints.

Photo credit: David Steinfeld

An alternative to trackwalking is the use of the bucket of an excavator to pack and imprint the soil surface. Different patterns of steel "teeth" can be welded on the face of the bucket to achieve the desired surface micro-relief. Figure 5-14 shows an excavator bucket, with four strips of angle iron welded to its face, to create a pattern of 3-inch-deep impressions. The excavator, in this example, moves topsoil to the site, shapes the cut and fill slopes, and imprints the surface, all with one operation.

5.2.3 MULCHES

Introduction

Mulch is defined as a protective material placed on the soil surface to prevent evaporation, moderate surface temperatures, prevent weed establishment, enrich the soil, and reduce erosion. Mulches, therefore, have many functions or roles in the recovery of native vegetation to a disturbed site. Confusion often arises around the use of mulches on revegetation projects unless the reasons for using them are clearly defined. In this discussion, mulches are grouped into four uses based on the revegetation objectives:

- Seed Covering
- Seedling Mulch
- Soil Improvement
- Seed Supply

For most projects, mulches are used to meet more than one objective but this is problematic when the methods for achieving more than one objectives are not compatible. For example, erosion-control products and practices that are effective for controlling surface erosion are not always optimal for establishing vegetation. For this reason, it is important to understand the objectives for mulching when selecting mulch types and application methods.

This section describes the objectives for applying mulches and the potential mulch sources. Many publications and much research are available on the effectiveness of mulches for erosion control and surface stabilization. This discussion focuses primarily on the characteristics of mulches for plant establishment.

Seed Covering

One of the principal reasons for applying mulch is to enhance seed germination and early seedling establishment. During this critical period, desirable mulches will:

- Protect seeds and young seedlings from soil splash, sheet erosion, and freeze-thaw
- Keep seeds moist during germination
- Keep soils moist during seedling establishment
- Moderate surface temperatures during germination
- Prevent salts from wicking to the surface and harming germinating seedlings

The characteristics of mulch materials that make an ideal seed covering are those that protect seeds from drying winds, solar radiation, high evapotranspiration rates, and surface erosion while still allowing seeds to germinate and grow through the mulch into healthy seedlings. Long-fibered mulches placed at the appropriate thickness, usually meet these characteristics. A long-fibered mulch is composed of particles that are long and thin (at least several inches long with a length to width ratios of greater than 4:1). Such materials include straw, wood strands, pine needles, and shredded wood (ground or chipped woody material).

When applied correctly, the strands of long-fibered mulch loosely pack over each other, much like "pick- up-sticks," forming large air spaces or pores (Figure 5-15). Large pores function much like the air spaces in building insulation by moderating extreme temperatures. The bridging effect of the long particles also makes some of these materials more stable, and less prone to erosion or movement. Depending on the long-fibered material and erosivity of the site, it may not be necessary to apply a tackifier, though heavier materials, such as shredded woods or wood strands are less susceptible to wind displacement than lighter material like straw.

Figure 5-15 | **Long-fibered mulches**

Long-fibered mulches, such as the wood strands shown below, create a good growing environment because seeds and seedlings are protected from excessive drying during germination and early seedling establishment. On sites where freeze-thaw is prevalent, long-fibered mulches can insulate the soil and protect emerging seedlings.

Photo credit: David Steinfeld

Long-fibered materials that are not recommended for mulch unless they are stabilized include shavings and materials less than two inches in length (Robichaud 2013).

Short-fibered mulches are much shorter in length and are typical of materials found in hydromulches. Comparing short-fibered mulches to long-fibered mulches, long-fibered mulches can be applied at greater thicknesses, which help maintain surface soil moisture and higher humidity around germinating seeds and emerging seedlings. In addition, long-fibered mulches can mitigate the effects of frost heaving at the soil surface (Kay 1978), significantly reduce high surface temperatures (Slick and Curtis 1985), and allow sunlight penetration, which enhances seed germination and seedling establishment. Large pores created by long-fibered mulches also allow better gas exchange between the soil and atmosphere (Borland 1990).

Short-fibered mulches usually have smaller pores and form denser seed covers. These materials are applied thinly (Figure 5-16); therefore, they offer less insulation than long- fibered mulches and have less value as a seed covering. Some researchers suggest that very fine textured mulches can increase surface evaporation by wicking moisture from the soil to the surface of the mulch (Slick and Curtis 1985; Borland 1990; Bainbridge and others 2001). These types of mulches are derived from several sources: paper fiber, which provides little cover or slope protection and more typically, wood fiber, which offers longer duration cover and slope protection. Short-fibered mulches are effective as an erosion-control cover when applied with a tackifier, but many are considered inferior to long-fibered mulches for germination and early seedling establishment (Kill and Foote 1971; Meyer and others 1971; Kay 1974, 1978, 1983; Racey and Raitanen 1983; Dyer 1984; Wolf and others 1984; Norland 2000). Recently developed products, like bonded-fiber-matrix (BFM) and High Performance Growth Media, are also applied hydraulically, but their fibers are mechanically kinked so that when applied at recommended rates provide loft and pore space suitable for better seed germination while also providing a high level of slope protection (Figure 5-17).

Compost are being used with increasing frequency on projects as a seed mulch. Composts are different from long-fibered mulches in that the fibers are much shorter in length (typically less than an inch) and composted. Because they have less loft, compared to long-fibered mulches, they do not perform as well, and may dry out faster, which could reduce germination rates on drier sites. When composts are applied to a slope with pneumatic blower or a high-speed conveyor to depths ranging from 1 to 2 inches, it is called a compost blanket. Seeding involves applying the compost blanket, then seeding and covering the seed with ¼” to ½” depth over the seed. Most pneumatic blowers can mix seed with the compost and apply it as a thin layer over the compost blanket as a final pass. This is the easiest method but if this is done, then increasing the seeding rate should be consider because some seeds will be near or on the surface of the compost, lowering the germination rate of the seed mix. Applying seeds with a pneumatic mulch blower is done by placing seeds in a “seed metering bin” attached to most mulch-blowing equipment. This equipment meters seeds into the mulch as it is being applied. The rate at which the metering system delivers seeds is calibrated prior to mulching to obtain the desired seed density (refer to Section 5.4.1 for seed calibration methods).

The application of a tackifier is important because the medium-length fibers of compost do not provide enough weight and bridging between particles to provide protection from wind and water erosion. With tackifiers, composts can adhere to steep slopes in high rainfall areas. Compost blankets have a high moisture holding capacity and its dark color captures heat which aids germination. In addition, compost blankets provide nutrients to plants, which eliminates the need for fertilizer, and over time increases soil organic matter. Compost derived from yard debris is readily available in some areas where it is produced to eliminate organic matter from the waste stream.

Erosion mats are another type of seed cover (Section 5.2.3, see Erosion Mats). These materials come in rolls or sheets, which are laid out on disturbed soils and anchored in place after seeds have been sown. They are composed of such materials as polypropylene, straw, coconut, hay, wood excelsior, and jute. Good characteristics of erosion mats for seed germination and

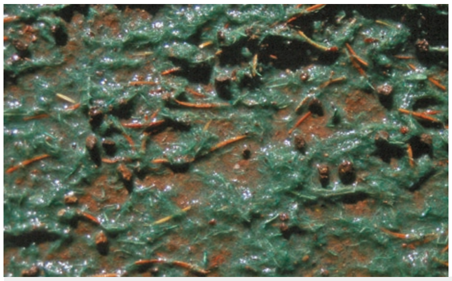


Figure 5-16 | **Hydromulch**

Hydromulch with tackifier can stabilize the soil surface for up to a year but does not necessarily create an optimum environment for germinating seeds. The short-fibered textures typically form a covering that is too thin to maintain moisture around the seeds during germination when the weather is dry. The hydromulch (dyed with a green tracer) shown in this picture is applied at approximately 1,500 lb/ac. This low application rate may be acceptable on sites where soil erosion potential is low and surface soil moisture is high and seeds do not need to be covered for germination.

Photo credit: David Steinfeld

Figure 5-17 | **High performance growth media**

At 4,000 pounds per acre, High Performance Growth Media, such as Flexterra®, provides a quarter of an inch of loft which creates a better environment for germination than hydromulch.

Photo credit: Profile Product

early seedling growth are those with enough loft, or porosity, to provide for optimum seed germination. Erosion mats create a micro-environment for seed germination while protecting the soil and allowing some sunlight to penetrate to the surface of the soil (Figure 5-18). It is important to recognize that the plastic netting in these mats degrade at varying rates depending on the climate and soil conditions. For example, on cool-dry sites, typical of high elevations, decomposition rates are slow and plastic may last for many years. Plastic netting that does not break down quickly can be a hazard to wildlife, entangling amphibians, reptiles, and birds. To reduce this hazard, many state DOTs are requiring that all erosion control mattings be fully biodegradable.

On sites where vegetation is expected to take several years to establish (e.g., arid, high elevation sites), it is important to apply a mulch with a longevity of more than one year. Materials with greatest longevity are most long-fibered wood mulches, as well as erosion mats made from coconut fiber. Straw, hay, and short-fibered products are less likely to be present after the first year however a High Performance Growth Media is available that is made of coconut fiber and it claims a 24-month functional life.

Mulching for seed covering is critical on sites that have high evapotranspiration rates during germination, unstable soil surfaces, susceptibility to freeze-thaw, or high soil pH. Mulching may be less important on sites where soil surfaces do not dry out during seed germination or on projects where seeds have been covered by soil.

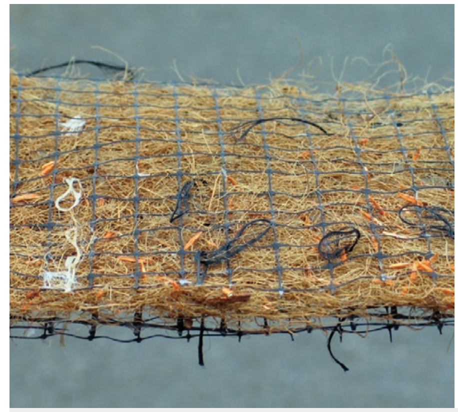


Figure 5-18 | **Erosion mat**

Erosion mats can be good seed covers. Mats with the highest loft create the best microenvironment for seed germination while allowing some sunlight to penetrate to the surface of the soil. A consideration of the use of these products is how fast they decompose and the effects on wildlife.

Photo credit: David Steinfeld

Seedling Mulch

Mulch is placed around newly planted or established plants to improve survival and growing conditions by:

- Reducing surface evaporation
- Preventing the establishment of competing vegetation
- Moderating surface temperatures
- Allowing water infiltration

Studies have shown that survival and growth of young trees are significantly increased by applying mulches around seedlings at the time of planting (DeByle 1969; Lowenstein and Pitkin 1970; Davies 1988a, 1988b). Mulching around seedlings results in the greatest benefit on hot and dry sites (typically south and west aspects) and sites with aggressive competing vegetation. It is less important to apply mulch around seedlings on sites that have a low potential for establishing competing vegetation the first several years after planting or sites that have low evapotranspiration rates or high rainfall during the summer months.

Seedling mulches are applied either as an organic aggregate, rock, or as sheet mulches. Organic aggregate mulches consist of shredded or chipped wood derived from bark, wood, branches, sawdust, or lawn clippings. Rock aggregate mulches consist of a layer of rocks placed around each seedling. Sheet mulches are large pieces of non- permeable or slightly permeable materials made from translucent plastic, newspaper, coconut fiber, or geotextiles (woven fabrics) that are anchored around planted seedlings (Figure 5-19).

Figure 5-19 | **Sheet mulch**

Sheet mulches come in a variety of materials, such as the paper/cardboard product shown in this picture. The size of the sheet mulch is large enough to keep competing vegetation away from the seedling. The 3-by-3-foot sheet mulch shown around this Pacific madrone (*Arbutus menziesii*) seedling is the minimum size for this site.

Photo credit: David Steinfeld

Sheet Mulches—A variety of sheet mulches are available commercially. These mulches are popular because of the relative ease of transport and installation. The effectiveness of sheet mulches increases with the size of the sheets. For most hot, dry sites, a 2.5-by-2.5-foot sheet is considered the minimum dimension (Cleary and others 1988). On harsher sites, 3-by-3-foot or even 4-by-4-foot sheets are necessary to control competing vegetation. When purchasing and installing sheet mulches, it is important to consider (after Davies 1988a, 1988b):

- **Selecting the right size**—The size of the mulch is based on site conditions and the type and amount of competing vegetation. For example, a hot, south-facing site with full cover of competing grasses will need a large sheet mulch; a north-facing slope with scattered forbs and grasses will suffice with a smaller size.

- **Ordering only opaque materials**—Translucent materials are not used as sheet mulches because weed seeds can germinate and grow under these materials. During summer, surface temperatures under translucent materials can be lethal to seedling roots.
- **Using sheet mulches with long life spans**—It often takes three to five years for seedlings to become established on hot, dry sites and for this reason it is recommended that the sheet mulch have a durability of three years (Cleary and others 1988). The use of fully biodegradable materials is recommended.
- **Weeding or scalp around seedlings prior to installation**—Sheet mulch cannot be installed properly without vegetation being completely removed.
- **Mulching immediately after planting**—In Mediterranean climates, waiting until later in the spring to mulch runs the risk that competing vegetation will have depleted soil moisture, thereby making the mulch ineffective during the first growing season. This can be avoided, by applying mulch during or immediately after seedlings are planted.
- **Staking or anchoring all corners of the mulch**—The sides of the mulch sheets can be easily detached by wind, animals, or competing vegetation growing under the mulch sheets. It is important that the corners are staked. Burying all edges of the sheets with soil provides the greatest effectiveness.
- **Visibility**—Sheet mulches can be very apparent in high visibility areas. Measures to reduce unsightliness of sheet mulches include covering with aggregate mulches such as hay, straw, or wood mulch, or selecting sheet colors that blend into the area.

Organic Aggregate Mulch—Organic aggregates are another group of materials that, when placed thickly around installed plants, will control the establishment of competing vegetation and reduce surface evaporation (Figure 5-20). These aggregates include hay, straw, or chipped and shredded wood materials. Organic aggregates are often used in highly visible areas because they are more aesthetic in appearance than sheet mulches. They are also used in planting islands for long-term control of competing vegetation.

The longevity of organic aggregate mulches is a function of the C:N ratio, texture, and depth. High C:N materials, such as uncomposted shredded wood, bark, or sawdust, will last longer than low C:N materials, such as composted yard materials, because these materials are in the initial stages of the decomposition cycle. Coarse-textured materials (Figure 5-21 A, B, C E, F), which include long-fibered mulches have greater longevity than finer-textured materials (Figure 5-21D) because coarser materials have less surface area per volume of material for microbial break down (Slick and Curtis 1985). Coarse-textured materials also tend to hold less moisture, which slows decomposition rates. The longevity of an organic aggregate mulch also depends on the application thickness—the thicker the layer of mulch, the longer it will last. In many climates, coarse-textured materials, such as shredded wood, can last for years on the surface of the soil.

The same factors that affect longevity (e.g., texture, C:N ratio, depth) also determine the effectiveness of aggregate mulches in deterring seed germination of unwanted vegetation around the seedling. Coarse-textured mulches are excellent because they hold very little moisture at the mulch surface and, therefore, are poor environments for seed germination of unwanted vegetation. Alternatively, fine-textured mulches create a more favorable environment for seed germination because they hold more moisture and are in closer contact with seeds. For this reason, many fine-textured materials, such as composts, are excellent growing media for weed seed germination and establishment. As discussed in Section 3.11.4, mulch materials with high C:N ratios discourage growth of weedy annuals because high C:N materials remove available nitrogen that would otherwise give these species a competitive advantage. The effectiveness of a mulch in discouraging the establishment of competing vegetation generally increases with the thickness with which it is placed on the soil surface (Baskin and

Figure 5-20 | **Mulch conserves soil moisture and inhibits the establishment of unwanted vegetation**

This photograph was taken in late summer, months after adjacent soils had dried out. The lack of competing vegetation and the low surface evaporation resulting from the placement of 3 to 4 inches of coarse sawdust resulted in very high soil moisture. In addition, the high C:N ratio of the sawdust was believed to be a factor in inhibiting the establishment of unwanted vegetation.

Photo credit: David Steinfeld

Baskin 1989). The most effective mulch thicknesses are between 3 and 4 inches (Pellett and Heleba 1995; Ozores-Hampton 1998), but thicknesses as low as 1.5 inches are effective for some small-seeded weed species that need sunlight for germination (Penny and Neal 2003).

Organic aggregate mulches have several advantages over sheet mulches. First, organic mulches can be applied over a much larger area than sheet mulches. Some projects have organic mulches covering the entire site, while other projects concentrate it in strategic areas, such as planting islands. Second, organic aggregate mulches moderate surface soil temperatures, whereas sheet mulches can increase surface temperatures. Mulch thicknesses of 3 inches have been found to reduce soil temperatures below mulch layers by 8 to 10 degrees F (Slick and Curtis 1985; Steinfeld 2004), which can benefit the growth of seedlings on very hot sites. The insulative quality of mulches also affects the seasonal heating and cooling patterns in the soil. Soils under thick mulches take longer to warm in the spring, but in the fall, take longer to cool down. Depending on the temperature and rainfall patterns of a site, this could influence seedling establishment.

Mulch can create problems to planted seedlings if it is placed in contact with the plant stem. The high moisture around the stem can be conducive to pathogenic injury. On southern exposures, heat will build up at the surface of, and directly above, the mulch, creating extremely high temperatures on warm summer days. The high temperatures can cause heat damage to stems of young seedlings. It is important, therefore, to keep mulch several inches away from the stem of planted seedlings.

Rock Mulch—Rock can be an effective mulch cover around seedlings. It consists of placing any size rock fraction (e.g. gravels, cobbles, stones) around each seedling. Rock protects the surface from erosion, evaporation, and weed establishment and it may be naturally available on a project site. As with organic aggregate mulches, rock is placed in a 1 to 2 feet radius around and at least several inches deep. Rock is kept away from the stem of the seedling to avoid heat damage. Prior to installation, unwanted vegetation is removed. One of the disadvantages of using rock mulch is that rock fragments can move downslope on steeper slope gradients and bury seedlings. Applying rock on gentler slopes or creating small planting benches where mulch can be placed around the seedling are recommended options.

Soil Improvement

Mulches are sometimes used specifically to increase the nutrient and organic matter status of a soil. Composted organic materials are used for these purposes and are characterized by having low C:N ratios, high nutrient levels, fine textures, and dark colors. While these materials are typically more effective when incorporated into the soil, they are sometimes applied to the surface of the soil where tillage is not feasible (steep and rocky) or tillage costs are unaffordable. Where composted organic materials are applied on the soil surface, the nutrient release rates will be much slower. Refer to Section 5.2.5 for more information on composts.

Seed Supply

The objectives for applying mulch on some projects are to spread materials that contain native seeds. Several mulch materials carry native seeds, including duff, litter, and straw from native seed production fields. When these materials are applied to the soil surface, seeds will germinate given favorable environmental conditions.

Litter and duff are organic layers that form on the surface of the soil under tree and shrub plant communities. They are years of accumulated leaves and needles at varying degrees of decomposition. Included in these layers are dormant seeds, many of which are still viable. When the duff and litter are collected and spread on disturbed sites, the environmental conditions for breaking the dormancy of the seeds present in the material may be met and seeds will germinate.

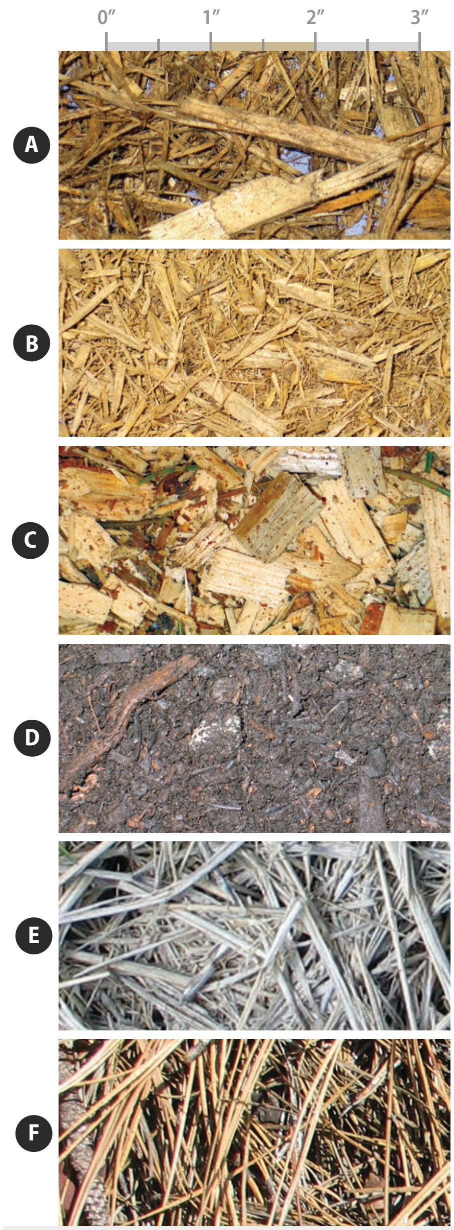


Figure 5-21 | **Different types and textures of organic aggregate mulches**

(A) freshly ground coarse shredded wood passing a 3-inch screen; (B) freshly ground coarse shredded wood passing a 1.5-inch screen; (C) freshly chipped wood; (D) composted mixtures of ground wood, biosolids, and yard wastes passing a 1.5-inch screen; (E) weathered straw; (F) ponderosa pine needles. All materials are coarse textured except compost (D).

Photo credits: David Steinfeld

Litter and duff can be collected from adjacent forest- or shrub-dominated sites or salvaged prior to slope construction. Reapplying them to disturbed sites completes several operations at once: supplies native seeds, covers seeds, and increases long-term nutrient capital. Although this practice might seem expensive or impractical, when compared with purchasing and applying seeds, fertilizer, and mulch separately, the costs could be comparable. Refer to Section 5.2.3 (see Litter and Duff) for more information on litter and duff.

One of the byproducts of native grass seed production is the stubble that remains in the fields after seed harvest. This stubble contains varying quantities of unharvested seeds which eventually end up in bales. If bales are stored in dry conditions, seeds can remain viable for several years. When hay bales that contain the native seeds are spread as a mulch on disturbed sites, seeds come into contact with soil and eventually germinate. It is important when acquiring native hay that the species and the source of the seed lot is appropriate for the site. Refer to Section 5.2.3 (see Straw and Hay) for more information on straw and hay.

Selecting the Appropriate Mulch Materials

A variety of materials can be used as mulches, including the following:

- Shredded wood
- Erosion mats
- Hay and straw
- Manufactured wood strands
- Duff and Litter
- Composts
- Hydromulch

The following sections describe these materials and how they are used in revegetation projects. Figure 5-21 shows examples of some of these mulches.

Shredded Wood

Mulches produced from woody materials are used primarily for seed covering and seedling mulching. There is usually a readily available source of wood material from project sites situated in forested environments. Branches, stems, bark, and root wads are typical waste products from clearing and grubbing that can be shredded, chipped or mulched on site to produce various types of wood mulch. In the past, this material has been burned or hauled to waste areas for disposal. With greater burning restrictions and higher hauling costs, chipping these materials and returning them to disturbed sites as mulch are practices that are becoming more common.

Shredded Wood Production—Creating mulch from right-of-way clearing woody material requires planning and coordination. First the road contractor piles the woody right-of-way clearing debris into "slash piles." These piles include tree boles, bark, branches, and stumps, but it cannot contain large rocks or other inert materials that can cause wear or damage to the equipment. When clearing and piling is completed, a company that specializes in processing wood waste is contracted (typically by the road contractor). In this operation, equipment is brought to each slash pile and materials in these piles are processed into mulch. The resulting wood mulch is either placed in piles adjacent to the slash piles or transported to designated storage sites (Figure 5-22). The timing of these operations may be limited by fire restrictions in the western United States from mid-summer through early fall.

If undesirable plant species are included in the slash piles, spread of these species is likely to occur when they are processed and applied as a mulch. This can be prevented by identifying these plant populations on site during the weed assessment (Section 3.11.6) and avoiding placing them into slash piles.

Figure 5-22 | **Shredded wood piles are kept below 12 feet for safety reasons**

Shredded wood piles generate heat as they compost (A). A 4-foot-long thermometer (B) can be inserted into the pile to determine internal pile temperatures. Some operations require piles to be turned when a specific temperature is reached.

Photo credit: David Steinfeld

It is important to define the desired mulch characteristics prior to processing the piles. For example, the size and shape of the wood particles will determine their stability and propensity to move down slopes. Long strains of wood particles tend to be more stable than short strains because they knit together and have greater weight. Obtaining the proper size and dimension can be difficult because there is a variety of wood waste reduction equipment that produce different dimensions and fibrosity (the degree that wood fibers are separated). Obtaining the desired the particle size and shape by specifying a screen size the material should pass does not always produce the desired material. Screens only sort for two dimensions, and not for length or fibrousness. Identifying the type of waste reduction equipment can narrow the type of mulch produced (Table 5-7). For example, mulch produced by shredders is long and fibrous (Figure 5-23 A and B), whereas mulch produced from chippers has sides that are of nearly equal lengths, with fibers still intact (Figure 5-23C). It is important that the correct equipment and screen sizes are used. It can be beneficial for the designer to request the contractor processing the material to send a sample of the different mulches that their equipment produces. In addition, being present at the beginning of the operations can assure that the proper material is being produced.

Table 5-7 | **General types of wood waste reduction equipment**

Modified from Re-Sourcing Associates and CPM Consultants 1997

General equipment types	Examples	Feedstock	Particle geometry
Chippers	Disc chippers, drum chippers	Whole logs, clean residuals	Clean edge, two-sided
Hogs	Swing hammer, fixed hammer, punch and die, mass rotor	Wood waste, stumps, land clearing debris	Coarse, multi-surfaced, fibrous
Shredders	Low speed-high torque, high speed	Wood waste, stumps, land clearing debris	Coarse, multi-surfaced, fibrous
Hybrids	Knife hogs, pan and disc	Wood waste, stumps, land clearing debris	Semi-coarse

Generally, the coarser the size of the mulch, the less expensive the production costs because more mulch of coarser size can be produced in a given time frame than smaller textured mulch. Other factors, such as tree species, moisture content, and portion of tree processed, affect the characteristics of the mulch. If the wood is wet during processing, it is more likely to be shredded; if it is dry, it will be more chip-like. There is also variation in mulches based on species of origin. For example, ponderosa pine (*Pinus ponderosa*) and western juniper (*Juniperus occidentalis*) tend to create more fibrous mulch than lodgepole pine (*Pinus contorta*). Processed root wads tend to be more fibrous than boles of trees. They may also contain large rocks which will damage processing equipment and need to be removed prior to processing or set aside and not used.

The shredded wood operation requires space to store the pre-processed woody debris, operate the processing equipment, and a storage site for the processed shredded wood. Depending on the operation, this could require a significant area. It is important to consider the size of the processed shredded wood piles when determining space requirements. Standards for pile heights of no greater than 12 feet are often used for fire and safety reasons. Piles larger than this height may be prone to spontaneous combustion. Long stemmed thermometers are available to monitor interior pile temperatures. One consideration for pile locations is the distance to the areas being mulched. Travel time between mulch piles and application areas can be as longer than the actual application of the material.

Purchasing Shredded Wood—On projects where waste materials are not available for mulching, purchasing shredded wood may be an option. Overall costs are much higher than processing waste wood on site because of the purchase of the material and transporting to the site. If commercial mulch sources are nearby, transportation costs are significantly reduced. Testing the shredded wood is important to obtain suitable material. Methods and specifications can be developed that are similar to those provided in Section 5.2.5.

Applying Shredded Wood—Shredded wood is applied in several ways—pneumatic mulch-blowing equipment, adapted manure spreaders, and rock slingers. Pneumatic mulch blowing equipment (Section 5.2.3, see Seed Covering) has varying transport capacities, ranging from 25 to 100 yards of material (Figure 5-23).

Figure 5-23 | **Blowing equipment is used to apply mulch on steep slopes**

Compost and shredded wood are applied on steeper slopes with mulch blowing equipment which is pneumatically delivered to the site through an application hose that can reach several hundred feet up steep slopes (A) with enough force for ample delivery of mulch (Image B is a close up of the application of mulch near the top of Image A). Large trucks can hold between 75 and 100 yards of mulch (A), while smaller trucks can hold up to 25 yards (C). A tackifier is added to compost to increase surface stability on steep slopes.

Photo credits: David Steinfeld

An application hose is positioned where mulch is to be applied and is pneumatically delivered from the mulch bins to the site. The amount of mulch applied depends on the revegetation objective. For seeding, application rates range from 100 yd^3/ac (0.75-inch thickness) to 135 yd^3/ac (1.0-inch thickness). For seedlings, mulch application ranges from 400 yd^3/ac (3-inch thickness) to 540 yd^3/ac (4-inch thickness). Note: The higher rates used for mulching seedlings are only used in close proximity to the plants. The remaining areas are mulched at a lower rate.

When applying shredded wood for erosion control objectives, the particle size of the material may be as important as the amount of material applied. On compacted soils, where overland flow is expected from heavy rainstorms, shredded wood lacking material smaller than an inch thick in length performs better in reducing sediment loss than material with finer wood. This coarse material can be applied at 50 to 60 percent ground coverage with good erosion control (Foltz and Wagenbrenner 2010).

Application rates depend on factors such as length and diameter of hose, blowing equipment, elevation rise, and dimensions of the area being covered. Rates of application typically range from 25 to 35 yd^3/hr. If mulch is applied at a 1-inch depth (134 yd^3/ac), it would take between 4 to 5 hours to cover an acre. These are optimum rates because they do not account for the time it takes to travel to the mulch source, load the mulch bin, and travel back to the application site. The time required to make these trips can sometimes be longer than the actual application time for mulching. Using larger transport capacities is one way to significantly reduce the time associated with refilling mulch bins.

Mulch blowing equipment can be used on any slope gradient that can be accessed by foot. By using ropes, slope gradients of up to 1H:1V can be accessed. Hose lengths can be attached to extend the delivery of mulch up to 400 feet. Because mulch is delivered through hoses, the system will plug if the size of the shredded wood exceeds the tube size. It is therefore important that mulch be free of large pieces of wood. Using a mulch blower is an excellent method for evenly applying shredded wood, but frequent monitoring by inspectors is important to ensure that the specified amount of mulch is being applied.

Shredded wood can also be applied with modified manure spreaders (Figure 5-24). Depending on the type of modifications, this equipment can apply shredded wood at a much faster rate than mulch blowing equipment, however this equipment generally is limited by the distance it can cast the material which is typically ranges from 35 to 75 feet depending if it is being applied upslope (less distance) or downslope (greater distances). Tackifiers are not typically applied to shredded wood after it is placed because this material is less susceptible to wind erosion than mulches that are finer textured and lighter.

Seed Placement during Mulching—Seeds can be sown prior to or during mulch operation. Seeds that are sown prior to mulching can be done with dryland sowing methods, hydroseeding, or through the pneumatic mulching equipment (Section 5.2.3, see Seed Covering). A thicker layer of shredded wood is applied in a second pass at a depth between 0.5 and 1.0 inches over the seed.

Figure 5-24 | **A manure spreader adapted to side cast shredded wood**

Shredded wood can also be casted from adapted manure spreaders. On this project, the seed mix was sown using a hydroseeder, then 0.75 inches of shredded wood was applied over the seeds.

Photo credit: David Steinfeld

Erosion Mats

Erosion mats (e.g. erosion control revegetation mats and rolled erosion control products) are manufactured blankets or mats designed to increase surface stability and control erosion. They are applied in direct contact to the soil surface for control of sheet erosion and to aid in the establishment of vegetation.

A multitude of products are on the market, with a range in design and costs. Determining which products will meet project objectives at the right price can be challenging. Several State Departments of Transportation periodically evaluate and compare the shear stress, soil erosion protection, longevity, and other characteristics for these products (Caltrans 2003; Kemp 2006), and these documents are available on the internet. State of Washington and State of Oregon DOTs are moving to require that all erosion control mattings be fully biodegradable. Because the installed costs of erosion mats can be expensive, it is important that the job is done correctly. Taking the time to select the appropriate erosion mats, native species mix, and seed placement techniques is essential for ensuring that revegetation is successful. Small field trials using different species and erosion mats can help in these decisions (Figure 5-25).

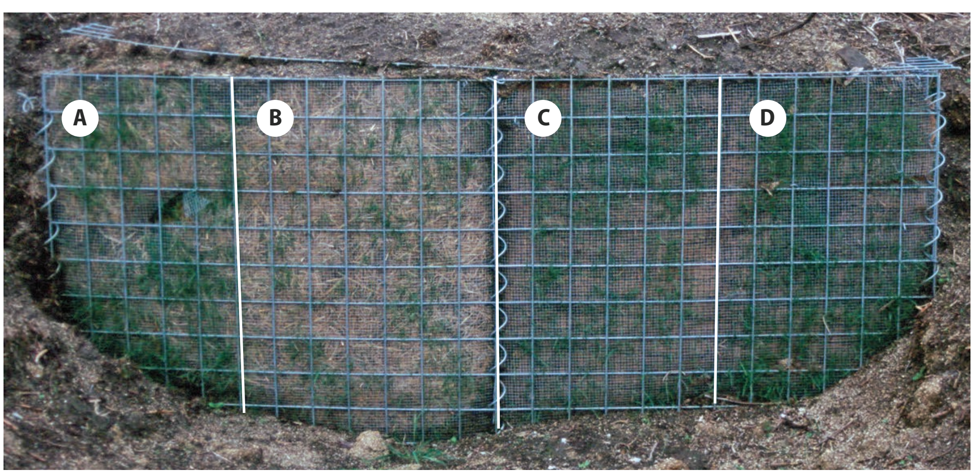


Figure 5-25 | **Field trials of species and materials**

Small field trials can help select the most appropriate species and materials for a project. The trial shown in this photograph compared straw mat (A and B) with a polywoven mat (C and D). It also compared the growth of blue wild rye (*Elymus glaucus*) and California fescue (*Festuca californica*) (A and C). The first-year results indicated that there was much better establishment of grasses on the polywoven erosion mat than the straw mat, yet no difference in species growth. Maintaining the trial for two years showed that California fescue outperformed blue wild rye. These results led to using California fescue and the polywoven erosion mat for the project described in Inset 5-3.

Photo credit: David Steinfeld

The same characteristics that create an optimum environment for seed germination in other mulches are also important to consider when selecting erosion mats. Typically, products that protect the seeds from drying out but allow light and space for germinating seeds to grow into seedlings will perform best for vegetation establishment. The thicker erosion mats with the most loft typically have better conditions for seedling establishment than thinner materials however, if the mat is too thick, seedlings will not be able to emerge from the fabric.

The drawbacks to erosion mats are generally not in the product itself but in how it is applied to the site. Poorly applied erosion mats can result in sheet and rill erosion under the fabric. To avoid this problem, several important measures can be taken when installing erosion mats. First the surface of the soil is smoothed to a uniform surface texture before the mat is placed. Landscape staples or pins are then installed at a specified spacing to hold the matting and ensure in intimate contact with the soil surface. The matting is trenched or keyed into the soil at the upper reaches of the fabric to prevent overland water flow from undercutting the mats.

Seeds are sown on the site prior to installing erosion mats. Because installation is commonly performed by the road building contractor, it is important that the designer works with the contractor to assure that seeds are being sown during the seeding windows. Seeding can be done using any type of seeding method (e.g., hydroseed, drill, or hand broadcast) however, once the slopes have been sown, care must be taken during and after mat installation to avoid disturbing the seed. Unless the seeds are extremely small, sowing seeds over installed erosion mats is not recommended because larger seeds will hang up in the fabric. Small seeds can be applied over erosion mats if tackifiers are not used and if the timing is such that sufficient rain will move it through the erosion mat to the soil surface.

Some manufacturers offer erosion mats that are impregnated with seeds, eliminating the need for sowing. This method is advantageous on steep slopes or soil-faced gabion walls (Inset 5-3) where placing seed prior to

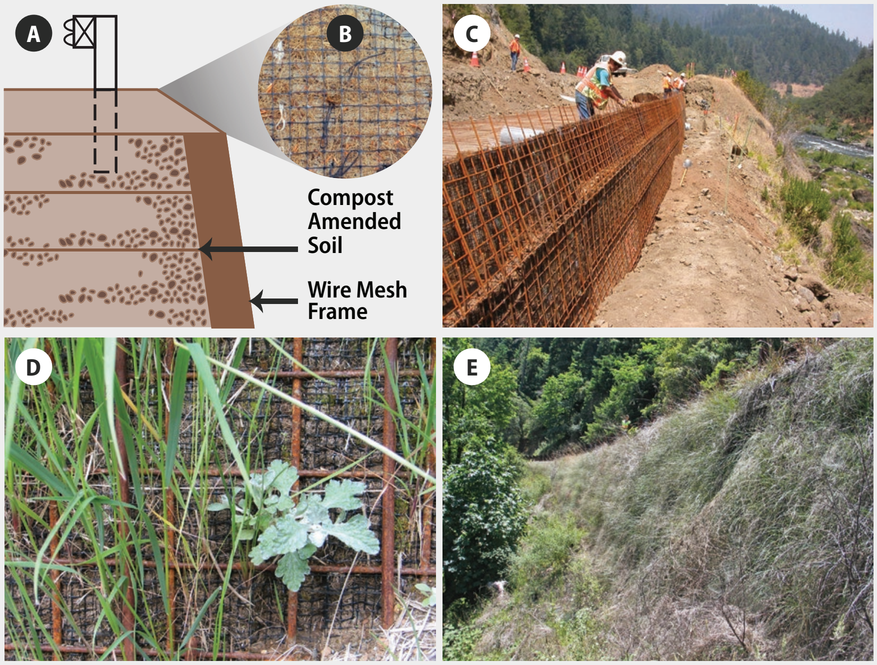
Inset 5-3 | **Case Study—Erosion mats with native grasses and forbs**

Reconstruction of the Agness-Illahe Highway required building long sections of gabion walls. Because this highway was visible from the Rogue River (a designated "wild and scenic" river in southwestern Oregon) and was heavily traveled by river runners and fishermen, it was important that the gabion walls be visually screened using native plants. Gabions were designed to hold 12 inches of compost-amended soil (topsoil was not available) on the face of the walls by wire mesh frames (Image A in the illustration below). Placement of seeds at the surface of the gabion wall was problematic. Several small plots using different erosion mats, seed mixes, seed rates, and seed-attaching methods were tested to determine how to best meet the revegetation objectives (Figure 5-25).

The results from these trials indicated that native grass and forb seeds could be attached to erosion mats using a tackifier (Image B). In 2003, the findings were applied to the construction project. Needing approximately 33,000 ft^2 of gabion wall facing, the erosion mats were prepared by rolling them out on a road surface, applying California fescue (*Festuca californica*), gluing the seeds to the mat, and re-rolling the erosion mats.

The seeds held tightly to the fabric during transportation and handling. At the construction site, seeded mats were attached to the wire mesh at the face of the wall (Image C) and compost-amended soil was placed behind the screen and lightly tamped. The gabion walls were built in the summer of 2003, but the seeds did not germinate until late fall after several rainstorms. Image D shows a close-up section of wall with newly germinating seedlings emerging through the erosion mat in late 2003, four months after wall construction. Image E shows 20- to 30-foot-high walls in July 2006, three years later, fully vegetated and effectively screening the walls from the road and river). For more detail, see the **Native Revegetation Resource Library**.

Photo credits: A, B, D and E by David Steinfeld, C by Scott Blower



mat installation is difficult. It is important to work directly with companies that provide these products by supplying them with source-specific seeds and specifying appropriate sowing rates. For successful germination, seeded erosion mats are installed so that seeds and fabric are in direct contact with the soil. This method works best in environments with reliable moisture during germination.

Straw and Hay

Straw and hay are long-fibered mulches used on many revegetation projects for seed cover and erosion control (Image E in the illustration in Inset 5-3). The terms "straw" and "hay" are often used interchangeably, however there are distinct differences—straw is the stubble left over after seeds have been harvested from commercial seed or grain crops while hay comes from grass/legume fields and usually the whole plant baled for stock feed. When hay is harvested, it usually contains seeds from a variety of pasture species.

Straw and hay are often used on revegetation projects because they are available, comparatively inexpensive, and generally successful in establishing grass and forb plants from seeds. The long stems of these materials create loft, or high porosity, that keeps moisture near the soil surface where seeds are germinating. This creates a favorable environment for young seedlings by allowing sunlight to penetrate and protecting the young seedlings during the early stages of establishment.

Straw is often preferred over hay because it generally contains fewer undesirable seeds and the seeds that are contained in straw are not always inappropriate for use in revegetation projects. For example, straw from some grain production fields (e.g., rice straw) has seeds of species that are not adapted to many environments and therefore may not become established. Straw produced from native seed production fields may have desirable seeds if the fields are grown from identified genetic sources and used for projects within the appropriate seed transfer zones (Inset 5-4). Using source-identified straw not only act as a mulch when it is applied, but it also supplies extra native seeds to the site. Some native grass species grown for seed production are very difficult to harvest and clean. One strategy for these species is to allow the seeds to ripen in the fields and bale the seeds and stems together. The seeded bales can be applied directly to the site through straw blowing equipment, accomplishing seeding and mulching in one operation.

Purchasing Straw and Hay—The drawbacks to using straw and hay are that these materials can contain seeds from undesirable species, are susceptible to wind movement, may have limited application distance, and decompose in a relatively short time compared to other mulches. Introducing seeds of undesirable species from straw and hay sources is an important consideration when choosing a source. There are many examples where, in the urgency of erosion control, straw or hay from unknown sources has been applied, resulting in the introduction of weed species. The assumption is that short-term control of soil erosion and sediment production outweighs the long-term introduction of undesirable plant species. The possible results from these assumptions need to be understood and agreed upon prior to applying hay or straw from unknown sources. Good integration of erosion control and revegetation planning can eliminate the need for last-minute purchase and application of unknown or undesirable hay or straw sources.

Many states have certification programs that inspect fields and certify that the bales are "weed free" which means that the material is free of the noxious or listed weeds of the inspecting state. There can be other seeds in the bales, however, that may not be considered weeds by the certifying state, but unwanted on the project site. A conservative approach is to examine the fields that will produce the bales and observe which species are present before they are harvested. It can be assumed that if a species of grass or forb is present in a field, seeds from these plants will show up in the bales.

Some things to require when purchasing straw or hay are as follows:

Inset 5-4 | **Source identified straw bales**

A secondary product from the seed production contracts is the straw that remains after harvest. This material can be used for erosion control or seed covering. It can be used as a mulch and has the additional advantage of being a source of unharvested viable seed. This product must be treated similarly to certified straw sources (**Section 5.2.3 (see Straw and Hay**). There should be no noxious or undesirable weed seed in the bales. A visit to the seed production fields prior to seed harvest will indicate if there are any unwanted species that will be present in the hay bales. Bales of each seedlot must be kept separate from other sources to prevent mixing. If straw bales are stored for any length of time, they must be protected from rain.

- Does the source exceed State Certification Standards for “weed free”? Many states have straw certification programs but for states where no standard programs exist, acceptance can be based on seed crop inspection reports and/or visual field inspections prior to harvest. Standards may also be set by the Government and listed on individual task orders.
- Is straw or hay baled and secured? Generally, bales should be less than 100 pounds.
- Are bales wet after harvest or during storage prior to delivery? Not only is wet material harder to handle and less effective, mold is often present, which can pose respiratory risks to applicators.

The quality of straw and hay varies among grass species. Rice straw, for example, is wiry and does not readily shatter, which makes it more difficult to apply as compared to wheat, barley, or oats (Kay 1983; Jackson and others 1988). Native straw is generally longer and stronger than grain straw (Norland 2000), although some native species have better properties as mulches than others. Larger stemmed grasses, such as blue wildrye (*Elymus glaucus*), mountain brome (*Bromus marginatus*), and bluebunch wheatgrass (*Pseudoroegneria spicata*) make good mulches because of their large leaves and stems.

Figure 5-26 | **Straw blower**

Straw blowers range in size from machines that can apply 30 to 60 bales per hour (shown here) to very large straw blowers that can shoot up to 20 tons per hour.

Photo credit: David Steinfeld

Application—Straw and hay can be spread by hand or with a straw blower. For large jobs, using a straw blower is the most practical application method. Many types of straw blowers are available, ranging from very small systems (Figure 5-26) that deliver from 30 to 180 bales per hour to large straw blowers that operate at rates up to 20 tons per hour. The distance that straw or hay can be blown depends on the hay-blowing equipment, wind conditions during application, straw characteristics, and whether the material is being applied upslope or downslope (cuts or fills). When wind is favorable, straw can be shot up to 100 feet. However, when wind is blowing against the direction mulch is being applied, the distance is reduced. Because of the limited application range, this equipment is limited to sites adjacent to roads. The upper portions of steep, extensive slopes are typically not reachable by straw blowers.

When straw is used as a seed mulch, it is important that the application rates are not so deep that a physical barrier is formed. A minimum depth that has been shown to control evaporation is 1 inch (Slick and Curtis 1985). Applying too much straw will restrict sunlight and growing space for establishing seedlings. A rule of thumb is that some surface soil (15 percent to 20 percent) is visible through the straw after application (Kay 1972, 1983; Jackson and others 1988). This equates to 1.5 to 2 tons per acre, depending on the type of straw and its moisture content, though this rate should be adjusted based on the climate of the site.

Straw is susceptible to movement with moderate to high winds. Tackifiers are often applied over the straw to keep it in place (Kay 1978). Products such as guar and plantago are used with low quantities of hydromulch to bind straw together. Straw can also be crimped, rolled, or punched into the soil. A puncher is a roller with a set of straight studs, greater than 6 in long, that push straw into the soil. A crimper is similar but has serrated disks attached to a roller. This equipment stabilize the straw by burying portions of the stems into the soil and increase erosion protection because of the greater contact of straw with the soil surface. Some soil types may not be suitable for crimping, especially sandy soils that may not have the strength to hold straw in place. It is important to consider the potential for soil compaction that may result from heavy equipment on soils.

Wood Strands and Wood Wool

Wood strands and wood wool are commercially available wood products used for mulch. Wood strands are long, thin pieces of wood produced from wood waste veneer, whereas wood wool, known as excelsior, is wood slivers produced from aspen, spruce, and pine wood. These products are developed as an effective erosion-control alternative to straw and hay (Foltz and Dooley 2003). The advantages of wood strands and wood wool over straw are that they are free of seeds, have greater longevity, and more resistant to wind.

Wood strands and wood wool form a stable surface cover with high porosity or loft; characteristics that are important for controlling soil moisture and temperature around the germinating seeds. The large spaces or pores created by the wood strands allow space, light, and protection for young emerging seedlings (Figure 5-15). Unlike straw, these materials keep their structure or porosity over time and do not compress with snow or lose fiber strength until they begin to decompose. The application rates for wood strands follow the guides for straw—at least 15 percent to 20 percent of the soil surface is visible. This may result in a lower application rate than recommended for erosion control. Installing small test plots of varying thicknesses of mulch is a good means to determine the appropriate thickness for optimum seed germination and erosion control. Wood strands are delivered in different size bales and applied by hand or through straw-blowing equipment (Figure 5-26). As with straw, this product is limited by the accessibility of the site by hay transportation and blowing equipment.

Litter and Duff

Litter is the layer of fresh and partially decomposed needles and leaves that cover the surface of most forest and shrub plant community soils. Duff is the dark, decomposed layer directly below the litter layer (leaves and needles are not identifiable in the duff layer) that is high in nutrients and humus. In addition to providing soil protection and nutrients, litter and duff can contain dormant, yet viable, seeds from species that make up the forest or shrub plant communities (Section 5.2.3, see Seed Supply). When litter and duff are collected, they should be matched to the appropriate revegetation site. For example, litter and duff collected from cool, moist sites should not be applied on hot, dry sites.

The depth that litter and duff accumulates will vary by species composition, age, and productivity of the plant community. The quality of the litter for erosion control and longevity varies by the dominant forest or shrub species. Pine needles provide the greatest benefit because the long needles interlock, reducing the potential of movement from rain or wind erosion (Inset 5-5) (Image F in Figure 5-21). Needles from species such as Douglas-fir are shorter and tend to compact, providing less surface stability. Litter from deciduous tree and shrub plant communities provides less protection because the leaves are less interlocking, provide less loft, and often form a mat that can be difficult for germinating seeds. Nevertheless, these materials should not be overlooked because they can be a source of seeds and nutrients.

In the western states, litter has typically been collected manually by raking. The collection of litter has been mechanized in the southern United States, and the pine straw industry is well developed in this part of the country. Baling equipment has been developed for this industry and could be applicable to the western United States. Collection of needles and duff is done when the litter and duff are dry. If these materials are not used immediately, they are placed

***Inset 5-5* | Pine straw industry**

Using forest litter as a mulch is not a new concept — pine needles have been a popular landscaping mulch in the southern United States for the past 25 years. The "pine straw" industry, as it is referred to, has been established to harvest needles in a sustainable manner from young plantations of southern pine species to meet this demand.

in small piles and covered with plastic to keep the materials dry. Excessive moisture can turn the piles into compost and possibly affect seed viability.

Litter and duff can be applied manually to disturbed sites. If the litter and duff is free of large materials, it can be applied in a variety of ways including pneumatic mulch blowers, straw blowers, and modified manure spreaders.

One method for determining the amount of viable seeds in a litter layer is to conduct a germination test at the project site over a several-year period by obtaining litter and duff from several potential collection areas and testing them on nearby sites. Dry litter and duff samples are collected from each plant communities and a known amount is weighed. The samples can either be spread in an area near the project (free of vegetation and topsoil) or on potting soil in a garden or greenhouse. In either case, the duff and litter is overwintered and a germination count is made in the spring. The numbers of seedlings per known volume or weight of litter and duff material is used to determine the rate of litter to be applied.

5.2.4 TOPSOIL

Introduction

Topsoiling is the salvage, storage, and application of topsoil material to provide a suitable growing medium for plants and to enhance soil infiltration (Rauzi and Tresler 1978; Woodmansee and others 1978; Natural Resource Conservation Service (NRCS) 1994). Topsoiling has been found to increase plant cover and biomass through an increase in nutrient availability, water-holding capacity, and microbial activity, including mycorrhizae (Claassen and Zasoski 1994).

While topsoiling has many benefits for revegetation, topsoiling cannot re-create the original undisturbed soil. In the process of removing and reapplying topsoil, soils undergo a loss of soil aggregation, organic nitrogen, arbuscular mycorrhizal fungi (AMF) inoculum, and microbial biomass carbon (Visser and others 1984). Minimizing topsoil disturbance is preferred to topsoiling, especially on sensitive soils, such as those derived from granitic and serpentine bedrock (Claassen and others 1995).

Salvaging Topsoil

Salvaging topsoil is done in areas that will be severely disturbed during construction. These areas are usually identified early in the planning stages. Topsoil within these areas can be surveyed to determine the depth and quality of the topsoil that can be excavated. If weeds are observed during the field survey, it is a good possibility that the seeds of these species are present in the topsoil. These areas can be avoided or undesirable vegetation treated prior to topsoil removal. Ideally, only the topsoil, and not the subsoil, is removed in the excavation process. Mixing subsoil into the topsoil will dilute microbial biomass and mycorrhizal inoculum and reduce the quality of the topsoil.

During topsoil excavation, the litter and duff layers are removed together with the topsoil. These layers are sources of decomposed and partially decomposed organic matter which will undergo some decomposition, releasing nutrients and organic matter to the soil during storage. There are circumstances where the duff/litter layer is removed and stored separately from the topsoil which is when the duff and litter are to be used as a native seed source or soil cover (Section 5.2.3, see Seed Supply).

Topsoil layers are typically removed with either the blade of a tractor or excavator bucket. Where precision is important, using an excavator bucket is the preferred tool. Thin topsoils, common on high elevation sites or soils where the subsoil cannot be mixed with the topsoils (e.g. subsoils with very high or low pH, high sodium, high salinity) can be scraped with the front of the excavator bucket to the desired depth. There is less depth control when using a tractor.

Topsoil is typically moved into berms at the bottom of fill slopes or the top of cut slopes and stored there until it is reapplied or transported to a storage area. This will require that the storage areas along the cut and fill slopes will have minimal amount of disturbance until the soil is reapplied. Typical berm dimensions are approximately 6 feet wide by 3 feet high. In areas where there is more topsoil than can be stored on-site, topsoil is trucked offsite to larger storage piles. When selecting off site storage areas, it is important to assess the site and surrounding area for unwanted vegetation because of the potential that this vegetation will become established on the topsoil piles. It is also important to plan salvaging operations so that there is a minimal amount of compaction prior to removal. This will require keeping large equipment travel on salvaged topsoil areas to a minimum.

To maintain optimum soil quality, it is best to excavate topsoil when soils are relatively dry. Under dry conditions, there is less potential to compact the soil, destroy soil aggregation, or oxidize organic matter. Dry topsoil store longer and maintain better viability than moist topsoil (Visser, Fujikawa, and others 1984). Restricting topsoil excavation operations to dry periods for large topsoil piles, or if topsoil is to remain in piles for more than one year, will increase the viability of the topsoil.

Storing Topsoil

The question often raised around storing topsoil is how long it can remain piled before it loses its viability. Studies have shown that stored topsoil can remain viable from six months (Claassen and Zasoski 1994) to several years (Miller and May 1979; Visser, Fujikawa, and others 1984; Visser, Griffiths, and others 1984,) but will decrease in viability after five years (Miller and May 1979; Ross and Cairns 1981).

Viability of stored topsoil is a function of moisture, temperature, oxygen, nitrogen, and time. Stockpiled topsoil has been compared to “diffuse composting systems” (Visser, Fujikawa, and others 1984) because, under optimum conditions, organic material in the topsoil will compost. Decomposition of organic matter in stored topsoil will reduce microbial biomass essential for nitrogen cycling (Ross and Cairns 1981) and fine roots that store mycorrhizal inoculum (Miller and May 1979; Miller and Jastrow 1992). Optimum environments for decomposition include high moisture, warm temperatures, and available nutrients, all conditions present in most topsoil piles. Climates with lower moisture and temperatures can be more favorable to long-term storage. A study in Alberta, Canada, for example, revealed that topsoil had very little respiration or organic decomposition after three years in a stockpile due to the influence of the cold, dry climate (Visser, Fujikawa, and others 1984). Dry topsoils store longer and maintain greater populations of viable mycorrhizal fungi (Miller and Jastrow 1992). Topsoil piles, that will be held over winter in areas of moderate to high rainfall, will benefit by covering with plastic to keep the soil dry. This will also keep the piles protected from erosion and weed establishment.

The size of the pile can also affect the viability of the topsoil. The interior of large piles maintains higher temperatures and are usually anaerobic, which can be detrimental to soil microorganisms. Microbial biomass levels and mycorrhizal fungi have been found to be very low in the bottom of large stockpiles (Ross and Cairns 1981; Miller and Jastrow 1992). Most projects limit topsoil piles to 3 to 6 feet in height. This is not always possible, especially when topsoil storage space is limited. Under these circumstances, the size of the topsoil pile can be quite large. To reduce the negative effects associated with very large piles, topsoils can be salvaged dry and kept dry during storage. They can also be stored for as short a time as possible. In addition to maintaining the viability of the topsoil, minimizing storage time will reduce the risk of weed infestation.

Standard specifications often call for temporary seeding of topsoil piles. The benefits of this practice are erosion control and maintenance of mycorrhizae inoculum through the presence of live roots. This practice also runs the risk of introducing undesirable plant species that may be present in the seeding mix if a non-native species mix is used. Alternatives to this practice include hydromulching without seeds or covering with plastic however, both practices lose their effectiveness with time.

Reapplying Topsoil

The depth of topsoil application is generally based on the amount of topsoil available and the desired productivity of the site after application. As a rule, the deeper that topsoil is applied, the greater the site productivity. If the objective is to restore a site to its original productivity, the placement of topsoil should be at a depth equal to or greater than the topsoil horizon of undisturbed reference sites. Sufficient topsoil quantities, however, are rarely available in the quantities needed to restore disturbed sites to their original topsoil depths. This often leads to applying topsoil too thinly across a project site. There may be a minimum topsoil depth below which the application of topsoil is not effective. Research on a northern California road construction site (Claassen and Zasoski 1994) suggests that a depth of 4 to 8 inches was required for an effective use of topsoil. On sites where the subsoil is unfavorable for plant establishment (e.g., very high or low pH, high sodium, high salinity), minimum depths of greater than 12 inches of topsoil may be considered (Bradshaw and others 1982).

Determining minimum topsoil application depths can be based on the minimum amount of nitrogen required to establish a self-maintaining plant community. A threshold of approximately 700 kg/ha (625 lb/ac) of total nitrogen in the topsoil has been suggested for sustaining a self-maintaining plant community in a temperate climate (Bradshaw and others 1982). Claassen and Hogan (1998) suggest higher rates, especially on granitic soils, of 1,100 lb/ac total nitrogen. Using total nitrogen levels from soil tests of topsoil in reference areas, the application thickness of topsoil can be determined using the calculations presented in Figure 5-27.

Some sites, like high elevation and desert environments, have very little topsoil to begin with. In these areas, salvage and application of topsoil may be less than 4 inches depending on the topsoil depth of the reference site. While this may not seem worth the effort, the addition of a thin layer of salvaged topsoil may provide soil organisms and seeds that are essential for restoring the site to original productivity and species composition.

A	**Total soil nitrogen (or other nutrient of interest) in salvaged topsoil**	0.14%	From soil test of post construction soils. Reported in gr/l, ppm, mg/kg, ug/g; divide by 10,000 for percentage
B	**Soil bulk density**	1.1 gr/cc	Unless known, use 1.5 for compacted subsoils, 1.3 for undisturbed soils, 0.9 for light soils such as pumice
C	**Fine soil fraction**	70%	100% minus teh rock fragment content; from estimates made from sieved soil prior to sending to lab
D	**Nitrogen for soil layer** *A * B * C * 270 =*	2,911 lbs/ac ft	Calculated amount of total nitro-gen in 1 acre feet of soil
E	**Minimum or threshold N levels**	1,100 lbs/ac	Determined from reference sites or minimum thresholds from literature
F	**Minimum topsoil application** *E / D * 12 =*	4.5 inches	The minimum thickness of topsoil to apply to meet minimum thresholds of nitrogen

Figure 5-27 | **Minimum topsoil thicknesses can be calculated from nitrogen tests**

Soil testing of salvaged topsoil can be used to calculate the thickness to apply to meet minimum nitrogen levels.

Once the desired topsoil depth has been established, then it can be determined if there is enough salvaged topsoil available. The quantity of topsoil needed can be determined based on the depth of topsoil from Figure 5-28. For example, if an average of 10 inches of topsoil is needed on a project, approximately 1,350 yd^3/ac topsoil will be required. If there is not enough topsoil to meet this depth, then an alternative approach may need to be taken, including strategic placement of topsoils, or areas where topsoil depths are reduced. The strategy might concentrate topsoil in areas such as planting islands, planting pockets, or in a mosaic pattern that blends with the natural vegetative community. In areas that have reduced or no topsoil, other mitigating measures could be used, such as incorporation of organic matter into the subsoil or mulching.

Manufactured Topsoil

The term manufactured topsoil (also referred to as "engineered topsoil") is used to define a soil created to perform like, or develop into, topsoil. It is usually manufactured offsite and transported to the area where it is applied. Manufactured topsoil is used in gabion walls, crib walls, or other bioengineered structures. It can also be used in planting pockets and planting islands.

Selection of the appropriate organic matter, soil texture, and soil amendments for manufactured topsoil will increase the success of the project. It is critical that manufactured topsoil be similar to the soils of the reference site with characteristics that will support the desired plant community. The basic components of a manufactured topsoil are the loam borrow, compost, and soil amendments.

Loam Borrow—Loam borrow is any material that is composed of mineral particles meeting a suitable texture class (Figure 5-29). Optimal loam borrow is low in coarse fragment content, is weed-free, and meets general soil quality specifications shown in Table 5-8. Testing loam borrow will determine if the material meets these general specifications. Loam borrow can come from many sources, such as subsoils, river sands, and terrace deposits. When loam borrow comes from subsoils or parent material, it can be assumed that beneficial soil micro-organisms, like mycorrhizae and nitrogen-fixing bacteria are not present. These microorganisms can be added to the loam borrow using inoculums (Section 5.2.7).

Compost—The organic component of manufactured topsoil (Section 5.2.5) is composted materials from of a variety of materials, including yard waste materials (grass clippings, leaves, and shredded wood of trees and shrubs), sawdust, and biosolids. The heat generated during

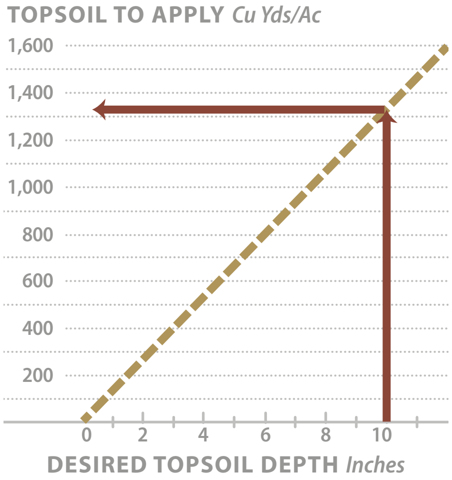


Figure 5-28 | **Determining the soil quantity needed for a specific topsoil depth**

The quantity of topsoil to apply to achieve a specified topsoil thickness can be estimated using this graph. For example, to create a topsoil, 10-inches deep, would require 1,350 yd^3 of topsoil.

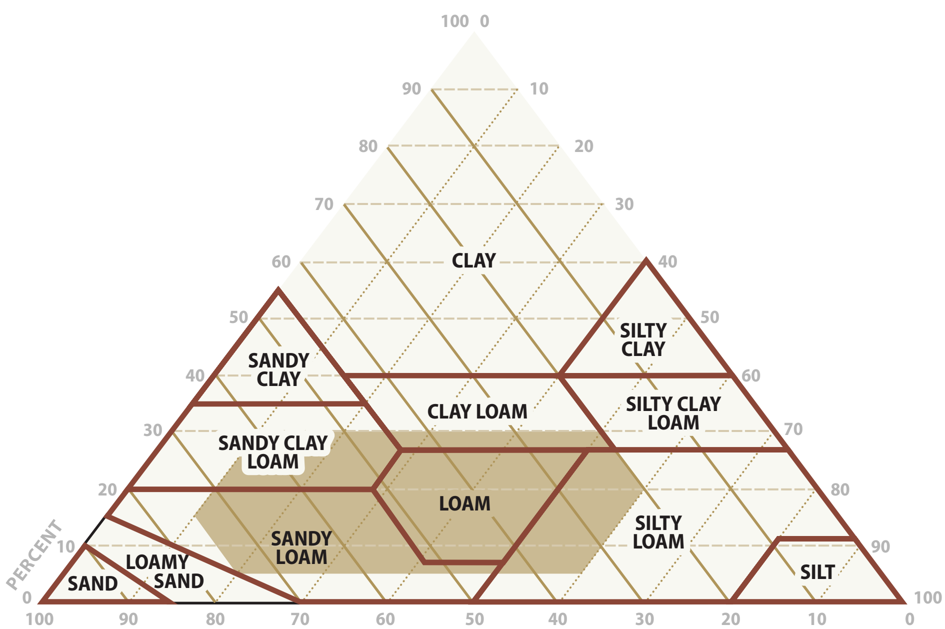


Figure 5-29 | **Soil textures suitable as loam barrow**

Soil textures that are suitable as "loam borrow" are shown in light brown on the USDA textural triangle.

Table 5-8 | **General specification ranges for loam borrow used in manufactured topsoil**

This table outlines the general specifications for loam borrow used in manufactured topsoil. It can be adapted depending on the soil characteristics of the compost and other soil amendments that will be used in the composition of the manufactured topsoil (modified after Alexander 2003b; CCREF and USCC 2006).

Test parameters	Test methods	Loam borrow
Physical contaminates (man-made inerts)	Man-made inert removal and classification (TMECC 0.308-C)	<1%
Trace contaminants	Arsenic, Cadmium, Copper, Mercury, Manganese, Molybdenum, Nickel, Lead (TMECC 04.06)	Meets US EPA, 40 CFR 503 Regulations
pH	1:5 slurry pH (TMECC 04.11-A)	5.0-7.5
Soluble salts	Electrical conductivity using 1:5 slurry method (dS/m)	<5
Biossay	Percent seedling emergence and relative seedling vigor (TMECC 05.05-A)	>80% of control
C:N ratio	(TMECC 05.02-A)	<25

composting effectively reduces pathogens, weeds, and insects that may be hazardous to humans and detrimental to the reestablishment of vegetation. To reduce the potential for spreading weeds, compost specifications call for material that is free of weed seeds and vegetative material that may propagate weedy plants (e.g., blackberry canes). Specifications also call for well-composted, or stable, which can be indirectly determined by a respirometry test or calculated using C:N ratios obtained from laboratory testing of nitrogen and organic matter. A stable compost will have a low respirometry rate (<8 mg CO_2-C per g organic matter per day) and low C:N (<25:1). A bioassay test that compares the rate of seedling emergence and seeds sown in compost to seeds sown in a control growing medium would be useful. Table 5-9 lists the laboratory tests for determining the optimum composts to use in manufactured topsoils.

To ensure the delivery of high quality organic materials, compost can be obtained from a facility that participates in the Seal of Testing Assurance (STA) program (Inset 5-6). Upon request, these compost facilities send the latest lab results of the material of interest. If compost is from a STA composting facility is not available, other sources can be considered but testing the quality of the compost will be the responsibility of the designer. Compost testing by the designer involves sampling the compost piles and sending the samples to an STA lab (a listing can be found at the Composting Council's website).

At the same time that compost piles are tested, they can also be visually inspected to ensure that noxious weeds are not present on or near the composting facility.

The compost application rates typically range from 10 to 30 percent by volume of the loam borrow. Section 5.2.5 describes how to determine specific organic matter rates.

Soil Amendments—Soil amendments, such as fertilizers, lime, and beneficial microorganisms, can be applied to the compost and loam borrow to bring the manufactured soil into acceptable ranges for pH, nutrients, and microbiological parameters. The type and amount of amendments to apply can be determined by conducting a lab analysis on a sample of the manufactured topsoil (e.g. the combination of loam borrow and compost at the specified mixing ratio). From the results of the soil analysis, a determination can be made for the application rates for fertilizers (Section 5.2.1), lime amendments (Section 5.2.6), and beneficial soil microorganisms (Section 5.2.7).

Table 5-9 | **General specification ranges for composted materials for composted materials in manufactured topsoil**

These generalized specifications for composts to use in manufactured topsoil can be adapted depending on the soil characteristics of the loam borrow and site conditions

Modified after Alexander 2003b; CCREF and USCC 2006

Test parameters	Test methods	Composted Material
Physical contaminates (man-made inerts)	Man-made inert removal and classification (TMECC 0.308-C)	<1%
Trace contaminants	Arsenic, Cadmium, Copper, Mercury, Manganese, Molybdenum, Nickel, Lead (TMECC 04.06)	Meets US EPA, 40 CFR 503 Regulations
pH	1:5 slurry pH (TMECC 04.11-A)	5.0-8.5
Soluble salts	Electrical conductivity using 1:5 slurry method (dS/m)	<5
Biossay	Percent seedling emergence and relative seedling vigor (TMECC 05.05-A)	>80% of control
% Moisture content	Percent wet weight (TMECC 03.09-A)	30-60
Total organic matter	Percent by dry weight, loss on ignition (TMECC 05.07-A)	25 to 60%
Stability	Respirometry. Carbon dioxide evolution rate — mg CO2-C per g OM per day (TMECC 05.088)	<8
C:N ratio	(TMECC 05.02-A)	<25
Particle size	Percent of compost by dry weight passing a selected mesh size, dry weight (TMECC 02.12- B)	▪ 3" (75mm): 100% ▪ 1" (25MM): 90-100% ▪ 3/4" (19mm): 65-100% ▪ 1/4" (6.4mm): 0-75% ▪ Maximum particle length of 6" (152mm)

Large quantities of manufactured topsoil can be mixed in a staging area. Using the bucket of a front-end loader or excavator, the compost and loam borrow can be measured out proportionately. For example, using a 5 yd^3 bucket, manufactured topsoil with a ratio of 25 percent compost and 75 percent loam borrow would have one scoop of compost applied to three scoops of loam borrow to produce 20 yd^3 of material. Additional amendments, such as fertilizers or lime materials, would be applied based on calculations for a 20 yd^3 pile. Once all the materials have been placed in the pile, it is thoroughly mixed using the front-end loader.

Purchasing loam borrow, compost, and topsoil requires a set of contract specifications that ensure product quality. The specifications in Table 5-8 and Table 5-9 were developed for the U.S. Department of Transportation by the Composting Council Research and Education Foundation (Alexander 1993b). The tests are based on the Test Method for the Examination of Composting and Compost (TMECC) protocols. These are general quality guidelines and can be broadened or made more constraining depending on the specifics of the project. When considering purchasing these products, it is important to request the latest lab analysis. An STA facility (Inset 5-6) will have these reports available while others might not. It is important that these tests be run by STA laboratories and that the sources be visited to determine whether there are undesirable or noxious weeds on or near the piles.

5.2.5 ORGANIC MATTER AMENDMENTS

Background

High-quality topsoil is not always available in the quantities needed to meet the objectives of a revegetation project. In such cases, infertile subsoils can be augmented by the incorporation of organic matter amendments. This practice can be an important tool to begin the process of rebuilding a soil and reestablishing native vegetation.

One immediate effect of incorporating organic matter into infertile subsoils is increased infiltration. Water that would typically run off the soil surface during rainstorms now enters the soil. Amended subsoils also have greater permeability and often increased water storage. Changes in these factors can improve the overall hydrology of the site, making soil less susceptible to runoff and erosion.

Incorporation of organic matter can often improve plant establishment and growth rates, especially if composted organic matter is used. Composted organic materials increase soil nutrients and rooting depth, which can create better growing conditions for native plant establishment. The use of non-composted organic materials, such as shredded wood, can restrict plant growth for the first several years after incorporation because of the immobilization of nitrogen. Nevertheless, non-composted materials may be important to consider when composted sources are not available or too expensive, and there is readily available sources of material from clearing and grubbing of trees and shrubs. This material will have an immediate improved effect on infiltration and permeability, as well as speeding the long-term rehabilitation of the soil.

Incorporated organic matter becomes the primary source of energy for soil organisms and, whether fresh or composted, is the driving force behind soil development. In the process of decomposition, soil organisms turn cellulose into complex organic compounds while slowly releasing nutrients for plant growth. Some of the resulting compounds act similarly to glues, sticking soil particles together into aggregates, which ultimately create soil structure. The slow decomposition of organic matter delivers a steady supply of nutrients to the establishing plant community for many years.

The strategy behind many current revegetation projects is to obtain immediate cover with the use of seeds, fertilizers, and other amendments without considering what is needed for long-term site recovery. It is not uncommon to find good establishment of vegetative cover immediately (within a year) after revegetation work, but several years later find that it was not sustainable. Life expectancy of many revegetation projects has often been found to be very short (Claassen and Hogan 1998). Incorporating organic matter takes a different approach. This strategy puts more emphasis on the development of the soils and less on the quick establishment of vegetation. It is based on the premise that creating healthy, functioning soils is the first step in reestablishing native vegetation. This cannot happen without basic minimum soil components, such as an organic source, nutrients, and good soil porosity. When these components are in place, a site can develop into a sustainable plant community. Incorporating organic matter into the soils of highly disturbed sites is an important component of meeting long-range revegetation objectives.

Set Objectives

Section 5.2.3 described the use of organic matter as a mulch for covering seeds. When used as mulch, organic matter protects the soil surface from erosion, enhances seed germination, and

Inset 5-6 | The Seal of Testing Assurance Program

Just as many products at the local market have seals of approval (e.g., "Approved by the FDA" or "USDA Inspected"), the United States Composting Council operates an approval system for composting facilities. The Seal of Testing Assurance (STA) is a voluntary program that requires compost manufacturers to regularly test their composts using an approved third-party testing facility. The procedures for sampling and testing are outlined in the Test Methods for the Examination of Composting and Compost (TMECC) protocols. The STA program ensures that the company is reputable. Compost can be purchased from companies that do not participate in the STA program but this leaves the sampling and testing up to the buyer. This may involve visiting the composting site, collecting samples from the compost piles, sending them to a qualified lab to run TMECC tests, and interpreting the results when they are returned. STA laboratories can be found at www.compostingcouncil.org. (after Alexander 2003).

with time, breaks down and improves surface soil properties. Applying organic matter on the soil surface may be far easier and more practical than incorporating it into the soil, however, the incorporation of organic matter into the soil offers the following additional advantages:

- Improves soils of "difficult" subsoils or parent materials
- Increases water-holding capacity
- Improves rooting depth
- Improves infiltration and drainage
- Encourages quicker release and availability of nutrients and carbon

Setting objectives clarifies why this mitigating measure is being considered and helps define the appropriate sources and application rates for incorporated organic matter.

Improving "Difficult" Parent Material—The parent material from which soils are derived often plays an important role in how soils will respond to disturbances. Soils originating from granitic rock respond poorly to the removal of topsoil. Subsoils from this parent material have very high bulk densities and low permeability rates. They can "hardset" when dry, restricting root growth and increasing runoff (Claassen and Zasoski 1998). Any positive effects of deep tillage are often short-lived on granitic subsoils (Luce 1997) because they quickly return to high bulk densities and soil strengths. Granitic soils can benefit from the incorporation of organic matter, not only because of increased nutrients, but because the soil's physical properties are improved. Organic amendments lower bulk densities and help to form pathways for water entry, soil drainage, and root growth. Organic matter can also increase the water-holding capacity of these soils.

Soils derived from serpentine rock have also been identified as difficult to revegetate because of heavy metals, low water-holding capacity, low nutrient levels, and a low calcium-to-magnesium ratio. When disturbed, these sites can take decades to revegetate, producing a continual output of sediments. In addition to using plant materials collected from similar serpentines sites, incorporating compost into serpentine soils can greatly improve revegetation success by increasing water-holding capacity (Curtis and Claassen 2005).

Increasing Water-Holding Capacity—The incorporation of organic matter can increase the water-holding capacity of soils with less than 9 percent available water capacity (Claassen 2006). These include soils with sand, loamy sand, and some sandy loam textures, as well as soils high in rock fragments. Incorporating organic matter to increase water-holding capacity can be critical on arid or semi-arid sites, or sites with very little summer rainfall. The increase in moisture-holding capacity depends on the type of organic matter and the degree of decomposition. Non-decomposed (fresh) organic sources, such as large wood chips, can decrease soil water-holding capacity because they act similarly to gravels and hold very little water. A test for determining how much soil moisture will be increased or decreased by the incorporation of organic matter is described in the Native Revegetation Resource Library. The results from this test will help determine the source and quantity of organic matter to incorporate. If there is no increase in percent soil moisture with the additions of organic matter over the soil with no organic matter additions, it means that in the short term, applying organic matter will not improve water-holding capacity. For a more accurate assessment, contact analytical laboratories that perform soil moisture tests.

Improving Rooting Depth—For species that have deep rooting requirements, such as trees, shrubs, and some wildflowers, incorporating organic matter into the subsoil can increase rooting depth. This can be beneficial for plant establishment and long-term site recovery, especially when applied to soils derived from "difficult" parent materials. Soils that are compacted can also benefit from deep incorporation of organic matter. The incorporation of organic matter to deeper levels is often accomplished by applying a thick layer of organic matter to the surface and then incorporating it to the desired depths with an excavator or methods discussed in

Section 5.2.2. It is important that the organic matter is thoroughly mixed through the soil profile during incorporation.

Improving Infiltration and Drainage—The hydrology of most disturbed soils is improved with organic matter incorporation. The degree to which infiltration and permeability are improved depends on the size and shape of the organic source and application rates (as described in the following sections). Finer-textured soils (e.g., clays, clay loams, silty clay loams, sandy clay loams) will have better infiltration and permeability when organic matter is uniformly incorporated into the surface of the soil. This objective is important in areas where water quality issues are high.

Improving Nutrients and Carbon—Incorporating organic matter into the soil can ensure that nutrients and carbon are available to decomposing soil microorganisms, which are essential for rebuilding a healthy soil. This objective is important for highly disturbed soils low in nutrients and carbon (e.g., sites lacking topsoil).

Select Organic Materials

There is a range of organic material sources that are available. Developing a selection criteria based on the following characteristics can be helpful:

- Source of organic matter
- Level of decomposition
- C:N ratio
- Size and shape of material

Recognizing how these characteristics will help achieve the objectives for incorporating organic matter will guide the designer in making the appropriate decision for each project.

Organic Sources—Most available organic sources originate from waste byproducts of agriculture, forestry, and landscape maintenance. They include yard & household waste (lawn clippings, leaves, food waste), wood residues (sawdust, bark, branches, needles, roots, and boles of trees and shrubs from landscape maintenance, land clearing, logging operations, or mills), manures (poultry or cattle), agricultural waste products (fruits and vegetables), and biosolids (treated sewage sludge meeting U.S. Environmental Protection Agency regulations). In the composting process, usually more than one source is used. A compost from one facility could include lawn clippings, leaves, yard waste, poultry manure, and shredded wood, while another facility could use yard waste, shredded wood, and biosolids.

Each organic source has a unique nutrient composition. Green alfalfa, for example, has a very different nutrient makeup than organic matter derived from wood residues of cleared right- of-way. Even within sources, there are very different nutrient compositions (Figure 5-30). For example, most of the nutrients of trees are concentrated in the foliage and branches, and very little in the bole of the tree. A chipped slash pile composed of higher proportions of branches and foliage will contain a greater level of nutrients than a pile composed primarily of tree boles and, as such, would probably be a more preferred organic source.

As organic sources decompose, they contribute their nutrients to the fertility of the soil. Knowing the source from which the organic matter was derived will give some indication of

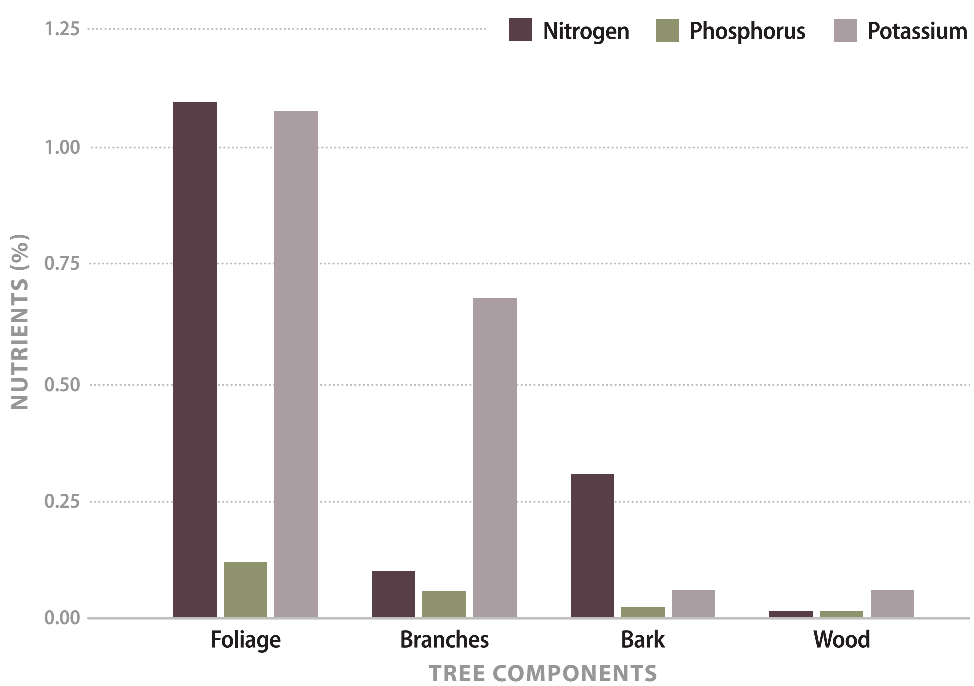


Figure 5-30 | **Nutrients in forest biomass**

Nutrients are held in different portions of the forest biomass, as shown for old growth Pacific silver fir. On a percentage basis, tree foliage is the storehouse for nutrients. Mulch derived from branches and foliage will have a greater nutrient content than mulch from bark and wood.

Adapted from Cole and Johnson 1981

the amount of nutrients that might be supplied to the soil. This information is important to determine whether target long-term nutrient levels will be achieved.

Knowing the source of the organic matter might also identify contaminants that could be harmful to plant growth. Additions of materials, such as fly ash, feedlot, and municipal and factory waste products, could decrease the quality of an organic source. Testing these materials for contaminants, pH, soluble salts, and bioassay will identify potential problems.

Level of Decomposition—Organic matter can be in various stages of decomposition, from fresh organic matter with minimal decomposition to compost that has undergone extensive decomposition. The level of decomposition is an important consideration when selecting an organic amendment. Additions of relatively undercomposed organic matter to the soil can have negative short-term effects on plant establishment and growth.

Fresh Organic Matter—Organic matter is recently ground or chipped material that has undergone very little decomposition is considered "fresh organic matter." These materials usually have very high C:N ratios and will immobilize soil nitrogen for months to several years after incorporation, depending on the characteristics of the organic source. Very slow establishment of plants can be expected when incorporating fresh organic matter unless a continuous source of supplemental nitrogen is applied (e.g., applications of slow release fertilizers, establishing nitrogen fixing plants). Nevertheless, applying fresh organic matter to highly disturbed soils can have a positive effect on slope hydrology and surface erosion. Fresh organic matter can increase infiltration and permeability in poorly structured soils by creating pathways for water flow.

Incorporating fresh organic matter is not generally practiced in roadside revegetation projects. However, considering the expense of purchasing and transporting composted materials to remote sites, as well as the availability and abundance of road right-of-way material that is typically burned for disposal, this is an option that may be worth considering (Inset 5-7). If shredded or chipped road right-of- way material is to be incorporated into the soil, it is best to allow it to age as long as possible in piles. Moving the piles several times to add oxygen will increase the rate of decomposition.

Aged Organic Matter—Some sources of organic matter have been stored in piles for long periods and are partially decomposed. They are darker in appearance than fresh sources, but the appearance of the original organic source can still be discerned (e.g., needles or leaves are still identifiable). These materials are sometimes referred to as "aged organic matter." Because only partial decomposition has occurred, the C:N ratio is lower than with fresh organic matter. Nitrogen immobilization, however, will still occur for a significant period after incorporation. Aged organic sources have not typically undergone extensive heating, like composts, and they can contain seeds of undesirable weeds.

Composted Organic Matter—Compost is the result of controlled biological decomposition of organic material. During the early stages of composting, heat is generated at temperatures that are lethal to weed seeds, insects, and pathogens (Inset 5-8). Fresh, moist compost piles will usually generate heat in the first few days of composting, reaching 140 to 160 degrees F, which will kill most pathogens and weed seeds (Epstein 1997; Daugovish and others 2006). The resulting material is a relatively stable, sanitized product that is dark brown to black and beneficial to plant growth (Alexander 2003a, 2003b). Composts are very suitable materials for increasing the water-holding capacity of sandy soils, increasing nutrient supply, and enhancing soil infiltration and permeability rates.

Inset 5-7 | **Highway 35**

The Oregon State Highway 35 road was frequently affected by high intensity storm events that eroded portions of the roadsides and added sediment into the tributaries of Hood River. A road project was implemented in 2011 and 2012 to reconstruct portions of the highway and improve the hydrology of the roadsides to withstand road surface runoff. Shredded wood was applied at an average depth of 6 in and mixed into the soil approximately 18 to 24 inches deep. The purpose of incorporating shredded wood was to create pathways for water to flow through the soil and thereby increase infiltration and soil drainage. The slopes with shredded wood responded favorably to extreme surface runoff events (A). Runoff from a non-paved road moved quickly into the soil depositing road sediments over the surface of the fill slope. On slopes that were not amended, runoff was not absorb into the soil and gullies were created, moving road and gully sediments off the project site (B). High rates of slow release fertilizers were applied to offset nitrogen tie-up due to the high C:N ratio shredded wood.

Photo credits: David Steinfeld

Inset 5-8 | **Compost production**

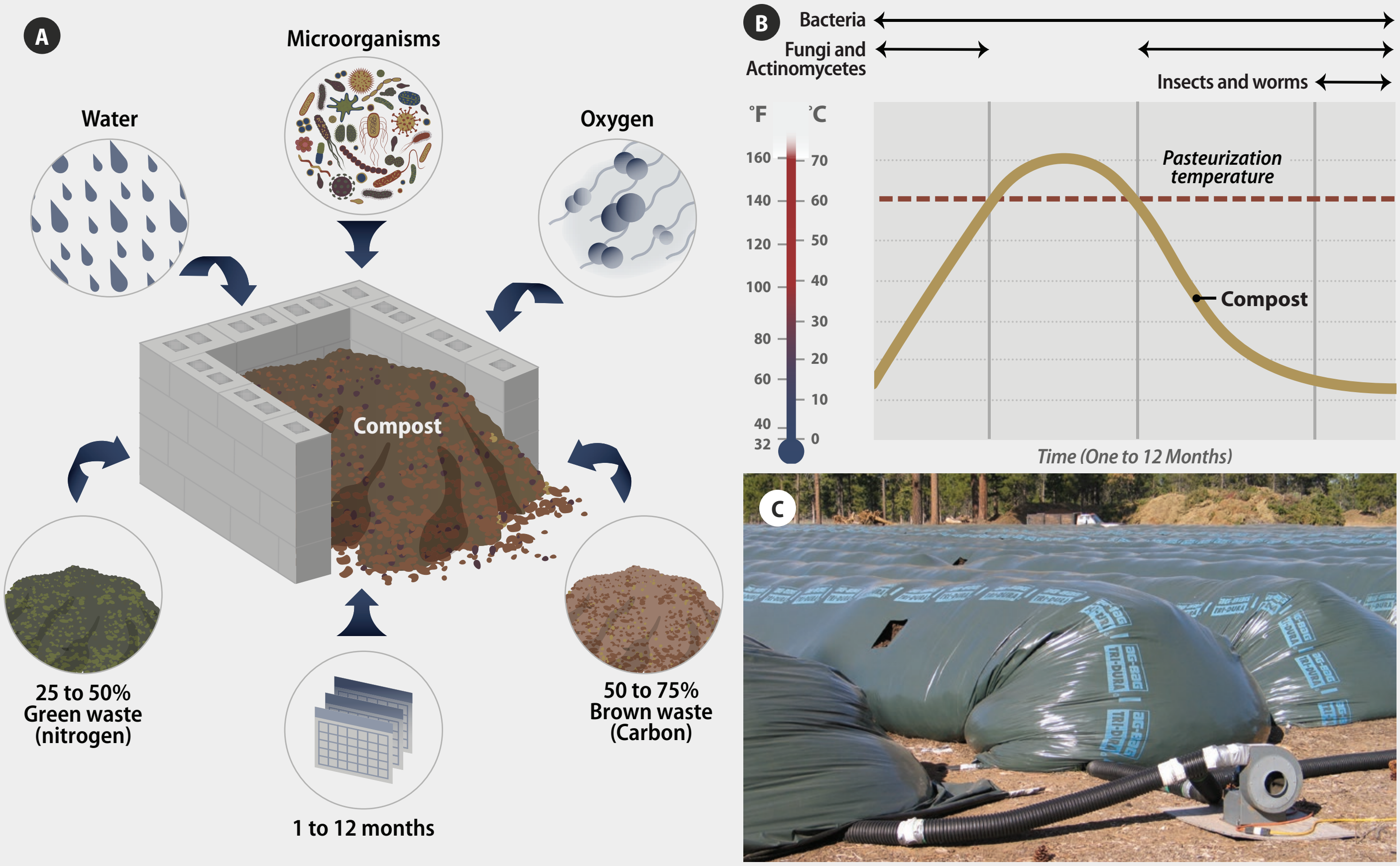
The production and use of compost in the United States has flourished as a result of a ban in many of states on yard wastes in landfills. Since 1988, the number of yard waste composting facilities in the United States has expanded from less than 1,000 in 1988 to more than 3,500 in 1994. With the formation of the Composting Council in 1989, research in compost manufacturing has increased significantly.

Composting is the biological decomposition of organic matter under controlled aerobic conditions. To start the composting process, there should be organic matter, water, microorganisms, and oxygen (Image A in the illustration below). Heat is also needed but is created by the microorganisms as they proliferate. Temperatures exceed levels that kill most pathogens and weed species (Image B).

With time, in a controlled composting environment, microorganisms release carbon dioxide and water from the organic matter. The rate at which these are released, and ultimately the composting time, is a function of the type of material being composted and the composting method.

A variety of composting methods have been developed. State- of-the-art facilities and equipment that control and monitor oxygen, moisture, carbon dioxide, and temperature levels throughout the composting process produce relatively uniform products. The picture shown in Image C is of a composting system that pumps oxygen through a pipe centered in the wrapped piles of compost. Temperature and carbon dioxide are controlled through a venting system (adapted from Epstein 1997).

Photo credit: David Steinfeld



Biochar and Black Carbon—Biochar is a carbon-based material, produced from biomass (e.g. wood chips and plant residues) in a low oxygen, high temperature environment in a process called pyrolysis. It is a type of "black carbon" — a continuum of charred residues that includes char, charcoal, bone char, carbon ash, carbon black, black carbon, carbonized carbon, coke, and soot — produced for the specific purpose of sequestering carbon (Spokas and others 2012). Biochar is very resistant to decomposition and lasts for hundreds of years in the soil, as compared to uncharred biomass which breaks down in decades returning carbon to the atmosphere. It's high porosity and large surface area makes it very absorbent to nutrients, metals, and water and for this reason is of interest in roadside management as a soil amendment for plant growth and removing contaminates from road runoff. Biochar can be used on roadsides for (1) sequestering carbon, (2) improving soil characteristics, and (3) enhancing water quality.

Applying biochar to roadsides for carbon sequestration has been limited because of the high costs and availability of the material. Other methods of sequestering carbon on roadsides are more cost effective such as mowing grasses less frequently, converting introduced annual grass and forb vegetation to perennial species, maintaining forested areas, using vegetation in lieu of traditional engineering solutions (e.g. living snow fences, slope stabilization), and converting open areas to shrub and forested species (FHWA 2010).

Depending on the soil type, incorporating biochar may immediately affect soil nutrition, water retention, or microbial activity which may improve soil productivity. In reviewing the literature, Spokas and others (2012) found that biomass yields increased in half of the studies where biochar or black carbon was added to the soil but either decreased or showed no significant differences in the other half. The reasons for conflicting study results are likely due to the variety of biochars used in these studies. Biochar properties range widely depending on type of material used (feedstock), temperatures (pyrolosis conditions), and how the biochar was stored. Differences in study findings may also be due to the soil type. Of the studies with positive results, a greater number of these studies were conducted on either weathered or degraded soils with limited soil fertility, similar to roadside conditions.

The large surface area and cation exchange capacity of biochars may immobilize plant nutrients, decreasing soil productivity and restricting plant growth. Combining biochar with compost, manure, fertilizer, and other amendments may mitigate these effects and be a good method for using biochar in soil remediation (Beesley and others 2011). It is important to understand the effects of applying biochar to a roadside project through trials or administrative studies. Applying biochar to roadsides for soil improvement has been done on a limited scale and research is needed to understand its value in improving these sites.

Biochar has the potential to be an effective sorbent for organic and inorganic contaminants in soil and water (Ahmad and others 2013). Used in storm water design, it holds promise in removing heavy metals and other road pollutants from road runoff, including brake lining dust, leaded gas, antifreeze, and herbicides. Mixed into the soil where road runoff concentrates (e.g. road shoulders, amended ditchlines, filter strips, bioretention swales, constructed wetlands) biochars may capture contaminants before they enter live drainages. Mixing 4 percent biochar into a roadside filter strip, Brown (2016) greater infiltration rates, lower runoff levels, increase in soil moisture content nitrate reduction.

The origin of biochar may be critical in the type of contaminant being absorbed. Biochars produced under high temperatures have higher surface area and are more effective in capturing organic contaminants while lower temperature biochars are more suitable for removing inorganic contaminants such as metals (Ahmad and others 2013). The same absorptive characteristics that make biochars good for water quality may also capture nutrients important for plant growth. For this reason, if biochars are being used in road runoff structures, it is important to consider its impacts on plant growth. As stated above, using composts, manures, shredded wood, fertilizers, and other amendments with biochar, may increase soil productivity and plant growth. Laboratory or field testing of biochar with soil amendments prior to use on projects will identify the effectiveness of these mixes in removing road contaminants.

Carbon-to-Nitrogen Ratio—The C:N ratio is one of the most important characteristics to consider when selecting a source of organic matter. It is an indicator of whether nitrogen will be limiting or surplus (Section 3.8.4, see Soil Nitrogen and Carbon). The higher the C:N ratio, the greater the likelihood that nitrogen will be unavailable for plant uptake. When an organic source with a high C:N ratio is incorporated into the soil, carbon becomes available as an energy source for decomposing soil organisms. Soil microorganisms need available nitrogen to utilize the carbon source. Not only do microorganisms compete with plants for nitrogen, they store it in their cell walls, making it unavailable for plant growth for long periods. As the carbon sources become depleted, the high populations of soil microorganisms die and nitrogen is released for plant growth (Figure 3-40).

When C:N is greater than 15:1, available nitrogen is immobilized but as ratios dip below 15:1, nitrogen becomes available for plant uptake. Most fresh and aged organic sources have C:N ratios greater than 15:1 (Table 5-10) and will immobilize nitrogen for some period of time when incorporated into the soil. When these same materials are composted, C:N ratios approach or even fall below 15:1 and provide a source of nitrogen to the soil. Co-composts, which are biosolids mixed into the compost, can have ratios between 9:1 and 11:1, indicating they are a ready source of available soil nitrogen. When materials with C:N ratios are below 10:1, they can be considered a fertilizer and labeled accordingly. The period of time that nitrogen remains immobilized in the soil is dependent on several factors:

- **Climate**—High moisture and warm temperatures are important for accelerating decomposition rates. For example, organic matter will decompose faster in Florida than in the mountains of Idaho.
- **Quantity of incorporated organic matter**—The more organic matter that is applied, the longer the immobilization. A small amount of incorporated sawdust will immobilize very little nitrogen as compared to several inches of the same material.
- **C:N ratio of organic amended soil**—The combined C:N ratio of soil and incorporated organic matter gives an indication of how the type and rate of incorporated organic matter will affect the soil C:N ratio. An amended soil with a high C:N ratio will have a longer immobilization period than a soil with a lower C:N ratio.
- **Depth of incorporation**—The depth to which high C:N materials are mixed into the soil will affect decomposition rates. For example, a layer of high C:N material near the surface of the soil will decompose slower than the same layer mixed to 12 inches deep because there would be less soil to organic matter contact.
- **Size and shape of organic matter**—The more surface area of the organic source, the faster decomposition will take place. A fine compost will decompose faster than a coarse, screened compost.
- **Nitrogen fertilization or fixation**—Nitrogen present in the soil or supplied from fertilizers or nitrogen-fixing plants will speed up decomposition rates.

It is difficult to predict how long nitrogen will be immobilized in a soil due to the incorporation of organic matter. The variety of available organic sources, unique soil types, and range of climates in the United States make this difficult. For practical purposes, it can be assumed that without supplemental additions of nitrogen (from fertilizers or nitrogen-fixing plants), the immobilization of nitrogen in soils with high C:N ratios will be in the order of months, if not years. To give some idea of decomposition rates, Claassen and Carey (2004) found that partially composted yard waste with a C:N of 18:1 took over a year for nitrogen to become available under aerobic incubation testing conditions.

Table 5-10 | **C:N ratios for common sources of organic matter**

From Rose and Boyer 1995-; Epstein 1997; Claassen and Carey 2004; Claassen 2006

Materials	C:N ratio
Wood: Ponderosa pine and Douglas-fir	1,200:1 to 1,300:1
Bark: Ponderosa pine and Douglas-fir	400:1 to 500:1
Wood: Red alder	377:1
Paper	170:1
Pine needles	110:1
Wheat straw	80:1
Bark: Red alder	71:1
Dry leaves	60:1
Dry hay	40:1
Leaves	40:1 to 80:1
Yard compost	25:1 to 30:1
Oat straw	24:1
Rotted manure	20:1
Alfalfa hay	13:1
Top soil	10:1 to 12:1

From Rose and Boyer 1995; Epstein 1997; Claassen and Carey 2004; Claassen 2006

A	**Total nitrogen (or other nutrient of interest) in compost**	10 lbs/yd^3	From laboratory report; most labs will report out nutrients in lbs/yd^3 of material
B	**Nitrogen deficit**	769 lbs/ac	Determine from reference sites or minimum thresholds from literature (see Figure 5-2 and Figure 5-3)
C	**Minimum application rates** *B / A =*	77 yd^3/ac	Volume of compost to apply to teh site to meet minimum thresholds
D	**Minimum application depth** *C / 135 =*	0.6 in	Thickness of compost to apply to the site to meet minimum thresholds

Figure 5-31 | **Determining application rates**

The following calculations can be used to determine the amount of compost to apply to a site. They are based on laboratory test results of the compost and threshold nitrogen levels obtained from reference sites.

The incorporation of materials with high C:N ratios may be beneficial to long-term soil aeration and water movement because the material will not break down as fast as materials with lower C:N ratios. For example, the incorporation of alfalfa hay (C:N =13:1) will decompose quickly, and the effects on soil structure might be short-lived. Alternatively, pine needles (C:N = 110:1) or shredded Douglas-fir (1,200:1) will be effective for many years. High C:N materials are also a longer-term energy source to soil organisms that help create soil structure (Inset 5-7).

Nitrogen-based fertilizers can be applied to offset the effects of high C:N ratios on soil productivity by making nitrogen available for plant growth. Section 5.2.1 describes fertilizer strategies for reducing the effects of high C:N soils.

Material Size and Shape—The range in sizes and shapes of organic matter plays a role in how quickly organic matter breaks down in the soil. Particles with greater surface area to volume ratios will decompose faster than particles with less surface area to volume under similar environments. Chipped wood, for example, has a low surface area to volume ratio and takes longer to break down than long strands of ground wood or fine screened sawdust, which have greater surfaces areas.

The particle size and shape of the organic source can also be important in slope hydrology by increasing infiltration and permeability rates. Long, shredded wood, for example, can create extended passageways for water movement. If applied at high enough rates, long fibers can overlap, creating continuous pores that will increase drainage. Wood chips applied at the same rates are less likely to form continuous routes for water drainage because of their shape.

Large undercomposed wood can significantly reduce soil water storage due to low water-holding capacity of the material. Incorporating large, undercomposed woody organic matter into soils with low water-holding capacities should be tested first to determine its effect (Section 5.2.5, see Background).

Determine Application Rate

The rates for applying organic matter should be based on the objectives for organic matter incorporation. Each objective described in Section 5.2.5 (see Set Objectives) will yield different application rates. For example, a project objective to increase permeability would require the addition of 6 inches of compost mixed into 24 inches of soil. This is a far greater quantity than if the objective was to increase nutrient supply, which would require 2 inches of compost added to the top 12 inches of soil.

Determining the rates of organic matter needed to improve nutrient status can follow the process outlined for calculating fertilizer rates in Section 5.2.1 (see Develop Nutrient Thresholds and Determine Deficits). If a nutrient, specifically nitrogen, is found to be deficient, the amount of organic material to apply should be determined. A nutrient analysis is necessary to make these determinations. Figure 5-31 provides an example of how to calculate the amount of organic matter to incorporate to meet minimum levels of nitrogen.

When organic matter is used to increase infiltration and permeability for water quality and soil erosion, a rate of 25 percent organic matter (by volume) to 75 percent soil (by volume) has been suggested by several researchers (Claassen 2006). This would require 4 inches of organic matter be incorporated for every 9 inches of soil (Inset 5-7). Actual field trials could be installed prior to construction to measure the effects of soil amendments on infiltration. By incorporating several rates of organic matter on plots in disturbed reference sites near the project, the infiltration rates of each treatment could be determined using rainfall simulation equipment.

If the objective for incorporating organic matter is to increase the soil's available water-holding capacity, the rate of organic matter application should be based on achieving a total available water-holding capacity for the desired vegetation of the project area (setting these targets is described in Section 3.8.2).

Ensure Product Quality

Purchasing compost requires a set of contract specifications that ensure product quality. Table 5-10 is a "model specification" developed for the U.S. Department of Transportation by the Composting Council Research and Education Foundation (Alexander 1993b) for composts used as soil amendments on roadways. The tests are based on the TMECC protocols. These are general quality guidelines and can be broadened or made more constraining depending on the specifics of the project. When considering purchasing compost or any other type of organic matter from a manufacturer, it is important to request the latest lab analysis. An STA facility (Inset 5-6) will have these reports available while others might not. It is important that these tests be run by STA laboratories. It is a good practice to visit the location of the organic sources to determine whether there are undesirable or noxious weeds on or near the piles. If these species are present, materials should not be purchased.

5.2.6 LIME AMENDMENTS

Introduction

Agricultural lime is used when soil pH of a disturbed site needs to be raised to improve plant survival and establishment (Section 3.8.4, see Salts). Liming low pH soils improves plant growth by reducing aluminum toxicity, increasing phosphorus and micronutrient availability, favoring symbiotic and non-symbiotic nitrogen fixation, improving soil structure, and enhancing nitrification (Havlin and others 1999).

Set pH Targets

Each plant community has an optimal pH range. Plant communities dominated by conifers, for example, function well between pH 5.0 to 6.5, whereas grass-dominated plant communities in arid climates perform well between pH 6.5 and 8.0. It is important to set a realistic post-construction target pH when considering liming because large quantities of lime materials are needed for even small changes in soil pH. For example, raising the pH of a sandy loam soil from 5.5 to pH 6.5 takes nearly twice the amount of lime necessary to raise it to pH 6.0. A half point pH difference in this case can result in an increase of more than 1,000 lb/ac in application rates.

As described in previous sections, it is important to understand the characteristics of the reference site topsoils and try to recreate these soil conditions after construction. On projects where topsoil is removed and not replaced, it is important to determine the difference between the pH of the reference site topsoil and the post-construction surface soil through soil testing. When the pH of the post-construction surface soil is significantly lower than the reference site topsoil, liming to raise subsoil pH to reference site topsoil levels (target levels) can be beneficial.

Select Liming Materials

There are several types of liming materials commercially available (Table 5-11) and selection of these materials is typically based on costs, reactivity, effects on seed germination, and composition of the material. All liming materials will raise soil pH but not at the same level as pure limestone. To account for this, all commercially available liming materials are rated against pure limestone for neutralizing effects. The rating system is called calcium carbonate equivalent (CCE). Burnt lime (CaO) for example, might have a CCE of 150, which means that it has a 50 percent greater neutralizing capacity than pure limestone and much less of this material needs to be applied to increase pH. A low CCE material, such as slag, might have a CCE of 60, which means that it has 40 percent less neutralizing capacity. Liming materials with high CCE, like $Ca(OH)_2$ (slaked lime, hydrated lime, or builders lime) and CaO (unslaked lime, burnt lime, or quicklime), can be caustic to germinating seeds and, if used, need to be applied several

Table 5-11 | **Calcium carbonate equivalents**

Liming materials are rated by how well they neutralize the soil using pure limestone as the baseline of 100 percent. The rating system is called calcium carbonate equivalents (CCE). Values for some commercially available products are shown below.

Campbell and others 1980; Havlin and others 1999

Material	Chemical formula	CCE
Slag	$CaSiO_3$	60-90
Agricultural limestones	$CaCO_3$	70-90
Marl	$CaCO_3$	70-90
Pure limestone	$CaCO_3$	100
Pure dolomite	$CaMg(CO_3)_2$	110
Hydrated lime, slaked lime, builders' lime	$Ca(OH)_2$	120-135
Burned lime, unslaked lime, quicklime	CaO	150-175

The particle size of the liming material determines how quickly the pH of a soil will increase. The finer the material, the faster the soil pH will increase. For example, a lime material passing a 100-mesh screen reacts faster and takes less quantity than material passing a 50-mesh screen. Finer lime materials are typically more expensive.

Determine Liming Rates

Determining how much liming material to apply is based on these factors:

- **Soil texture**—Soil texture plays an important role in lime requirements because the higher the clay content, the more lime that must be added to the soil to raise the pH. A soil with a clay loam texture requires over three times more lime to raise the pH from 5.0 to 6.0 than a sandy soil. This is because finer-textured soils and organic matter have higher CEC (Inset 5-9).
- **Soil organic matter**—Soil organic matter (in humus form) has a high CEC and requires more lime material to raise pH.
- **Percentage of rock fragments**—Rock fragments have little to no CEC because they are massive and typically unweathered. Rocky soils will require less lime materials to raise pH.
- **Depth of liming material**—Lime materials are relatively insoluble and only change the pH of the soil around where they were placed. Liming rates are adjusted based on the soil depth to which the lime material is mixed.
- **Lime material composition**—Each liming material is rated by how well it neutralizes the soil. Less materials with high CCE (Section 5.2.6, see Select Liming Materials) are required as compared to low CCE materials.
- **Fineness of liming material**—The fineness of the liming material determines how quickly the pH will change. Very fine materials change pH quicker than coarse materials. Therefore, less quantity of finer-grade materials will be required for immediate pH soil change.

Inset 5-9 | **Cation exchange capacity (CEC)**

The capacity of a soil to hold positive ions (referred to as bases or cations) is called the cation exchange capacity (CEC). A soil with a high CEC holds greater amount of cations, such as calcium and magnesium, than a soil with a low CEC. For this reason, a high CEC soil requires more liming material to raise it to the same pH level. Cation exchange capacity is directly related to the amount of clay and organic matter present in the soil—the higher the clay or organic matter content, the higher the CEC. Rock fragments have little or no CEC because they are massive in structure. Rates of liming on high coarse fragment soils are reduced proportionally.

For a quick approximation of liming rates, refer to the Excel workbook titled "Calculating Liming Rates Procedure" in the Native Revegetation Resource Library, which is based on the lime application rate curves shown in Figure 5-32. However, for a more accurate assessment of rates, the Shoemaker-McLean-Pratt (SMP) Buffer method is available. This test requires samples of the post-construction surface soils be sent to a soils laboratory. Results are reported in a table that shows the quantity of lime needed to raise the soil sample to pH 7. The information can be graphed and used in a similar fashion to the example in Figure 5-32. The SMP test is well adapted for soils with pH values below 5.8 and containing less than 10 percent organic matter (McLean 1973). The future of the SMP test however, may be short-lived because of the hazardous chemicals that are used and other tests, such as the Sikora Buffer method may be used in its place (Anderson and others 2013).

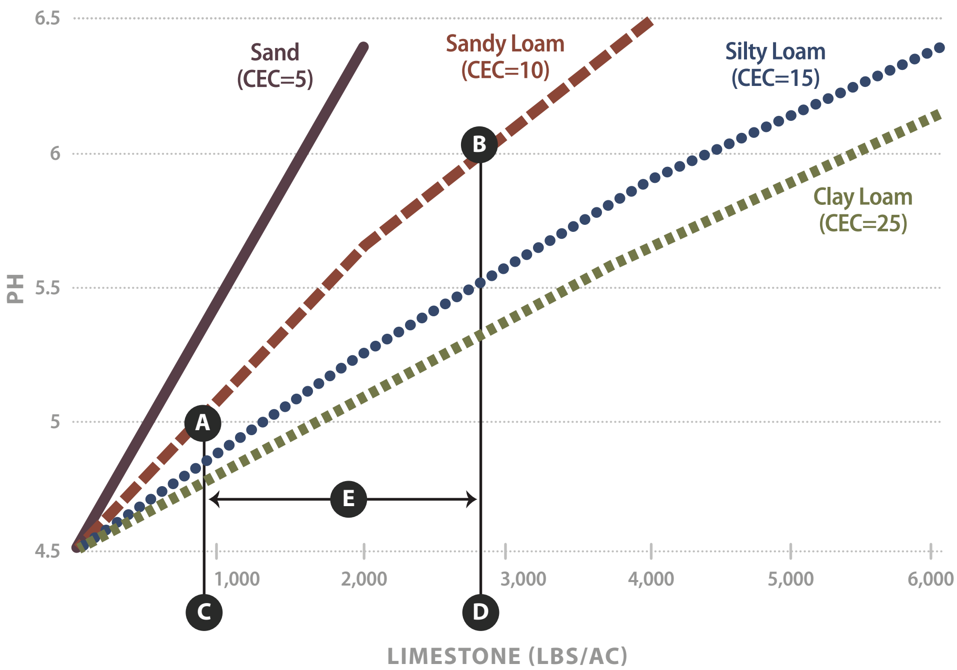


Figure 5-32 | **Approximate liming rates for disturbed soils**

This chart can be used to approximate the liming application rates for disturbed soils. The chart is based on measuring pH changes of four soil textural classes as limestone is incorporated into the surface 7 inches of soil (chart modified from Havlin and others 1999). For example, a sandy loam soil has an existing pH of 5.0 (A) and a target pH after liming of pH 6.0 (B). The amount of limestone to apply (E) is 1,900 lb/ac, which is calculated by subtracting 900 (C) from 2,800 (D). Refer to the Calculating Liming Rates Procedure workbook for a quick determination of rates and materials. More accurate lab results obtained from the SMP Buffer method for determining lime requirements can be substituted for values obtained in this graph.

Apply Liming Materials

Limestone materials are commonly applied in powder form through fertilizer spreaders or hydroseeding equipment. Pelletized limestone, which is very finely ground material that has been processed into shot-sized particles, is easy to handle and can be used in fertilizer spreaders. Hydroseeding equipment, however, is probably the best method for spreading liming materials, especially very fine liming materials which can be difficult to apply through fertilizer spreaders.

Because liming materials are relatively insoluble in water, surface applications of lime, without some degree of soil mixing, renders the lime ineffective for immediate correction of soil acidity. Several studies have indicated that it can take more than a decade for surface-applied lime (not incorporated) to raise soil pH to a depth of 6 inches (Havlin and others 1999). It is important, therefore, to incorporate liming materials into the soil at the depth where the pH change is desired.

Incorporation can be accomplished on gentle slope gradients using tillage equipment, such as disks and harrows (Section 5.2.2). Liming materials can be mixed on steep slopes using an excavator. However, if equipment is not available for mixing on steep sites, applying very finely ground limestone through hydroseeding equipment is a possible way of raising the surface pH (Havlin and others 1999). This material raises pH faster and depending on the soil type and slope gradient, can increase the pH in the surface 3 or 4 inches of soil over time. The size specifications for very fine lime is 100 percent passing a 100-mesh sieve and 80 percent to 90 percent passing a 200-mesh sieve.

5.2.7 BENEFICIAL SOIL MICROORGANISMS

Background

Beneficial microorganisms are naturally occurring bacteria, fungi, and other microbes that play a crucial role in plant productivity and health. Some types of beneficial microorganisms are called “microsymbionts” because they form a symbiotic (mutually beneficial) relationship with plants. In natural ecosystems, the root systems of successful plants have several microbial partnerships that allow them to survive and grow even in harsh conditions (Figure 5-33). Without their microsymbiont partners, plants become stunted and often die. Frequently, these failures are attributed to poor nursery stock or fertilization, when the real problem was the absence of the proper microorganism.

As described in Section 5.2.7 (see Sources and Application of Arbuscular Mycorrhizal Fungi) it is important to consider beneficial microorganisms as part of an overall strategy to conserve existing ecological resources on the site. These strategies include the following:

- Minimizing soil disturbance
- Conserving and reapplying topsoil and organic matter
- Leaving undisturbed islands or pockets on the project site
- Minimizing use of fast-release fertilizers

On projects where soil disturbance will be minimal or where topsoil is still present and contains functional communities of beneficial microorganisms, reintroducing the organisms will usually not be necessary. However, most road projects involve severe disturbances and, therefore, healthy populations of beneficial microorganisms may be depleted or even absent. Soil compaction and removal of topsoil, which is routine during road construction, is particularly detrimental to beneficial soil microorganisms. In addition, beneficial bacteria and fungi do not survive in soil for long periods of time in the absence of their host plants and may be killed during the topsoil storage period. Reintroducing beneficial microorganisms may be an important component in establishing and maintaining native vegetation and in restoring soils.

Appropriate beneficial microorganism can be reintroduced by inoculating seeds and plants with the beneficial microorganism, or introducing the microorganism in the planting hole. Applying inoculum however, does not always result in the colonization of the root system with the beneficial organism. As will be discussed, colonization depends on the quality of the inoculum and the soil environment. Plants with well colonized root systems may establish more quickly and with less water, fertilizer, and weed control, than non-colonized plants, thereby reducing installation costs.

The two most important microsymbionts for revegetation projects are mycorrhizal fungi and nitrogen-fixing bacteria.

What are Mycorrhizae?

Mycorrhizae are one of the most fascinating symbiotic relationships in nature. “Myco” means “fungus” and “rhizae” means “root”; the word “mycorrhizae” means “fungus-roots.” The host plant roots provide a convenient substrate for the fungus and also supply food in the form of simple carbohydrates. In exchange for this free “room-and-board,” the mycorrhizal fungus offers benefits to the host plant:

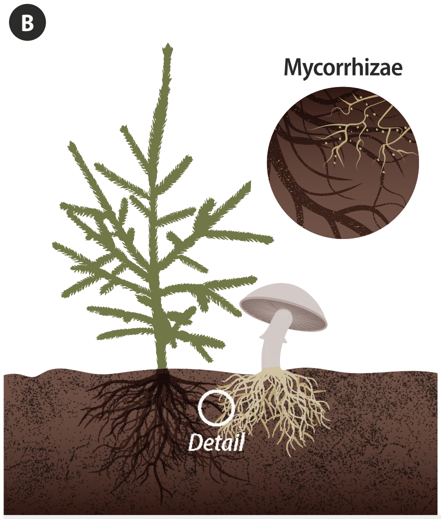


Figure 5-33 | **Symbiotic relationships of plants**

Many plants rely on symbiotic relationships to survive and grow in nature (A). The mushrooms under this spruce are the fruiting bodies of a beneficial fungus that has formed mycorrhizae on the roots (B).

Photo credit: Thomas D. Landis

Increased Water and Nutrient Uptake—Beneficial fungi help plants absorb mineral nutrients, especially phosphorus and micronutrients such as zinc and copper. Mycorrhizae increase the root surface area, and the fungal hyphae access water and nutrients beyond the roots (Figure 5-34). When plants lack mycorrhizae, they become stunted and sometimes chlorotic (yellow) in appearance (Figure 3-29 and Figure 5-34B).

Stress and Disease Protection—Mycorrhizal fungi protect the plant host in several ways. With some fungi, the mantle completely covers fragile root tips (Figure 5-34A) and acts as a physical barrier from drying, other pests, and toxic soil contaminants. Other fungal symbionts produce antibiotics that provide chemical protection.

Increased Vigor and Growth—Plants with mycorrhizal roots survive and grow better after they are planted on the project site. This effect is often difficult to demonstrate but can sometimes be seen in nurseries where soil fumigation has eliminated mycorrhizal fungi from seedbeds. After emergence, some plants become naturally inoculated by airborne spores and grow much larger and healthier than those that lack the fungal symbiont (Figure 5-34B). Mycorrhizal fungi form partnerships with most plant families, and three types of mycorrhizae are recognized:

- Ectomycorrhizal fungi (ECM) have relatively narrow host ranges and form partnerships with many temperate forest plants, especially pines, oaks, beeches, spruces, and firs.
- Arbuscular mycorrhizal fungi (AMF) are also known as endomycorrhizae or vesicular-arbuscular mycorrhizae. These fungi have wide host ranges and are found on most wild and cultivated grasses and annual crops, most tropical plants, and some temperate tree species including cedars, alders, and maples as well as flowering forbs use by pollinators.
- Ericoid mycorrhizal fungi form partnerships with the Epacridaceae, Empetraceae, and most of the Ericaceae; plants affected include blueberries, cranberries, crowberries, huckleberries, azaleas, rhododendrons, and sedges. Because these mycorrhizal associations involve unique species of fungi, few commercial inoculants are available and the best option is to use soil from around healthy plants.

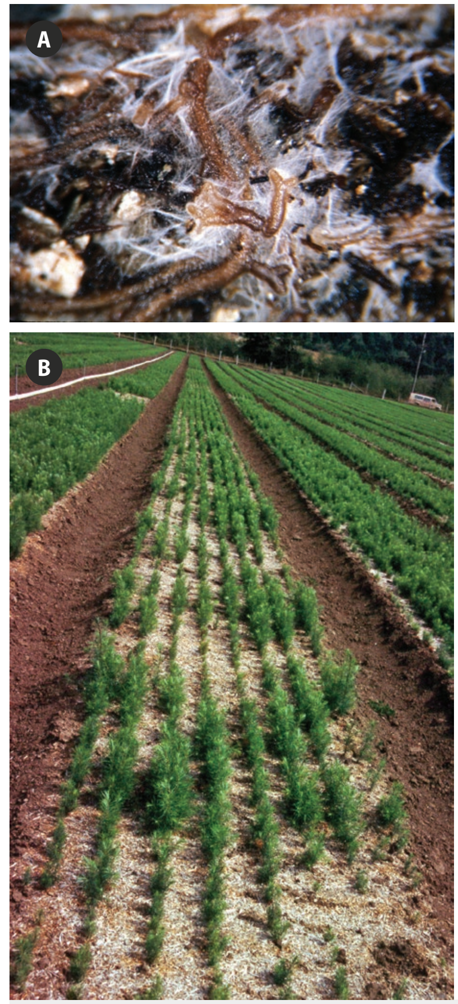


Figure 5-34 | **Mycorrhizal fungi benefits host plants**

Mycorrhizal fungi offer many benefits to the host plant. The fungal hyphae increase the area of absorption for water and mineral nutrients, whereas fungal mantle covers the root and protects it from desiccation and pathogens (A). Seedlings grown in nurseries soils that are low in mycorrhizae are often stunted as shown in this patchy nursery bed (B).

Photo credits: Thomas D. Landis

For restoration purposes, the important thing to remember is that different plant species have specific fungal partners. ECM fungi are generally specific to one genus, whereas AMF fungi can colonize a wide range of genuses. Conserving existing topsoil and organic matter is a key practice to protecting existing populations of beneficial microorganisms. Where disturbed soils are expected, practices may be necessary to reintroduce the key microsymbionts. Applying mycorrhizal inoculants is one option but it must be based on the target host plants and the site condition. Identifying whether the host plant is endomycorrhizal, ectomycorrhizal, ericoid, or non-mycorrhizal is important in selecting inoculum. Conifer seedlings, for example, require very specific ectomycorrhizal fungi for successful inoculation. Endomycorrhizal species, on the other hand, are broad in range and therefore a general mix of several endomycorrhizal species can be used for a broader range of plant species.

Sources and Application of Ectomycorrhizal Fungi

Three common sources of ECM inoculants are soil, spores, or pure culture vegetative inoculum.

Soil—Topsoil, humus, or duff from beneath ECM host plants in or near the project can be used for inoculum if done properly (Figure 5-35A). Because disturbance and exposure to direct sunlight may kill these beneficial fungi, inoculation using these sources need to be done as quickly as possible. For the best results, small amounts topsoil, humus or duff are collected from several different locations and mixed into the soil prior to planting.

Spores—Spore suspensions are sometimes available from commercial suppliers. These spores are collected in the field from ripe fruiting bodies like mushrooms and truffles (Figures 5-35 B and C). The quality of commercial sources can be variable so it is important to verify the quality of the inoculum. It is also possible to make inoculum from spores by collecting ripe

Figure 5-35 | **Soil inoculum can be collected in the field**

Inoculum can be obtained by collecting topsoil or duff from areas with similar plant species (A) or from the spores of mushrooms (B), puffballs, or truffles (C) collected from around the host plant.

Photo credits: Thomas D. Landis

fruiting bodies of mushrooms, puffballs, or truffles from beneath healthy plants. They are then rinsed and pulverized in a blender for several minutes to make a slurry. Fungal spores do not have a long shelf life and benefit from being refrigerated and applied as soon as possible.

Pure Culture Inoculum—Mycorrhizal fungi are available commercially as pure cultures, usually in a peat-based carrier. Most commercial sources contain several different species of ECM. Because this type of inoculum is made from pure fungal cultures and does not store well, it is rarely available from suppliers.

Application rates and methods for ectomycorrhizal inoculums vary by species. Because these mycorrhizal fungi are very specific to their host species, it is important to work closely with company representatives when using ectomycorrhizal inoculum. Nurseries can inoculate plants with ECM and if this service is desired, it needs to be stated in the seedling-growing contract. However, as stated above, there is no guarantee that the plants that are inoculated with have colonized roots when they are planted at the project site.

Other ectomycorrhizal fungal inoculums are applied at the time of planting with the objective to get the inoculum in contact with the plant roots. Some formulations are mixed with water and the slurry is applied to the roots of nursery stock. However, the effectiveness of many of these applications has not been verified by research under roadside revegetation conditions.

Verifying the Effectiveness of ECM Inoculation—It is fairly easy to recognize ECM with the naked eye on the root system of a seedling. The short feeder roots of the seedling is covered with a cottony-white or a brightly colored mantle or sheath over the roots (Figure 5-36). Unlike pathogenic fungi, mycorrhizae will never show signs of root decay. Sometimes, mushrooms or other fruiting bodies will appear alongside their host plants which is an indicator of the species of mycorrhizae that is present. If mycorrhizae is not visible on the roots systems, plant samples can be sent to a laboratory where they analyzed for inoculation effectiveness.

Figure 5-36 | **Ectomycorrhizae fungi are visible on roots**

Ectomycorrhizae are visible on plant root systems as white or colored structures with a cottony or felt-like texture.

Photo credit: Thomas D. Landis

Sources and Application of Arbuscular Mycorrhizal Fungi

The two main sources of arbuscular mycorrhizal fungi inoculants include "pot culture," (also known as "crude" inoculant), and commercially available pure cultures.

Nursery Pot Culture—With this option a specific AMF is acquired either commercially or from a field site as a starter culture, and then added to a sterile potting medium. A host plant such as corn, sorghum, clover, or an herbaceous native plant is grown in this substrate and as the host grows, the AMF spores multiply (Figure 5-37A). At maturity the shoots of host plants are removed and the substrate, now rich in roots, spores, and mycelium, is processed (Figure 5-37B). The resultant inoculum can be incorporated into growing media or planting beds before seeds are sown. This is a highly effective technique for propagating AMF in the nursery and could also be used on the planting site. For details, refer to *Arbuscular Mycorrhizas: Producing and Applying Arbuscular Mycorrhizal Inoculum* (Habte and Osorio 2001).

Figure 5-37 | **Arbuscular mycorrhizal fungi**

Because of their wide host range, AMF fungi can be raised on host plants like sorghum (A) producing spores and colonized roots that can be chopped-up for inoculum (B).

Photo credits: Thomas D. Landis

Commercial Products—Several brands of commercial AMF inoculants are available and usually contain a mix of several fungal species. Coarser-textured products are incorporated into soil or growing media, and finer-textured products are applied as wetable powders through sprayers or injected into irrigation systems. Inoculation effectiveness has been shown to vary considerably between products, so it is wise to install tests before purchasing large quantities of a specific product. Laboratories can provide a live spore count, which is the best measure of inoculum quality.

Application of AMF Inoculants—AMF inoculums typically come in a granular form with different grades of fineness. Coarse-grade products are mixed in the soil prior to sowing seed. Finer-grade inoculums, which are more expensive, may be mixed with water and applied directly onto seeds or as a root dip. Use of fine-grade inoculum through hydroseeding equipment is another way to combine AMF with seeds as they are sown. There is little research on AMF inoculation effectiveness on roadside revegetation sites.

Verifying the Effectiveness of AMF Inoculation—Unlike ectomycorrhizal fungi, AMF are not visible to the unaided eye. To verify the effectiveness of AMF inoculation, roots are stained and examined under a microscope for the percent of the root system that is colonized by AMF.

Management Considerations for Mycorrhizal Fungi

It may be helpful to work with a specialist to selecting the application rates and appropriate mycorrhizal partners for the plant species and outplanting sites. Some management modifications may be required to promote formation of mycorrhizal partnerships in the field. Fertilization is probably the most significant adjustment. Mycorrhizal fungi extend the plant's root system to extract nutrients and water from the soil. In some cases, fertilizer applications can be reduced by half or more due to the increased nutrient uptake by mycorrhizal fungi. Fertilizer type and form are also important. For instance, high levels of soluble fertilizers may inhibit mycorrhizae. An excessive amount of phosphorus in the fertilizer may inhibit the formation of the partnership; therefore, phosphorus fertilizers should be reduced. If nitrogen is applied, ammonium-N is better used by the plant than nitrate-N (Landis 1989). Controlled-release fertilizers are preferred because they release small doses of nutrients gradually, compared to the more rapid nutrient release from traditional products. Applications of certain herbicides, pesticides, insecticides, fungicides, and nematicides are detrimental to mycorrhizal fungi. See Inset 5-10 for an example of contract specifications for purchasing mycorrhizal inoculum.

Inset 5-10 | **Example of contract specifications for purchasing mycorrhizal inoculum**

Purchase of Mycorrhizal Inoculum. The mycorrhizal inoculum must have a Statement of Claims that certifies:

- ✓ the date inoculum was produced
- ✓ mycorrhizal fungi species present in the inoculum
- ✓ number of propagules per pound of product, and
- ✓ the type and grade of carrier.

Product Specifications. Date of inoculum application will be within one year of production date. The storage, transportation and application temperatures of the mycorrhizae shall not exceed 90 degrees F. Inoculum must consist of at least 5 species of (choose endomycorrhizal, ectomycorrhizal or a combination of endo and ectomycorrhizal) fungi with no one species making up more than 25 percent of the propagules.

- ✓ The inoculum will contain these species: ______________________________.
- ✓ The inoculum will contain __________ live propagules per pound (Typical rates for endomycorrhizal inoculums average around 60,000 to 100,000 propagules per pound and 110,000,000 propagules per pound in ectomycorrhizal inoculums.)
- ✓ *(For applications to the soil surface only)* Live propagules must be smaller than 0.3mm.
- ✓ *(Optional)* A one ounce sample will be collected from each inoculum and sent to __________ laboratory for analysis using the __________ standardized test to determine the number of propagules.

Application of Endomycorrhizal Inoculum to Soil Surface

- ✓ Endomycorrhizal inoculum will be applied at a rate of ________________ live propagules per acre (typical rates range from 1,000,000 to 3,600,00 live propagules per acre).
- ✓ Inoculum will be applied in the same operational period as seed application.
- ✓ If inoculum is applied through a hydroseeder, it should be applied within 45- minutes of being mixed in the hydroseeding tank.

Application of Mycorrhizal Fungi to Planting Holes

- ✓ Mycorrhizal inoculum will be applied at a rate of ________________ live propagules per seedling.

Nitrogen-Fixing Bacteria

Nitrogen-fixing bacteria live in nodules on plant roots and accumulate (fix) nitrogen from the air and share it with their host plants (Inset 5-11). Unlike mycorrhizal fungi, which are found on most trees and other plants, only certain species of plants form symbiotic partnerships with nitrogen- fixing bacteria.

Inset 5-11 | **How does biological nitrogen fixation work?**

The symbiotic partnership between plants and their nitrogen-fixing microsymbionts works this way:

Nitrogen fixing bacteria, present in the soil, are attracted to flavonoids secreted from the roots of host plants and invade the root cracks or deformed root hairs. In response, a root nodule appears and an environment for nitrogen bacteria is created. Within the low oxygen environment of each nodule, millions of bacteria convert atmospheric nitrogen to ammonia (NH3) through an enzyme call nitrogenase. This requires a relatively high amount of energy that the plant supplies to the bacteria. In return, the plant receives ammonia, which is converted to amino acids and used to synthesize proteins for plant growth. When the “nitrogen-fixing” plant sheds its leaves, or dies, the nitrogen stored in the plant’s tissues is released into the soil and becomes available to other plants. This process, part of the nitrogen cycle, is the major source of nitrogen fertility in most natural ecosystems.

The role of nitrogen-fixing bacteria and their partner plants is important in revegetating roadsides. Because nitrogen-fixing plants are often pioneer species that are the first to colonize disturbed sites, they are ideal for revegetation or restoration projects. These species help restore fertility and organic matter to the project site. Nitrogen-fixing bacteria form nodules on roots of host plants (Figure 5-38A) and accumulate nitrogen from the air (Figure 5-38B). While plants that form this association are sometimes called "nitrogen-fixing plants," the plant itself is not able to fix nitrogen by itself. It is only through the partnership with bacteria that these plants are able to obtain atmospheric nitrogen. In this partnership, the bacteria supply the plants nitrogen, and in exchange, the bacteria is given a place to grow and carbohydrates from the plant for energy. Without these bacterial partnerships, plants are not able to make direct use of atmospheric nitrogen.

Soil on restoration sites, however, may not contain the proper species of bacteria to form a symbiotic partnership with the plant. This is particularly true for compacted subsoils. Inoculating plants ensures that "nitrogen-fixing" plants form an effective partnership to fix nitrogen. Therefore, use of nitrogen-fixing plants can be an important part of accelerating rehabilitation of degraded land.

Two genera of nitrogen-fixing bacteria that are important in revegetation are Rhizobium and Frankia. Rhizobium grow with some members of the legume family (Figure 5-39A and B) and plants of the elm family. They form nodules on the roots and fix nitrogen for the plant. Frankia are a different kind of bacteria. Frankia partner with non-leguminous plants, such as casuarinas, alders, bitterbrush, and buffaloberry (Figure 5-39C and D) and more than 200 different plant species distributed over eight families. The species affected by Frankia are called "actinorhizal" plants (Table 5-12).

Figure 5-38 | **Nitrogen-fixing bacteria**

Nitrogen-fixing plants, such as legumes, have symbiotic bacteria residing in nodules (blue inset) on their roots (A) which can chemically "fix" atmospheric nitrogen into forms that can be used by plants as fertilizer (B).

Photo credit: David Steinfeld

Figure 5-39 | **Nitrogen-fixing plants**

Nitrogen-fixing bacteria include Rhizobium that forms relationships with plants in the legume family including lupines (A) and clovers (B), and Frankia that forms relationships with other non-leguminous plants such as snowbrush ceanothus (C) and mountain-avens (D).

Photo credits: Tara Luna

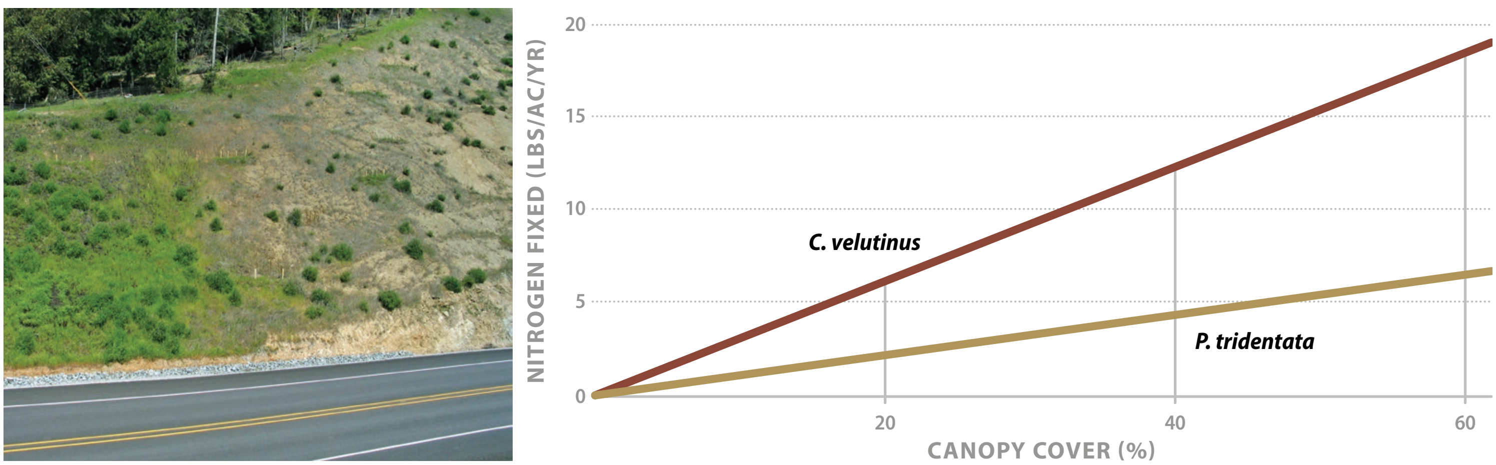
Uses for Nitrogen-Fixing Plants in Revegetation

Only a fraction of native species are nitrogen-fixing host plants. In the western United States, the most common are the lupines, vetch, bitterbrush, ceanothus, alder, and wax myrtle (Table 5-12). On nitrogen-poor sites, sowing or planting a higher proportion of these species can help a site to recover nitrogen fertility and organic matter (Figure 5-40A). The amount of nitrogen that is produced is related to the area of vegetative cover in nitrogen-fixing host plants, the productivity of the plants, and climate factors such as temperature and moisture. If percent cover of nitrogen-fixing host plants is low, then the amount of nitrogen supplied to the site will be correspondingly low (Figure 5-40B). Likewise, dry or cold conditions tend to result in slower accumulation of nitrogen. While many native and introduced nitrogen-fixing plants are attractive to pollinators, they are also attractive forage for large herbivores.

Figure 5-40 | **Amount of nitrogen is related to the cover of nitrogen-fixing plants**

The accumulation of nitrogen by N-fixating bacteria is directly related to the cover of nitrogen-fixing host plants on a site. The large plants shown in this photograph are N-fixing lupines (A). The nitrogen-fixing potential of a 15-year-old stand of *Ceanothus velutinus* and *Purshia tridentata* was directly proportional to plant cover (B) (adapted after Busse 2000).

Photo credit: David Steinfeld



A plant survey of disturbed and undisturbed reference sites can indicate which nitrogen-fixing plants will do well on a revegetation project. Observing the abundance of root nodules on these plants can provide some indication whether they are fixing nitrogen.

Inoculating with Nitrogen-Fixing Bacteria

Nitrogen-fixing nursery stock with nodulated root systems generally exhibit faster early growth than seedlings than un-nodulated root systems. Nursery inoculation can reduce costs in establishment and maintenance; several dollars' worth of inoculant applied in the nursery is inexpensive compared to applying nitrogen fertilizer. Faster establishment can also lead to greater herbaceous cover that can shade out unwanted vegetation. When nitrogen-fixing plants shed leaves or dies, the nitrogen stored in the plant's tissues is cycled into the soil and eventually taken up by adjacent plants. Early establishment of nitrogen-fixing plants accelerates natural nutrient cycling on disturbed sites and promotes the establishment of sustainable plant communities.

Table 5-12 | **Nitrogen-fixing bacteria and their plants**

Nitrogen-fixing bacteria	*Family*	*Subfamily*	**% Nitrogen fixing plants**	**Common plant species**
Rhizobium spp.	Legume	Caesalpinioideae	23	Redbud, honeylocust
	Legume	Mimosoideae	90	Mesquite, acacia
	Legume	Papilionoideae	97	Lupine, milkvetch, black locust, clover
Frankia spp.	Birch			Alder, birch
	Oleaster			Silverberry, buffaloberry
	Myrtle			Myrtle
	Buckthorn			Cascara, snowbrush, deerbrush
	Rose			Mountain mahogany, cliffrose, bitterbrush

It should be noted that in many cases, uninoculated seedlings may eventually form a partnership with some kind of Frankia or Rhizobium strain after they are outplanted. These may not be with optimal or highly productive bacterial partners, and it may take months or even years on highly disturbed sites. Until they become naturally inoculated, plants are dependent on nitrogen fertilizers and may become out-competed by weeds. Inoculating in the nursery ensures that plants form effective, productive partnerships in a timely fashion.

Acquiring Nitrogen-Fixing Bacterial Inoculants—Nitrogen-fixing bacteria are very specific; in other words, one inoculant cannot be used for all plants and a different inoculant strain for each nitrogen-fixing species is usually necessary. Superior strains can yield significant differences in productivity and growth rate of the host plant—in some cases over 40 percent better growth (Schmit, 2003).

Two forms of inoculant can be used: pure cultured inoculant and homemade (often called "crude") inoculant. Pure cultured inoculant is purchased from commercial suppliers, seed banks, or sometimes, universities. Crude inoculant is made from nodules collected from roots of nitrogen-fixing plants of the same species to be inoculated. Whichever form is used, it is important to handle the inoculants with care because they are very perishable. Storing the inoculants in cool, moist conditions away from light will help maintain their viability.

Pure culture inoculants usually come in small packets of finely ground peat moss (Figure 5-41A). The inoculants are added to chlorine-free water to create a liquid slurry (allowing a bucket of tap water to stand uncovered for 24 hours is a good way to let chlorine evaporate). If a blender is available, using it to blend some inoculant in water is a good practice to ensure the bacteria will be evenly mixed in the solution. If a blender is not available, a mortar can be used. Five to ten grams (about 0.2–0.4 ounce) of manufactured inoculant can inoculate about 500 seedlings, usually exceeding the recommended 100,000 bacteria per seedling. Once seedlings begin to nodulate, nodules from their roots can serve as the basis for making crude inoculant as described below. This way, inoculant need only be purchased once for each plant species grown, and thereafter, crude inoculant can be made from nodules.

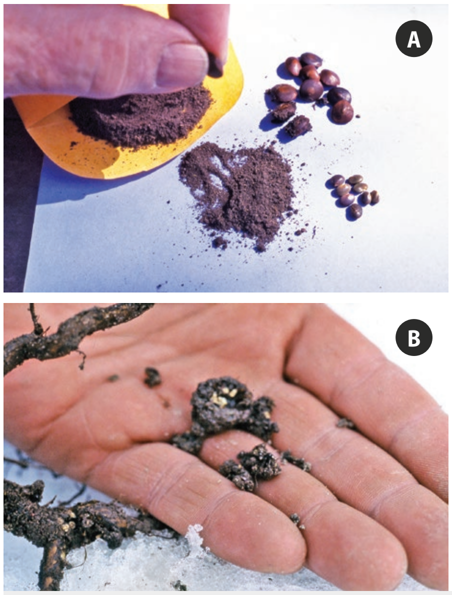


Figure 5-41 | **Nitrogen-fixing bacteria are commercially available**

Nitrogen-fixing bacteria are commercially available as pure culture inoculant, often in a carrier (A), or can be prepared by collecting nodules from roots of plants in the wild (B).

Photo credit: Tara Luna

Preparing Crude Inoculant—Crude inoculant is made using nodules; each of which can house millions of bacteria. For Rhizobium, observing a brown, pink, or red color inside the nodule is usually a good indicator that the bacteria are actively fixing nitrogen. For Frankia, desirable nodules will be white or yellow inside. Grey or green nodules indicate that the structures are not viable.

To make a crude inoculant, select healthy, vigorous plants of the same species as the plants to be inoculated. If available, choose seedlings that were inoculated with select bacteria. Search for nodules with the proper color and pick them off cleanly. If possible, collect nodules from several plants and place them in containers. As soon as possible after collection (within a few hours), put the nodules in a blender with clean, chlorine-free water. About 50 to 100 nodules blended in a liter of water are enough to inoculate about 500 seedlings. This solution is a homemade liquid inoculant, ready to apply in the same method as cultured inoculant as described below. If they are to be stored, place in refrigerated conditions to maintain viability.

Applying Inoculant—It is important to apply inoculant when seedlings are just emerging, usually within two weeks of sowing. This helps ensure successful nodulation and maximizes the benefits of using inoculants. One liter of liquefied inoculant made from either nodules or cultured inoculant as per the instructions above is diluted in water. For 500 seedlings, about 5 liters of chlorine-free water is used. This solution is then watered into the root system of each seedling using a watering can. In the field, for direct seeding applications, the slurry of commercial or crude inoculant can be added to the hydroseeder tank along with the seed mix.

Management Considerations for Nitrogen-Fixing Inoculations

Verifying the Nitrogen-Fixing Partnership—Allow two to six weeks for indications that seedlings have formed a symbiotic partnership with nitrogen-fixing bacteria. Signs include the following:

- Seedlings begin to grow well and are deep green despite the absence of added nitrogen fertilizer
- The root systems give off a faint but distinctive ammonia-like scent
- Nodules are usually visible on the root system after about four to six weeks Figure 5-40A and Figure 5-42), and nodules are pink, red, or brown (for Rhizobium), or yellow or white (for Frankia)

Post-Planting Care—Several factors are of primary concern when using inoculants for nitrogen-fixing bacteria:

- **Fertilization**—The use of nitrogen-fixing bacterial inoculant requires some adjustments in fertilization. Excessive nitrogen fertilizer will inhibit formation of the partnership.
- **Water quality**—Excessive chlorine in water is detrimental to Rhizobium and Frankia. The water source may need to be tested and a chlorine filter used if excessive chlorine is a problem.
- **Micronutrients and soil quality**—Some nutrients are necessary to facilitate nodulation, including calcium, potassium, molybdenum, and iron. Excessively compacted soils, extremes of pH or temperature also inhibit nodulation.

Figure 5-42 | **Nitrogen-fixing bacteria will multiply as inoculated plants grow**

After successful inoculation, nitrogen-fixing bacteria will multiply on the root system as plants grow. The circle points to a visible Frankia nodule on an alnus seedling.

Photo credit: Tara Luna

Other Beneficial Microorganisms

In nature, communities of bacteria, fungi, algae, protozoa, and other microorganisms in the soil make nutrients available to plants, create channels for water and air, maintain soil structure, and cycle nutrients and organic matter. A healthy population of soil microorganisms can also maintain ecological balance, preventing the onset of major problems from viruses or other pathogens that reside in the soil. The practice of protecting and reestablishing beneficial micro-organisms is key for revegetation. As a science, however, the use of beneficial microorganisms is in its infancy. Although thousands of species of microorganisms have been recognized and named, the number of unknown species is estimated to be in the millions. Almost every time microbiologists examine a soil sample, they discover a previously unknown species (Margulis and others 1997). Conserving, maintaining, and creating healthy soils will help to create and sustain the natural populations of beneficial microorganisms.

5.2.8 TOPOGRAPHIC ENHANCEMENTS

Introduction

Topographic enhancements are alterations to the roadside landscape designed to improve the growing environment for plants. Topographic enhancements are important when site resources such as topsoil, organic matter, and water are limited (Section 3.10). It is often better to concentrate limited resources in key areas where resources can be most effective rather than spread them across the larger project area and dilute them to the point of having little benefit to reestablishing native vegetation. An additional benefit of topographic enhancement features is that most are designed to capture water related to road drainage. This improves water quality by reducing peak-flow water to watersheds and capturing sediments.

Topographic enhancement integrates three components into the roadside design: soil improvement, site stability, and water harvesting (Figure 5-43). Soil improvement can occur when limited topsoil and organic matter are strategically used to create growing areas with optimum rooting depth (Section 3.8.2, see Rooting Depth). Stable landforms are created that reduce surface erosion and increase slope stability (Section 3.8.5 and Section 3.8.6). Water harvesting can result when local topography is modified to capture runoff water and concentrate it in areas where it can be used by plants (Section 3.8.1, see Road Drainage) (for background on water harvesting, see Fidelibus and Bainbridge 2006). The integration of these three components will determine the success of a topographic enhancement design.

Topographic enhancement strategies are considered during the road planning stage and the design of any features are in collaboration with the planning engineer. There are many types of topographic enhancement structures. This discussion is not exhaustive but is rather intended to introduce the designer to a variety of structures that can be installed during road construction to enhance the establishment of native plants.

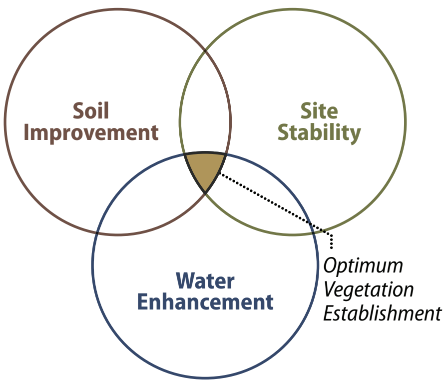


Figure 5-43 | **Topographic enhancement strategies**

Optimal topographic enhancement for establishing vegetation occurs when the roadside design includes soil improvement, site stability, and water capture treatments. It is important to consider topographic enhancement strategies early in project design.

Planting Pockets and Microcatchments

When terraces are filled with growing media (topsoil or amended subsoil) and planted, they are referred to as planting pockets. Planting pockets are designed to have adequate soil depth and good water holding capacity to store intercepted water and support the establishment of planted seedlings. The surface of the planting pocket is in-sloped to capture water and sediment and the face of the pocket is protected from surface erosion using a mulch (Figure 3-15).

Fill slope microcatchments are structures that capture runoff from outsloped road surfaces and compacted shoulders into terraces and berms where it can be used for plant growth (Figure 3-14). Microcatchments include storage basins and berms. Berms are typically 4- to 8-inch-high obstacles placed on the contour. They are formed from soil, woody debris (logs), or manufactured products such as straw wattles or compost berms. Manufactured products and woody debris are “keyed” (partially buried) into the soil surface to prevent water from eroding under the structure. Compost berms are continuous mounds of compost that can slow water and filter sediments. Seedlings can be planted immediately above berms or obstacles to access captured water. Unless species that propagate vegetatively are used in these structures, it is important to avoid planting where sediment will bury the seedling.

Planting Islands

Planting islands are used where resources, such as topsoil and organic amendments, are limited. They are designed into such revegetation projects as obliterated roads, view corridors, disposal sites, staging areas, and other highly disturbed sites. The strategy behind planting islands is to create areas of ideal growing environment for tree seedlings that replicates the natural topography and tree distribution observed in the surrounding landscape.

Islands can be created by excavating to a depth of several feet and backfilling with either topsoil or compost-amended material (Figure 5-44). Alternatively, compost and other soil amendments (including lime and fertilizers) can be spread over planting islands at the depth needed to amend the soil profile and mixed thoroughly through the soil with an excavator or backhoe. After planting, mulch can be applied across the surface of the entire island. Planting islands will generally occupy less than a quarter to a third of the entire site, leaving the remainder as "inter-island." The inter-islands will be much less productive than the planting islands. Grass and forb plant communities are therefore more suited to these areas (Figure 5-45).

Figure 5-44 | **Planting islands focus resources and work in concentrated areas**

Planting islands were created on this highly-compacted waste disposal site that lacked topsoil or organic matter. Spaced 15 to 20 feet apart, the planting islands were composed of 5 cu ft of compost/shredded wood mixed to a 2-ft depth using a backhoe (A). Two trees were planted at each island (B). The inter-island was seeded with a native grass and forb mix and covered with straw.

Photo credits: David Steinfeld

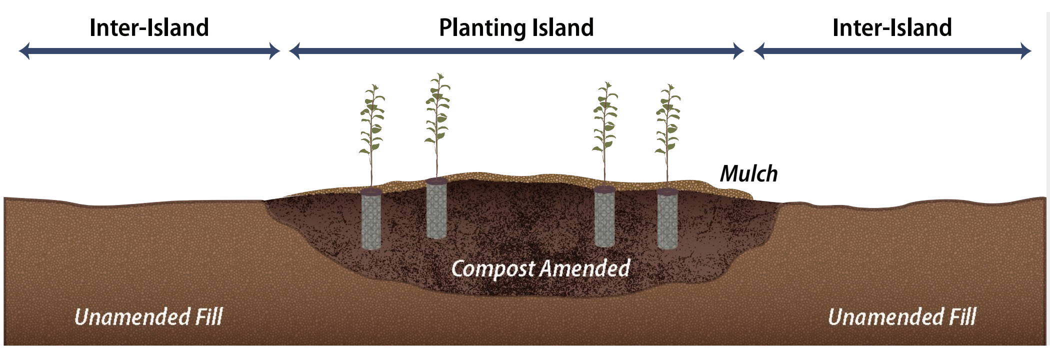


Figure 5-45 | **Planting island cross section**

Illustration of a typical cross section of a planting island where soil depth is enhanced for tree establishment. Inter-island areas are planted to shrubs and grasses.

Amended Ditches

The purpose of amended ditches is to treat road runoff before it reaches live channels. Amended ditches are designed for areas where there is not enough room along the roadside for vegetated swales but they differ in that they are not terraced, nor as wide. Because of

Figure 5-46 | **Amended ditches**

On the North Umpqua Highway project, amended ditches were created by mixing shredded wood and compost to a depth of 18 inches (A). The ditchlines were then formed using the bucket of the excavator (B). Surfaces were seeded, mulched, and lightly irrigated with a water truck being used for dust abatement. Within 6 weeks the ditches were stabilized with grasses and ready for the fall rainstorms (C).

Photo credit: David Steinfeld

their high infiltration rates, these structures retain more sediment and runoff as compared to typical ditches.

Amended ditches are designed to have high infiltration rates and good water storage capacity. These soil characteristics allow road runoff water, originating from low to moderate rainstorm events, to be absorbed and stored in the soil below the ditch. As rainfall intensities increase, the amended ditches become saturated and convey water. To stabilize the channel surface from downcutting during high rainstorm events, the ditches are designed to support a continuous vegetative cover. The organic matter that is added to the ditches during construction, not only keeps the soils open and supports vegetative cover, has been shown to sequester road pollutants (Grismer and others 2011).

One method of constructing an amended ditch is to place 6 inches by 3 feet layer mixture of shredded wood/compost along the ditchline and incorporating it into the soil to a depth of 18 inches with an excavator (Figure 5-46). The shredded wood/compost mixture is produced by mixing 3 parts shredded wood with 1 part compost. The shredded wood adds structure and drainage while compost adds slow release nutrients for establishing and maintaining vegetation. Compost reduces or eliminates the need for fertilizing which is important because fertilizers placed in ditchlines may enter stream courses and decrease water quality.

It is important to establish a vegetative cover on the ditches prior to when heavy precipitation periods are expected. Grass seeds, composed of species appropriate to the site, are applied to the amended ditches and covered with weed-free straw or shredded wood as soon as the ditches are constructed. If seeding is done in the summer, in areas where rainfall is low, it may be necessary to irrigate to encourage the quick establishment of vegetation. The schedule of watering depends on the site however, a simple rule is to water when the surface of the soil, beneath the straw, just begins to dry out. Watering can be coordinated with the dust abatement operation.

Biotechnical Engineering Structures

Topographic enhancement includes a variety of engineering structures that integrate vegetation into the design. These include vegetated retaining walls, brush layers, vegetated riprap, and live pole drains. Attention to the quality of topsoil is important in most biotechnical engineering structures. For instance, the quality of topsoil and how it is placed in vegetated retaining walls is critical for establishing vegetation (Figure 5-47). Where riprap is to be vegetated, it may require a deep layer of high quality composts cover placed over and between the riprap (Figure 5-48).

Figure 5-47 | **Vegetated retaining walls**

The MSE walls on the Blaine Road project required topsoil to be placed in one foot wide baskets faced with native seeded erosion mats. The 6 inch ledges between baskets were planted with native shrub seedlings (A) and within several years after planting, the walls were covered with shrubs and grasses (B).

Photo credits: David Steinfeld

Figure 5-48 | **Vegetated riprap**

Riprapped culvert outlets were reconstructed along the Nestucca River, an Oregon State Scenic Waterway, and required that they be revegetated with native riparian species. A compost blanket was installed over the riprap at a depth of 8 inches (A). It was planted with seedlings of a variety of riparian species shown in (B) a year later.

Photo credits: David Steinfeld

Runoff Strips and Constructed Wetlands

Runoff strips are catchment structures constructed in areas where intermittent concentrated road drainage occurs. These are typically at the outlets of culverts or in road drainage dips. Runoff strips capture concentrated runoff into small ponds or catchment basins. These areas can be planted with riparian species, such as willows (*Salix* spp.) and cottonwoods (*Populus* spp.), or wetland species, such as rushes (*Juncus* spp.) and sedges (*Carex* spp.). Runoff strips are placed in draws or concave topography and are composed of engineered impoundment barriers, using riprap, logs, or gabion baskets, which store water from runoff events. The barrier must have a spillway (a low point in the structure) and be keyed into the sides to ensure that concentrated water does not erode around its sides. Where runoff strips are on gentle gradients, constructed wetlands may possibly be developed (Figure 5-49).

Figure 5-49 | **Constructed wetlands are effective at capturing runoff water**

Constructed wetlands capture water from roadside runoff and filter sediments before water enters perennial streams. Constructed wetlands can create favorable habitat for unique flora and fauna.

Photo credit: David Steinfeld

5.3 OBTAINING PLANT MATERIALS

Obtaining the appropriate species, seed source, and stocktype for a revegetation project requires advanced planning and lead time. Obtaining genetically adapted materials, for example, may involve targeted collections of plant materials near or in the general geographic area of the project site several years prior to project implementation. The group of implementation guides in the following section focuses on three types of plant materials: seeds, cuttings, and plants. Section 5.3.1 covers how to determine the amount of wild seed to collect, wild seed collection methods, cleaning techniques, storage conditions, and quality testing. Methods for collecting the stems of willows and cottonwoods in the wild (as well as several other native species that propagate vegetatively) are described in Section 5.3.2. Salvaging plants from the wild and replanting them on project sites are described in Section 5.3.3.

For most projects, the collection of wild seeds, cuttings, or plants is not sufficient to meet project objectives. To increase plant materials, wild collections should be sent to native plant nurseries for propagation. Section 5.3.4 outlines the basic steps necessary to work with nurseries in establishing seed production beds for increasing seed banks of grass and forb species. Producing large quantities of cutting material of willow and cottonwood species can be accomplished by establishing stooling beds from wild collections at nurseries, covered in Section 5.3.5 and Section 5.3.6 describes how to work with nurseries to obtain high quality bareroot or containerized seedlings.

5.3.1 COLLECTING WILD SEEDS

Introduction

Wild seeds can be collected from native stands of grasses, forbs, shrubs, trees, and wetland plants found in or near project sites or other locations as determined via processes described in this report. The primary objective for wild seed collection is to obtain genetically appropriate, locally adapted seeds for starting nursery-grown plants (Section 5.3.6), nursery seed production (Section 5.3.4), and/or occasionally to sow directly on a disturbed site. Because seed and seedling propagation hinges on the availability of wild seeds, propagule collection is one of the first major tasks of a revegetation plan and should be initiated as early as possible while a project is in the planning stage. Depending on the purpose, the lead-time for collecting wild seeds could be up to three to four years before sowing or planting the project site (Figure 5-50). Seed collectors need to get approval from Project Engineer if harvesting is planned in ROW adjacent to an active roadway. Following safety practices near traffic). This lead-time is important because it requires multiple growing seasons to establish plants in the nursery or in grower’s seed increase field.

Grass and forb species are often seeded directly onto disturbed sites. In order to obtain enough seeds for direct seeding, wild seed collections may be "increased" in nursery production or agricultural seed fields (Section 5.3.4) depending on the size of the revegetation project. Trees and shrub seeds, however, are not typically sown directly on disturbed sites but are instead sent to nurseries for seedling propagation, then outplanted one to three years later depending on the stocktype and seedling size specifications. Seeds from wetland genera, such as sedges (*Carex* spp.) and rushes (*Juncus* spp.), are often collected for both seed and seedling production purposes.

Revegetation plans are seldom finalized before wild seeds are collected. At a minimum, planning should have identified revegetation units, described reference areas, determined species to propagate, and completed a survey of the construction site to determine the amount of area to be revegetated. The quantity and location of wild seed collection are based on these early surveys.

Collecting wild seeds can be expensive. Multiple collection trips are often needed to monitor and collect populations because each species has a small ripening window, and most species do not ripen at the same time. In addition, many species do not consistently produce seeds from year to year, requiring multiple years to generate adequate foundation collections.

Before collecting wild seeds or setting up collection contracts, it is advisable to the Natural Resources Conservation Service, determine if other genetically appropriate species seed sources are already available for the project. Often local agencies or commercial producers will have seeds in storage for many of the species growing near the project area, especially species used for reforestation.

Develop Timeline

Wild seed collection should be one of the first tasks to consider when beginning revegetation planning. Three to four years are often necessary in order to locate, collect, clean, and test wild seeds, and still allow the nursery or seed producer enough lead time for plant and seed production (Figure 5-50).

Seed collection contracts are typically awarded prior to the growing season to provide the contractor enough time to locate and assess the collection areas, source populations, and potential seed crop. Seeds are monitored periodically and collected when ripe. Wild seed harvests are cleaned, tested and certified, and stored prior to shipment to the nursery or grower for seed increase.

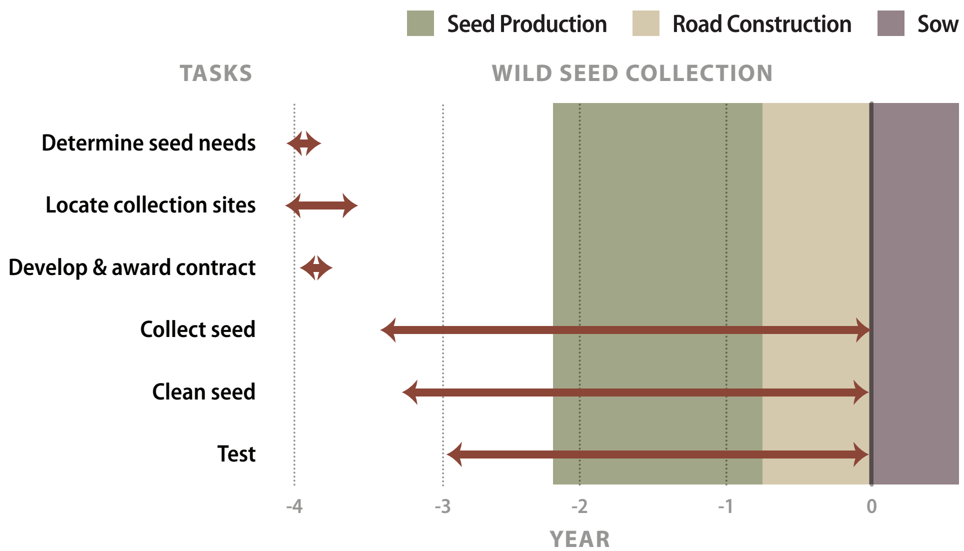


Figure 5-50 | **Early planning is essential when collecting wild seeds**

Wild seed collection is often one of the first contracts developed during planning. Seeds are needed to implement seed and seedling propagation contracts. A lead-time of three to four years is typically needed for wild seed collection. The collection time span for could be continuous up to the time of sowing depending on whether the collected seed is utilized for seed increase/plant propagation or if the collected seed is directly sown on the project site.

Determine Wild Seed Needs for Seed Production

Wild seed collection and the nursery seed increase contracts are often developed simultaneously because the information needed for wild seed collection is based on the expected seed yields of the seed increase contract. This section describes how to calculate the amount of wild seeds to collect based on the amount of seeds expected from a commercial seed producer. The designer will most likely need to work directly with the contracted seed producer to better understand the potential seed yields of a specific crop grown in a specific location.

The amount of uncleaned wild seeds to collect for seed propagation contracts requires the following information (used in the calculations in Figure 5-51):

- Seed needs
- Years in seed production
- Sowing rates
- Annual seed yields
- "Cleaned-to-rough cleaned" seed percentage

The quantity of wild seeds to collect can be determined from this spreadsheet. Pearly everlasting (*Anaphalis margaritacea*) is used in this example.

A	**Seed production needs**	22 lbs	From seed needs plan
B	**Years in production**	2 years	Seed production can span several years depending on lead time of project
C	**Sowing rates**	1 lbs/ac	Consult with seed producer or reference tables
D	**Annual seed yields**	50 lbs/ac/yr	Consult with seed producer or reference tables
E	*A / B / D*	0.22 ac	Area seed producer needs to sow
F	*E * C =*	0.22 lbs	Cleaned wild seeds that seed producer needs to sow
G	**Cleaned-to-rough-cleaned seed ratio**	33%	Estimated
H	*(100 / G) * F =*	0.67 lbs	Rough weight of seeds to collect

Figure 5-51 | **Determining wild seed needs**

The quantity of wild seeds to collect can be determined from this spreadsheet. Pearly everlasting (*Anaphalis margaritacea*) is used in this example. For sowing rates, annual seed yields, refer to Table 5-15 and Table 5-16, or discuss with the seed producer.

Seed Needs—The total seeds needed for each species on a revegetation project is based on the total planned revegetation acreage, seedlot characteristics (germination, purity, seeds per pound), site limitations (e.g., how well seeds will survive), and the desired seedling densities after seeds have germinated. Refer to Section 5.3.4 (see Determine Seed Needs for Seed Production) for methods to calculate how many seeds are needed for each species in a revegetation project.

Years in Seed Production—Every species has its own seed production characteristics. For example, species such as blue wildrye (*Elymus glaucus*) and California brome (*Bromus carinatus*) produce high seed quantities the first and second year, then level off or decline in years three and four. Species such as fescues (*Festuca* spp.) and Junegrass (*Koeleria* spp.) yield few seeds in the first year, but seed harvest levels increase to full production in the second or third year. For these species, a minimum of two years should be scheduled for seed production. Refer to Section 5.3.4 (see Determine Seed Needs for Seed Production) for discussion of first- and second-year yields for some commonly produced species.

Given proper storage conditions (Section 5.3.4, see Seed Storage), seeds of many species can be stored for several years or longer and still maintain good viability. For this reason, seed production does not have to occur all in one year. For projects that have several years lead time, maintaining production fields gives the designer more flexibility.

Sowing Rates—Commercial growers require a minimum amount of clean wild seeds (e.g., a foundation collection) to establish a seed increase field to produce a given quantity of seeds. While these rates differ somewhat between seed producers, general sowing rates for some commonly propagated species in the western U.S. are shown in Table 5-15 and Table 5-16.

Annual Seed Production Yields—The amount of seeds that are produced annually varies by species, geographic location of the fields, weather conditions, and experience of the seed producer. Understanding what yields can be expected from seed producers will determine how many acres will be under production. Average seed yields for some species used in revegetation in the western U.S. are presented in Table 5-15 and Table 5-16.

Cleaned-to-Rough-Cleaned Seed Ratio—Foundation seed collections from the wild can include stems, chaff, and flower parts (Figure 5-52). This material should be cleaned as much as possible by the seed collectors before it is sent to a seed extractory for final cleaning. The amount of non-seed material can be a substantial part of the wild seed collection weight. "Cleaned-to-rough-cleaned" seed ratios (Table 5-13) can help calculate the extra weight of seeds to collect in the wild to compensate for seed cleaning. Dividing the desired amount of cleaned seeds by this ratio will yield the amount of wild seed that needs to be collected. This information can be provided by the seed extractory or specialists familiar with the cultivation practices of a certain species.

Determine Seed Needs for Seedling Production

The quantity of wild seeds to collect for propagating seedlings at plant nurseries will be based on an estimate of the quantity of seedlings needed, the percent seed germination, the percent seed purity, seeds per pound, and the nursery factor. An estimate of germination, purity, and seeds per pound can be obtained through published sources, seed inventories, or from seed extractory managers. The nursery factor is a prediction of the percentage of viable seeds that will become "shippable" seedlings. Each nursery has developed a set of factors based on culturing experience and practices. Nursery managers should supply nursery factors for each species or information on the amount of seeds to collect to meet the seedling order. Nursery factors are often less than 50 percent.

Using the following equation, the amount of wild seed to collect can be estimated:

$$\frac{\textit{Quantity of seedlings needed}}{[\,(\,\%\text{ of germ} / 100\,) * (\,\%\text{ purity} / 100\,) * (\,\text{seeds} / \text{pound}\,) * (\,\text{nursery factor} / 100\,)\,]}$$

Figure 5-52 | **Wild collected seed needs to be cleaned**

Field-collected seeds include stems, chaff, flower parts, and seed attachments. Species such as cutleaf silverpuffs (*Microseris laciniata*) have a low "clean-to-rough" seed percentage and should be sent to a seed extractory for cleaning prior to sending to seed producers. The intended seeding method also strongly influences cleaning requirements.

Photo credit: David Steinfeld

Locate Plants in the Wild

Potential collection areas are identified during the vegetation analysis phase (Section 3.6.1). General collection locations can be established by the designer with consult of a botanist or revegetation specialist familiar with the local vegetation. Contracts often require seed collectors to identify individual collection areas for approval prior to collection.

Wildland seed collections should incorporate genetic principles and guidelines for ensuring local adaptation and genetic diversity in the resulting seedlot. These include collecting seeds from multiple, well-distributed locations within an established seed zone or other biogeographically defined area. Genetic diversity may be enhanced by collecting seeds in approximately equal quantities from approved collection areas, and collecting from a large number of widely

Table 5-13 | **Typical ranges of "cleaned-to-rough cleaned" seed recovery percentages**

To obtain the amounts of "rough" seeds to collect, divide the amount of cleaned seeds needed by the "cleaned-to-rough cleaned" factor. For example, if 5 pounds of cleaned seeds of prairie Junegrass (*Koeleria macrantha*) are needed, a minimum of 12.5 pounds of rough cleaned seeds should be collected (*5 / 0.40 = 12.5*) The cleaned recovery percentage can vary greatly depending on seed collection method (e.g., stripping seed versus clipping seed heads which increases trash impurities.

Chart based on Pacific Northwest Region Forest Service seed collections data.

Common name	Scientific name	Cleaned-to-rough cleaned factor
Bluebunch Wheatgrass	*Pseudoroegneria spicata*	0.25 to 0.33
Idaho Fescue	*Festuca idahoensis*	0.33 to 0.50
Prairie Junegrass	*Koelaria macrantha*	0.20 to 0.40
Squirreltail	*Elymus elymoides*	0.20 to 0.25
Yarrow	*Achillea spp.*	0.20 to 0.25
Sandberg Bluegrass	*Poa secunda*	0.33 to 0.40
Blue Wildrye	*Elymus glaucus*	0.50 to 0.65

spaced or unrelated parent plants per area (over 50 is optimal). Plant populations growing in unusually harsh or challenging environment conditions (e.g., weedy sites) may be good candidates to consider due to natural selection pressures and genetic adaptations that may produce offspring with improved fitness and competitive ability (Strauss and others 2006; Leger 2008). Within any site, generally no more than 50 percent of the seed crop should be collected in a given year, and repeated collections in subsequent years should be minimized or avoided to preserve viability of native plant population and dependent wildlife, including pollinators (Section 3.13.2).

Collection sites should be free of any plants listed as noxious weeds by the State Agency or any species on the Federal Noxious Weed List because of the potential of seed contamination. Once located, the collection sites should be documented in GPS and/or marked with flagging at a point easily visible from the road used to access the site. When seed collection is conducted outside of the project area or agency-administered lands, permission should be obtained from the landowner or manager.

Collect Seeds

Only viable seeds that are visually sound and sufficiently mature should be collected. Seeds are considered sound when the embryo has developed normally and there is no evidence of insect, disease, climatic, or other types of damage. Seed maturity in plants with fleshy fruits (many shrub and some tree species) often corresponds with changes in color (e.g., color changes from green to red, blue, purple, or white), taste (higher in sugars when mature), or hardness (fruit softens with maturity). Wind-dispersed seeds, which include many of the conifer species, usually change from green to brown when ripe. For grass species, a quick test for seed maturity can be determined by how seeds respond to being squeezed (Inset 5-12). A more effective method is to cut the seed and identify the development of the embryo under a hand lens or microscope. Because seed ripeness is influenced by the local weather

For the Designer

The seed collection methods and processes described in this section require a high level of expertise and familiarity with the target species. Designers should seek input from botanists, geneticists, and revegetation specialists as needed.

Inset 5-12 | **Stages of grass seed maturity**

For grasses, the stages of seed ripening can be determined by squeezing a seed between the thumb and forefinger. The stage of seed maturity is broadly defined by the following response:

- **Milk stage—**A milky substance is secreted, indicating an immature seed lacking viability.
- **Soft-dough stage—S**eed has a doughy texture, indicating it will have low germination and viability if collected.
- **Hard-dough stage—**No excretion of dough or milky substance when squeezed. Seeds are collected at this stage. Seeds can be collected at the transition between soft-dough and hard-dough stages. If collection occurs between these stages, seeds should not be stripped from the plant. Instead, seed heads should be cut and placed in collection bags where seeds will continue to mature.
- **Mature—**Seeds in this stage are usually too hard to bite. Collection should begin immediately because seeds can dislodge from the stem at any time.

and microclimate, determining seed ripeness often requires several monitoring trips to the field prior to collection.

Seed collection techniques are tailored to the species being collected. Grass and forb species, for example, can be hand-harvested by stripping or clipping stems just below the seed heads and placing them in collection bags or containers. Collection containers should be made of materials that allow airflow, such as paper or fine mesh. Plastic bags or plastic containers should not be used. Other methods of collecting grass and forb seeds include mechanical flails and vacuums. While these methods can increase seed harvesting rates significantly, they should be done on nearly pure stands of a single species to avoid contaminating the seedlot with more than one species. Some forbs, such as lupine (*Lupinus* spp.), have indeterminate inflorescence, which means they continuously bloom, starting from the bottom of the flower head and progressing to the top (Figure 5-53). These species present a problem in seed collection because seeds ripen continuously through the growing season. Seeds from these species are often obtained by making multiple trips to the field and collecting seeds from the lower portions of the stem without disturbing the flowers or immature seeds above. Multiple collection trips may also be required if there is substantial variation in seed ripening among different type of microsites.

Seeds of many shrub species are often collected by holding a bag or tray under the plant and shaking the plant or flailing the branches with a stick or tennis racket. While the seeds of some shrub species ripen and remain on the seed head, others, such as *Ceanothus* spp., shatter when mature and should be collected as soon as they ripen. Because multiple collection trips can be expensive, an alternative approach is to enclose the seed head of each plant in a mesh or paper bag before the seeds have begun to ripen. At the end of the season, ripened seeds will have dispersed into the bags which can be processed or transferred to other containers. Seeds or seed-bearing fruits should not be collected from the ground, although in some cases paper or cloth may be placed under the plant to catch the seeds (e.g. forbs and shrubs whose seeds shatter upon maturity).The seed collection contractor should specify the methods that will be used for collection.

Site location and other details of the collection can be documented on a form to include the following:

- Species (scientific name)
- Geographic location information (GPS point) or latitude/longitude or UTM coordinates
- Date of collection
- Name of collector
- Number of populations collected
- Elevation
- Road project name

Each seed collection bag or container should be clearly identified in the field using a label similar to the Forest Service identification tag shown in (Figure 5-54). These tags are generally available at Forest Service district offices or seed extractories. To ensure the identity of the seedlot in case the tag is accidentally removed during handling or shipping, it is a good idea to duplicate the tag and place it inside the collection bag. Field collections should be grouped into seedlots prior to sending these collections to the seed extractory for cleaning. Individual collections within a species are generally only maintained as separate seedlots if the objective is genetic testing or research. The expense of cleaning, packaging, and keeping records of a multitude of collections outweighs the necessity of storing them separately.

Figure 5-53 | **Seed ripens throughout the season for some plant species**

Species such as lupine (*Lupinus* spp.) have indeterminate inflorescence bloom and set seeds all summer. Seeds ripen first at the bottom of the stem and continue to ripen up the stalk as the season progresses.

Photo credit: David Steinfeld

For the Designer

State certification agencies can provide seed certification and other quality assurance services to agencies and other clients to help ensure that seed and plant products meet accepted standards. These services may be especially useful when an agency is unable to monitor all stages of plant material production from seed/cutting collection through seedling propagation and seed increase. Seed certification regulations and procedures are regulated by the Association of Official Seed Certifying Agencies **(AOSCA).**

Forest Reproductive Material Identification Tag | *U.S.D.A. Forest Service*

1) Identification Code:

_____ – _____ – _____ – _____ – _____ / _____ – _____ – _____

Species | *Forest* | *BZ/Seed Zone* | *Type Coll.* | *Elev.* | *Band* | *Year* | *Cert.*

2) Number of Trees ________

3) Ranger District ________

4) Elevation ________
Feet above sea level

5) Tree Numbers ________

6) Area of Collection ________
T. __ *R.* __ *S.* __

7) Accession No. __ __ __ __ __ __
TI Collections: affix bar code tag if available

8) Plant Association ________

9) Alpha Code ________

10) Collection Date __/__/__

11) Signature ________
Person filling out tag

Figure 5-54 | **Recording seed collection information is imperative**

A plant material collection tag like the Forest Service example in this figure should be completed and attached to each collection bag sent to the seed extractory. A copy should also be placed inside the bag.

Clean and Test Seeds

Wild seed collections should be cleaned to a standard that can be uniformly applied through seed sowing equipment for seedling production or seed increase. The method of application may determine the type of cleaning required e.g. hand broadcast may need less processing than drill seeding. Seed extractories have the experience and equipment to clean wild seeds of many plant species that are frequently used in revegetation projects throughout the U.S. Seed cleaning is typically completed in two to three steps: (1) removing seeds from cones or seedpods (conifer species and some hardwood tree, shrub, and forb species), (2) detaching structures from seeds, and (3) removing all non-seed materials from collections. Removing seeds from most conifer cones involves using tumbling equipment to allow seeds to separate from scales. Some conifer species and many shrub and hardwood species require specialized equipment to break open the seedpod without damaging the seeds. Detaching seed structures involves the mechanical removal of awns (grasses) and fleshy structures, wings or other appendages. Once seed structures are detached, non-seed materials, including stems and chaff, can be removed from the collections, leaving high purity seeds (e.g., greater than 90 percent) or some user-specified level depending on the species and intended use of the particular seedlot. Seeds sown in seed increase fields with high precision equipment, for example, are generally cleaned to a higher purity level than seeds that will be hand sown or spread as mulch directly on a project site.

Seed extractories will dry, package, and store seeds, as well as test seeds on-site or send seed samples to a testing facility. It should be noted that seed extractories cannot improve a poorly collected seedlot. Seed extractories cannot completely remove weed seeds, damaged seeds, or immature seeds from a collection, nor separate seeds from different crop species mixed in a seedlot. Removing contaminants from a seedlot becomes increasingly difficult and expensive as the size, shape, density, color characteristics of the undesirable material are more similar to the seed of the target species. Prior to collecting wild seeds, it is important to contact the seed extractory manager to discuss which species will be cleaned and for what purpose. Seed extractory managers are valuable sources of information on collection and care of a variety of native species seeds.

Cleaned seeds should be tested for germination, purity, seeds per pound, and presence of noxious weeds (Inset 5-13) by an approved seed testing laboratory (Inset 5-14). Testing requires representative samples be collected from each seedlot. Seeds are usually stored in large sealed drums or bags. If there are multiple containers per seedlot, samples from each container should be drawn in proportion to the size of the container. Because the amount of seeds needed for testing may vary by species and laboratory, seed testing facilities should be contacted prior to submitting samples for special instructions. Ideally, seed sampling is

For the Designer
See the list of Association of Official Seed Analysts (AOSA) members **and their contact information.**

conducted by a person who is trained and certified in this work, and preferably by a third party if contracts or purchasing documents are in place that contain seed quality requirements and specifications.

Seed viability usually decreases with longer durations in storage. Seed testing should be conducted every few years, or at least the year before it is sown, to obtain the most accurate germination information. Copies of seed tests should be retained in contract files and on seed inventories.

5.3.2 COLLECTING WILD CUTTINGS

Introduction

Using cuttings can be a viable alternative to planting seedlings or sowing seeds to reestablish native vegetation. Vegetative material is collected from stems, roots, or other parts of donor plants and directly planted on the project site or sent to a nursery to produce rooted cuttings. The potential to produce roots from vegetative cuttings varies by species—from easy to propagate to extremely difficult. The most common species propagated from vegetative cuttings are shrubs typical of riparian ecosystems and some trees. Many deciduous species that grow well in riparian settings, such as willows (*Salix* spp.) and cottonwoods (*Populus* spp.), have a high success rate when propagated from cuttings. Shrubs with characteristics desirable to pollinators include ninebark (*Physocarpus* spp.) and twinberry honeysuckle (*Lonicera* spp.). Most temperate evergreen trees and shrubs, however, only root under very controlled environments with specialized propagation techniques.

The intent of this section is to provide the designer with a greater understanding of how to select and collect cuttings in the wild. The primary focus will be on the species in the genera *Salix* and *Populus*, because these are these are most frequently used for direct planting of cuttings. With some exceptions, such as *Ribes* and *Cornus* species, most other temperate tree and shrub species should be sent to the nursery for the production of rooted cuttings before they are installed on project sites. In tropical and subtropical areas, a wider variety of species can be collected as wild cuttings. If temperate species other than willow and cottonwood are considered for propagation, nurseries should be contacted to determine the best methods for selecting, cutting, and handling the material.

Cuttings can be obtained from wild collections or from cultivated stands of donor plants, called stooling beds. Stooling beds are established at nurseries or other agricultural facilities from wild collections. In this section, the focus is on how to obtain cuttings from wild locations. The discussion of producing cuttings from stooling beds is provided in Section 5.3.5.

Wild cuttings are used in revegetation projects when seeds or seedlings are difficult to obtain, when seeds germinate poorly in the nursery, or when cuttings are needed for biotechnical engineering objectives. Seed yields can be low for many species due to a variety of reasons, including poor pollination, disease, and insect damage. Some species, such as pinemat manzanita (*Arctostaphylos nevadensis*) and Pacific yew (*Taxus brevifolia*), produce seeds that can be very difficult to germinate in nursery environments. Other species, which include many tree species, produce seeds irregularly and there may be many years between seed crops. Some seeds are difficult to collect either because they are inaccessible (in the upper portions of trees) or the window of seed collection is very narrow (e.g., *Ceanothus* spp.). For these species, starting plants in the nursery from rooted cuttings may be the only viable and economical alternative (Section 5.3.6, see Select Stocktypes). Vegetative cuttings can also be very useful in biotechnical engineering projects when installed as living structures. These projects combine the physical strength of cuttings with root strength of establishing plants to increase surface and slope stability (Section 5.4.3).

> ***For the Designer***
> **It is critical that vegetative cuttings are harvested during the period when donor plants are dormant, especially if the material is to be stored for any length of time prior to outplanting. Also remember that cuttings, like seed, are living material and must be handled as such during collection and outplanted to ensure good plant survival and growth.**

When considering the use of cuttings over seeds or seedlings, the benefits should outweigh the potential limitations. Some factors that can limit the successful establishment of cutting material are the accessibility and availability of donor plants, how well the material roots (rooting potential), and how well the material survives once it has rooted. A common oversight when working with cuttings is forgetting that this material is alive and subsequently handling the material poorly during collection and outplanting. Another oversight is collecting cuttings outside of dormancy, when plants are actively growing. Neglecting either of these facts often leads to failed revegetation projects. This implementation guide covers the major factors that are important to consider when working with wild cuttings.

Figure 5-55 | **Wild cutting collection timeline**

Collecting wild cuttings requires a lead time of several years depending on whether it is used to propagate stooling beds, rooted cuttings, or direction installation.

Develop Timeline

Locating cutting areas in the field might seem like a simple task, but it can be difficult when faced with such realities as land ownership, accessibility of the cutting areas, winter weather conditions, and poor quality of plant materials. For these reasons, a lead time of several years should be considered for projects requiring large quantities of wild cuttings (Figure 5-55). On large projects, sufficient lead time allows for the location of potential collection sites and testing of the rooting potential of cutting material. If cuttings are used to propagate stooling beds (Section 5.3.5), which are recommended for large projects, cuttings need to be collected at least two years or more to establish the beds. If the material is to be used to produce rooted cuttings at a nursery, the material should be collected at least a year prior to installation. When the materials are cut for direct installation on a project site, the cuttings will be made in the fall through winter prior to planting.

Locate Cutting Areas

The vegetation assessment during the planning phase (Section 3.6.1) is an opportunity to locate potential sources of cuttings. During this field survey, cutting sites are mapped and assessed for the following characteristics:

Proximity and Accessibility—Good sources for cuttings are not always found within the project site, so it is necessary to survey over large areas within the seed zone (Section 3.13.2, see Seed Zones and Transfer Guidelines). Sometimes good collection sites are miles away from the project, which can substantially increase costs. However, the benefits of collecting quality plant materials far outweigh the additional transportation costs. The large size and weight of cutting materials often limits collections to areas adjacent to and accessible from roads. Poor road conditions during the winter, when cuttings are most likely to be collected, should be considered in site selection because of the potential of being closed by snow or winter road damage. It is often possible to collect quality cutting material within the right-of- way clearance, which is identified during the vegetation assessment.

Ownership—Some of the best collection sites may be on private lands. Always obtain permission from the landowner prior to collecting. Cutting from areas located on Federal, State, and local government managed lands should be coordinated through these agencies. Observe collection standards for size and quantity dictated by the landowners. Care should be taken not to over-harvest a source population.

Inset 5-13 | **Seed tests**

Modified from Tanaka 1984

Seed testing is used to evaluate seedlot quality and provide information for determining sowing rates for seed and seedling production. Test results also provide a basis for determining seed costs when based on Pure Live Seeds (PLS), so are important for commercial seed trade, as well as for monitoring longevity and changes in germination or viability from harvest through cleaning and storage. Methods used for seed testing are based on rules of the Association of Official Seed Analysts (AOSA). A number of tests are normally conducted on each seedlot to evaluate physical and biological seed characteristics. See a list of AOSA Labs and their contact information.

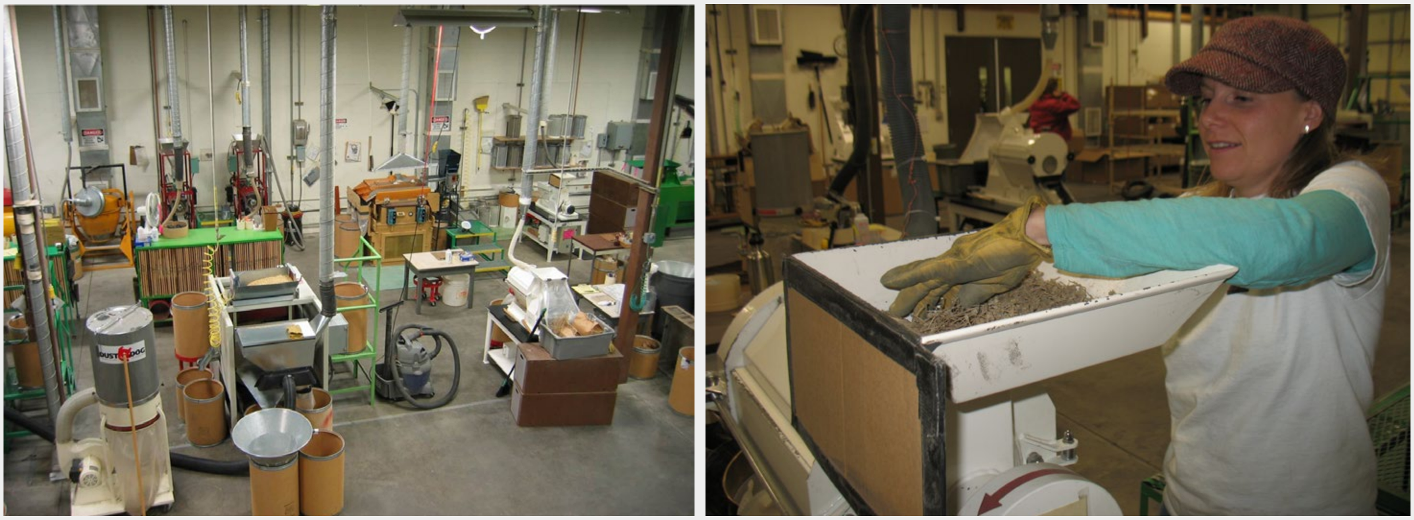
Physical Characteristics

- **Purity—**Purity tests are used to determine the percentage by weight of four components: pure seeds of the desired species, seeds of other species, weed seeds, and inert matter, such as stems, chaff, scales, and small stones (Note: A purity test is based on 250 seeds and noxious seed on 2,500 seed sample). Graminoid seeds with more than 10 to 15 percent inert matter will be difficult to apply through a rotary seeder or rangeland drill. Purity tests should verify the seedlot contains no "prohibited" noxious weed seeds and meets or exceeds standards for "restricted" or "other weed seeds" according to state standards for Certified Seed. Because each state has different lists of prohibited and restricted noxious weeds, it is important to request an "All-States Noxious Weed Exam." While not prohibited or restricted by the state, some aggressive non-natives found through seed testing may still pose a threat to native plant communities.
- **Moisture content—**Seed moisture content for most species is determined by oven-drying. Seed samples are weighed and heated at 105° C (221° F) for 16 hours, then weighed again. Seed moisture is expressed as the percentage of the weight of the water lost over oven-dry weight. Electronic moisture meters are also frequently used but are not as accurate as the oven-drying method. They give rapid measurements when checking moisture in a large number of seedlots. Moisture tests are important for determining the storability of seeds. Typically, seed moistures for long-term storage should be less than 10 percent.
- **Seeds per pound—**Seeds per pound is the weight of a given number of seeds of the desired species and does not include seeds of other species or weed seeds. The method weighs 100 seeds of 8 random samples and converts the values to number of seeds per pound.

Biological Characteristics

- **Germination—** germination test conducted in a controlled environment is the most reliable method for testing seeds. At least 400 seeds from the pure-seed component of the purity test are used in the test. Depending on the species, the seeds are usually divided into 4 replicates of 100 seeds each and chilled (stratified) for a pre-determined period and placed on trays in controlled germination chambers. At 7-day intervals, the number of seeds that have germinated (when all essential structures appear normal) are counted (AOSA 2002).
- **Tetrazolium staining—**Although controlled-environment germination tests are reliable, they are also time-consuming, particularly for those species requiring chilling. A rapid method of estimating viability is tetrazolium (TZ) staining. This test is preferred if results are needed immediately or if species to be tested have unknown chilling or germination requirements, which is often typical of many native species (Rauch 2006). The TZ test requires seeds to be immersed in 2,3,5-triphenyl tetrazolium chloride. Living cells stain red as the chemical is reduced by dehydrogenase enzymes to form a stable red triphenyl formazan, which is insoluble in water. Seeds are cut and the embryos that are red-stained are counted as viable seeds. This test is useful for native species that produce seeds that are dormant and will not germinate without after-ripening (that is, seeds placed in an environment where they will continue to ripen) or without special germination enhancement treatments (stratification, scarification, gibberellic acid, etc.). In these cases, germination tests usually report out lower viability rates than actually exist. Because TZ tests measure the percentage of live embryos, they typically give a better indication of potential germination percentage. Parallel TZ and germination tests can be conducted to determine how many of the ungerminated seeds are viable or dead.
- **X-ray—**At least 400 seeds, divided into 4 replicates of 100, are X-rayed and evaluated for the presence of mature embryos, insect damage, filled seeds, damaged seeds, and other seed characteristics that could affect germination. X-raying is a fast and relatively inexpensive test, but not as accurate or informative as germination or TZ tests. It's also useful to conduct on a seed sample collected prior to harvesting to decisions on the timing of harvest initiation, or on post-harvest samples to evaluate the need for seed conditioning treatments to improve seed quality.

Inset 5-14 | **Seed Processing, Testing, and Storage—USFS Bend Seed Extractory**



From left: Various seed processing equipment at USFS Bend Seed Extractory; Loading grass seed into a brush cleaner.
Photo credit: Jim Barner, US Forest Service

The US Forest Service Bend Seed Extractory (Bend, OR) is dedicated to seed, and only seed. Established in 1952, the Extractory is a full service state-of-the art seed processing and storage facility for all native species, including conifers, hardwood trees and shrubs, grasses, forbs, and succulents. Their staff also provides training and consultations to designers and other revegetation specialists on seed use planning, collection methods, and seed handling, testing, and storage requirements.

Processing Seed— Prior to use or storage, wild collected seed must generally be hand-screened, stripped, or mechanically cleaned to remove impurities such as excess chaff, stems, leaves, trash, dirt, and seeds of non-target species. The Bend Seed Extractory has a complete line of specialty and small lot cleaning equipment to handle the broad array of native species that are collected by National Forests and other federal, state, and county agencies (including Federal Highway Administration and state DOTs). Each year the Bend Extractory processes 10,000-15,000 pounds of seed from more than 2,700 different species. Any seedlot size can be accommodated.

Seed Testing—After cleaning, Bend Extractory conducts seed quality testing on every seedlot, including purity, seeds per pound, percent filled seed, and seed moisture content. At the client's request, additional testing (e.g., seed viability and percent live or dead seed) can be arranged at other approved facilities.

Storing Seed—The Bend Extractory also provides storage facilities, regardless of whether the seed is cleaned in-house or by other processors. Extractory staff work with clients to select the optimum seed storage — granary (55° F), cold storage (34° F), or freezer (14 ° F). Prior to storage, cleaned seed is sealed in 6 mil plastic to ensure longevity. Stored seed can be quickly removed from inventory at any time, and shipped to other facilities or field locations at client's request.

From left: Assessing seed viability during a seed and cone training workshop; Cleaned seed in 6mil polybags; Large volume of cleaned seed in storage; Examples of cleaned seeds.
Photo credits: Phillip Chi, US Forest Service(far left); Jim Barner, US Forest Service

Viability—The quality of the cutting material is an important criterion for determining the suitability of a collection site. Determining the viability of the collection material should be completed prior to selecting the collection site (Section 5.3.2, see Determine Rooting Potential)

Genetic Considerations—It is important to determine if the species to be collected is monoecious (male and female reproductive parts on the same plant) or dioecious (male and female reproductive parts on different plants). If the species is dioecious (Inset 5-15), such as willow or cottonwood, it's desirable to collect cuttings from both male and female plants in approximately equal amounts to promote genetic diversity and long-term species viability and sustainability. Determining the sex of donor plants is easiest during the reproductive period when floral structures are fully formed and most visible, typically early spring. (See Inset 5-15). This might add an additional year to the timeline. To further preserve genetic integrity, it is recommended to collect from a minimum of 50 donor individuals within the seed zone or other biogeographically defined area (Section 3.13.2). Differentiating between genetically distinct individuals within an area can be difficult with clonal species, such as willows and cottonwoods, because what often appear as a group of individual plants are actually offshoots (ramets) of a single parent plant.

Diameter Size—The project objectives will determine which stem diameters should be collected (NRCS 1997). This should be assessed when a collection site is evaluated.

Small diameter—Small-diameter materials, called branched cuttings or whips, average less than 1.0 inch in diameter and are derived from the fine branches of healthy, dormant donor plants. This material is tied into long bundles to form live fascines (Section 5.4.3, see Live Fascines) or laid on the surface of the soil to form brush mattresses. Live fascines are placed in shallow trenches on slope contours to function like small water and sediment collection dams, or they are placed at an angle to the slope to facilitate slope drainage (Section 5.4.3). Small-diameter materials are also used for branch packing and to vegetate geogrids and rock gabions. Additionally, small-diameter materials are used for rooted cutting production at nurseries. The typical diameter size preferred by most nurseries ranges from ⅜ to ½ inch.

Medium diameter—Medium-diameter cutting materials are used to make live stakes (Section 5.4.3, see Live Stakes), which range in size from 1.0 to 3.0 inches in diameter. Stakes are tamped into the ground at right angles to the soil surface to secure small slumps, live fascines, and erosion control materials. Joint plantings are stakes that are driven between rocks or riprap and should be greater than 1.5 inches in diameter and several feet long. Materials ranging from to 2.5 inches are used to revegetate live crib walls. Crib wall cuttings should be long enough to reach 4 to 6 feet back to the end of the wall.

Large diameter—Larger-diameter materials called poles are used as dormant post plantings to stabilize streambanks. The diameter of these poles range from 3 to 5 inches and they are 7 to 9 feet long. Large poles are not always easy to obtain in the wild but can be produced from nursery stooling beds.

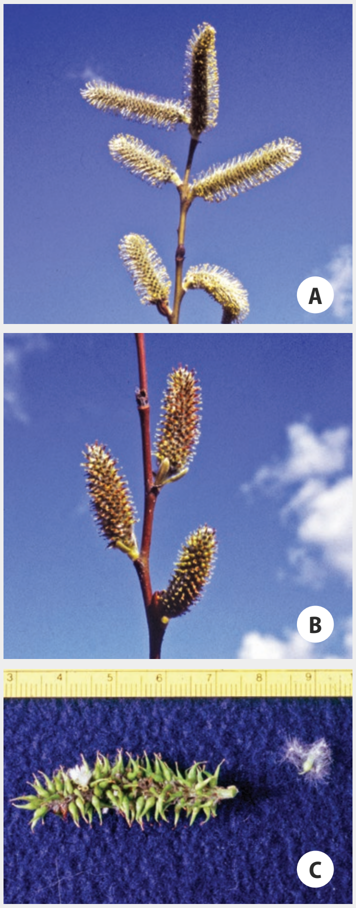
Cutting Footage—The total length of cuttings available for harvest should be estimated for each potential cutting area. This can be roughly calculated by evaluating 10 to 20 donor plants and estimating the average length and number of usable stems (by diameter size categories) that could be obtained from each. The average length is then multiplied by the estimated number of plants in the cutting area to obtain a total estimated cutting footage. This will be the high end of an estimate because most landowners are likely to place a restriction on the amount of cuttings that can be harvested at one time. For example, a landowner might limit the amount of cuttings that can be taken from an area to 25 percent in a riparian area. The cutting footage would be 25 percent of the total length of the cuttings.

Determine Rooting Potential

Not all cuttings will root and become established plants when installed on a project site. The success rate of those that do become plants is dependent on the percentage of cuttings

Inset 5-15 | **How to tell the difference between male and female willows and cottonwoods**

Identifying the sex of dioecious plants is easiest when they are flowering or fruiting. Willow (*Salix* spp.) catkins may appear before, during, or after new leaves appear in spring. Identifying anthers in male catkins (Image A in the illustration below) and pistils in female catkins (Image B) with a hand lens is relatively easy, especially with practice. Female plants can easily be identified when the cottony seeds are mature (Image C). During the winter dormant season, it is possible to identify the sex of dormant cottonwoods by dissecting floral buds, although this is more difficult with willows. Detailed instructions on how to sex willows and cottonwoods can be found in Landis and others (2003).



that form roots when placed in an ideal growing environment (or the rooting potential) and the percentage of viable cuttings (those that root) that become established after a growing season (or the survival potential).

Rooting potential is analogous to germination percentages obtained from seed testing. Seed tests are performed under uniform, ideal growing conditions and are a measure of the potential of seeds to germinate (Section 5.3.1, Section 5.3.4 and Section 5.4.1). Rooting potential is similar to germination in that it assesses the potential of cutting materials to produce roots under an ideal rooting environment. The potential of cutting materials to initiate roots is the basis for determining how many cuttings to collect and the density to plant. For example, if the rooting potential of a specific collection is low, more cuttings will need to be planted at closer spacing to compensate for those cuttings that do not root.

Root potential tests have been developed for measuring the viability of nursery-produced plants (Ritchie 1985), but there are no standardized tests for determining the rooting potential of cuttings. Labs that offer seedling quality tests might, on request, use or adapt the root growth potential tests developed for seedlings to assess the rooting potential of vegetative materials. Inset 5-16 describes one possible method for assessing rooting potential.

Rooting potential is affected by several plant factors, the most important of which are species, genotype, date of collection, portion of plant collected, age of material, condition of material, and preparation techniques.

Species—A small percentage of temperate tree and shrub species will root consistently from cuttings. Those that root well can be cut and used directly on revegetation projects. Other species initiate roots only under controlled nursery environments and should be grown into rooted cuttings before they can be planted on a project site. A list of commonly used native species in the western US that root from cuttings is provided in Table 5-14.

Table 5-14 | **Common species that can be propagated from vegetative material**

Species	Vegetative material	Rooting Potential	
		In field	*In greenhouse*
Willows *Salix spp.*	Stems	Easy*	Easy*
Cottonwoods *Populus spp.*	Stems	Easy	Easy
Snowberry *Symphoricarpos albus*	Stems	Easy to Mod[1]	Easy to Mod[1]
Pacific ninebark *Physocarpus capitatus*	Stems	Easy to Mod[1]	Easy to Mod[1]
Black twinberry *Lonicera involucrata*	Stems	Easy to Mod[1]	Easy to Mod[1]
Douglas spirea *Spiraea douglasii*	Stems	Mod[1]	Mod[1]
Salmonberry *Rubus spectabilis*	Stems	Mod[1]	Mod[1]
Quaking aspen *Populus tremuloides*	Roots	Poor	Mod
Redosier dogwood *Cornus sericea*	Stems	Mod[2]	Mod
Chokecherry *Prunus virginiana*	Roots	Mod[2]	Mod
Golden currant *Ribes aureum*	Stems	Poor	Mod[2]
Woods' rose *Rosa woodsii*	Stems	Poor	Mod[2]
Manzanita *Arctostaphylos spp.*	Stems	Poor	Mod

Several species, such as S. scourleri, *are difficult to root*

Genotypes—Within each species, there is variability in rooting potential. Some donor plants (genotypes) will have greater rooting potential than other plants. Unless tests are conducted, it is hard to know which donor plants are optimal rooters.

Date of Collection—The optimal time to collect cutting material is during plant dormancy. For most willow and cottonwood species, this period extends from mid-fall, after the donor plant drops its leaves, to bud swell in late winter to early spring. It is safe to assume that if donor plants have lost their leaves, cuttings will be at their highest rooting potential.

For the Designer
It is important to collect cuttings either from wild sources or in a nursery setting during the dormant period of a given species.

Planting unrooted cuttings within the dormancy period is not always possible because most construction work is curtailed during winter months. If unrooted cuttings must be planted outside the dormancy period, establishment rates will significantly decrease. Several alternative measures can be taken: collect cuttings during dormancy and keep in cold storage until they can be installed (Section 5.3.2, see Long-Term Storage); collect cuttings outside the dormancy period and plant more cuttings to compensate for the anticipated attrition (Section 5.3.2, see Determine Survival Potential); or use rooted cuttings in lieu of unrooted cuttings.

Collecting plant materials outside the dormancy period has been tried in biotechnical engineering projects with varying degrees of success (Figure 5-56). Species that root easily, such as most willows (*Salix* spp.) and cottonwoods (*Populus* spp.), will root from cuttings collected outside dormancy, albeit at very low success rates (Steinfeld 2002, 2005). In some instances, however, this may be the only option available to the designer but should be considered a last resort. When these are the circumstances, collecting outside the dormancy period should be done with an understanding of how establishment rates will be affected and whether the overall project objectives will be met. For large projects, it is important to conduct rooting and survival potential tests (Inset 5-16) several years before cuttings are installed so that the appropriate amount of cuttings can be collected and planting densities can be determined (Section 5.3.2, see Determine Survival Potential). An alternative to dealing with low survival potential of wild cuttings is to establish stooling beds (Section 5.3.5).

Figure 5-56 | **Designers should avoid harvesting actively growing material**

Collecting cuttings outside of plant dormancy, as was done for the project shown in this photograph, can lead to extremely poor results. If this practice is considered, rooting potential tests should be performed first.

Photo credit: David Steinfeld

Portion of Plant—Most cuttings are taken from stems and branches. However, the rooting potential for some species is greatest when cuttings are taken from roots (Table 5-14).

Age of Material—The rooting potential changes with the age of the donor plant. Many species have greater rooting potential from new growth, while others perform better when materials are collected from older branches or stems. Species that have a higher rooting potential in the older portions of the plant make excellent live stakes because the size of the material is often large enough to withstand being driven into the ground (Darris and Williams 2001).

Condition of Material—Vegetative material from donor plants can be affected by insects and disease, which can severely reduce rooting potential (Section 5.3.5).

Preparation Techniques—Several practices can potentially enhance rooting potential. One method involves soaking dormant cuttings in water immediately prior to planting. Schaff and others (2002) found that soaking black willow (*Salix nigra*) for up to 10 days in water doubled the survival rates of large diameter, dormant cuttings over unsoaked cuttings. Some designers have reported an increase in rooting potential of cuttings collected outside the dormancy period by stripping leaves from stems, while others have found this ineffective (Steinfeld 2002). Soaking cuttings in hormones can increase rooting in some species (Shaw 2004), although it can be detrimental to others (Darris and Williams 2001). Testing rooting treatments on a small scale through rooting potential tests should be conducted prior to applying these methods on a larger scale.

Determine Survival Potential

Not all cuttings that initiate roots under ideal testing conditions will establish when outplanted into field conditions on a project site. The percentage of viable cuttings that root and survive one year after planting is called the survival potential. The survival potential is controlled by climate, soils, planting methods, and maintenance practices for each project. It can be determined though field testing conducted prior to installing cuttings or estimated from previous field experience on similar sites using unrooted cuttings, rooted cuttings, or planted seedlings.

Climate—Survival potential is strongly influenced by the water loss potential of the site (Section 3.8.3). Sites with low moisture stress during root initiation (typically spring through early summer) will have high survival potentials. The longer that cuttings can initiate and grow roots without being under moisture stress, the greater the potential for survival. Climates with high humidity during root initiation occur in riparian areas.

Within a project area, survival potential often changes with aspect and microsite variation (e.g., true riparian zone verses upland zone). Cuttings subjected to hot, dry conditions of south aspects typically will have a lower survival potential than north aspects. Survival potential also increases in areas that have occasional summer rainstorms that wet the soil profile. Survival potential may decrease in more upland planting zones given the greater depth to the water table.

Soils—Survival potential is affected by soil water storage and accessibility (Section 3.8.2). Soils with low water-holding capacity will have lower survival potential than those with high water-holding capacity. Installation of cuttings on compacted soils will result in lower survival than loose or tilled soils. Areas that have high water tables during the growing season, such as slumps, seeps, and springs, will have higher survival potential for riparian species.

Installation Methods—Compensations can be made for sites with poor soils or dry climates. One option is to install longer cuttings. Studies have shown that higher survival rates and greater vegetative growth can be achieved with longer cuttings (Rossi 1999). This is especially important on drier sites, because longer cuttings can access deeper soil moisture. Cuttings up to 2 feet in length have been shown to produce better survival and growth on harsher sites (McElroy and Dawson 1986; Rossi 1999). In areas where freeze-thaw potential is high (Section 3.8.5, see Freeze-Thaw) shorter cuttings have a greater likelihood of being pushed out of the ground before they can form roots to anchor them in place. Survival rates are also affected by the quality of planting methods. For example, there can be a significant decrease in survival when cuttings are planted without good soil–to-stem contact and many large air pockets. Section 5.4.3 covers the different methods of installing cuttings.

Plant Maintenance—Survival potential can also be increased if the plants are maintained during the first year after planting, including the control of competing vegetation and protection from animal browse (Section 5.5).

For the Designer
Good soil-to-stem contact is one of the most, if not the most critical factor in determining high survival and plant vigor.

Determine Cutting Needs

Once the survival and rooting potential have been determined, the quantity of cuttings to collect can be calculated. The information needed for determining cutting quantities and cutting spacing (density) is as follows:

- Rooting potential
- Survival potential
- Target plant density
- Area to plant
- Desired established plant densities
- Length of cuttings

An example of how to calculate cutting quantities and planting spacing is shown in Figure 5-57. In this example, the project objective is to stabilize the slope by installing willow stakes. In the short term, this practice will increase slope stability by physically "pinning" the surface soil. The primary benefit to slope stability, however, will develop over time as the roots of the establishing willows begin to tie the soil particles together and increase soil strength. The desired spacing between established plants is 6 feet for most shrub species, but may be wider for cottonwood and willows depending on the site and project objectives. When inventories are taken one year after planting, there should be an established plant approximately every 6 feet (D), or approximately 303 established plants for the entire planting site (E).

A	**Area to plant**	0.25 acres	Area that will be planted with cuttings
B	**Rooting potential**	68%	Percent of cuttings that root under ideal rooting environment
C	**Survival potential**	35%	Percent of cuttings that root which are established one year after planting
D	**Target plant spacing (First year)**	6.0 feet	Desired distance between established plants after one year
E	*[43,560 / (D * D)] * A*	303 plants	Desired number of established plants after one growing season
F	*E * (100 * B) * (100 / C) =*	1,271 cuttings	Number of cuttings that need to be planted
G	**Cutting length**	2.5 feet	Approximate length of cuttings
H	*F * G =*	3,178 feet	Total footage of cuttings to collect for site
I	*SQRT [(43,560 * A) / F] =*	2.9 feet	Distance that cuttings must be planted from each each other

Figure 5-57 | **Determining the needed amount of cuttings**

This spreadsheet can be used to calculate the number of cuttings to collect and how close to plant them on the project site.

To achieve the desired density of established plants, it should be determined how many cuttings to plant and the average spacing between installed cuttings. This determination is based primarily on the rooting and survival potential (Section 5.3.2, see Determine Rooting Potential and Section 5.3.2, see Determine Survival Potential). If these are unknown, cutting needs can be based on the desired number of plants per area, with a significant buffer added in for projected losses. In this example, the rooting potential was 68 percent based on rooting potential tests. The survival factor was estimated to be around 35 percent from previous experiences on similar sites. These factors are used in the equation shown in Line

Inset 5-16 | **Testing method for determining rooting potential for willow and cottonwood species**

Testing the viability of willow and cottonwood cuttings takes much of the guesswork out of establishing plants through this method of propagation. While is not a common practice in revegetation work, testing the viability of cuttings should be considered for similar reasons as seed testing. Most designers would not think of applying seeds on a project without first testing for germination, purity, and seeds per pound, yet they do not think twice about using cuttings without having tested them first. This oversight can lead to higher costs, as well as low establishment rates.

There are no established testing procedures for assessing rooting potential of cutting materials. Until these tests are established, the following means of root assessment is presented which can be used to compare results from year to year. Ideally, a controlled environment, such as a greenhouse, is the best place to conduct a rooting potential test. Temperatures should range between 65° and 75° F. Using bottom heat or rooting hormones is not necessary; in fact, for some species, it can be detrimental for rooting (Darris and Williams 2001). Where a greenhouse is not available, use an indoor space where relatively constant temperatures can be maintained. Grow lights should provide at least 12 hours of light per day.

Fifteen samples, at a minimum, should be randomly collected from different donor plants at each collection area. They should be of the same size and treated in a manner similar to what would be expected under normal operations. For example, if stakes with diameters between 2 and 3 inches are to be collected in August and soaked for 10 days before planting, then the cuttings used for the tests would be of similar size, collected in August, and soaked in the same manner, and planted. Prepare each sample by cutting them into 12-inch lengths. Stick them 3 inches apart in pots that are at least 16 inches deep, filled with 1 part peat to 4 parts perlite. Cuttings should be stuck so that two buds are exposed above the media.

After planting, water the pots and set them in their testing location. At weekly intervals, observe the cuttings and note the status of the leaves developing from the buds. At 28 days, record how many cuttings have developed new leaves, gently remove the media from around the cuttings, and lightly wash the stems. Viable cuttings should have developed roots during this period. Record how many cuttings did not initiate roots (refer to the cutting on the left in photograph below). For those cuttings that did establish roots, a quantitative estimate of root initiation can be measured by removing the roots from the stem and weighing the new roots or counting the number of new roots for each cutting.

To interpret this data, assume that any cutting that did not initiate roots or develop foliage during 28 days probably will not immediately initiate roots in the field. A comparison of average root weights or number of roots between testing samples can indicate which collection sites or treatment methods will produce the best rooting materials, or if additional sites need to be located to meet genetic guidelines and broaden diversity. Those test samples with high average root weights should perform better than those with lower weights.

Photo credit: Tara Luna

F to calculate the number of cuttings needed to install. To obtain 303 established plants, it would be necessary to install approximately 1,271 cuttings. This is approximately four times the number of established plants. It is necessary to install this many to compensate for the number of cuttings that either do not root, or that root and do not survive the summer. The planting spacing is calculated using the equation in Line I. Cuttings should be installed at half the distance of the desired established plant spacing. Because the site conditions in this example are harsh, the cuttings will need to be planted deeply to access soil moisture. For this reason, the cutting lengths are approximately 2.5 feet. Multiplying 2.5 feet by the number of cuttings needed (F) gives the total length of cuttings that should be collected (H). Knowing that 3,178 feet of cuttings are needed, the number and location of cutting areas can be selected from a cutting area map and a contract can be developed.

Long-Term Storage

If cuttings are not installed immediately, long-term storage will be required. Dormant cuttings collected in the fall or winter and stored until the following spring or summer should be held in refrigerated units. The optimum temperatures for long-term storage range between 28 to 31 degrees F. Freezing temperatures prevent disease and curtail respiration, thereby increasing cutting viability. If freezing is not possible, then storing cuttings at temperatures between 33 and 35 degrees F should maintain cutting viability for several months.

For long-term storage, cuttings should be relatively free of leaves and other material that might mold in storage. They should be packaged in plastic or storage bags so they will not dry out. Cuttings should not be wrapped in moist burlap, especially if cuttings are not frozen. Diseases could potentially develop that will rot the stems.

Develop and Administer Contracts

A good plan that includes the location of cutting sites and how the cuttings will be treated, transported, and stored will be the basis for the development of a collection contract. The contract should specify the following:

Cutting Locations—A map or GPS locations should identify cutting areas and specify an estimated range of cutting quantities (Section 5.3.2, see Locate Cutting Areas). If the contractor elects to collect from other areas, then these areas should be approved prior to cutting. For each cutting area, the percentage of the donor population that can be collected should be specified. Typically, this is no greater than 25 percent of the population. Donor populations should not be over-harvested.

Dates of Collection—The contract should specify a period of time that cuttings should be collected (Section 5.3.2, see Determine Rooting Potential). Collecting outside this time period should be discussed in advance with the designer.

Collection Size, Lengths, and Quantities—Quantities should be specified for each size category. For example, if material is to be used for stakes, then a specification might require 200 stakes, 18 inches long, with a range of diameters between 1.0 inch to 3.0 inches.

Collection Methods—The contract should identify how the contractor will collect the cuttings. For example, it should state how the contractor will identify which end of a stake is basal and which is terminal. This is typically done by cutting the basal end of each stake at an angle. The contract should also specify how the cuttings will be packaged or bundled. Contracts often call for all stakes to be aligned with basal ends of the cuttings in the same direction. Bundle sizes or weights should be specified. The bundles should be light enough to be transported by one person (45 pounds or less). The contract should also state that the bundles should be securely tied or bundled together for hand transportation.

Source Identification—Each bundle should be identified with an identification tag such as the seed label described in Figure 5-54, which specifies the species, collection location, elevation, and date of collection among other information.

Special Treatments—Special measures, such as soaking and use of anti-dessicants, should be stated in the contract. If soaking is required, then the location of the soaking area should be identified on a map (Section 5.3.2, see Determine Rooting Potential).

Temporary Storage and Transportation—The contractor should address how cuttings will be temporarily stored when the weather is warm or dry. Cuttings should not be allowed to dry out once they are collected. Temporarily storing in shaded areas covered by plastic sheets or wet burlap are acceptable methods. Delivery of cuttings should be done in a manner that does not allow the cuttings to dry. Closed transportation or covering with plastic for long distances should be considered.

5.3.3 COLLECTING WILD OR SALVAGED PLANTS

Introduction

Wild seedlings, commonly referred to as wildlings, are indigenous plants growing in their native habitat (Therrell and others 2006). They are naturally reproduced outside of a nursery but can be transplanted directly into a restoration site or into a nursery for culturing and future use.

The collection and use of wildlings in native plant restoration can be a viable alternative to direct seeding, nursery seedlings, or rooted cuttings. As with wild cutting collections (Section 5.3.2), wildlings can be used where it is difficult or impossible to collect or use seeds for plant production because of the following (Priadjati and others 2001; St John and others 2003):

- The plant either does not produce seeds or produces seeds very infrequently
- Seeds are often unfilled or non-viable
- Seeds have a very narrow collection window
- Seeds have already dispersed prior to collection planning
- Insects or animals are a problem with collection

There are several advantages to using wildlings in restoration plantings. Unlike cuttings, wildlings can be available immediately with little to no transport costs, and no direct nursery costs if installed shortly after collection. They can be an effective strategy for obtaining a large number of seedlings of known origin relatively quickly. Also, large wildlings provide "vertical relief" (visual prominence) more quickly to a site than other methods and, depending on the species and environment, will establish and spread quickly (Hoag 2003). Use of wildlings reduces the risk of introducing non-native organisms such as weeds and pathogens (Therrell and others 2006). If reproduction of the plant is more successful via rhizomes (e.g., sedges), transplanting wildlings may be the most efficient and effective method for reestablishing these species (Steed and DeWald 2003). In addition, if plant propagation is difficult from seeds or rooted cuttings, use of whole plants may be the only alternative for a particular species.

Transplanting of wildling plants, however, can be unsuccessful for a number of reasons. Wildlings often grow in stressful conditions and do not recover from transplanting shock as quickly as cultivated seedlings. Wildlings often have smaller, coarser root systems than cultivated seedlings or heavier taproots that are not easily removed from soil in their entirety (St John and others 2003). Successful transplantation requires experience, skill, proper handling, ideal temporary storage, and proper care of the plant both before and after transplanting.

Develop Timeline

Although wildling plants may provide an opportunity for quick establishment of larger plants on restoration sites, several factors should be considered in the planning process that could impact their availability. Suitable locations that can provide the number of plants required should be determined. If large quantities of plants are necessary, several years may be required to identify these locations. Once sites are identified, one or two seasons of plant preparation prior to removal, transport, and transplanting may be required (Section 5.3.3, see Collection and Handling).

Wildling plants may be removed from their native site and either transplanted immediately or transported to a nursery, potted, and cultured for future outplanting. Transplanting following removal may occur if the plant source is an undisturbed area outside the restoration site. If plants are removed prior to site disturbance or if additional time is needed for production of sturdy plants, culturing in a nursery for a specified period of time may be necessary. Lead time of one to two years may be necessary for nursery-assisted wildlings depending on the situation. This lead time may include contract procurement and administration for both collection and nursery culturing.

For the Designer
Note that removal of wildlings creates a disturbed area that may require mitigation and, at a minimum, monitoring for invasive species introduction and spread. Wildling harvest is best considered when a vegetated area is going to be impacted by construction.

Locate Wildling Collection Areas

Potential sources for wildling plants can be identified through field surveys during the vegetative assessment phase (Section 3.6.1) Sites with high potential for damage to soil resources or the plants that are to remain should be avoided. Sites should be located on maps, and both plants and sites should be assessed for the following traits:

Accessibility—Proper handling of wildling plants during removal and transport is a critical factor in ensuring survival. Smaller seedlings of some species (sagebrush) may be handled successfully similar to bareroot seedlings. In other cases, roots may require protection if the rootball is not totally contained in soil. Plants may be heavy if the rootball is intact. Therefore, it is necessary that collection sites be accessible by roads. Because most collections will be taken in fall or early spring, it is also necessary to determine whether road conditions at these times of year will preclude collection.

The best collection areas may not always be found within the project site, so large areas surrounding the project may need to be surveyed for plants. Costs will increase substantially if it is necessary to transport plants for long distances.

Land Ownership—Permission to remove plants should always be obtained from either the private landowner or public land management agency. In addition, any required permits should be obtained from State or Federal agencies to ensure compliance with regulations (Hoag 2003). In some cases, environmental analyses (e.g., NEPA) may need to be completed.

Viability—If possible, areas of healthy forest or rangeland should be designated as collection sites (Priadjati and others 2001). Sites should contain healthy, vigorous, and adequately sized material with a minimum number of unhealthy plants (St John and others 2003). Stunted needles, off-color foliage, and poor annual growth are indications of stress; these plants should not be collected. Plants should only be removed from sites that show good regeneration over the area (Hoag 2003). Determining the viability of the collection material and timing of use (Section 5.3.3, see Determine Transplanting Versus Nursery Culture) should be completed prior to selection of the collection site. It is important to transplant wildlings into similar growing environments. For example, plants growing under shade should be placed back into a shaded environment to achieve optimum viability.

Genetics—One of the disadvantages or limitations of using wildlings, or any form of asexual propagation, in restoration is the potential to restrict the genetic diversity of the plant population. As adequate population sampling is important to maintain this diversity, it may be advisable to identify several sites over a large area from which to collect within the seed zone. Collecting many plants over a large area will help capture both inherited and environmental variation. However, donor sites should be chosen carefully so that they are reasonably similar to conditions of the outplanting site.

Prior to collection, it is necessary to determine whether species are monoecious (male and female reproductive structures on the same plant) or dioecious (male and female reproductive structures on different plants). If the species of interest is dioecious, both male and female plants will need to be collected in somewhat equal proportions to ensure that installed populations can persist into the future via sexual reproduction. If one of the objectives for using dioecious species is to promote, restore, or increase species, then target plants should be located when reproductive phenology is evident, which is typically spring through summer.

Determine Transplanting Versus Nursery Culture

Although cost may be the biggest deciding factor in whether wildlings are collected for immediate transplant or growing in a nursery, other factors should enter into the decision in the restoration plan.

Timing—Wildling plants should be transplanted into their new location as quickly as possible. If plants are to be collected from sites outside the disturbed area, these can potentially be removed and transplanted to the restoration site within the same time frame. However, if plant removal is part of a salvage operation where plants are located within the area of disturbance, then plants could be transported to a nursery or similar growing situation. Plants should be transplanted into pots and maintained until the appropriate outplanting season.

Species—Some plant species have characteristics that are more conducive to direct transplanting from one site to another. Plants that spread underground or with stolons will generally perform well, for example, although dry, compacted sites will slow the rate of spread significantly (Therrell 2006). Species that recover quickly from root damage, such as willows (*Salix* spp.) and cottonwoods (*Populus* spp.), will also perform well when large plants are needed quickly. These types of plants may lend themselves easily to transplanting within the same time frame as removal.

Plants with taproots, such as conifers and many shrubs, and plants with long, brittle horizontal roots, such as heather or vine maple, are difficult to transplant. Special care should be taken during removal to extract as much of the roots as possible. To ensure a higher success rate, further culturing in an optimal environment following removal may provide a healthier, more viable plant for outplanting.

Size and Availability—If wildling plants of the target species are plentiful and appropriately sized on undisturbed sites, immediate transplant during the appropriate season is feasible. However, if available wildlings are smaller than desired, an additional one or two years of nursery culture may provide a better plant for colonization of the site.

Certain plants have the ability to root by layering, such as pinemat manzanita (*Arctostaphylos nevadensis*). If entire plants are not plentiful, portions of individual plants can be removed and cultured in a nursery for outplanting the following year.

Collection and Handling

Date of Collection and Timing of Transplanting—The season during which collection and transplanting occur has been shown to dramatically affect the survival and growth of wildling plants (Yetka and Galatowitsch 1999). Plants allocate carbohydrates and nutrients during various phases of phenological development. Different levels of tolerance to transplanting stress during the year are the result of physiological needs shifting among shoot and root growth, flowering and seed production, and storage. In addition, seasonal variation in environmental factors, such as soil moisture and temperature, can affect planting establishment (Steed and DeWald 2003).

Timing of collection will depend on whether the wildlings are to be transplanted in the same time frame or cultured in a nursery. If wildlings are to be transplanted into the restoration site following collection, the chances for survival will increase for most species if operations occur in winter to early spring. The seedlings are dormant during this period and can handle the stresses associated with transplantation. There is also less chance of damaging new roots that are initiated during the spring and fall. In addition, planting early extends the period for root growth prior to soil-drying in summer.

Collection could occur in either fall or spring if wildlings are to be cultured in a nursery. However, if plants are collected in the fall, care should be taken to avoid excessive root damage because plants will not be dormant. Due to the perishable nature of wildlings, the timing of collection should be coordinated with the nursery to ensure that the facilities, supplies, equipment, and labor are available following harvest (Figure 5-58) (St John 2003). Once collected, plants should be transplanted immediately into containers.

Genetics—Collection of wildlings can consist of a single plant, a clump, or several pieces of a plant that have rooted through layering (NRCS 1997). A collection of individual plants should be large enough to ensure adequate population sampling. A minimum of 50 plants from within the same seedzone as the restoration site is recommended.

Source Identification—Every collection should be identified with a tag which specifies the species, collection location, elevation, and date of collection (Figure 5-54).

Quality and Size—Only healthy, turgid, moderately vigorous and adequately sized wildlings should be collected for transplanting or nursery culturing. Unhealthy or stressed plants should be avoided.

Although species dependent, successful transplantation typically increases as plant size decreases (St John 2003). Transplantation of large shrubs and trees is usually unsuccessful. Their root-to-shoot ratio is unbalanced, and these plants often do not survive transplantation

For the Designer
Harvesting wildlings during the dormant season can significantly reduce plant stress and increase transplant survivorship and growth.

Figure 5-58 | **Salvaged wetland plants**

Wetland plants are often salvaged from areas that are planned for disturbance. Removing plants from wetland settings can be difficult due to wet soils and massive root systems of many species. The heavy weight of these plants makes transportation and handling difficult. Tubs (A) are used for hand-transporting to planting sites, and pallets (B) have been used for large quantities.

Photo credits: David Steinfeld

shock. Transplantation of larger willows, sedges, or herbaceous material into riparian zones, however, may be appropriate depending on the vegetative competition and other establishment conditions (Hoag 2003; Steed and DeWald 2003).

Handling, Transport, and Storage—Collection of wildling plants will be most successful if the soil is moist during plant removal. If precipitation has not occurred, irrigation prior to lifting would be desirable. Removal and transplantation should only occur in the mornings on cool, cloudy days when the plant is fully turgid.

A tile spade or similar flat-bladed shovel is the best tool for small to medium plant removal. Using the "dripline" of the plant as a guide, make shovel cuts with the blade as perpendicular to the surface of the ground as possible because maintaining an intact ball of soil around the roots is important (Figure 5-59 and Figure 5-60). Root morphology should also be considered in this process. Roots growing in deep soils or arid soils will tend to grow down rather than laterally. Roots growing in shallow soils will tend to spread laterally, requiring a much larger area of disturbance (Therrell 2006).

The shovel, and hands, can be used to lift the root ball gently out of the hole while attempting to keep the root ball intact. Hand pruners can be used to cut away woody roots that do not come free with the shovel. The root ball can then be transferred to a suitable container (large bucket, pot, burlap, or plastic bag) for transport to the transplanting site (Therrell 2006). If wildlings are to be transported to a nursery, plants should be placed in plastic bags in coolers. Plastic bags should also contain moistened towels or similar material if roots are not covered with soil.

A tree spade can be used if larger plants are to be excavated and transplanted (Figure 5-61). The factors important for using a tree spade are that the terrain is accessible to the tree spade equipment (slope gradients less than 20 percent), soils are relatively free of cobble-sized rock fragment, and soils are moist. In this operation, planting holes are created first, then plants are excavated, moved, and replanted. The size of the plant to be transplanted depends on the soil volume that can be removed by the tree spade. Typically plants up to 6 feet tall can

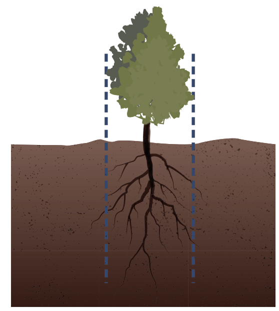


Figure 5-60 | **Salvage as much of the root ball as possible**

Plants can be excavated from the soil using the drip line (dashed lines) as a guide.

Figure 5-59 | **Included soil with salvaged plants**

Select small plants with a protective ball of soil around the roots (A). Do not attempt to transplant plants if the soil falls off the root system (B).

Photo credits: Thomas D. Landis

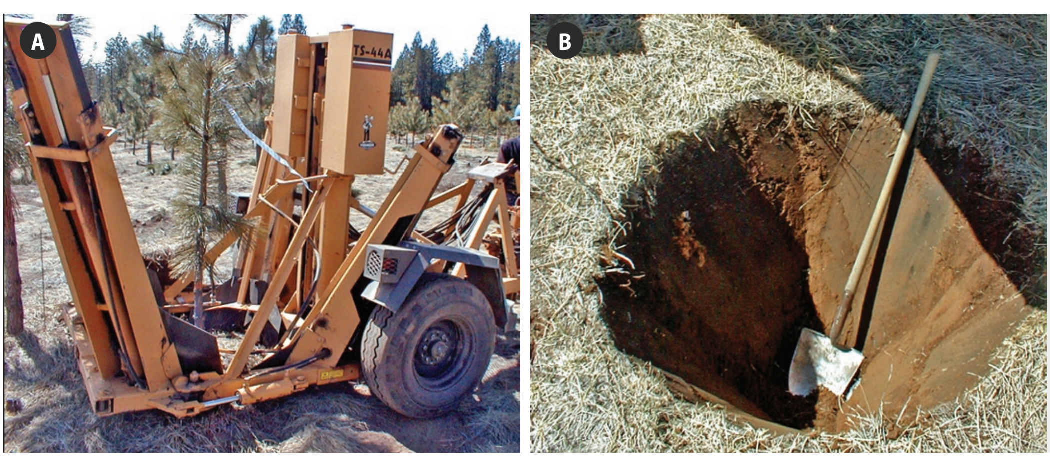


Figure 5-61 | **Mechanical tree spade**

Mechanical tree spades (A) can extract large plants quickly. A planting hole should be excavated prior to transplanting (B). and this can be accomplished with a tree spade.

Photo credit: Chris Jensen, USFS

be transplanted with success. Taller trees should be irrigated into the soil to improve survival. Using a backhoe has also been successful in transplanting large willow clumps (Hoag 2003).

Wildlings should be transplanted into their new location as quickly as possible, with minimal to no storage time. All vegetative material should be kept cool and moist during the process. If wildlings are transported to a nursery, the plants should be kept in a cooler and transplanted into pots within one to two days of collection.

Survival Potential

As with rooted cuttings (Section 5.3.2, see Determine Survival Potential), not all wildlings will become established and thrive following transplantation. Survival is controlled by climate, soils, planting methods, and maintenance practices on the project.

Climate—Water loss potential (Section 3.8.3) is probably the main determining factor for survival on many sites in the western United States. Sites with low moisture stress during root initiation (spring through early summer) and sites that have the potential for longer root initiation periods will have higher survival.

Within a project area, aspect can also affect root initiation and survival. Transplanted wildlings subjected to hot, dry conditions on southern aspects have a lower potential for survival than those on cooler northern aspects.

Soils—Survival of wildlings is affected by soil water storage and accessibility (Section 3.8.2). Soils with low water-holding capacity or compacted soils will have lower survival than those with high water-holding capacity and greater porosity.

Planting Methods—Good transplantation techniques will improve the survival rates of wildlings significantly (Figure 5-62). Planting methods are the same for wildlings and nursery-grown seedlings. Common mistakes include planting too shallow or too deep, planting too loosely, damaging roots by exposing them to air, or failing to place root systems properly (Therrell 2006).

Ideally, transplantation should occur on a cool, cloudy day. Planting holes should not be allowed to stand empty for an extended period of time, as soil will dry rapidly. When possible, microsites should be used (rocks, logs, depressions, etc.) to provide protection from the sun or wind.

Plant Maintenance—Survival potential can also be increased if the plants are maintained during the first year after planting. Such practices include the control of competing vegetation and protection from animal browse. For large wildlings, irrigation during summer will improve survival. In addition, large wildlings could need additional support depending on such site conditions as wind and snow.

Develop and Administer Contracts

A plan that includes the location of collection sites and procedures for how the wildlings will be handled, transported, transplanted, and stored (for short periods of time) will be the basis for the development of a collection contract. The contract should specify the following:

- **Collection locations**—A map or GPS location should identify wildling collection areas and specify a range of quantities that can be expected. If the contractor elects to collect from other areas, then these areas should be approved prior to collection. For each collection area, it should be specified what percentage of the natural population can be collected.
- **Dates of collection**—The contract should specify a period of time during which the collections can be made (Section 5.3.3, see Collection and Handling). Collection outside of this time period should be discussed in advance with the designer.
- **Collection quality and size**—Minimum and maximum plant sizes should be specified in the contract. In addition, specifications for health and vigor should be included.

Figure 5-62 | **Transplant wildlings immediately after collection**

Transplant wildlings immediately following collection to minimize moisture stress.

Photo credit: Thomas D. Landis

- **Collection, handling, and storage methods**—The contract should identify how the collections will be made, how the wildlings will be handled and processed following removal, and how wildlings will be temporarily stored prior to transplant or transport to the nursery.

The contractor should address how plants will be temporarily stored when the weather is warm or dry. Wildlings should not be allowed to dry out once they are collected. Refer to Section 5.3.3 (see Collection and Handling) for proper handling and storage methods.

5.3.4 NURSERY SEED PRODUCTION

Introduction

Many revegetation projects require large quantities of grass or forb source-identified seed. The most common approach to obtaining such quantities is to establish seed increase fields in nurseries or agronomic environments. Here, plants can be irrigated, fertilized, and cultured specifically to produce a large amount of seed adequate for large-scale seedings (Figure 5-63). Usually the seeds are produced by the end of the first or second year of production. The field-grown seed can then be direct sown in restoration projects, or stored in a warehouse in anticipation of future needs.

Considering the costs and amounts of seeds that can be obtained from wild seed collection, propagating grass and forb seed is very efficient. For example, mountain brome (*Bromus carinatus*) can require 8 pounds of wild seed to sow a 1-acre seed field. At the end of the first year, the seed collected from these fields can average 800 pounds, a hundred-fold increase. For many grass species grown in production beds for two years, the yield is at least 50 pounds of seed produced for every pound of wild seed collected and sown. In some cases, 100 pounds are collected per pound of wild seed sown. The efficiency of large-scale seed increase will vary with species, quality of starter seed, grower, and geographic region. This section outlines the steps required for developing and administering seed increase contracts.

Figure 5-63 | **Commercially grown native seed grow-out fields**

A variety of species can be propagated for seed. In this photograph, small seedlots of forbs are being propagated at the USFS J. Herbert Stone Nursery in southern Oregon. The beds in the upper left (A) are western buttercup (Ranunculus occidentalis); lower left (B) is fragrant popcorn flower (*Plagiobothrys figuratus*), and the bed on the right (C) is elegant calico flower (*Downingia elegans*).

Photo credit: David Steinfeld

Develop Timeline

Seed production varies by species and weather condition during production, but typically it takes three years to obtain the desired quantity of seed. This involves one year to obtain seed from wild collections and at least two years for seed production (Figure 5-64). A series of steps or tasks are required to obtain seed, which are described in detail in this section:

- Determine seed needs
- Obtain starter seed
- Develop and award contract
- Administer contract
- Store seed

Early in the planning phase a rough approximation of the quantity of needed seed for each species should be determined. Seed quantities will be refined as planning progresses, but because of the amount of time that is takes for wild seed collection and seed production, it is important to make an estimate early in the planning stages. Developing and awarding wild seed collection contracts is the first task and this can take several months (Section 5.3.4). To avoid missing the seed collection window, these contracts should typically be awarded by early spring for most species, otherwise an additional year will be needed for wild seed collection.

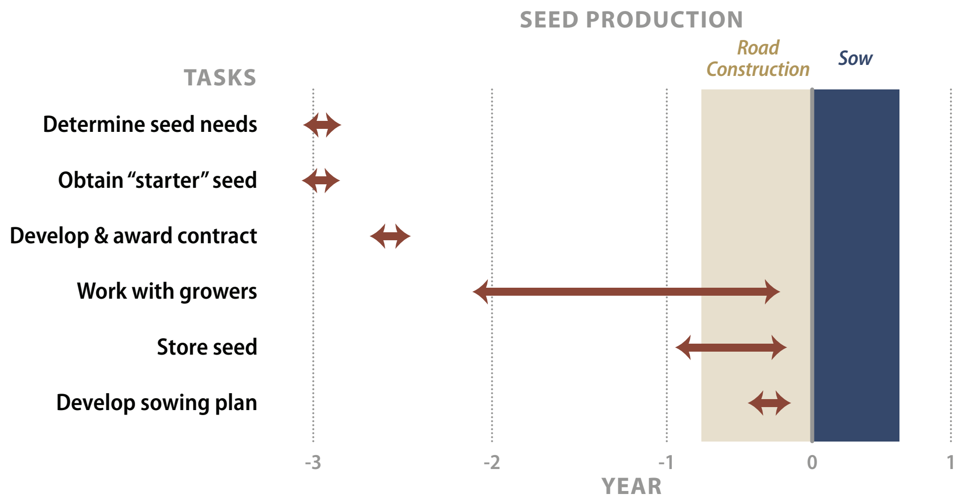


Figure 5-64 | **Plan early for seed production**

Up to three years should be allowed when obtaining nursery-grown seed because of the time it takes to obtain wild collected seed and obtaining seed from seed producers.

Seed production contracts should typically be awarded by mid-July for fall sowing and late January for spring sowing. It is important to prepare and award seed increase contracts well in advance of sowing to allow the seed producer enough time to prepare and sow their fields. Specific sowing dates will differ for each seed producer because of differences in geographic location, climate, or experience. If growers are certifying the seed crop through a state program, requirements that the fields are isolated from other fields of different accessions of the same species may involve additional planning and preparation time as well It is beneficial to contact the potential growers prior to award of contracts to find out when sowing and first harvests are expected. Once wild seed has been collected, cleaned, and tested, it is delivered to the seed producers.

Seed increase contracts should cover a span of at least two years to account for the possibility of a low first year harvest. Seed harvests occur during the summer and seed cleaning in the fall of each year. Once seed has been cleaned, the grower submits a sample from each seedlot to a seed laboratory for seed quality testing. Seed is placed into climate controlled storage until it is needed. If the seed that is harvested in the summer is needed for immediate fall sowing the designer should communicate with the grower to ensure that those seedlots are prioritized for processing and testing.

Determine Seed Needs for Seed Production

Determining total seed quantities for a revegetation project should be done as soon in the planning process as is feasible because wild seed collection contracts and seed propagation contracts are based on these figures. At this point, only a rough approximation of seed needs is required.

Calculating the needed quantities of seed is performed for every species that will be used on a revegetation project. Each species requires a set of data that needs to be estimated because specific seed data is unavailable at this point in planning. The information that is needed includes an estimate of the following factors:

- Pure live seeds per pound
- Field survival
- Target seedling density
- Target species composition
- Area to seed

Pure Live Seeds per Pound (PLS/lb)—The quality of wild collected seedlots can vary greatly. One method to assess seed quality is to calculate percent pure live seed (PLS). This value represents the percent of the gross seed weight composed of viable seeds. For example, if a seed producer did not clean the harvested seed of a seedlot very thoroughly, the PLS would be low because there would be a lot of additional weight associated with non-seed debris. Seedlots that were cleaned well, however, would have a higher PLS because the debris weight would have been removed. Seedlots that have higher germination rates also have higher PLS. These two factors, percent purity and percent germination, when multiplied together and divided by 100, give the PLS of a seedlot. The concept of PLS is illustration Figure 5-65. In this example, purity of a grass seedlot is 95 percent and germination is 83 percent, which result in a PLS of 79 percent.

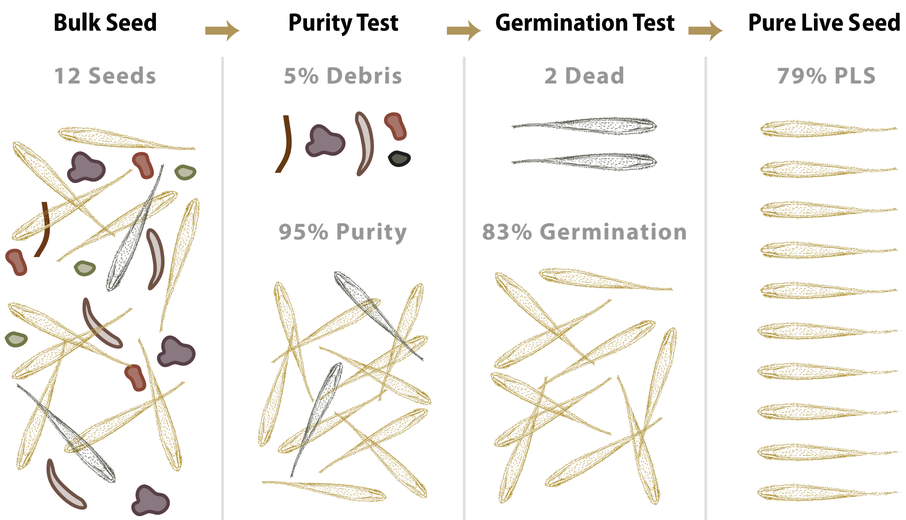


Figure 5-65 | **Pure live seed**

Pure live seed (PLS) is the percent of the bulk seed weight that is composed of viable seed. In this example, 95 percent of the bulk weight is composed of seed and, of this seed, 83 percent was found to germinate from seed tests. Multiplying percent purity by percent germination and dividing by 100 gives percent pure live seed.

Another example of calculating PLS/lb is shown in Figure 5-66 for western pearly everlasting (*Anaphalis margaritacea*). For this seedlot, the estimated purity is 60 percent, which indicates that more than half of the gross weight of seed is actually viable seed and the remaining part is either debris or non-viable seed. Multiplying this value by the percent of seeds per pound and by the percent of germination yields the number of viable seeds per pound. In this example, the number of seeds in a pound of a western pearly everlasting seedlot is tested at 8,000,000. Multiplied by 60 percent purity and 85 percent germination gives a value of approximately 4,080,000 PLS per pound of bulk seed. This value can be used in sowing calculations, as shown in the example. Note that for each additional seedlot in a mix, similar calculations will have to be made. Estimates for purity, germination, and seeds per pound can be obtained from Table 5-15, seed inventories, or seed extractory managers.

Field Survival—Field survival factors account for the viable seeds that, for one reason or another, do not grow into plants within the year after seeding. It accounts for viable seeds that did not germinate because of the harsh site conditions or did germinate but could not survive the site. The field survival factor reflects the harshness of the site. For example, seeds that are sown under mulch on a moist, cool site will survive better than seeds sown on hot, dry sites without mulch, in which case the survival factor would be much lower. Only an estimate of field survival can be made at this time based on a general understanding of the site (Section 5.4.1, see Determine Sowing Rates). Choosing a survival factor between 3 percent (poor site conditions and poor seeding practices) and 25 percent (good site conditions and practices) should be sufficient for this estimate. In Figure 5-66, the field survival was set very low because of the harshness of the site.

Target Seedling Density—The target first-year density indicates the number of plants per square foot that is desired one year after sowing. This is the target number of seedlings for all species sown in a 1 square-foot area. Seedling densities range from a target of less than

A	**Number of seesd/lb**	8,000,000 seeds/lb	From Table 5-15 or other sources
B	**Purity**	60%	
C	**Germination**	85%	
D	*(A * B / 100) * (C / 100)*	4,080,000 PLS/lb	Pure Live Seeds (PLS) per bulk pound of seed
E	**Field surivival**	3%	Estimate of the pure live seeds that become seedlings (as low as 3 percent for harsh sites and up to 25 percent for excellent sites)
F	**Target seedling density**	25 seedlings/ft^2	Desired number of seedlings per square foot, all species (10 to 30 for grasses adn forbs)
G	**Target composition**	10%	Percent of total plants composed of ANMA
H	*(F * E) * G =*	83 PLS/ft^2	PLS of ANMA to sow per ft^2
I	*(43,560 * H) / D*	0.9 lbs/acre	Pounds of ANMA to sow on a per acre basis
J	**Area to seed**	25 acres	Total area for seed mix
K	*I * J =*	22 lbs	Total ANMA needed

Figure 5-66 | **Determine amount of seed needed**

Determining the quantity of seed that will be needed for a revegetation project can be made by completing this spreadsheet for each species. The estimated pounds of seed determined for each species can be the basis for ordering seed through a seed increase contract. This example calculates the quantity of western pearly everlasting (*Anaphalis margaritacea* [ANMA]) seeds needed for a project. A spreadsheet for seed calculating is available in the Native Revegetation Resource Library.

one plant per square foot for shrub and tree species to 10 to 25 seedlings per square foot for grasses and forbs (Section 5.4.1, see Determine Sowing Rates).

Target Species Composition—The target composition defines the percent of established plants that are made up of each sown species. For example, if three species are sown, the target composition of plants might be 50 percent species A, 35 percent species B, and 15 percent species C. The target species composition is developed from reviewing field surveys of disturbed and undisturbed reference sites. In the example shown in Figure 5-66, only 10 percent of the composition of plants is targeted to be pearly everlasting.

Area to Seed—This is the total area that is planned to be revegetated from seed based on the estimated acres presented in the preliminary road plans.

In the example shown in Figure 5-66, the seed needs for pearly everlasting is calculated to be approximately 22 pounds for the entire 25 acre project. This might seem like a very low amount of seed for a project of this size, but it reflects the high live seeds per pound for this species.

Obtain Starter Seed

Once the seed needs for a project are determined, then the next step is to obtain starter seed to supply to the seed producer. Seed furnished to the seed producer should be of high quality and tested for purity, germination/viability (Tetrazoleum or TZ), seeds per pound, and noxious weed content (Section 5.3.1, see Clean and Test Seeds). Seedlots with high weed content will produce weedy fields. It is very expensive to weed non-target species out of seed production fields or clean non-target seeds from harvested seedlots, so it is important to give seed producers only the highest quality starter seed. It is worth the investment, and almost always essential, to send wild seed collections to a seed extractory to be cleaned prior to sending to the seed producer. Section 5.3.1 (see Determine Wild Seed Needs for Seed Production) describes how to determine how much wild seed to collect for starting seed production crops.

For some projects, it may be difficult to collect enough wild seed in a single year to establish a seed increase field. In these cases, the seed may be stored and additional collections made over time until a sufficient quantity of seed is obtained for field establishment. The seed may also be first sown in small plugs (1 to 2 cubic inch size) at a nursery, and then transplanted into a seed production field at low densities (<1 seedling per foot). This will reduce the overall amount of seed needed to establish a seedbed, and seed production from these beds is often greater because plants are evenly spaced.

Develop Contract

The seed production contract should state for each seedlot being grown:

- Seedlot ID
- Years each seedlot will be in production
- Minimum annual seed yields for each seedlot
- Minimum purity and germination rates

Minimum annual seed yields and average germination and purity rates can be obtained from Table 5-15 and Table 5-16. For species and regions not represented here, this information can be obtained from agencies such as the NRCS, private growers, and the Native Seed Network (www.nativeseednetwork.org). The years that a seedlot will be in production will vary by species and lead time (Section 5.3.4, see Develop Timeline).

In addition, the seed production contract should address what is required or expected of the contractor in respect to the following criteria:

- Seed production experience
- Timelines
- History of production field
- Isolation distance from fields planted with other seedlots of the same species (to avoid cross-pollination and maintain genetic integrity of the seed crop)
- Irrigation system
- Culturing practices
- Control measures for non-target species
- Seed harvest methods
- Seed cleaning, packaging, and labeling
- Seed testing

The response to these criteria becomes the basis for selection of contractors.

Seed Production Experience—Native seed production is a specialized form of agriculture requiring highly customized growing strategies and equipment. While many seed producers have transitioned in seed production easily, it still requires several years of experience with any given species to understand how to efficiently grow native seed on a commercial scale. Many seed producers who have moved into growing native seed have previous experience growing vegetable or commercial pasture and turf grass seed. These seed producers bring great experience and perspective to the native seed industry. Seed producers, who have had little experience growing native seed often start small with easier species (e.g., many workhorse species) to gain experience. It is important to know the capability of each seed producer and make frequent site visits. Those with a long history of good seed production can be contracted for species that are more difficult or have not been grown before. It is good to request production records, as well as seed tests and to include species, seed yields, seed quality, and clients served by the producer.

Seed Production Timelines—Seed producers are located throughout the United States that encompass a broad range of climates affecting when seeds are sown and harvested. It is important to know the general growing schedule of each seed producer in your region to determine when to supply starter seed to the seed producer and when the first shipment of harvested seed can be expected. Some seed producers wait until spring to sow seed crops, in which case the seed harvest in the first year may be significantly reduced. Depending on the climate and species, seed harvests can occur as early as May to as late as August. It is important to specify a date in the contract when seed will be delivered, especially if the seed will be used in the same year it is harvested.

History of Production Fields—Every field will have some amount of residual seeds from previous crops that will germinate along with the starter seed supplied by the designer. Knowing the history of the fields during the planning stages helps determine whether these non-crop plants pose a problem for seed production. Noxious weeds or undesirable non-native species are a concern, but many of these species can be rogued out of the seed beds prior to harvesting. Of more concern are fields where the same native species, but from a different seed source (especially from a different climate), were grown. For example, a field is being prepared for sowing California fescue (*Festuca californica*) from a seed source in the Blue Mountains of northeastern Oregon. The field had previously grown California fescue from a seedlot collected west of the Cascades. Because seed from the previous fescue crop would germinate in the same bed, the resulting crop would include both seedlots. Because the plants from these seedlots would appear almost identical, it would be impossible to weed out the plants that came from the previous crop. Even species in the same genera are difficult to distinguish by untrained weeders and cannot be weeded out of beds.

Fields that previously produced seed from the same or similar appearing species should be evaluated for the risk of seed contamination from previous seed crops. Seed producers can take measures to reduce contamination risks. These include growing non-seed crops for several years between seed crops, rotating between grass and forb seed production (forb seed is easy to discern from grass seed), and fumigating between seed crops. These strategies should be discussed with the seed producers. State seed certification guidelines and standards are becoming increasingly available for many native species.

Location of Other Seedlots—Equally important to the history of seed production fields is the location of nearby seed crops of the same species. If seedlots of the same species are being grown close by, the risk of cross-pollination between crops increases and the genetic integrity of the proposed seed crop could be compromised. There can even be cross-pollination between similar species. For example, blue wildrye (*Elymus glaucus*), bottlebrush squirreltail (*Elymus elymoides*), and bluebunch wheatgrass (*Pseudoroegneria spicata*) are known to cross-pollinate. Local botanists or geneticists should be consulted about which species can potentially cross breed. Seed crops that can cross-pollinate should also be separated by a minimum isolation distance. Under most circumstances, the isolation distances should be in accordance with State Certification Standards (certified class). These standards can be found at the AOSCA website or the departments of agriculture for each state. State seed certification specialists can often provide recommendations for species of interest that lack official isolation standards.

Irrigation System—Many native species should be grown under irrigation to meet the quantities of seed specified in the contract. Seed producers that have minimal or no irrigation capacity are often unlikely to meet seed production requirements and time frames. Only those species that do not require irrigation should be offered to growers lacking irrigation systems.

Culturing Practices—A review of culturing practices, which include irrigation, fertilization, disease, and insect control, should be done to determine whether they are appropriate for the production of the species being grown. Culturing practices are often written up in propagation protocols that can be found on the Native Plant Network. Many university nurseries and NRCS Plant Material Centers also publish propagation protocols and useful plant guides and fact sheets.

Control Measures for Non-Target Species—Specific attention should be given to how weeds and other non-crop species will be controlled. Typical measures include the use of herbicides prior to sowing and after the crop has been established, and manual weeding of non-target species. The most important period of weed control is just prior to seed harvest because of the importance of eliminating potential non-target seed before harvesting occurs.

Table 5-15 | **Seed increase reference table for native grass species**

This table show the approximate maximum cleaned seed needed for a seed producer to produce a 1-acre production field. It also shows average first and second year yields and germination and purity standards for commonly produced species in the Pacific Northwest US.

Species	Sowing rates (lbs of clean seed to sow per acre)	Average first year yields (lbs/ac)	Average second year yields (lbs/ac)	Average seeds per pound	Average germination/ purity of harvested seeds
Bluebunch Wheatgrass *Pseudoroegneria spicata*	8	200	300	140,000	75/95
Blue Wildrye *Elymus glaucus*	6	450	200	110,000	65/96
Bottlebrush Squirrel-tail *Elymus elymoides*	6	0	125	110,000	75/90
California Oatgrass *Danthonia californica*	8	25	250	125,000	75/90
Basin Wildrye *Leymus cinereus*	8	25	160	130,000	75/95
Idaho Fescue *Festuca idahoensis*	4	50	400	450,000	75/90
Indian Ricegrass *Oryzopsis hymenoides*	6	0	200	120,000	80/85
Lemmon's Needlegrass *Achnatherum lemmonii*	8	150	750	150,000	50/95
Mountain Brome *Bromus carinatus*	10	800	600	70,000	85/90
Needle and Thread *Hesperostipa comata*	6	0	150	100,000	50/95
Pinegrass *Calamagrostis rubescens*	2	0	130	2,500,000	75/75
Prairie Junegrass *Koeleria macrantha*	2	150	500	2,315,000	80/97
Sandberg Bluegrass *Poa secunda*	3	300	600	1,314,000	75/97
Slender Hairgrass *Deschampsia elongata*	3	600	350	2,000,000	80/95
Thurber's Needlegrass *Achnatherum thurberianum*	5	0	150	225,000	50/95
Tufted Hairgrass *Deschampsia caespitosa*	2	110	510	2,500,000	75/90
Western Needlegrass *Achnatherum occidentale*	5	100	190	275,000	50/95
Common Yarrow *Achillea millefolium*	2	165	165	3,000,000	85/98
Western Pearly Everlasting *Anaphalis margaritacea*	1	50	50	8,000,000	60/85

Seed Harvest Methods—Most seed harvests are conducted with specialized equipment that detaches seed from the stock, separates it from plant and soil debris, and collects it into storage containers (Figure 5-67). It is important to know the seed harvesting equipment that will be used for each species and how it will be cleaned between individual crops to prevent the possibility of contamination among seedlots.

Figure 5-67 | **Seed harvesting equipment**

Seed harvesting equipment varies by seed producers and species being harvested. Discuss with the seed producer how each species will be harvested and make sure that equipment is cleaned between seedlots.

Photo credit: David Steinfeld

Species with indeterminate inflorescences (seeds that ripen on the seed stock all summer long) should be collected more than once in the summer. This repeated harvest can be done manually or with specialized equipment such as motorized leaf blowers that are operated in reverse as vacuums. Periodic seed harvests of these species should be planned so that the full range of seed can be collected. The designer should anticipate higher financial costs for indeterminate species given the extra harvest efforts. The seed producer should address how these species will be harvested to obtain the maximum seed yield.

Seed Cleaning, Packaging, and Labeling—After seed is harvested, it should be dried and further cleaned. Seeds are air dried (Figure 5-68). Seeds are then extracted and cleaned. Awns and flower parts are removed, and then dirt, stems, and other debris are separated from the bulk seed. Understanding the cleaning operation is important because viable seeds can be damaged or discarded during this process.

For typical warehouse storage, dry cleaned seed should be packaged in "breathable" woven poly bags at uniform weights Industry standards are 25- or 50 pound bags. Bags of seed should be clearly identified with an affixed tag stating the species name (scientific and common), seedlot identification/source code, percent germination, percent purity (including other crop seed, weed seed, and noxious weeds), date of seed test, and seed producer's name. Additional certification tags or labeling information may be requested, such as project name, National Forest or BLM office, or seed owner name.

Figure 5-68 | **Seed harvesting and drying**

Seed is harvested and dried prior to cleaning and storage. This photograph shows a recently harvested seedlot in drying trays prior to being set on a forced air drier. Seed ID tags are attached to the side of each seed drying bin.

Photo credit: David Steinfeld

Table 5-16 | **Seed increase reference table for native forb species**

This table shows the approximate maximum cleaned seed needed for a seed producer to establish a 0.1-acre production field for key forb species in the Pacific Northwest US. Also listed is the timing and method of field establishment, field longevity, and average seed yields per 0.1 acre plot for years 1-3. A complete forb seed increase table can be obtained in the Native Revegetation Resource Library.

Species	Seed quantity needed to plant 0.1 ac plot (ounces)	Timing of planting	Planting method*	Field longevity (years)	Production yield per 0.1 acre plot (lbs/year; years 1, 2 and 3)		
Western yarrow *Achillea millefolium*	3-4	Summer	DS	3-4	5-15	30	30
Nettlelead giant hyssop *Agastache urticifolia*	5-6	Fall	Tubes/DS	2-5	2-5	5-10	10+
Bigflower Agoseris *Agoseris graniflora*	5-6	Spring/Fall	Tubes/DS	2-3	40	40-80	—
Basin big sagebrush *artemisia tridentata*	3-4	Fall	Tubes	10-15	0	10-20	20-40
Showy milkweed *Asclepia speciosa*	6-8	Spring/Fall	Tubes/DS	3	0	20	40
Canadian milkvetch *Astragalus canadensis*	5-7	Spring/Fall	Tubes/DS	3-4	0	20-40	40+
Basalt milkvetch *Astragalus filipes*	5-7	Spring/Fal	Tubes/DS	3-4	0	20-40	40+
Douglas' Dustymaiden *Chaenactis douglasii*	5-6	Spring/Fall	Tubes/DS	1-2	20-30	50	—
Clarkia *Clarkia* spp.	3-4	Spring/Fall	DS	1	30	—	—
Yellow Spiderflower *Cleome lutea*	3-4	Spring/Fall	DS	1	50-60+	—	—
Grand collomia *Collomia grandiflora*	3-4	Fall	DS	1	15+	—	—
Blue Muontain prairie clover *Dalea ornata*	5-7	Spring	Tubes	4-5	0	20-40	60+
Threadleaf Fleabane *Erigeron filifolius*	3-5	Spring/Fall	Tubes/DS	3	0-5	15+	15+
Shaggy Fleabane *Erigeron pumilus*	3-5	Spring/Fall	Tubes/DS	3	0-5	15+	15+
Aspen Fleabane *Erigeron speciosus*	3-5	Spring/Fall	Tubes	3-4	0-15	30-100	100+

**DS = Direct Snow*

Seed Testing and Acceptance—The contract should state the minimum acceptable standards for each species and seedlot. Acceptance and payment should be based on meeting the standards set for the following:

- Germination
- Purity
- Weeds
- Moisture content

Seed testing is typically the responsibility of the contract grower. Seed samples used for testing and contract performance should be taken by a certification agency representative or a contract inspector who is trained and certified in proper seed sampling methodologies. Samples should be tested by a state certified seed laboratory (Section 5.3.1, see Clean and Test Seeds) Seed test results should be identified by the seed source identification and task order number. Test results should be satisfactory to the project's owner agency before final acceptance of the seed is made.

Establishing minimum germination and purity rates can be based on averages obtained from commonly produced species shown in Table 5-15 and Table 5-16 and other available sources, or through discussion with seed extractory managers. The contract should address what actions the contract- grower can take to increase either germination or purity if these rates fall below the standards. Lower purity rates can be accepted if seed will be used in a hydroseeder (Section 5.4.2). A TZ test may be made in lieu of a germination test for a seed viability test depending on time constraints and species involved. All State Noxious Weed examinations are required, and if any of these species are present, then the seedlot should either be rejected or re-cleaned. The seed moisture test should also be conducted, and seed should not exceed 10 percent moisture.

Administer Contract

Figure 5-69 | **Visit seed producers to assess crop quality**

It is important to visit seed producers to assess isolation distances, noxious weeds, culturing practices (e.g., irrigation, fertilization), and expected seed yields. The best time to visit is during seed ripening and seed harvest.

Photo credit: Marlo Fisher, USFS

Seed producers are required to maintain adequate records to allow the Government to monitor contract progress. Records should include information and dates of field preparation, seed sowing, field treatments, fertilization, seed harvest, cleaning, storage, seed yields, and any other activity relating to seed production. It is a good practice to make contact either by phone or by visiting the seed producers two to three times a year to go over the progress of the contract. The best time of year for field visits is just prior to or during seed harvest (Figure 5-69). A visit or phone contact in fall is important to discuss the potential of keeping seedlots additional years. Visiting in the late summer or fall is also a good time to observe the seed extraction and cleaning processes. Unless it is stated in the contract, seed production fields are likely to be plowed under once the seed orders have been met. If seed in excess to the order is produced, contracts often specify that the Government has first right of refusal for the additional amount, often at a reduced or negotiated price.

During these visits, it is important to note the condition of the seedlots and how they are being identified throughout the production phase and subsequent processes. Are there clear labels stating the seedlot identification in the field, during drying, extraction, and storage? Are seed harvest and extraction equipment being thoroughly cleaned between seedlots or are there remnant seeds remaining in the equipment that can contaminate the next seedlot being processed? Note the condition of the fields prior to seed harvest. Are the fields weedy and will there be a final weeding before harvest? Are seeds being handled with care or are they roughly handled? These same questions and practices are also used during the state seed certification process.

A good working relationship with the seed producer is essential in meeting the overall seed increase objectives. It should be realized that some factors, such as weather, are beyond the control of seed producers, and in some years seed harvests will fall short of the minimum amounts stated in the contract. Good communications with the seed producer will allow designers to learn of crop failures or fall down in orders as soon as they occur so that alternative measures can be taken. An inventory of the number of acres in each seedlot and the condition of the crop should be supplied by the contract grower upon request.

Seed Storage

Seeds can remain viable in properly controlled storage for many years after harvest. How well seeds keep depends on the moisture content of the seed, the quality of the seed being stored, the storage conditions (temperature and humidity) and presence of damaging agents such as rodents, insects, or mold). Seeds typically store poorly when seed quality is low, or seed moisture content is above 10 percent. Fluctuating temperatures will also shorten seed longevity. If seedlots are stored for more than a couple of years, it is important to periodically test the seed for germination.

Granary Storage—Most seedlots are stored for short periods before they are used on projects (usually less than five years). For this reason, granary storage is the most common and economical form of seed storage, especially for larger quantities of grass and forb seed. Granary storage units are enclosed rooms sheltered from rainfall and temperature extremes. Storage temperatures are ideally near 10° C, with humidity less than 20 percent. Storage containers are typically insulated and protected from rodents and insects. While some seedlots can be stored for long periods, low quality seed should be used first because it is more likely that this seed will lose viability in storage compared to high quality seed.

Freezer or Refrigerator Storage—Freezer storage (~9° C) is usually reserved for seedlots that will be stored for many years. Conifer and shrub seeds, as well as small forb and grass wild seed collections, are usually stored under these conditions. Berries, however, cannot be frozen, as the moisture content may be too high and could damage the seed embryo. Instead, berries are best stored in refrigerators at temperatures ranging from 1 to 3 degrees C. Seed of some species, such as maples, also need to be stored in refrigerated conditions but may require special pre-treatments, even for short-term storage.

Seed extractory managers are excellent sources of information for more detailed guidance on proper storage conditions for particular species.

5.3.5 NURSERY CUTTING PRODUCTION

Introduction

Obtaining cutting materials in the wild for restoration and bioengineering applications can be a difficult and expensive task, especially if populations of parent material are small or access is limited. Native plant nurseries can be an alternative source for a variety of woody cuttings. Understanding how nurseries establish and manage "stooling beds" can be a great help to designers and project engineers.

What are Stooling Beds?

"Mother plants" are established in nurseries for the sole purpose of providing a ready source of cuttings. Stooling beds are hedge-like rows of mother plants that are established in bareroot nurseries or in vacant fields (Figure 5-70A). Stooling beds are more commonly referred to as "cutting beds".

Stooling beds take advantage of the ability of many broadleaved woody plants to sprout profusely from the base after being cut off just above the root crown (i.e., coppiced). Plants remain in the juvenile state, which means they have a higher tendency to sprout and produce roots. Once stooling beds are established, annual cutting ensures that juvenility can be prolonged for multiple years. After repeated harvests, stooling beds will lose productivity after a few years. However, new beds can be created using cuttings from declining beds such that the unique genotypes in a given bed can be preserved for many years.

Stooling beds allow for the efficient collection of dormant hardwood cuttings during winter when it may be difficult or impossible to make field collections (Figure 5-70B). Because the

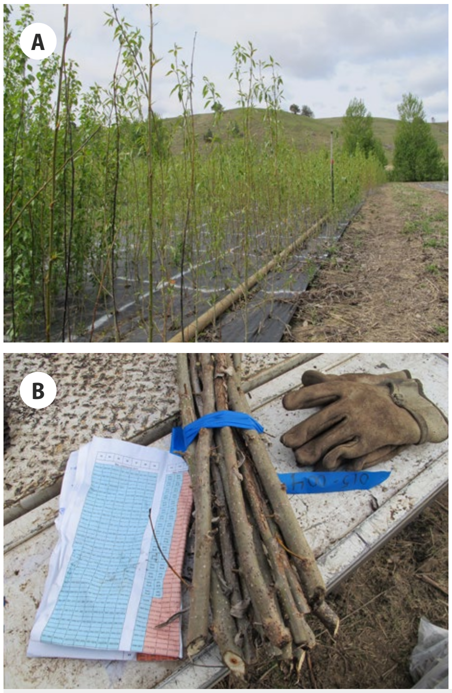


Figure 5-70 | **Stooling beds produce cuttings**

Stooling beds (A) are an efficient way of ensuring that a ready supply of hardwood cuttings of the proper species and source are available (B).

Photo credit: Matt Horning, USFS

beds are located in agronomic settings, they can be irrigated and cultured; processing and storing the cuttings is also much more efficient and cost-effective. Cuttings from stooling beds have several advantages over wild collected cuttings.

Maintaining Genetic and Sexual Diversity—It is much easier to correctly identify different plant species and ecotypes from labeled stooling beds as compared to wild collections. For example, willows often grow together along streams and can be difficult to identify during the winter dormant season. Stooling beds offer the ability to produce a large number of cuttings of unique species or ecotypes quickly and easily.

Many government nurseries have established stooling beds of the species and ecotypes that are adapted to local seed zones areas and can thus be a potential source starter material for private growers or out-planting materials for designers. Private native plant nurseries also establish stooling beds of desirable species for their local areas, and several specialize in riparian and wetland species. For specific revegetation projects, however, the odds of a nursery having existing stooling beds of the proper species and local ecotype are low. Therefore, collecting cuttings and establishing stooling beds should be done early in the planning process so a good supply of cuttings will be available when needed.

Some plants, such as willows and cottonwoods, are either male or female, which is an important consideration in restoration (Landis and others 2003). If a balanced mixture of male and female plants is not collected from the project site, the resultant stooling beds will not produce both male and female cuttings. When working with dioecious plants, the sexual identity of potential mother plants should be determined prior to collection (Section 5.3.2). It is essential that a restored population is contains a mix of female and male plants to ensure the established population's capacity for sexual reproduction.

Producing Healthy and Vigorous Cuttings—One of the most practical advantages of establishing stooling beds is that the cuttings from the beds are often healthier and more vigorous than those collected from the project site. Wild stands of willows are host to many insects and fungal pests, such as galls and cankers (Figure 5-71). They are also subject to animal browsing. These factors can significantly lower the quality of wild-collected cuttings. Cuttings from the stooling beds can root at over 99 percent, thereby lowering establishment costs and keeping the project on schedule (Dumroese and others 1998).

Reducing Costs—It might seem that collecting cuttings in the wild would be the least expensive means of obtaining cutting materials. This is not necessarily the case. Inefficiencies of driving to remote locations, pulling cutting materials to roadways, using make-shift cutting practices, and working under severe winter conditions all add up to high costs per cutting.

Select Species Suitable for Stooling Beds

Poplars, cottonwoods, and willows are the species most often used in stooling beds. It should not be assumed, however, that all species of the willow family are good candidates for stooling beds. Some species have growth characteristics that reduce their potential. For example, trials at the Colorado State Forest Service Nursery in Fort Collins have shown that narrowleaf cottonwood (*Populus angustifolia*) and narrowleaf willow (*Salix exigua*) do not "stool" well and should be propagated by other methods (Grubb 2007).

There is great potential for using other woody species that have the propensity to sprout and form roots easily. For example, redosier dogwood (*Cornus sericea*) is commonly grown in stooling blocks and used as a source of cuttings for restoration sites. Outplanting success is higher than with wild cuttings collected on the project site and has ranged from 50 to 90 percent (Hoag 2007). In North Dakota, twinberry honeysuckle (*Lonicera involucrata*) is being investigated (Morgenson 2007). Native species that root easily from hardwood cuttings have the potential to be grown in stooling beds to generate cuttings. Species that have inherent deep seed dormancy characteristics, such as snowberry, honeysuckle, elderberry, and some

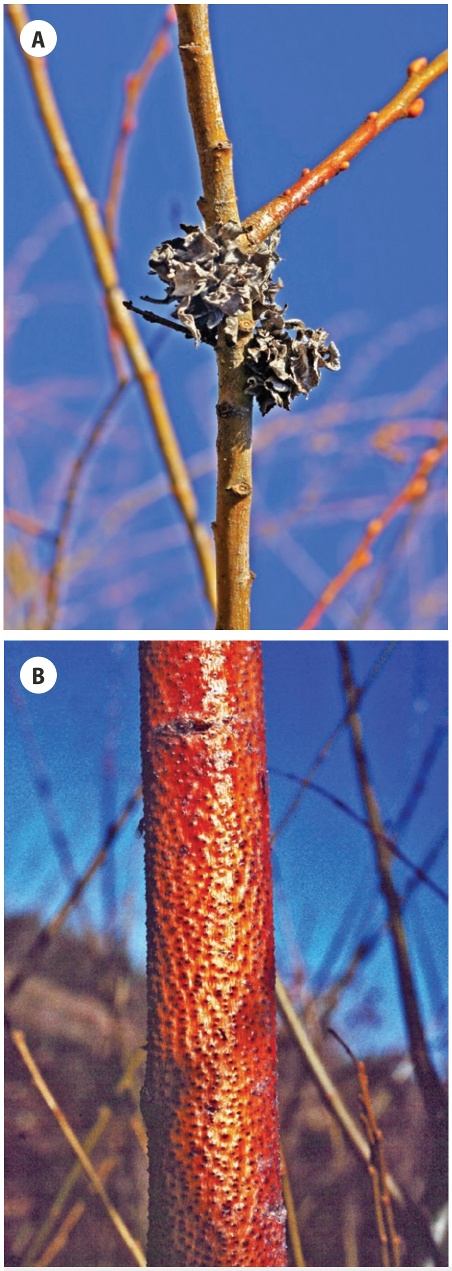


Figure 5-71 | **Stooling beds are managed production facilities**

Stooling beds can be cultured to prevent the occurrence of insect galls (A) and fungus cankers, such as *Cytospora* spp. (B).

Photo credits: Thomas D. Landis

species of currants, could be more easily propagated in the nursery using stooling beds than sowing seeds to produce seedlings. Species that have consistently low seed viability, such as mock orange and ninebark (*Physocarpus* spp.), may also be produced more economically in stooling beds.

The Plant Materials Centers of the NRCS identified the potential of a wide variety of woody native plants that would be suitable for stooling beds (Table 5-17). For example, Crowder and Darris (1999) discuss which plants are suitable in the Pacific Northwest and provide a wealth of information on the installation and culture of stooling beds.

Darris (2002) performed extensive greenhouse and field trials to test the potential of several woody plants for live stake applications. Common snowberry (*Symphoricarpos albus*), salmonberry (*Rubus spectabilis*), Pacific ninebark (*Physocarpus capitatus*), and twinberry honeysuckle (*Lonicera involucrata*) have proven to be effective as live stakes for soil bioengineering in the Pacific Northwest. Notably, several have proven to be superior to willow on some sites, such as salmonberry in wet, shaded environments, and snowberry on drier, exposed locations.

Table 5-17 | **Native woody plants of the Pacific Northwest with potential for propagation in stooling beds**

Species	Rooting ability	Growth rate	Establishment success (1=Poor, 5=Good)
Coyotebursh *Baccharis pilularis*	Fair to Good	Moderate	3
Redosier dogwood *Cornus sericea*	Good	Fast	3
Indian plum *Oemleria cerasiformis*	Poor to Good	Moderate	1
Pacific ninebark *Physocarpus capitatus*	Good to Very Good	Moderate to Fast	4
Lews' mock orange *Philadelphus lewisii*	Fair	Moderate	1
Black cottonwood *Populus trichocarpa*	Fair to Very Good	Very Fast	3
Woods' rose Rosa woodsii	Poor to Fair	Moderate to Fast	1
Peachleaf willow *Salix amygdaloides*	Excellent	Very Fast	5
Narrowleaf willow *Salix exigua*	Very Good	Fast	4
Arroyo willow *Salix lasiolepis*	Excellent	Very Fast	5
Scouler's willow *Salix scouleriana*	Good to Very Good	Very Fast	4
Rose spirea *Spiraea douglasii*	Very Good	Fast	4
Common snowberry *Symphoricarpos albus*	Very Good	Fast	4

Modified from Crowder and Darris (1999)

Select the Type of Cutting Material

Several different types of cutting materials can be collected from stooling beds. Nurseries can use small propagation cuttings (perhaps short as one inch) to start their own bareroot or container plants. Stooling beds can also provide several types of unrooted cuttings used in restoration (Figure 5-72).

Live Stakes—Live stakes are so named because, in addition to providing stability on restoration sites, they are expected to root and sprout after installation (Section 5.4.3, see Live Stakes). Because they are often pounded into the ground, live stakes are cut from relatively straight sections of second- or third-year wood. Live stakes are typically 18 to 24 inches in length and from 1 to 3 inches in diameter (Figure 5-72A). Depending on the plant species, it can take two to four years for a stooling bed to produce large enough branches for live stakes. Some of the smaller willow species will never grow large enough.

Whips—Whips (not shown in Figure 5-72) are similar to live stakes except they have a much smaller diameter of less than an inch. Whips can be planted by "sticking" them directly in the ground. Because of their small diameter no tools are necessary to install them.

Branched Cuttings—Bioengineering practices, such as live fascines, waddles, vertical bundles, brush layers, and pole drains (Section 5.4.3) require a large number of branched hardwood cuttings (Hoag and Landis 2001). The size of this material ranges from 0.5 to 2 inches in stem diameter and 4 to 15 feet in length (Figure 5-72B). Stooling beds may take two or more years to produce significant numbers of harvestable branched cuttings.

Pole Cuttings—Pole cuttings (Figure 5-72C) are large diameter (3- to 6-inch) main stems that have all side branches with the top 1 to 2 feet of stem removed. They are used in restoration projects where stability is a main concern. Because of the large size of the plant material necessary for pole cuttings, nursery stooling beds are ideal. Larger trees, such as cottonwoods and tree-sized willows (e.g., Goodding's willow [*Salix gooddingi*]), have primarily been used for pole cuttings. Other large woody plants with the potential to sprout may also prove to be viable material (Dreesen and Harrington 1997).

Develop Timeline

Obtaining cutting materials from established stooling beds takes between one and five years, depending on the type of material. A minimum of one year is necessary to produce branched cuttings; two to four years to produce live stakes; and pole cutting may require more than four years (Figure 5-73). In the planning stages of the revegetation project, the number, type, and species of cuttings needed for the project should be determined. Procedures for making these calculations are outlined in Section 5.3.2 (see Determine Cutting Needs). Nurseries or government facilities that specialize in stooling bed production can be contacted to see if they will establish stooling beds for the project. Managers of these facilities can provide information regarding costs and the time frame for meeting the orders. While some cutting materials will be produced in the first year, full production of stooling beds does not occur until several years after installation.

Most stooling beds are started from cuttings taken from the wild. The sources of starter material should be located in the field during the summer or fall prior to installation of the beds. The sexual identity of dioecious plants should be determined during the appropriate season prior to collection. This is not a simple task and requires the expertise of a skilled botanist or native plant specialist. Section 5.3.2 (see Locate Cutting Areas) provides an outline of the steps necessary to obtain starter material. The nursery managers will provide information regarding the number of feet of starter material (or number of cuttings), the quality of the wild collections (age, size, condition), and packaging and shipping methods necessary to meet the order. Wild cuttings are collected when the donor plants are dormant (i.e., no leaves present). Depending on the climate of the site, collections can begin in mid to late fall and end from late winter to

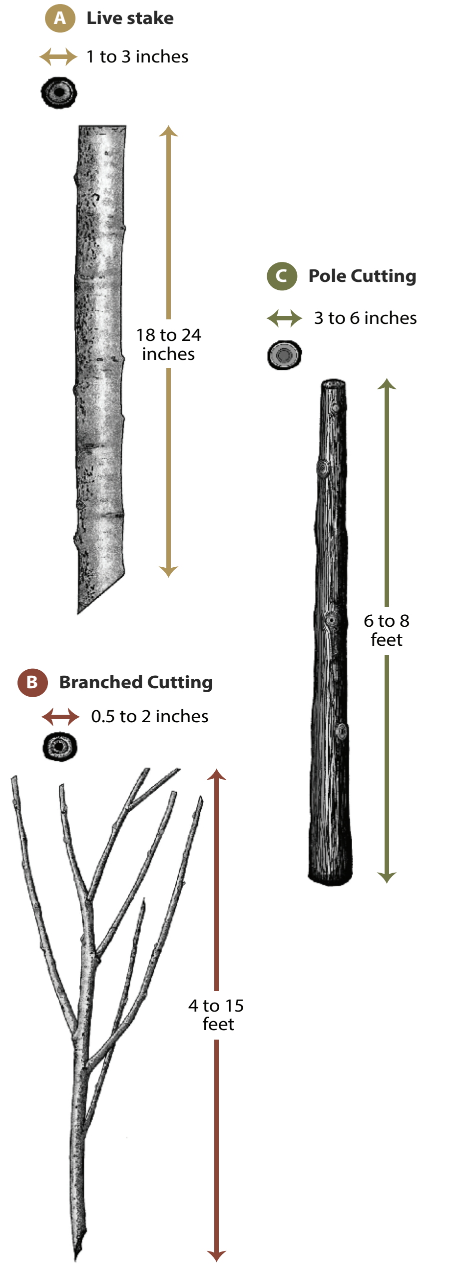


Figure 5-72 | **Different cutting types serve unique purposes in revegetation**

Several types of hardwood cuttings can be obtained from stooling beds, including cuttings for propagation at the nursery or live stakes and branched cuttings for restoration projects. Note that larger plant materials require extra time to produce.

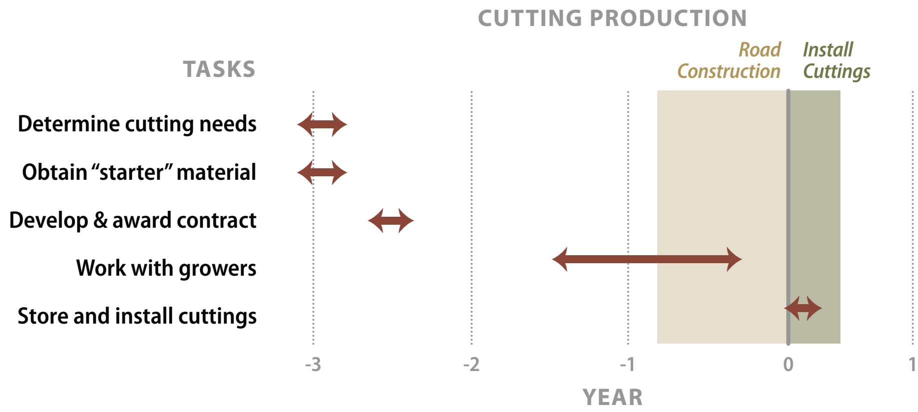


Figure 5-73 | **Plan early to ensure cuttings are ready for a project**

Obtaining cutting materials from stooling beds can take up to four years, depending on the type of material requested. Branched cuttings can be obtained from stooling beds after the first growing season, while live stakes can take from two to four years. Pole cuttings can take even longer. The following is a timeline for producing branched cuttings and some smaller live stakes. Add several years for large stakes and some poles.

mid-spring. Wild cuttings are usually sent immediately to the nursery where they are prepared for installing in stooling beds. Most stooling beds are started directly from cuttings that are stuck in the spring. Cuttings root quickly in the spring and, with irrigation and fertilization, grow into large plants by the end of the summer. The following winter, the beds are ready for harvest. Because stooling beds are relatively uniform, the material can be harvested and processed in a production-oriented manner. Cutting materials are cut to specifications and stored in either freezer or cold storage facilities until delivery is requested.

The development of stooling beds is a long-term investment, and they often take several years to fully establish. However, they can remain productive for many years depending on species, ecotype, nursery cultural practices, and pest management. For cottonwoods, stooling beds typically remain productive for four to eight years, after which vigor and productivity start to decline. Importantly, cuttings from declining beds can be used to create new beds ensuring the preservation of individual genotypes and this eliminates the need to return to the original source location in the field. However, other nurseries have maintained stooling beds of willow and cottonwood for 12 to 15 years without decreases in vigor. Cytospora canker, caused by fungi of the genus *Cytospora* spp. (Figure 5-72B), is a particularly serious pest of all Salicaceae and, because it is transmitted and thrives in wounded stem tissue, can ruin a productive stooling bed. The productivity and longevity of a stooling bed are a direct function of the amount of care given. Because stooling beds are an investment with long-term payoffs, finding local partners (watershed councils, federal, state, and county land managers) who can utilize these beds after project needs are met can be a service to the local community.

5.3.6 NURSERY PLANT PRODUCTION

Introduction

Planting stock with established root systems is often optimal for certain species, or for use in restoration projects that occur on very harsh or disturbed sites. This may be accomplished by growing plants from seed or rooted cuttings in nursery beds or in containers in a greenhouse for a period of time ranging from several months to several years. Woody plants are critically important because they quickly provide vertical structure and aesthetic relief on roadside revegetation projects. When planted within areas seeded with grasses and forbs, trees and shrubs provide the essential matrix of a successful revegetation project. Direct seeding is rarely used to establish woody plants on restoration projects because they are often slow to germinate and take several years to become established. Depending on site characteristics, many sizes of nursery stock can be used. If large plants are used, their physical size and deep roots allow them to more quickly access soil moisture at deeper levels, and their expansive lateral root systems help stabilize soils while also reaching more surface moisture. On some harsh rocky sites, smaller plants may have better initial survival and are more likely to colonize the area. In addition to providing wind protection and shade to lower growing vegetation, trees and large shrubs provide habitat for insects, birds, and other animals and can greatly accelerate the development of a sustainable plant community.

Grasses and forbs establish quickly and easily from seeds, so they are less frequently grown in nurseries. However, nursery stock is warranted under certain circumstances including the following:

- Sufficient quantities of grass and forb seeds are rare or hard to collect;
- Increasing grass and forb seeds by seed growers is difficult or excessively expensive;
- Establishing grasses and forbs is difficult due to site conditions;
- Restoring threatened or sensitive species is a high priority;
- Using nursery stock is more effective in restoring wetlands;
- Installing nursery stock is the best and fastest way to achieve a desired plant composition;
- Aggressive weeds are a serious problem.

This report outlines the steps needed to obtain quality seedlings, transplants, or rooted cuttings from native plant nurseries. Typically, it takes one to two years to grow nursery plants; therefore, the designer should develop growing contracts and establish timelines several years in advance.

Develop Timelines

Obtaining some nursery stocktypes can take a considerable amount of lead time and planning. Although most native plant nurseries carry a wide variety of species, it is unlikely they would have plants that are genetically suitable for a specific project. However, it is worth investigating the available sources for genetic appropriateness as this can save time and funding. The large nursery stocktypes that will survive and grow on challenging restoration sites typically require several years to produce (Figure 5-74). It is therefore often necessary to develop contracts that will ensure that the correct genetic material is being propagated and that the resulting plants are of the highest quality that will survive and grow when planted on the revegetation site.

A project's plant needs are determined early in the revegetation planning stages, including the number of plants, types of species, and size of plants. From the list of species, seed sources or "starter" plant material sources are located from suppliers or collected in the wild. This can typically take at least a year. Several years before the construction site is ready for planting, a

For the Designer
When investigating plant material sources, designers can enlist the assistance of plant geneticists to help determine if a given source is genetically appropriate for a certain project area.

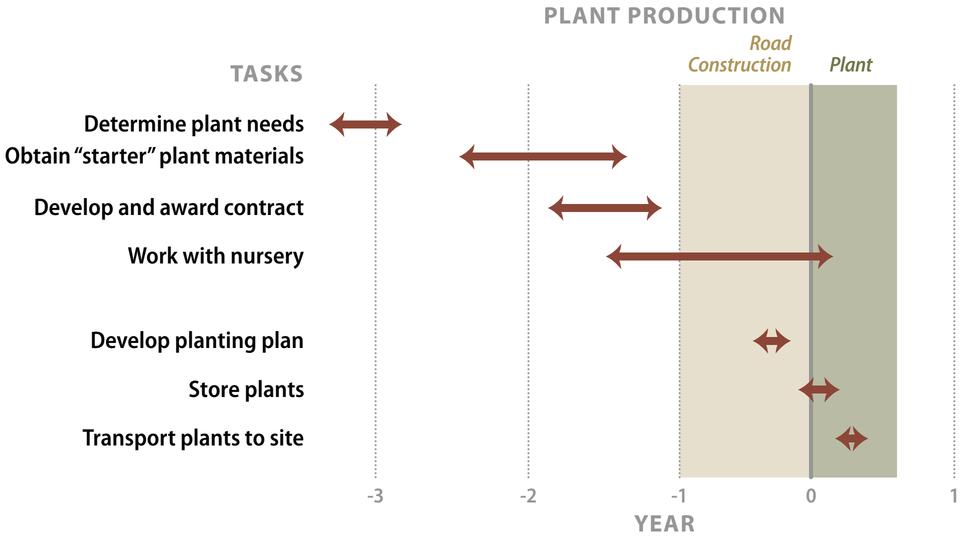


Figure 5-74 | **Engage nurseries early for plant materials**

Obtaining nursery-grown plants often requires two to three years of advance planning, although the timeline for different species can vary considerably. This timeline can be shortened by up to a year if "starter" plant materials, such as willow cuttings or seedlings for transplanting, are available. Certain woody plants require long seed treatments or grow slowly, so timetables should be adjusted accordingly.

contract for growing plants is developed and awarded. Once awarded, seeds and "starter" plant materials are sent to a nursery so that sowing, transplanting, or rooting of cuttings can begin.

The growing time for large container stock can extend from one to two years, depending on the species. The nursery will take a final seedling inventory during the middle of the final growing season. At this time, a planting plan can be finalized. Road construction will be moving into its final stage and the planting plan can be tailored to specific on-site conditions. From start to finish the whole process, including lifting, storing, and transporting plant materials, can take two to three years.

Determine Plant Needs

Early in the planning stages, a general idea of plant needs is developed based on the desired future condition for each revegetation unit. The information required to determine the quantities for each revegetation unit includes the following:

- Area to plant
- Species mix
- Survival potential
- Plant spacing (density)

Using calculations similar to those presented in Figure 5-75, an estimate of the number of seedlings to order from nurseries can be determined. Calculations should be performed for each revegetation unit, because species mix, plant spacing, and survival will change considerably between units.

A	**Planting area**	0.75 acre	Area that will be planted
B	**Target plant spacing**	8 feet	Desired distance between established plants
C	**Avg. survival potential**	75%	Percent of seedlings that survive after one growing season
D	*(A * 43,560) (B * B) =*	510 plants	Desired number of established plants after one growing season
E	*D * (100 / C) =*	681 plants	Number of nursery plants that need to be planted
	Species mix		
F	**Ponderosa pine (PIPO)**	50%	Percent of total established plants composed of PIPO
G	**Quaking aspen (POTR5)**	30%	Percent of total established plants composed of POTR5
H	**Serviceberry (AMAL2)**	20%	Percent of total estalished plants composed of AMAL2
I	*E * F / 100 =*	340 plants	Number of PIPO to order
J	*E * G / 100 =*	204 plants	Number of POTR5 to order
K	*E * H / 100 =*	136 plants	Number of AMAL2 to order

Figure 5-75 | **Determining planting needs**

A spreadsheet can be used to determine how many plants should be ordered for each species. Each revegetation unit should have separate calculations because the units will have different survival rates, species mixes, and plant spacing.

Planting Area—Summarize the acreage of all planting areas within each revegetation unit.

Species Mix—Good survival and establishment of plants fundamentally rests on selecting the most appropriate species from locally adapted seed sources. Selecting the species mix for each revegetation unit should be based on an evaluation of disturbed and undisturbed reference site descriptions that includes an understanding of the site limiting factors that will affect plant survival.

Survival Potential—Survival potential is an estimate of the percentage of planted seedlings that will survive and become established. Many factors determine how well nursery-grown plants will survive after outplanting. Factors that can be controlled include the following:

- Selection of appropriate species and seed source for the site;
- Quality of nursery plants;
- Appropriate storage and transportation conditions;
- Care in stock handling and planting.

High rates of plant mortality are usually the result of an oversight or neglect of one or more of these factors. Projects with high plant mortality may indicate poor planning or implementation. However, aiming for 100 percent survival is often unreasonable because of the high associated costs. Most projects should aim for a plant establishment rate of 85 to 90 percent, but plan for 75 percent. It is more economical to plan for some small extra plants and care now to insure adequate survival up front, than to be faced with a new plan for additional plant material growing and planting at a future date.

There are many reasons why plants may not survive on a project site and one of the most important considerations to address is seed source and genetic appropriateness. If genetic considerations are not addressed and a planting fails, the designer cannot identify possible causes because seed source will confound all other aspects.

Target Plant Spacing—The target plant spacing is the desired distance between established plants. The spacing or density of established plants is an estimate that should be based on site productivity and project objectives. The reference sites can be reviewed to determine the densities and species mix a site could support. Note how the different plant species are naturally spaced on each reference site. Some grasses and forbs exhibit uniform spacing, but many woody plants have a more random or clumped pattern.

For example, an undisturbed reference site description shows that an average density for an established stand of trees is 500 trees/ac, with a species mix of 80 percent ponderosa pine and 20 percent quaking aspen (density can be converted to plant spacing by taking the square root of 43,560 divided by plants per acre). The selection of species often determines the planting densities. Shrubs, for example, typically grow at much closer spacing than trees, and this should be considered when species mixes are determined for a revegetation unit.

Revegetation unit objectives often require higher plant densities than typically occur on reference sites. Quick visual screening as the overriding objective will require high-density planting. Selecting a higher plant density than typically occurs in the project area should be done with some projection of how the area will appear many years later. High-density planting can create overstocked stands of trees within 10 or 20 years of planting (Figure 5-76). Overly dense stands often lead to stressed trees and high fire hazard conditions, and could require thinning at a later time. Furthermore, dense stands of vegetation adjacent to roadways can provide cover for wildlife, resulting in conflicts with vehicles. In Oregon a clear zone off the roadway is kept with only low growing vegetation.

Select Stocktypes

Plants are grown, or cultured, in a variety of ways—indoors or outdoors, in native soil or artificial media, and for several months or up to several years. The nursery industry categorizes plants

1,500 trees/acre

250 trees/acre

Figure 5-76 | **Determining plant spacing**

Determining plant spacing should be based on short- and long-term objectives. Where the short-term objective is quick visual screening and site stabilization, high-density plantings of 1,500 trees/ac (A) will produce the short-term desired outcome. These trees may need to be thinned to reduce competition to avoid creating an unhealthy stand of trees with a high fire risk. Reducing tree densities to 250 trees per acre will produce a mature stand of trees (B). Planting at these lower densities will reduce the need for thinning, but tree cover will take longer to dominate the site.

Photo credits: David Steinfeld

into “stocktype” groups based on plant age, size, and morphology. The “American Standard for Nursery Stock” provides a good summary of stock types and is considered the definitive reference for ensuring that plant size and container type conforms to the accepted industry standard. The American Standard for Nursery Stock deals primarily with commercial nursery stock and less with native forbs or shrubs. Individual stocktypes can be defined by the following:

- Plant type (bareroot or container)
- Years in the nursery
- Size or shape of the container for container stock

Plant Type—Nursery plants are grown in containers or bareroot in open fields. Bareroot seedlings are lifted from the nursery with their roots freed from the soil in which they were grown, while container stock is outplanted with its original nursery soil medium. Understanding the benefits and limitations of each system relative to the planting site can help designers choose the best plant types for success.

Root depth and configuration are important factors in successful seedling survival and site colonization. Bareroot seedlings often have a large, hardy shoot and root mass. This typically larger stem caliper and seedling hardiness may better withstand damage from animal browse than container stock. Root systems of bareroot stock are often limited to 12 inches or less due to culturing practices. In contrast, the wide variety of available container shapes and sizes provide the ability to develop target container seedlings with the optimal root mass based on the species and planting site conditions. The large root mass of bareroot seedlings can more readily colonize in native soils, but can be more difficult than container stock to plant in rocky, shallow soils. The fine roots more typical of container stock allow improved water and nutrient uptake, which is particularly important on drier soils.

Bareroot seedlings require more specialized handling and storage procedures than container stock. This can present challenges where timing of outplanting is variable or proper equipment is limited. Typical operations for bareroot seedlings include lifting in the winter (or before the ground freezes) and subsequent storage for several months. This may limit the planting window from early winter through late spring. Once they are lifted, bareroot seedlings must be kept in coolers at the proper temperature and humidity to prevent respiration and mold development prior to planting. Operationally, container seedlings can be extracted, packed, and stored in a similar manner to bareroot. However, they may also be left in containers until planting is imminent allowing more flexibility in meeting operational timelines for planting. This allows for extending the planting season, or postponing until the following season if necessary. This method requires additional space for transport and storage, but eliminates the need for coolers and specialized handling.

Although bareroot seedlings are usually less expensive than container stock, for most roadside revegetation sites, container stock is recommended. Container stock is usually more appropriate for highly disturbed project sites. They are better suited to take advantage of limited soil moisture, which is a common limiting factor on these sites. The size and scale of these projects often require small numbers of multiple species which are more appropriate for container seedling production. The extended planting window, often necessary to meet dynamic project timelines is more easily met using container stock.

Container Size—The size and age of a nursery-grown plant are controlled by the size of the container. Typically, the larger the container, the larger the plant and the longer it takes for roots to fill the container. In Figure 5-77, plants are grouped into broad categories based on how fast they typically fill out various container sizes. Many deciduous tree species, which include willows, cottonwoods, maples, alders, and ash, tend to be very fast growing species and can fill out a range of container sizes in just one growing season. Conifer species (firs, pines, cedars, and hemlocks) will fill smaller containers the first year and can be transplanted into larger containers for another one or two growing seasons. Faster-growing shrub species (ceanothus and bitterbrush,) are often grown in small containers in the spring and transplanted

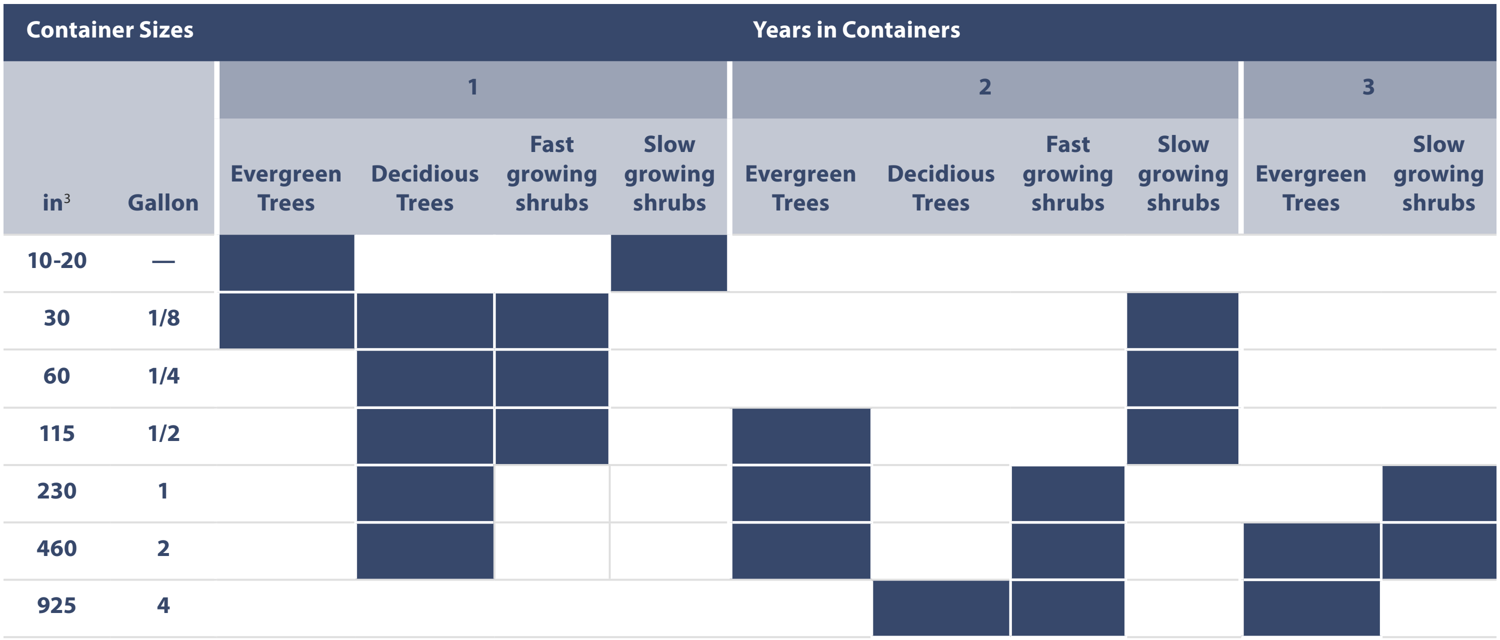


Figure 5-77 | **Carefully consider container size**

Native plants have differing growth habits and rates; therefore, it is important to match container size with species growth characteristics. Shaded blocks represent recommended container sizes for each species type in years 1, 2, and 3.

into larger containers several months later. They will fill a ⅛ to ½ gallon container in one growing season. Slower growing shrub species should remain in the smaller cells for a full growing season before transplanting.

Container Design—Container shape is also an important consideration in stocktype selection because it determines how easily the root plug is extracted from a container, the degree of root spiraling, what planting methods will be used during installation, and ease of handling (i.e., form factor). The depth and taper of the container walls govern how easily a root plug can be extracted from its container. Generally, the greater the taper, the easier a root plug can be extracted. Taper becomes more critical as container walls become longer with respect to the diameter of the opening. Straight-walled "tall pots," made from PVC pipe, are very long in comparison to the diameter of the opening. Root plugs from this container are difficult to extract without the placement of Vexar tubing inside the container. Pulling the Vexar tubing during extraction brings out the entire root plug without undue stress to the stem or root system. Other nurseries offer tall pots with the PVC pipe cut in half lengthwise and held together with electrical ties. Before planting, the ties are cut, which allows easy access to the root system.

Several container design features affect root development and plant quality. When plant roots grow out and hit the sides of the container, they often grow downward in a spiral pattern. When roots reach the bottom holes, they should "air prune." If kept too long in the container, the circling roots will eventually form a tight mesh which, after outplanting, can continue to circle and "strangle" the plant. Most containers have vertical ribs that guide roots down the sides of the container walls to prevent root spiraling. Some smaller containers feature copper coating on their walls to chemically prune the roots as they grow. Other container walls have vertical air slits that air prune the roots. When container roots are so cultured, the root system is more fibrous with more root tips which allows for vigorous growth when planted.

Root condition is a critical factor to discuss at the time that growing contracts are being developed. Roots that have excessive spiral growth should be pruned before they are planted. This is most easily done at the nursery during harvesting. This extra processing step should be stipulated in the growing contract.

Matching Nursery Plants to Outplanting Site—A wide variety of nursery stocktypes are available (Figure 5-78). Site factors should be considered before placing an order. The depth and width of containers are very important for seedling survival and growth. Sites with low precipitation during spring, summer, and fall should be planted with larger container sizes. Where soil moisture-holding capacities are low or vegetative competition for soil moisture

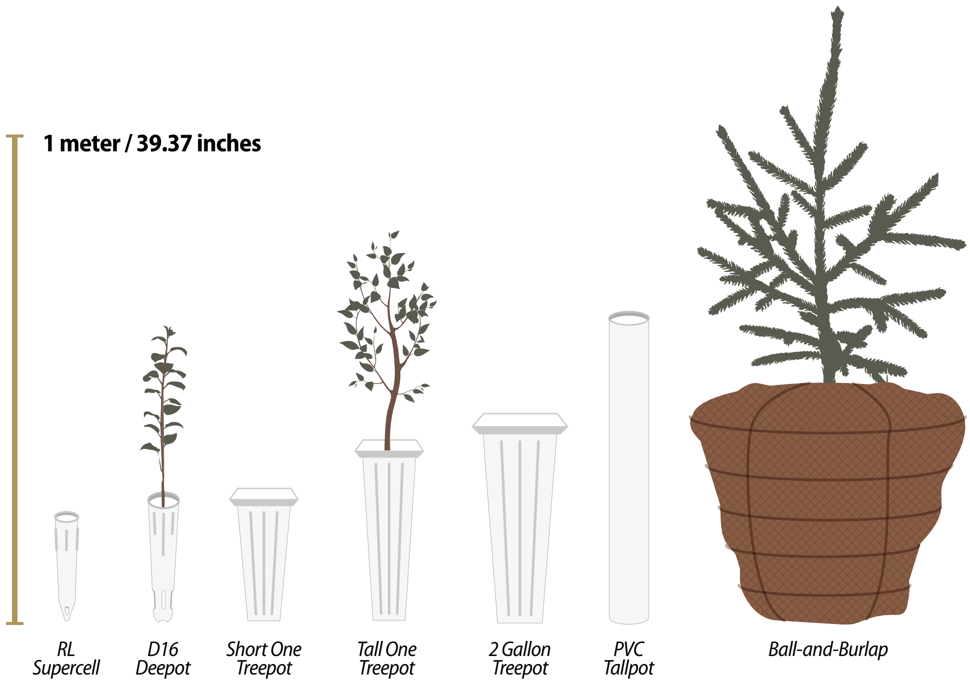


Figure 5-78 | **Match stocktype to site conditions and planting method**

Nurseries can produce plants in all shapes and sizes. The best stocktype for a project will depend on site conditions and time and method of planting.

is high, long containers should be considered. Where rock content is high and it is hard to excavate a planting hole, shorter container stocktypes should be used. Additional post-planting care should be implemented to compensate for shorter roots (Section 5.4.4). The planting method dictates the size of the root plug. For example, the expandable stinger and power augers require plug diameters no greater than 4 inches. Large seedling stems and tops are required where animal damage is expected.

Stocktype selection often determines seedling survival rates and how fast they grow in the first years after planting. Typically the larger the root system, the better the survival and growth. Larger stocktypes cost more, so it is important to target the stocktype to the needs of the site and the revegetation objectives. For example, if quick establishment of vegetation for visual screening is an important objective, then a large stocktype would be ordered. Alternatively, if a revegetation unit is relatively unseen and the site has few limitations to plant survival, a small, less expensive stocktype would be ordered. While larger stocktypes are generally more expensive than smaller stocktypes, the total costs of establishing seedlings should be considered before settling on a smaller plant. Costs for replanting a site where smaller seedlings died in the first year can be far more expensive than planting larger plants in the first place.

Years in the Nursery—Bareroot stocktypes are often defined by the years they are grown at the nursery, whereas container plants are typically described by the size of the container. This is important when ordering plants because many species take longer than one year to grow to the desired plant size. If plants are needed for a project within one year, the designer will need to order smaller size containers to ensure that the roots can fill the plug.

Unbalanced or Holdover Stock—A common mistake is growing container plants with tops larger than the root system can support. This is often the result of poor planning, delay of projects, or poor selection of stocktype. For example, road projects are frequently delayed for a year, leaving the designer with the problem of what to do about the seedlings that are being grown. Typically under these circumstances the nursery manager is asked to hold the seedlings in the same containers an extra year. While most will comply, they will do it reluctantly. The result is plants that are top heavy—the shoots are too large for the root system to support (Figure 5-79A). The results are often deceiving. The plants have not shown stress because they have been pampered under greenhouse conditions and care. Yet, once seedlings are outplanted on a typical harsh site, the plants will struggle to grow enough roots to keep the tops healthy and alive. Plants respond to the lack of moisture in what is referred to as "transplant shock (Figure 5-79B) by shutting down growth and often turning yellow or "chlorotic." Roadsides are stressful sites that require the very best quality plant material. A good example of the difference between well balanced and poorly balanced nursery stock is shown in Figure 5-80.

Delays are common in roadside projects, so two viable options can be considered: transplant the stock into larger containers or reject the plants and place a new order. Option one is appropriate if the plants are being grown in small containers and a larger container is available for transplanting. If growing plants in a large container, it makes little sense to transplant into a still larger one. This option is often more costly than option two, which is to start over with the order, but starting over assumes available seeds and other starter plant materials are available and there is enough time to reorder. For plants that are not used, the designer or nursery manager can contact land managing agencies and landowners in the general geographic area to determine if they are interested in these plants. If not, watershed councils or environmental groups often appreciate the donation of such plants for their projects.

Develop Growing Contract

All nurseries experience weather extremes, insect or disease losses, equipment failures, and other production problems that can severely decrease the quantity and quality of the stock. Therefore, it is a good strategy to reduce these inherent risks by growing plants at more than one nursery. In doing so, the strengths and weaknesses of each nursery can be determined, which is helpful for future orders.

Nursery Selection—Very few nurseries will offer plants from source-identified plant materials specific to a project, even in geographic areas of the country with an abundance of nurseries that grow native plants. Obtaining genetically appropriate plants will require finding nurseries willing to grow seedlings from specified genetic material. A current national list of native plant nurseries can be found online in the National Nursery and Seed Directory (Inset 5-17).

When considering a nursery for plant production, consider the following factors:

- **Proximity**—Is the nursery close enough to visit occasionally?
- **Service**—Is the staff easy to contact? Do they promptly return phone calls or e-mails? Are they friendly and helpful?
- **Expertise**—Are they knowledgeable in restoration and revegetation?
- **Years in business**—Has the nursery been in business for at least three years?
- **Seedling quality**—Is the overall seedling quality high?
- **Seedling quantities**—Are the orders regularly met or do they consistently run short?
- **Price**—Are prices competitive?
- **Willingness**—Will the nursery try new things?

If there are doubts about one or more of these factors, consider using another nursery. Ultimately, the selection comes down to personal experience with nurseries and word-of-mouth from other designers.

Seedling Orders—A plant production contract should detail the information developed in previous sections of this chapter:

- Species
- Genetic source
- Starter plant material
- Stocktype

Figure 5-79 | **Well-balanced nursery stock**

The shoots of these pine seedlings have grown too large for the size of the root system which increases moisture stress after planting. In addition, the buds have broken dormancy, which means the plants will not tolerate rough handling (A). Poorly balanced or conditioned nursery stock will struggle to survive and grow after planting and exhibit signs of "transplant shock" (B).

Photo credits: Thomas D. Landis

- Net amount of plants
- Month and year for plant delivery
- Minimum seedling specifications
- How they will be processed and stored

A few phone calls to nurseries will provide an idea of which nurseries will grow the species, stocktype, and quantities necessary for the project. Nurseries can still be used if they can only meet a portion of the order. Other nurseries can produce the remainder because there is less risk by sending plant orders to several nurseries. Contracts can be developed once it is known what portions of an order a nursery can produce.

Plant Processing and Storage—Once seedlings have reached the target size and age at the nursery, they are harvested, stored, and processed for shipping. If the plants are bareroot seedlings, they are lifted from the soil, graded, and packaged. Container seedlings can be extracted from the containers, graded, and packaged, or sent to the planting site in containers and extracted immediately before planting. Either way, most stocktypes will be held at the nursery for one to six months, depending on when they are needed for planting. "Planting windows" are described in more detail in Section 5.4.4.

Storage times are longest for seedlings planted in the late winter and spring. For these orders, plants are extracted from their containers or lifted from the soil in the winter when they are least susceptible to the stress or damage associated with extraction, handling, and packaging. Plants in this condition are dormant. The onset of plant dormancy for deciduous plants is often around the time when plants have lost their leaves in late fall; the end of dormancy begins just before the buds begin to swell in late winter to spring. The dormancy period for conifer species is not visibly discernible, but typically follows a similar time frame as deciduous species. Seedling dormancy in the western United States typically extends from December through February, but the dates will vary by nursery. If plants are to be extracted and held in cold storage for long periods, it is important to know when the nursery is extracting and handling the seedlings to be sure these operations are done when seedlings are dormant. Seedlings that are extracted or lifted outside the seedling dormancy period and stored for any length of time will survive and perform poorly.

When plants are lifted from bareroot beds or extracted from containers, they are also being graded for size and appearance. Unless otherwise agreed, the size specifications stated in the contract will be the grading criteria (Figure 5-81). It is helpful to be at the nursery during lifting/extraction and grading to see which seedlings are being thrown away and which seedlings are considered shippable. Bareroot and smaller container plants are graded and boxed for refrigerated or freezer storage. Storage containers will have important information about the plants, such as seedlot, date packed, client name, and the number of seedlings in the container. Plants are typically held in cooler storage (32 to 35 degrees F) from a few weeks to two months. If longer storage is required, freezer storage (28 to 31 degrees F) is recommended to maintain seedling quality and reduce the chance for storage molds.

Large container stocktypes (typically those equivalent to a half gallon or larger) are stored and transported in the containers in which they are grown. They are typically stored in shadehouses or other sheltered storage. In cold climates, the roots should be insulated to protect against cold injury. During unseasonably warm periods in late winter or early spring, large container stock should be monitored for drying and irrigated if necessary.

Grading Specifications—Although it is an excellent resource, the American Standards of Nursery Stock deals primarily with plants of horticultural origins they do not adequately provide standards for the growth patterns of native species. Therefore, you must establish some criteria should be established for accepting or rejecting plants. Being present at the time of packing is the most effective way to negotiate grading standards with the nursery and ensure that quality plants are received.

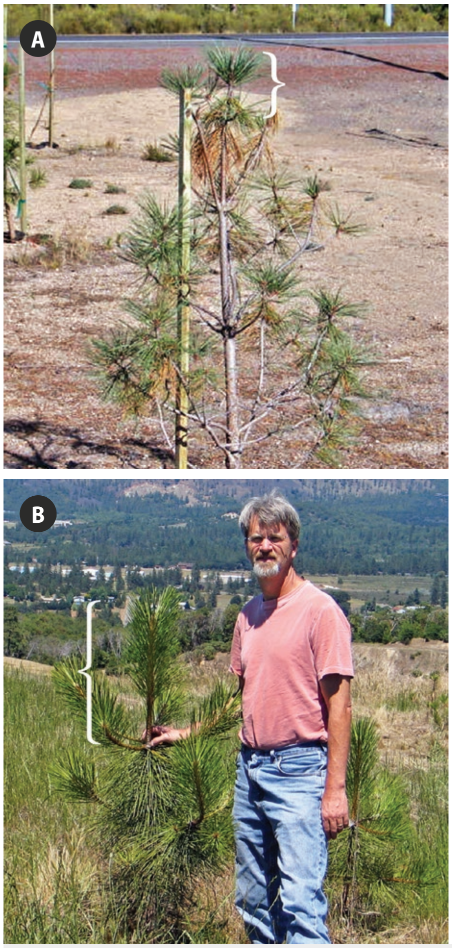


Figure 5-80 | **Effects of transplant shock can last years**

The ponderosa pine seedling (A) was grown for four or five years at a nursery and outplanted on a semi-arid site. The photograph was taken one year after outplanting and shows the seedling has undergone transplant shock due to the imbalance, or high shoot to root ratio, of the seedling when it was planted. The seedling was root-bound when it was planted. The tree responded by dropping most of its nursery needles and grew very little in height in the first year. A different ponderosa pine seedling (B) was grown in a one-gallon container for one year, then outplanted. Because this seedling had good balance and was not root-bound, it did not undergo transplant shock after it was outplanted. After two years, this seedling is well established. The brackets in both photos show the current year leader growth.

Photo credit: David Steinfeld (A) and Greg Carey (B)

Typical grading standards can be divided into the following categories (Figure 5-81):

- **Root system**—The root system of the plant should be examined carefully. A healthy, vigorous root system is one of the most important determinants of plant survival and growth, especially in low rainfall areas and challenging revegetation sites. For bareroot stock, the roots should be well developed and fibrous and approximately the same area as the crown. For container stock, the root "plug" should be firm but not root-bound. Roots should not be spiraled or form a tight mass at the bottom of the seedling container.
- **Stem diameter at root collar (caliper)**—Stem caliper is another important morphological measure of nursery plant quality and has been consistently correlated with outplanting survival and growth. Diameter is not necessarily a good measurement for rooted cuttings because the size of the stem is dependent on the original diameter of the cutting. A typical grading specification for many bareroot and container stocktypes is a minimum diameter of 3.5 to 4.0 mm for one-year-old seedlings, and greater than 4.0 mm for plants grown for two years. Discuss these specifications with the nursery because not all species will grow to these sizes in this time frame.
- **Shoot height**—The height of the plant is measured from the root collar, or original ground line, to the top of the terminal bud. Some species do not form a terminal bud, so the swollen meristem tip or even the average top of the crown is used.
- **Seedling balance**—Nursery stock should have a good ratio between the amount of foliage and the root system. This is traditionally expressed as a shoot-to-root ratio (S:R) and typically ranges from one or two part shoots to one part roots (an S:R from 1:1 to 2:1). This grading standard is a qualitative determination as to whether the root system is large enough to support the above- ground portion of the plant.
- **General plant health**—During grading, nursery stock should be inspected for physical injury or disease. Root disease is a particular hazard of container stock, and soft or moldy roots should be suspect (Inset 5-18). Scraping the roots with the blade of a knife should reveal white healthy tissue.

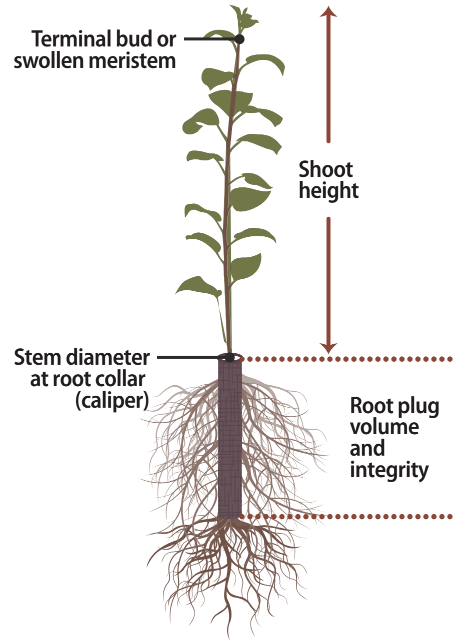


Figure 5-81 | **Seedling grading criteria**

Grading criteria for seedlings are based primarily on stem diameter, height, terminal bud, root volume, and integrity.

Administer Contract

The nursery manager should be required to maintain records on how the plants were cultured. The basic information should include date plants were started; the type, rates, and timing of fertilizer applications; irrigation schedules; greenhouse settings (temperature, lighting, humidity); pesticide applications; and any significant problems that might have occurred with the seedlot. The nursery is also required to provide an accounting, or inventory, of the plant orders by late summer.

It is important to visit nurseries at least yearly, but more often is better. These visits will provide an indication of the quality of the stock that will be received and whether the number of seedlings ordered is being met. It also helps strengthen the relationship between the designer and the nursery manager, which often leads to more attention being given to the orders. One of the best times to visit is during the initial plant establishment phase in late spring or early summer after seeds have germinated or seedlings and cuttings have been planted. Stock problems are most likely to be observed at this time. If there is a fall-down in the inventory or the seedlings look unhealthy, this can be discussed with the nursery manager. If caught early enough, there can be time to start more plants. At a minimum, the early identification of problems will provide time to adjust the planting plans and other contracts that depend on the plant inventory.

Another important time to visit the nursery is during the processing of plants for storage or shipment to answer questions that might arise about grading specifications, packaging materials, pruning, and other operations. It also provides a good idea of what type of stock will be received when it is shipped to the planting areas to avoid any unwelcome surprises.

Inset 5-17 | **Forest Service Nurseries—Dorena Genetic Resources Center**

US Forest Service Nurseries have a long history of growing plants that are genetically appropriate and locally adapted for use in reforestation and restoration of public lands (Dumroese and others, 2005). These nurseries also establish new growing protocols, continue to improve cultural practices, and provide technology transfer in seedling production and quality. While the focus of most nurseries is on plant production, the USFS Dorena Genetic Resource Center (Cottage Grove, OR) nursery has expanded its services to more effectively accomplish restoration to meet the needs of its diverse clientele. Dorena has become the primary plant development center for the USFS Restoration Services Team (RST), created in partnerships with Western Federal Lands and OR and WA State Departments of Transportation. This membership in the RST is the driving force for expanding the nursery capabilities to a full service restoration center.

The restoration species at right are grown at the USFS Dorena Genetic Resource Center nursery and used on RST restoration projects.

Dorena offers complete services beginning with project initiation through successful site restoration. Beginning with project consultation, including recommendations on stocktypes, species mix, plant quantities, and timing, their staff provide knowledgeable input matching plant materials to the client's specific project needs. Following this initial consultation, a range of other services are available to help clients fulfill their project objectives. These include the following:

- Assistance in on-site seed and vegetation collection;
- Container plant production of native conifers, hardwoods, shrubs, forbs, and grasses;
- Development and technology transfer of propagation protocols for species without established growing regimes;
- Specialize in small quantity, multiple species orders, and difficult to grow species;
- Consultation and assistance in outplanting including development of innovative tools and techniques;
- Full range of project monitoring design and implementation;
- Assistance with restoration project management through the RST.

Dorena continues to strengthen and expand its partnership base and its role in providing innovative solutions to current biological challenges. For example, current emphasis on pollinators has resulted in Dorena growing a variety of plant species specific to enhancing pollinator habitat. The nursery continues to adapt to new challenges in meeting the changing needs of restoration.

Mock orange *Philadelphus lewisii*
Photo credit: Lisa Winn

Bunchberry dogwood *Cornus canadensis*
Photo credit: Lisa Winn

Snowberry *Symphoricarpos albus*
Photo credit: Lisa Winn

Coastal black snakeroot *Sanicula laciniata*
Photo credit: Clare Gilmour

Inset 5-18 | **Assessing poor quality nursery stock**

Poor quality planting stock can be caused by biotic (e.g., diseases, insects) or abiotic factors (e.g., imbalance of soil moisture, temperature, nutrients, and pesticides) in the nursery resulting in detrimental, and sometimes devastating, effects on seedling survival and growth when outplanted. Infection with various pathogens, or biotic causes, may not necessarily be manifested in a nursery but may cause stunting or mortality once seedlings are under stress following outplanting. Designers should be aware of the possible nursery diseases in order to either recognize or discuss with nursery personnel during visits to inspect their seedlings.

Diseases caused by fungi, water molds, bacteria, and viruses can often be difficult to distinguish from damage caused by abiotic events or factors. If damage or chlorosis of seedlings is noted, it is recommended to check with the nursery manager to determine the history of the seedlings, what pathogens are traditionally a problem at the nursery, and what, if any, have occurred during the current growing season. Hamm and others (1990) and Landis and others (1990) provide more detailed information on nursery pests.

Shoot and foliage diseases can be caused by a variety of organisms, with various levels of impact on seedlings. Fusarium hypocotyl rot (caused by *Fusarium* oxysporum) can cause large losses in the nursery from July through October. Gray mold (caused by *Botrytis* cinerea) can cause significant damage to densely grown bareroot and container seedlings, as well as nursery stock stored in less than optimal conditions (Hamm and others 1990). The mycelium and gray spore clusters are often easily visible to the naked eye. Botrytis can girdle infected seedlings, increasing mortality rates following outplanting. Minor shoot and foliage diseases, such as shoot blight (caused a number of organisms, including Sirococcus spp., Phomopsis spp., and Phoma spp.) and needle-casts and other foliage diseases tend to deform or stunt seedlings but do not result in significant mortality in the nursery or in an outplanting situation.

Root diseases may be the most insidious of nursery seedling diseases. Because seedlings are cultured under optimum conditions for growth, symptoms are often masked throughout the growing season, manifested only during outplanting stress or drought stress in succeeding years. Most conifers, and many native species, are susceptible to root diseases and root rots caused by Phytophthora spp., Fusarium spp., and Cylindrocarpon spp. These diseases are manifested in the nursery in pockets of symptomatic seedlings or mortality, particularly in areas of poor drainage or previous infestation. Outplanting seedlings infected with these pathogens will result in reduced survival. In addition, transfer of these organisms to outplanting sites may result in infection of the planting area. This specifically is a problem with the root disease Phytophthora lateralis. The spread of this disease from infected seedlings can devastate populations of established Port Orford cedar.

Not all seedling quality problems are caused by biotic factors—many are one-time damaging events that occur during a short span with a regular distribution throughout the field or greenhouse (Mallams 2006). If foliage discoloration, foliage or stem wilting or die-back, seedling stunting, or mortality occur in large patches or over large areas in the nursery, the causes are often abiotic. Outplanting seedlings that have been stunted or damaged in the nursery can reduce seedling growth and survival, as well as increase the time required for site recovery. However, the symptoms of abiotic damage are often more apparent, and the consequences more easily predictable, than damage caused by pathogens.

Although designers have little to do with nursery cultural practices and disease mitigation in the nursery, several options exist to prevent or control disease problems on restoration sites. Disease mitigating measures are similar to insect mitigating measures: (1) only plant healthy stock because weakened or stressed seedlings are more susceptible to diseases both in the nursery and on the outplanting site, (2) plant a variety of species to avoid outplanting failure due to infestation of any single disease, and (3) create a healthy soil environment—seedlings grown on poor sites or on sites outside of the species environmental ranges will be stressed and more susceptible to disease infection.

5.4 INSTALLING PLANT MATERIALS

Once the project site has been prepared (Section 5.2) and the plant materials have been obtained (Section 5.3) the vegetation can be installed on the project site. The following implementation guides cover the methods for installing seeds, cuttings, and plants. Section 5.4.1 discusses the different methods of seeding, how to formulate seed mixes, determining seeding rates, and ensuring quality. A specialized form of seeding, hydroseeding, is discussed in Section 5.4.2. Section 5.4.3 outlines cutting installation techniques most commonly used in biotechnical engineering designs. Section 5.4.4 discusses techniques for planting bareroot and container plants. It also discusses seedlings, plant handling, storage, and quality control measures.

5.4.1 SEEDING

Introduction

Seeding is the distribution of seeds for the purpose of establishing seedlings at a desired density and species composition. In addition to careful site preparations and seed treatment, optimal seeding operations should incorporate how seeds are uniformly distributed over an area; where seeds are placed vertically (that is, in, on, or under the soil surface); species composition in the seed mix; and when seeding takes place. These factors should be adapted to each revegetation unit to account for the unique climate, soils, and species requirements.

Seeding is often coupled with other operations, such as fertilization, soil amendment applications, and soil stabilization treatments. While accomplishing these objectives at the same time as seeding often makes practical sense from an economic and scheduling standpoint, it might not always be best for the short-term establishment of native vegetation. It is important to consider the effects of combining too many operations into the sowing operation. It may be necessary to plan some of these operations at different times. For example, fertilizing, which is often done during the seeding operation, might best meet objectives if applied separately from seeding (Section 5.2.1).This section describes the seven steps in developing a seeding plan: (1) identifying seeding areas, (2) determining seed application methods, (3) developing seed mixes, (4) determining sowing rates, (5) preparing seed mixes, (6) selecting sowing dates, and (7) applying seed and ensuring quality.

Identify Seeding Areas

It is important to visit the project site as soon as possible and specifically identify seeding areas on the ground. If road construction is a multi-year project, finished slopes should be assessed for seeding while the remaining construction continues. This may be the case if water quality permits are required given that they have specific timeframe requirements for slope stabilization (i.e., earthwork must be permanently stabilized with 14 days of completion). While most seeding areas will conform to the revegetation units developed during planning, sites often look different after construction. A field review should note where topsoil has been placed, the presence of surface rock, surface roughness, accessibility by equipment, microclimate, soil compaction, and other site factors. These factors will be used to develop seeding methods, sowing dates, seed mixes, and seeding rates for each of the seeding areas.

Seeding areas are located on a map and by road station. For each seeding area, acreage can be calculated using the methods described in Table 5-1. These calculations should consider the areas where seeding will actually occur. For example, seeds should not be applied in areas where herbicides will be used for maintenance. At the end of the field survey, the total acreage for each seeding area should be summarized and used to develop seed mixes for each seeding area (Section 5.4.1, see Prepare Seed Mixes).

Determine Seeding Methods

A variety of methods for applying seeds are available to the designer. A challenge lies in matching these methods to the sites encountered in mountainous terrain. Typically, the site characteristics of each seeding area will dictate the type of seeding method used. For example, a road project might have three revegetation units: a steep, north-facing slope; an obliterated road; and a rocky south slope. Hydroseeding could be planned for the steep, north-facing slope where other equipment cannot reach. On the obliterated road, several ground-based seeding methods could be used, including mixing seeds into the soil or broadcasting on the surface and covering with a mulch. The south-facing slopes could be hand-seeded, then covered by a mulch to keep the seeds from drying out during germination or hydroseeded

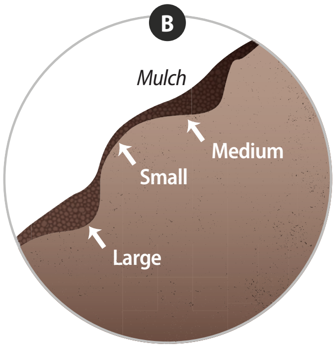


Figure 5-82 | **Seed mix on variable substrate**

When a seed mix, ranging from small to large seeds, is applied to an uneven surface (A) and covered by a long-fibered mulch (B), a range of germination environments are created. Optimum germination environments for large seeds occur in depressions where deeper seed cover occurs; optimum germination environments for small seeds, needing less cover, occur on the ridges where mulch is not as thick.

Photo credit: David Steinfeld

using a bonded fiber matrix mulch. Each project will most likely have site-specific seeding strategies to provide optimal conditions for seed germination.

Moreover, each plant species have unique seed covering requirements. While seeds of most species should be buried in the soil or covered by mulch to germinate, some species require partial exposure to light to germinate and should not be covered very deeply. A general rule for seed covering is to bury seeds at depths from twice (Munshower 1994) to three times (Monsen and Stevens 2004) the seed diameter. The deeper the seeds are covered, the less likely they will dry out during germination. The tradeoff, however, is that seedlings will have to expend more energy to emerge from deeply buried seeds. This can ultimately affect early seedling establishment.

The ideal seedbed, as defined in Monsen and Stevens (2004), is "one in which the seed is firmly enclosed within soil particles to provide hydraulic conductivity of moisture to the seed. Seeds should be placed deep enough to prevent rapid drying but shallow enough to allow natural emergence." Creating an ideal seed environment is an important practice, especially in nurseries, farms, or gardens where the objective is to create a uniform plant crop. All operations in these settings should be standardized and uniform (e.g., correct seed depth, optimum lighting, uniform irrigation, and uniform seed densities). While uniformity and standardization can be applied to wildland revegetation, an alternative strategy could be considered. This strategy starts from the premise that information about the specific germination and early seedling growth requirements of different native species at each seeding site is difficult to obtain. For this reason, a variety of environments, or "regeneration niches" (Grubb 1977), should be created where seeds might find the right conditions for germination (Figure 5-82). Further, a range of native species should be applied to fill these environments. With roadside revegetation, uniformity is not the objective. In fact, some randomness will most likely fit with the surrounding plant communities.

Vertical seed placement, where seeds are vertically distributed in soil or mulch layers, can be grouped into the following categories:

- Broadcast onto the surface
- Pressed into the soil surface
- Mixed under the soil surface
- Drilled under the soil surface
- Covered with long-fiber mulch
- Mixed into long-fiber mulch
- Covered with hydromulch
- Mixed into hydromulch

Vertical seed placement methods are discussed in the following sections in the context of how they affect germination and seedling establishment.

Seeds Sown on the Soil Surface—One of the most common forms of seeding is broadcast seeding, which is casting seeds on the surface of the soil with a rotary spreader or by hand. Broadcast seeding is almost always the least expensive form of seeding. Rotary spreaders can be attached to most types of vehicles, including all-terrain vehicles and pickups, and used where vehicle accessibility is adequate. Where slope gradient or accessibility limits mechanical seeding, the use of a hand-held broadcast seeder is a viable option. Because of this, although manual broadcast seeding might be considered a low-tech method, it still has an important place in revegetation.

Manual broadcast seeding offers the opportunity to spot-seed microsites at different seed rates and seed mixes. For example, two people could hand seed a steep cut slope requiring two different seed mixes—the lower portion of the slope sown with a grass and forb seed mix and the upper portion with a shrub and seed mix. In another instance, a fill slope composed

For the Designer
Because broadcast seeding often results in poor seedling establishment, 50 to 75 percent more seeds should be used in broadcast applications.

of rocky outcrops interspersed among deep soils is composed of two distinct microsites that could be seeded separately with different seed mixes. With knowledge of the road objectives, several hand seeders can apply seeds across a project area that mimics the vegetative patterns of the landscape. Spot-seeding can also be a method of applying valuable seeds or "unique" species to strategic locations. For example, showy forbs that may have benefits to pollinators might be expensive to obtain or require a specific habitat can be spot-seeded in those locations.

The disadvantage of broadcast seeding is that seeds are not covered by soil or mulch (Figure 5-83). Because seeds need intimate contact with soil to germinate, broadcast seeding typically results in low establishment of seedlings. If greater quantities of seeds are sown; however, some seeds will find microsites with high humidity (between surface gravels or rock) or will be covered by soil particles that have been moved through erosion processes. An estimated 50 to 75 percent more seeds should be sown to compensate for the inability of seeds to germinate or the loss of seeds to rodents (Monsen and Stevens 2004). Survival factors should be adjusted downward when calculating sowing rates for seed mixes (Section 5.4.1, see Prepare Seed Mixes). Broadcast seeding on roughened surfaces can potentially increase germination rates, especially if seeds are sown in the fall. The probability that seeds will be covered by sloughing soil over time is increased (Stevens and Monsen 2004), so it is important that the soil surface be left as rough as possible where broadcast seeding will be used.

Seeds Pressed into the Soil Surface—Seed that is sown on the surface and pressed into the soil increases germination rates over broadcast sowing. Seeds are in firm, intimate contact with the soil, that increases available water to the seeds (Stevens and Van Epps 1984, Figure 5-84). Imprinting produces a variety of microsites that may benefit the germination of multiple species (Stevens and Monsen 2004). This type of seeding is accomplished with imprinting equipment (Section 5.2.2, see Roughen Soil Surfaces). In this operation, seeds are dropped from a seeder mounted in front of the imprinter and then pressed into the soil. Imprinting works well for small- to medium-sized seeds; seeds are in firm contact with the soil but not buried too deeply to affect seedling emergence. In some cases, imprinting small- and medium-sized seeds can result in germination as good as, or better than, drilling seed (Haferkamp and others 1985). Larger seeds should be covered by soil or mulch for adequate germination. Imprinting seeds cannot occur on steep slope gradients or slopes with high rock content. Sites that are too steep for tractor access are too steep for current imprinting equipment.

Seeds Mixed under the Soil Surface—Mixing seeds into the surface of the soil is one of the best ways to achieve optimum germination (Figure 5-85). Mixing is done in two stages: seeds are applied on the soil surface by either broadcast seeders or by using a seedbox and drop tubes, and then seeds are incorporated into the soil by dragging anchor chains, disk chains, cables, pipe harrows, or other implements behind a tractor or other all-terrain vehicles. Specialized, equipment has been developed for wildland conditions that will apply and incorporate seed in one operation. The "ripper-seeder-harrow" (Figure 5-86) is a specialized seeder that simultaneously subsoils, broadcasts seeds, and mixes in one operation. Use of this equipment is limited to slope gradients of 1V:3H or less and non-rocky soil surfaces.

On steeper slopes, any method that scarifies the soil surface after seeds have been broadcast will mix the seeds into the surface (Figure 5-87). Using a hand rake to incorporate broadcast seeds into the surface works well and can be used in areas where expensive or valuable seeds have been applied. This type of seed placement requires that the seed depth be monitored to ensure that it is not buried too deeply. Seeds should not be mixed deeper than 1 inch.

These application methods allow seeds to be mixed evenly through the soil and not be concentrated in rows, as they are with drilling (see below). However, soil is left loose around the seeds, which decreases water-holding capacity and seed-soil contact. If seeds are sown in the fall and do not germinate until the following spring, natural packing of soil around the seeds will occur.

Figure 5-83 | **Broadcast seeding**

Broadcast seeding leaves seeds exposed on the soil surface where they have reduced contact with the soil.

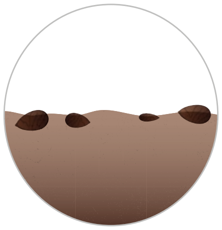


Figure 5-84 | **Seeds pressed into soil surface**

Pressing seeds into the soil surface improves germination by increasing seed-soil contact.

Figure 5-85 | **Seeds mixed under soil surface**

Seeds mixed under the soil surface puts them in direct contact with the soil, greatly improving germination.

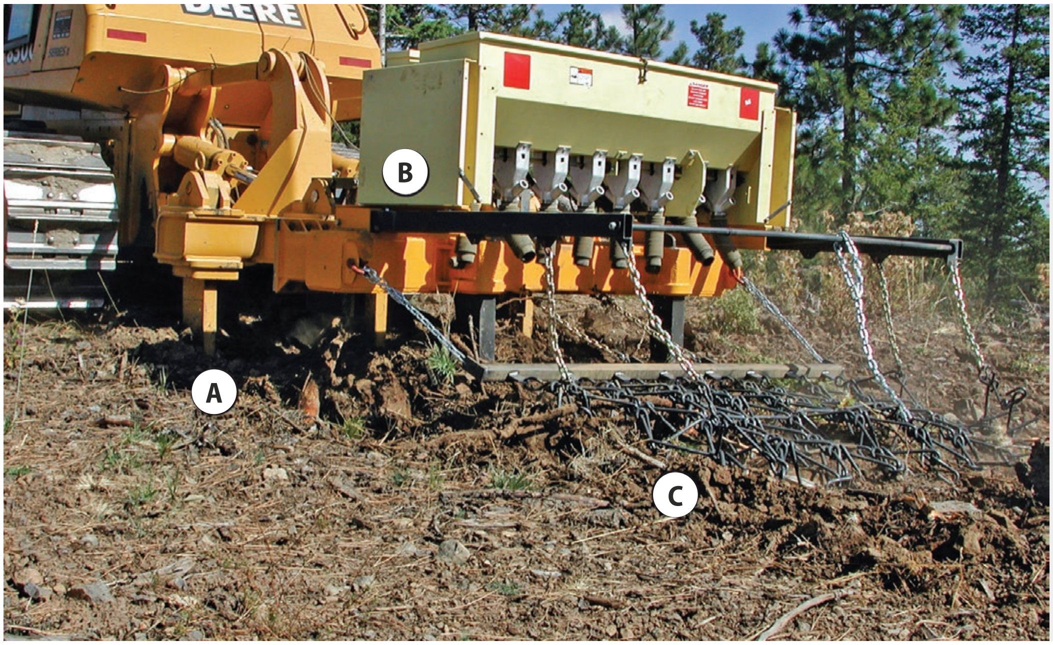


Figure 5-86 | **Ripper-seeder-harrow equipment**

The "ripper-seeder-harrow" equipment was developed by the Umatilla National Forest. This equipment prepares the soil surface and mixes the seeds into the surface in one operation. Soils are loosened using subsoil tines, leaving a roughened soil surface (A). Seeds are metered from a seedbox through drop tubes onto the soil (B) where the seeds are mixed into the soil using a chain harrow (C). Blueprints for this equipment can be obtained from the USDA Forest Service, Missoula Technology Development Center.

Photo credit: Scott Riley

Figure 5-87 | **Seed sowing and mixing equipment**

Seed sowing and mixing equipment can be attached to most types of ground-based equipment, including all-terrain vehicles. A seed spreader attached to the back of an all-terrain vehicle broadcasts seeds on the soil surface and a chain harrow mixes seeds into the soil.

Photo credit: Scott Riley

Seeds Drilled under the Soil Surface—Using a seed drill is another method for covering seeds with soil. Seeds are not actually drilled into the soil, as the name implies, but sown just under the surface in rows. Seed drills first open the surface of the soil with a disk or tine; drop seeds from a seedbox through tubes into open furrows; close the furrows with a disk; and finally pack the soil firmly around seeds with a press wheel. Cropland drills have been developed for the agricultural industry. However, this equipment has limited applicability on highly disturbed sites because rocky soils and uneven soil surfaces create difficulties in placing seeds at proper soil depths. Several drills have been developed for rangeland restoration that compensate for these limitations. The Rangeland and Truax® drills were specifically developed for seeding rocky, uneven surfaces and would work well on roadsides with shallow cross slopes. The Truax® drill was an improvement on the Rangeland drill and includes three seed boxes that can independently distribute seeds at different depths corresponding to the size and shape of the seeds (Stevens and Monsen 2004).

Seed drills concentrate seed into rows (Figure 5-88), creating a greater potential for competition between emerging seeds within rows than if seeds were broadcast. For example, a seed mix with an aggressive species will emerge and dominate the row of seeds at the expensive of less aggressive species. The three seedboxes on the Truax® seed drill can be used to compensate for this potential problem. The less aggressive species are placed in separate seedboxes and sown in separate rows. If more than one seedbox is used, separate sowing rates should be calculated for each box. Moreover, the three seed boxes can each accommodate a different type of seed such as very small or large seeds or fluffy seeds. The various seedboxes allow for these seeds to be sown separately into different rows to account for the required sowing rates. Typically, lower seed rates are used in drilling operations because the seeds are concentrated in rows and closer together. Fewer seeds are also used because of increased seedling establishment due to the improved seed-soil contact that results from using this equipment and technique. Where rodents are present, drilled seeds are more prone to being excavated by rodents that simply follow a row of seeds (Stevens and Monsen 2004).

Seeds Covered with Long-Fibered Mulch—Optimum seed germination is obtained under long-fibered mulch. The mulch provides a moisture barrier that protects seeds and keeps soil from drying (Figure 5-89). Soil moisture is maintained longer around seeds than if they were only covered by soil. This is a two-stage operation in which seeds are broadcast on the soil surface and then covered by mulch. The thickness at which the mulch is applied depends on the seed size and the type of mulch. Small seeds will require less cover than large seeds. The rate at which mulch can be applied varies by the characteristics of each type of mulch. Wood strands and straw, for example, can be applied at higher rates (thicker layers) than composts or chips because more light is able to penetrate these mulches, allowing seed germination and seedling establishment. Refer to Section 5.2.3 for further discussion of mulches.

Sowing seed mixes that contain a variety of seed sizes will require that the mulch not be uniformly applied. One strategy is to begin with a roughened seedbed, as shown in Figure 5-86. Because the surface is not even, mulch will settle in depressions and be thicker than on the ridges. Monitoring the application rates is important to ensure that seeds are covered with the proper mulch thickness. While covering seeds with long-fibered mulch is the most favorable method for optimum seed germination, it is also the most expensive. On slopes tackifier can be used to strengthen the cross linking of fibers and the mulch's bond with the soil.

Seeds Mixed into Long-Fibered Mulch—Seeding and mulching are often combined into one operation (Figure 5-90). Most mulch blowers have seed metering systems that distribute seeds with the mulch as it is being applied to the soil surface. Seeds in this operation are distributed within the mulch, as opposed to being placed between the soil surface and mulch layer. Although combining these applications in one operation is more efficient, seed germination and seedling emergence rates are typically lower than when seeds are broadcast on the surface and covered with mulch. When seed is mixed with the mulch, much of the seed will end up on the surface of the mulch and not in contact with the soil. Unless the mulch has a high water-holding capacity, moisture around the seeds will be limiting during germination and seedling emergence. It is important to know how much moisture a mulch can hold when deciding whether seeds will be mixed with the mulch or broadcast applied first then covered with mulch (Section 3.8.1, see Rainfall Interception) for determining moisture-holding capacities of mulches). Composts, for example, have high water-holding capacities, and seeds will typically germinate well in this material; ground or shredded wood mulch and wood strands have very little water-holding capacity and seed germination will be lower. Seed rates should increase relative to how much moisture the mulch is expected to hold. For low water-holding

Figure 5-88 | **Seeds drilled under soil surface**

Seed drills place seeds in rows under the surface where they are in direct contact with the soil.

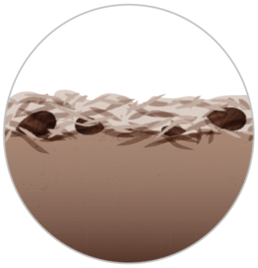


Figure 5-89 | **Seeds covered with long-fibered mulch**

Covering broadcast seeds with long-fibered mulch is effective in conserving moisture around the seeds.

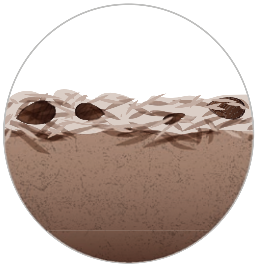


Figure 5-90 | **Seeds mixed into long-fibered mulch**

Seeds mixed into long-fibered mulch have less contact with soil, which can reduce germination.

For the Designer
Seed rates should be increased 20 to 50 percent for application with low water-holding capacity mulches.

capacity mulches, seeds in the upper portions of the mulch will not germinate or will germinate poorly. Seed rates in this type of mulch should be increased by 25 to 50 percent.

Seeds Applied in Hydromulch—When seeds are applied through a hydroseeder (Section 5.4.2), they will lay on the soil surface surrounded by a covering of fine-textured wood fibers (Figure 5-91). Contractors sometimes apply seeds in hydromulch at less than the manufacturer's application rate and when this occurs seeds will be covered with less than 0.25 inch of mulch, with some seeds not covered. As rates approach 3,000 lb/ac, mulch thickness increases to over 0.25 inch, with most seeds being covered. Some products have a recommended application rate of 4,500 lb/ac. Hydromulch has a high water-holding capacity, maintaining thousands of times its dry weight in water. This can be beneficial to seeds during germination. However, unless very high rates of hydromulch are applied, many seeds in the slurry are not covered by the hydromulch. Some hydroseeding operations try to apply a thin mulch slurry with tracer dye and tackifier and with all the seeds first and then covering the seeds with hydromulch in a second pass. Critically, the total mulch thickness will be determined by the second pass. Hydroseeding is a common method of seeding for roadsides because large areas can be covered in a short time and it holds seed in place with the soil to germinate. Some damage to the seeds can occur through the pumps and agitators or by hitting the ground at very high speeds during application.

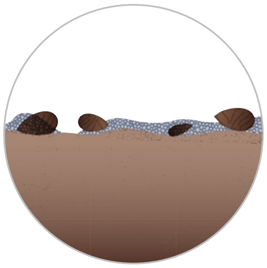


Figure 5-91 | **Seeds applied in hydromulch**

Because of numerous factors such as application rate and site topography, application of seeds in a hydromulch often results in a portion of seeds on the soil surface and some suspended in the hydroseeding matrix above the surface.

Hydroseeding is one of the most common methods of applying seeds to road construction disturbances. It is often the only way to place seeds on steep, rough terrain encountered in mountainous regions. Hydroseeding strategies that maximize good germination include increasing the amount of seeds, applying seeds in the first pass then covering with hydromulch in the second pass, and applying rates of mulch not less than manufacturer's recommendations. Fall hydroseeding also increases establishment rates. Over-wintered seeds are ready to germinate on the first warm days of late winter or early spring when humidity levels are high. In addition, hydraulic mulches are more likely to stay moist for longer periods. Hydroseeding is simpler than dry seeding because there is no seed metering system; seed mixes are simply mixed into the hydroseeder tank and applied. However, even though there is no metering system, applications can be calibrated, therefore having well-trained applicators a key for successful hydroseeding. Refer to Section 5.4.2 for more discussion on hydroseeding.

Seeding with Compost Blanket—A recent addition to seeding methods is the use of the compost blanket. This can be seed, tackifier and medium (or coarse) compost applied in a 2 inch thick layer, but because many seeds are too deep in the compost matrix, a better method is to apply a 1 ½ inch thick layer of medium (or coarse) compost with tackifer to a prepared slope, then apply another ½ inch layer of compost with tackifer and seed. A third method is to install the 2 inch layer of compost, tackifers and hydroseed on top of that. The compost when tacked in place, provides erosion control, retains moisture (but not too much, that is the reason fine compost is the wrong material for compost blankets) and the dark color of the compost captures heat that helps germination. The compost material adds organic material to the site which provides the seeds with nutrients and it jump-starts the development of a soil biotic community. On steep slopes measures may need to be taken to key the compost blanket in place, like installing straw wattles, staked in place, prior to installing the compost.

Formulate Seed Mixes

The seed mix refers to the species composition being applied over a seeding area. It is important to avoid applying a single species to a site. Because highly disturbed sites typically are extremely variable in soil temperatures, fertility, soil moisture, solar radiation, and other site factors, it is important to apply a number of species in a seed mix to ensure that all possible microsites are populated (Monsen and Stevens 2004). Microsites that are unfavorable to one species might be favorable to others. Applying a mix of species also ensures that if there is a problem with the germination of one species, the other species will fill in. The composition of seed mixes and sowing rates should be based on the growth habits of each species and the soils and climate of the site.

It is preferable to avoid mixing slow-growing species with fast growers because the fast growers will out-compete the slow growers for space and resources (Monsen and Stevens 2004). Separating slow growers from fast growers is not always possible. The seed quantities should therefore reflect higher ratios of slow growers to fast growers to achieve some degree of success. Shrubs and trees are typically less aggressive than grasses during the establishment phase and should be applied in a separate mix or planted as seedlings. Grasses tend to be more aggressive than forbs. However, if the Truax® seed drill is used, they could be applied in the same area but in different rows using the separate seed boxes. Although this does not guarantee that the grasses won't out-compete the forbs therefore the preferable approach is to seed the forbs separately if possible (e.g. forb "islands" or patches). Some species take several years to develop. A mixture of fast-growing annuals and slow-growing perennials will ensure that there is cover the first year, yielding to more robust perennials in the succeeding years.

Disturbed reference sites can be good indicators of species that are adapted to the climate and soils of the project area. Vegetative surveys conducted during the planning stages should show the proportions of species that can be expected, and these findings should become the basis for developing species composition and ratios of each species. Prior to determining sowing rates, the proportion of each species within each seed mix should be set. This information will be used to determine seeding rates for each species.

Determine Sowing Rates

The sowing rate is the amount of seeds of each species in a seed mix that are applied in a given area. Sowing rates are calculated for each species that compose a seed mix. These calculations are performed twice—once during the development of seed increase contracts to obtain an approximate quantity of seeds to propagate for the entire project, and several months prior to actual seeding when seed inventories are known and exact seeding areas are located. The calculations made prior to seeding will be used to assemble the seed mixes for each seeding area.

Each species requires a set of data to calculate the total pounds of seeds needed in a seed mix, which includes the following:

- Pure live seeds per pound of bulk seeds
- Estimated first-year survival
- Target first-year seedling density for all seeded species
- Percentage of density composed of each species
- Area that will be seeded with seed mi

Figure 5-92 shows one method for calculating the amount of seeds needed of each species in a seed mix. Because a seed mix is comprised of several species, calculations should be performed on each species. In this example, blue wildrye (*Elymus glaucus*) is one of several species included in a seed mix. The end result of these calculations is the number of pounds of blue wild rye seeds that should be added to each seed mix bag.

Pure Live Seeds per Pound(PLS/lb)—When purity and germination are multiplied together and divided by 100, the resulting value is the percent PLS. This represents the percentage of the gross seed weight that is composed of viable seeds (Figure 5-65). For example, if germination is 89 percent and purity is 92 percent, the PLS would be 82 percent. When PLS is multiplied by the number of seeds per pound, the result is the pure live seeds per pound of gross seeds (PLS/lb). This value is often used in seed and sowing calculations, and it states the approximate number of seeds that will germinate in a pound of bulk seeds under ideal (test) environments. For example, the PLS in Figure 5-92 is 82 percent, and the number of seeds per

A	**Number of seeds per pound**	128,000 seeds/lb	From seed tests
B	**Purity**	92%	From seed tests
C	**Germination**	89%	From seed tests
D	*(A * B / 100) * (C / 100) =*	104,806 PLS/lbs	Number of PLS per pound of bulk seed
E	**First year survival**	20%	The estimate of PLS of ELGL that become seedlings
F	**Target first year seedling density**	20 seedlings/ ft^2	Desired number of seedlings (per ft^2) of all species in seed mix after 1 year
G	**Target composition**	35%	Target percent of total first year plants composed of ELGL
H	*(F / E) * G =*	35 PLS/ft^2	PLS of ELGL to sow per ft^2
I	*43,560 * H / D =*	14.5 pounds/ acre	Pounds of ELGL to sow on a per acre basis
J	**Area to seed**	5.5 acres	Total area for seed mix
K	*I * J =*	80 lbs	Total ELGL needed for seed mix
L	**Quantity of containers**	4 bags/acre	For handling
M	*I / L =*	3.6 pounds/ bag	Total weight ELGL to put into each seed mix bag

Figure 5-92 | **Seed mix sowing calculations**

Assembling a seed mix requires sowing calculations for each species in the mix. This figure shows one way to calculate the quantity of seeds for one species (*Elymus glaucus* [ELGL]) in a mix. These calculations should be made for each of the remaining species in the mix. Seed mix calculating spreadsheets are availabale in the Native Revegetation Resource Library (seed calculator and seed mix calculations).

pound is 128,000. The total PLS/lb is *(82 / 100) * 128,000 = 104,806* (Line D in Figure 5-92). Tests for purity, germination, and seeds per pound are conducted by State Certified Seed Testing Laboratories and obtained from the seed producer or supplier.

First-Year Survival—Not all viable seeds develop into established seedlings after being sown on a disturbed site. The conditions encountered on revegetation sites are generally unfavorable for germination and plant establishment. The first-year survival factor reflects the effect of the harshness of the site on plant establishment (Line E Figure 5-92). It is a prediction of the percentage of PLS that germinate and become established plants after the first growing season. A favorable site, for example, will have a high survival factor because a high percentage of live seeds will germinate and establish into plants; a harsh site will have a low first-year survival factor because seeds will germinate poorly, resulting in plants less likely to survive over the dry summer months. Unfortunately, there are currently no established field survival factors for the western United States. Therefore, the designer will have to make estimates based on experience and an understanding of site factors, seed handling, and sowing methods.

How much fall down actually occurs? Even under very controlled growing environments, such as those found in seedling nurseries, survival factors are much lower than most would think. It is not uncommon for bareroot seedling nurseries to set first-year survival values between 65 and 75 percent (USFS 1991). Compare the highly controlled environment of a nursery to seeding in the wild, where precipitation is intermittent and soils are depauperate. Only 10 to 20 percent of the live seeds sown in the wild actually turn into live plants the first year after seeding (Monsen and Stevens 2004; Steinfeld 2005).

Estimating first-year survival is always a guess. It is interesting that very exact data from seed tests are used for a portion of the sowing calculations, followed by a broad approximation of how well viable seeds will actually germinate and become established in the field. Unfortunately, this information is hard to obtain. Monitoring data collected in the spring and fall, after the completion of each seeding project, can be used to develop a basic understanding of how seeds perform in the field under various soils, climates, and mitigating treatments. First-year monitoring that measures seedling density is useful in this regard. The number of seedlings can be counted in a series of photoplots, and the average number of seedlings per square foot can be calculated. The average seedling density, divided by the average number of PLS sown per square foot (Line H of Figure 5-92), provides the survival factor for that project area. Steinfeld (2005) performed this type of monitoring for several seeding projects six months after sowing on southwest Oregon sites and found the results to be very low (15 percent of viable seeds became established plants). If this type of assessment is conducted over a range of seeding projects, survival factors could be developed for a range of soil and climate conditions. It would be good to understand how survival factors change with different types of seed-covering methods.

Factors to consider when estimating field survival are listed in Table 5-18. Sites with low first-year survival would have a large number of limiting factors. Very poor sites can have survival factors below 5 percent, whereas favorable sites can have factors as high as 20 percent.

Table 5-18 | **Factors to consider when estimating survival rates**

First-year seedling survival is dependent on the quality of the germination environment. This table is a guide to setting first-year survival rates based on factors that influence germination. High first-year survival rates might be closer to 20 percent; low survival is often less than 5 percent.

	Estimated field survival	
	Low	*High*
Seed cover	None	Mulch
Spring rainfall	Low	High
Humidity	Low	High
Water-holding capacity	Low	High
Sowing method	Poor	Good
Season sown	Spring	Fall
Seed treatments	Poor	Good
Freeze thaw	High	Low
Surface erosion	High	Low
Aspect	South	North
Fertility	Low	High

Target First-Year Seedling Density—The target first-year density is the number of plants/ft^2 desired the first year after sowing (Line F of Figure 5-92). Establishing target density factors is often based on the objectives of the project. For example, projects where the objective is fast plant establishment for either erosion control or weed prevention would usually require the target first-year densities to be relatively high. Target densities are also based on the growth habits of the species to be sown. Fast-growing species with large spreading growth habits would have low target densities. Shrubs and trees would have target first-year densities of less than 1 plant/ft^2, whereas grasses might have densities up to 25 seedlings/ft^2. Critically, these target first-year densities help to inform seeding rates. For example, shrubs might have a reduced seeding rate compared to grasses given these different target first-year densities. Moreover, monitoring sites after one year can provide a good indication of what densities can be expected from each species and what densities are most appropriate for meeting project objectives.

Understand that there is a point of diminishing returns, where applying more seeds does not necessarily produce more seedlings. There is a limit to how many seedlings can survive on a site, and no amount of seeds applied will change this fact. While applying excess seed errs on the conservative side, it can be wasteful and costly. It can also favor the aggressive species over the less aggressive species (Monsen and Stevens 2004). When using high seeding rates, it is important to reduce the ratio of aggressive species to non-aggressive species to ensure that non-aggressive species can become established.

Target Composition—The target composition is the proportion of each species that will comprise the seedlings found in a given area (Line G of Figure 5-92). An example of a target seed mix composition is one that would produce a stand of grass and forb seedlings comprised of 35 percent blue wildrye (*Elymus glaucus*), 35 percent California fescue (*Festuca californica*), and 30 percent common yarrow (*Achillea millefolium*). Refer to Section 5.4.1 (see Formulate Seed Mixes) for further discussion.

Area to Seed—The area to seed is the total acreage of a seeding area to which a seed mix will be applied (refer to Section 5.4.1 (see Identify Seeding Areas) for a discussion on how seeding areas are determined).

Prepare Seed Mixes

Once sowing calculations are completed for each species, seed mixing operations can begin. The objective of these operations is to put together seed mixes in packages that are organized, easy to handle, and ready to use. This is an important step because there can be no room for confusion in seeding operations or time for reorganizing seed mixes. The seed mixing operation involves weighing seeds from each species or seedlot, mixing seedlots, placing seeds in bags, and labeling.

The seed bag is the basic handling unit used in seeding. Before mixing begins, determine how much area a bag of seed mix will cover. This will depend on the seeding method. For hydroseeding contracts, seed bags can be no larger than the area a slurry unit will cover (Section 5.4.2). For example, if a 1,000-gallon hydroseeder tank covers a quarter acre, then the bags of seed mix would have enough seeds to cover a quarter acre. In this example, the seed mix is divided into four bags per acre (Line L of Figure 5-92). The most typical seed bag coverage is a quarter of an acre because of the increased flexibility, reduced weight, and ease of handling.

The sowing method is an important factor in assembling the seed mix. If the mix is to be used in a seed metering system (Inset 5-19), each seedlot should be thoroughly mixed together to ensure a uniform distribution of seeds of each species on the site. However, if the seed mix is placed in a hydroseeder, it is not necessary to mix the seeds because all seeds will eventually be mixed in the hydroseeder before application. Other packaging will be required if more than one seedbox is used (e.g., the Truax® seed drill).

Drilling different-sized seeds may also require two or more seed boxes. The Truax® seed drill has three seedboxes that are adjusted to sow various seed sizes and shapes.

Other materials can also be included in the assembly of the seed mix. Mycorrhizal inoculum can be mixed with the seeds, as well as dyes to make seeds easier to see after seeding. Mycorrhizal inoculum and dye will change the rates that seeds will flow. Seed metering systems will have to be calibrated for these materials. Very small-seeded species may need to be sown with carriers, such as rice hulls (Stevens and Munson 2004). For small, fluffy seeds, wheat bran can be added to help prevent them from migrating upward in the seed mix (Dixon and Carr 2001b).

Inset 5-19 | **Seed metering and delivery systems**

The seed metering system is key to uniform application of dry seed mixes. Seed boxes should contain a mechanical seed agitator (as shown in photo) that constantly mixes the seeds to prevent seed bridging. The rate of seed flow should also be easy to adjust to allow for changes in sowing rates. Some systems, such as those found on mulch blowers, have remote controls that allow the applicator to turn the metering system on and off.

Several types of seed delivery systems are available, and the choice of the system will depend on project objectives. Some systems have more than one seed box to keep several species separate. This might be necessary when working with seed mixes that include chaffy or fluffy seeds. Specialized seed boxes that are manufactured with a semi-circular seedbox, auger agitator, and pickerwheel, as developed by the Texas Agricultural Experiment Station (USDA/ USDI 2005), can be used for these types of seeds.

Photo credit: Scott Riley

When calibrating seeds for mulch blowing operations, it will be necessary to create more small seed bags that represent smaller calibration areas (Inset 5-20).

Determine Seeding Date

The best date to sow varies by site and by species. For example, it may be preferable to seed warm season gasses (that grow most vigorously during the spring and summer) in the spring. Whereas it may be preferable to seed cool season grasses (that grow most vigorously during the spring and fall) in the fall. But typically, especially in the western US, fall sowing dates are common. On cool, arid sites, seeding later in the fall is better to prevent premature germination prior to the onset of winter (Monsen and Stevens 2004). On warm, moist sites (e.g., often found in the Midwest US), sowing can take place in the late summer and early fall, anticipating that seeds will germinate with early fall rains and become established prior to winter. If seeds are sown in the spring or early summer, seed mixes should be composed of species that germinate quickly and do not require a long natural stratification period.

Ensure Quality

There are several factors to monitor during seeding to ensure operations are administered correctly. Depth of seed placement, uniformity in application, target seed densities, and seed handling should be monitored throughout the process. It is important to periodically measure seed depths, especially at the beginning of the operation or when any new site is being seeded. Seed dyes are sometimes applied to make seeds more visible. However, these are not useful when seeds are applied through hydraulic seeders or mulch blowers. Uniformity of seed application can be monitored as seeds are being distributed through seed metering or delivery systems. Sometimes seed systems plug or malfunction, resulting in sporadic application of seeds. Poorly applied seeds, where the applicator either misses spots or applies over seeded areas, will also result in an uneven application.

Seed densities can be monitored indirectly by measuring the area where a known weight of seed has been applied and matching it to the estimated acreage it was targeted to cover. For example, on a project where a seed mix is split into quarter-acre bags, the area seeded with one bag of seed mix would be measured. If a quarter-acre bag covered only 0.2 acre, the seed was sown more thickly and the density was increased by 25 percent (*0.5 / 0.2*). If the seed bag had been applied over 0.30 acre, the seeds would have been spread across more area and the seed density would have decreased by 17 percent (*0.5 / 0.3*). These measurements should be done as each seed mix is being applied. If there is a significant change in density, adjustments to the seeding operations can be made.

Measuring a seeding area unit is important not only for determining if seeding rates are being applied correctly, but also for accurately paying the seeding contractors. Contract administrators should be measuring the area that each seed bag or known seed quantity is being sown during, or immediately after, seed application. Table 5-1 describes a method to measure area by measuring the slope length that has been seeded at each road station marker and multiplying it by the distance between markers.

Proper seed handling should also be monitored. Seed bags should be stored in suitable conditions and always handled with care. Seed bags should not be thrown or dropped or left in unsuitable conditions.

***Inset 5-20* | Calibrating seed densities for mulch blowing**

Calibrating seed metering systems on mulch blowers to obtain the target seed density can be accomplished by laying out several plots of identical area (e.g., 1,000 square feet) with flagging. The seed required for each plot is determined and measured:

Seed weight = *Plot area (sq ft) * (Target pounds of seed mix / acre) / 43,560*

For example. if the seed mix application rate is calculated at 30 lb/ac and the plot size is 1,000 ft^2, the weight of seed to apply per plot is *1,000 * 30 / 43,560* , or 0.69 lb. Make at least six seed calibration bags. Prior to applying mulch, place the seeds from the calibration bag into the seed metering bin. Apply the mulch to the plot at the target depth while one person monitors the seeds being metered out. When all seeds are dispensed, stop the application and estimate the area covered by mulch. If the mulched area was approximately half of the 1,000 ft^2 plot (500 ft^2), the seed densities would have been doubled. Adjustments to the seed metering controls would need to be made to deliver 50 percent of the seeds. After these changes are made, mulch would be applied to another plot to determine if seeding rates were closer to the target rates.

5.4.2 HYDROSEEDING

Introduction

Figure 5-93 | **Hydraulic seeder**

The hydraulic seeder is composed of a tank that holds and mixes a slurry, and a pump system that moves the slurry through a nozzle for application to the soil surface.

Photo credit: David Steinfeld

Hydroseeding is a method of hydraulically applying seeds, stabilizers, and soil amendments to the surface of the soil for the primary objective of revegetation. Although the term hydromulching is often used interchangeably with hydroseeding, there is an important distinction: hydromulching is the application of hydraulic mulch and surface stabilizers for the primary purpose of erosion control. Hydromulching is typically conducted on multi-year construction projects when surface soils need to be temporarily stabilized for soil erosion or dust abatement. While hydromulching and hydroseeding operations both should stabilize the soil surface, hydroseeding has the additional and overriding goal of placing viable seeds in a surface environment to germinate and grow into healthy plants. Meeting the dual objectives of erosion control and plant establishment in one operation is often a balancing act. The best methods for soil stabilization are not always optimal for seed germination and plant growth. This section focuses on hydroseeding, not hydromulching, and the discussion includes how to best meet the needs of early plant establishment using hydraulic sowing methods. For information regarding the stabilization of the surface through hydromulching, refer to the many articles on this subject and to the manufacturers of hydromulching products.

Hydroseeding equipment is composed of a tank that holds a slurry of water, seeds, soil amendments, and stabilizing products; paddles or agitation jets in the tank to mix the slurry; a high-pressure pumping system; and a hose and nozzle (Figure 5-93).

Tanks come in a variety of sizes, from a few hundred gallons to more than 3,000 gallons. As the size of the tank increases, the speed and efficiency of the operation improve. Because the travel time is the same for any size hydroseeding unit, the farther the water source is from the project site, the more efficient larger tanks become.

The hydroseeding tank is analogous to a large mixing bowl filled with various ingredients and blended together with water to make a slurry. Typical hydroseeding ingredients fall into these categories:

- Seed
- Hydraulic mulch
- Tackifier
- Fertilizer
- Soil amendments
- Dye (typically in the hydraulic mulch)

The mixture of ingredients is called a slurry. When a slurry is applied to an acre, it is referred to as a slurry unit. The quantity of each material added to a slurry tank is only limited by the ability of the mixture to be pumped through a hose and shot through a small nozzle without clogging. The tank can only hold so much material before the mixture becomes too thick to pump. Finding the right mix and rates of ingredients is important for efficient use of the

For the Designer
There is an art and science to successful hydroseeding and hydromulching operations. There are many facets to carefully consider.

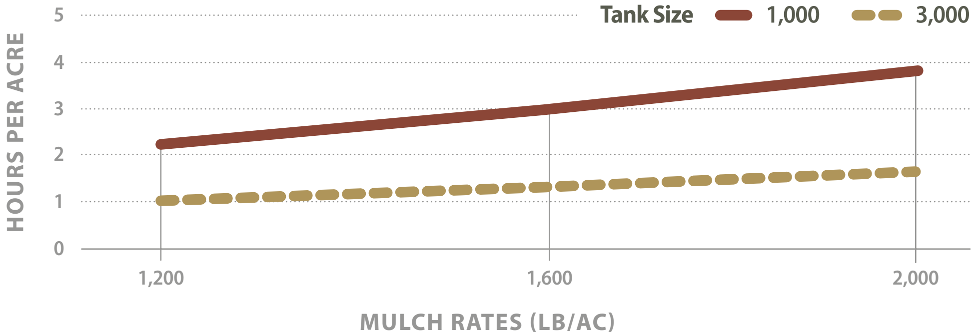


Figure 5-94 | **Hydromulch application time estimate**

Hydromulch application time can be roughly calculated from the size of the mixing tank and the application rate. The cycle time (the time it takes to drive from the water source to the spray area, discharge the slurry, and return) used in this analysis was 60 minutes for a 3,000-gallon tank and 45 minutes for a 1,000-gallon tank.

Modified after Trotti 2000

equipment. The applicators and manufacturers of these products can recommend optimum product rates.

Hydroseeding ingredients should be thoroughly blended prior to application to achieve uniform seed coverage. The two types of hydroseeding mixing systems are those that mechanically stir and those that mix using a hydraulic jet. The first system employs rotating paddles to blend the slurry in the tank and a centrifugal pump or positive displacement gear pump for slurry delivery. The second system uses a centrifugal pump to both agitate the slurry and deliver the slurry to the site. However, there is anecdotal evidence that these centrifugal pumps might be more likely to damage seed. It is suggested that designers discuss the type of hydroseeder mixing system that a contractor might use and perhaps adjust seed mixes to account for the potential increased seed damage in a centrifugal pump.

During application, the slurry is pumped to the nozzle for application. The applicator has a choice of nozzles, use of which depends on the site and slurry conditions. Slurry application can be from a "gun" mounted on the top of the hydroseeding unit or from a hose pulled manually to the application site. Stationary application (using a hydroseeding gun) is accomplished where the hydroseeding equipment can easily access the site. These areas are typically cut and fill slopes. Depending on the consistency of the slurry, the pumping system, and wind conditions, slurry can be shot 200 feet or more. Hoses are laid out for sites that cannot be reached this way. Depending on the diameter of the hose and the pumping system, hoses can reach sites more than 300 feet from the hydroseeding unit.

Hydroseeding is used when other seeding methods are impractical (Section 5.4.1). Typically, these are steeper sites where ground--based seeders are limited. Hydroseeding has the advantage over other seeding methods of applying soil amendments, fertilizers (with non-native species), soil stabilizers, and seeds together in a multi-step application.. In addition, seeds that are used in hydroseeding operations do not have to be as clean (that is, free of straw, awns, chaff) as for other seeding methods. This can reduce the cost and time associated with seed-cleaning operations.

The time it takes to hydroseed is a function of the size of the mixing tank, the proximity of a suitable water source and the amount of hydraulic mulch that is applied on a per acre basis (Figure 5-94). The amount of hydromulch applied varies with aridity, slope, and soil characteristics of a given site. The greater the amount of hydraulic mulch applied per acre, the longer it will take. For example, it takes almost twice as long to apply 2,000 lb/ac of hydraulic mulch through hydroseeding equipment as it does to apply 1,200 lb/ac. For this reason, determining the appropriate amount of hydraulic mulch is important from a cost standpoint. Cost includes not only the cost of purchasing the product, but also the time to apply it. Tank size is also an important factor in application rates; the larger the tank, the less application time it takes. A 3,000-gallon mixing tank, for example, takes less than half the time to cover an acre than a 1,000-gallon tank.

Hydroseeding in wildland revegetation has a number of limitations (Stevens and Monsen 2004) that may have relevance in roadside revegetation for pollinators:

- Some seeds may not be placed in the soil depending on application method

For the Designer

Typically a 2 step method is used to hydroseed with native species. A first pass is conducted with seed and water and a second pass with hydromulch.

For the Designer

Many factors such as slope, soil characterisitcs and solar exposure help to inform the hydroseeding and hydromulching approach.

- Seeds and seedlings can dry out
- Some seedlings cannot grow through paper fiber type of hydraulic mulch
- Seeds can be damaged by agitators and pumps
- Precocious germination can occur as a result of moisture in the hydraulic mulch
- Hydroseeding requires large quantities of water

With good planning, implementation, and monitoring, many of these limitations can be managed, resulting in successful revegetation. Ultimately, the success of any hydroseeding project comes down to the availability of water during germination and seedling establishment. As with other seeding methods the timing of hydroseeding applications should be determined in part by the climate at a project site. Hydroseeding is successful in the landscaping business because seeds are irrigated after hydroseeding until a stand of grass has become established. As one applicator stated, "what people don't understand is you can do the best hydroseeding job in the world but if they don't water it, it's not going to grow" (Brzozowski 2004). The challenge in roadside revegetation is that, for most projects, irrigation is not available. To make hydroseeding successful, strategies should be developed that maintain moisture around the seeds and in the soil during early plant establishment.

Integrate Hydroseeding into Revegetation Strategy

From a revegetation standpoint, hydroseeding serves as a method of seed placement, a means of stabilizing the soil surface for controlling erosion and to allow seedlings to become established, and a way to apply fertilizers and other soil amendments. These objectives cannot always be met in one hydroseeding operation. It often requires that each objective be considered independently and then integrated into an overall strategy. Clarifying objectives, based on the site-specific conditions of the project, and determining the best way to achieve them using hydroseeding equipment as part of the approach will lead to the best revegetation results. For example, seed placement and fertilizing are different objectives, yet meeting both objectives is often accomplished in one hydroseeding operation out of convenience. However, the best time to apply fertilizers on many projects is after the seeds have germinated (Section 5.2.1). Instead of meeting fertilizer and seeding objectives in one hydroseeding operation, separating them into two different applications would be a better strategy for meeting overall project objectives.

On a site with high surface rock, for example, the main objective would be seed placement. Little importance would be placed on surface stabilization because the rock has already created a stable surface. The best potential sites for seedling germination on this harsh surface would be between the surface coarse fragments where seeds are protected and moisture collects. Yet a common mistake that occurs in many hydroseeding projects is to include the same rates of tackifiers as would be used on a soil surface. Under these circumstances, tackifiers adhere seeds to the rock surface, preventing the seeds from washing between the gravel and cobbles that cover the surface. The objective of stabilizing the surface is not only unnecessary in this example, it would negatively affect placement of seeds.

Hydroseeding should always be accomplished within a strategy of creating an optimum seed environment. The hydroseeding operation places seeds on the surface of the soil, which is often a poor environment for germination. Hydraulic mulch is inferior to long-fiber mulches in reducing surface temperatures, maintaining soil moisture, and moderating surface temperatures, especially in more arid climates (Section 5.2.3). The term "hydraulic mulch" is misleading because some materials that fall into this category like paper fiber mulch, lack many of the important properties associated with mulches (Section 5.4.2, see Select Hydraulic Mulch and Determine Rates). By their nature, hydraulic mulches are more like a growing medium than mulches because of their capacity to absorb water (most hydraulic mulches hold greater than 1,000 times their weight in water). As a growing medium, hydraulic mulch maintains high moisture around the germinating seeds, but once the hydraulic mulch dries out, which is often very quickly on dry sites, it no longer protects the seeds from drying as a mulch would and germination rates are compromised.

The literature is scant and inconclusive on the benefits of hydraulic mulch to seed germination and seedling establishment in wildland conditions. Carr and Ballard (1980) found no difference in plant establishment when seeds were applied with and without hydraulic mulches, but only low rates of hydromulches were compared. One approach to increasing seed germination that is often used in drying climates is a two-pass application system where seeds and a minimum amount of hydraulic mulch are applied in the first pass, and then covered by a thick application of hydraulic mulch in a second pass. While this application method appears to have some advantage over a one-pass operation because the seeds are covered with a greater thickness of hydraulic mulch, it is not known what the difference in germination and seedling establishment rates might be. The benefits from a germination standpoint are probably not seen until the hydromulch rates are high (3,000 lb/ac or greater). Even then, on arid sites receiving less than 6 inches precipitation, higher hydraulic mulch rates can intercept the low amount of precipitation that is received, preventing moisture from reaching the seeds (Section 3.8.1, see Rainfall Interception). Because it is uncertain whether hydraulic mulches improve germination, it is better to base mulch rates on surface stability objectives than on seeding objectives and use other methods to improve seed germination. For example, it might be more effective to reduce the amount of hydraulic mulch to the minimum amount necessary to apply seeds and, with the costs savings, apply a long- fibered mulch in a second operation.

Identify Hydroseeding Areas

Hydroseeding should take place after the final slope shaping and topsoil placement have been completed. Several months before hydroseeding is to occur, the site should be visited to finalize an implementation plan that includes the locations of where the plants or cuttings are to be installed and where seeding will take place. While most of the hydroseeding areas will conform to the revegetation units developed during planning, the site always looks different after construction. In this field review, the exact locations of the areas that will be hydroseeded are drawn on a road map and areas are identified where different seed mixes, fertilizer types/rates, or hydraulic mulch rates will be applied.

The acreage for each hydroseeding area is calculated using methods described in Table 5-1. This method partitions the cut and fill slopes into rectilinear units by road stations and calculates acreage between each unit. This information is then summarized in a hydroseeding table (shown in Inset 5-21) that is used to develop task orders. It can also be used in the field for keeping a record of acreages and the location of hydroseeding operations.

The proximity to streams should be considered when locating hydroseeding areas. If hydroseeding areas are adjacent to ditches or waterways that drain into live streams, a buffer should be included around these features to avoid fertilizers entering the stream system. Fertilizers applied to these sites have the potential of entering ditches during rainstorms and eventually reaching a stream course as nutrient pollution. Road runoff can be a significant contributor of nutrients to water systems (Reuter and others 1998).

Determine Seeding Rates

Sowing rates for hydroseeding are calculated using the same method outlined in Figure 5-92. The designer is referred to this section for determining seeding rates for any type of sowing method. These sowing calculations assume that the method of sowing does not damage the seeds. This might not be a good assumption with hydroseeding, which has been shown to increase the risk of seed breakage in the hydraulic seeder tank during mixing (Kay and others 1977; Wolf and others 1984; Pill and Nesnow 1999). Additions of fertilizers further increase the risk by exposing seeds to high salt levels when seeds are in the slurry tank and also after they are applied to the soil surface (Brooks and Blaser 1964; Carr and Ballard 1979; Brown and others 1983). Taking precautions to reduce the risk of seed damage during hydroseeding will increase the seed germination rates and reduce the amount of seed needed for the project.

Considerations that can reduce the risk of damaging seeds include the following:

- Type of hydraulic seeder
- Seed condition
- Duration in slurry
- Seed moisture
- Hydraulic mulch
- Nozzle and nozzle position
- Fertilizers

Hydraulic Seeders—Hydraulic seeders that use centrifugal pumps for agitation and delivery can have a higher potential to damage seeds than systems with paddles and rubber-coated gear pumps (Kay 1972a; Kay and others 1977). Kay (1972a) found that germination of intermediate wheatgrass (*Agropyron trichophorum*) seeds was reduced from 80 percent (control) to 10 percent germination after one hour in a centrifugal agitation system; after two hours, germination was reduced to 1 percent. There was no reduction in germination after one hour using paddle agitation, but germination declined to 59 percent after two hours. Pill and Nesnow (1999), however, found that centrifugal pumps did not reduce germination rates of Kentucky bluegrass (*Poa pratensis*) and perennial ryegrass (*Lolium perenne*) after mixing for an hour in a slurry tank.

Seed Condition—Grass seeds are enclosed by sets of bracts, called the lemma and palea. These structures provide a protective covering (Figure 5-95) and are believed to reduce seed breakage during hydroseeding agitation and application. In the aforementioned study, Pill and Nesnow (1999) believed that one of the primary reasons there was no decline in germination after an hour of mixing in a slurry tank was because the lemmas and paleas were still intact around the seeds. The association between presence of these seed structures and protection from seed breakage during hydroseeding should be considered when cleaning seeds for hydroseeding. Seed cleaning is necessary for storage and seeding (Section 5.3.1 and Section 5.3.4). However, seeds for use in hydroseeding operations do not have to be as clean as seeds used in other seeding methods. Each species has different cleaning requirements for hydroseeding. Some require thorough cleaning, while others might require very little cleaning. It would be beneficial to discuss the level of seed cleaning for hydroseeding with seed extractory personnel and seed increase contractors.

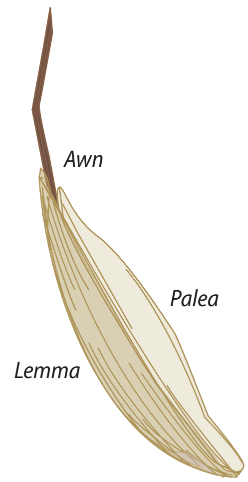


Figure 5-95 | **Grass seed morphology**

Grass seeds are protected by sets of bracts called the lemma and the palea (the lemma is the larger, outer covering, and the palea is the shorter, interior sheath). The awn is a fibrous bristle that extends from the midrib of the lemma. The awns for most grass species are removed during cleaning for easy sowing. The lemma and palea should be kept on the seeds to protect them from seed damage during sowing, especially in hydroseeding operations.

Duration in Slurry—The longer seeds are mixed in the slurry tank, the greater the potential for breakage. Kay and others (1977) found that after 20 minutes of agitation, seed germination decreased significantly for Bermudagrass (*Cynodon dactylon*) (Figure 5-96). For this reason, it is important to add seeds immediately before application.

Seed Moisture—As a general rule, moistened seeds have less potential for breakage than dry seeds because they are more flexible when impacted. Kay and others (1977) found that soaking Bermudagrass seeds for 1.5 days prior to application significantly increased germination over dry seeds (Figure 5-96). Longer soaking periods (4 days) had negative effects on germination because radicles were emerging and were damaged with mixing.

Soaking seeds prior to hydroseeding will unfortunately initiate seed germination, which is not usually desirable for hydroseeding projects. Pill and Nesnow (1999) suggest seed priming as an alternative to soaking. Priming is a seed treatment that partially moistens seeds without initiating seed germination (Pill and others 1997). Seed is mixed at 1 part seed to 10 parts moist

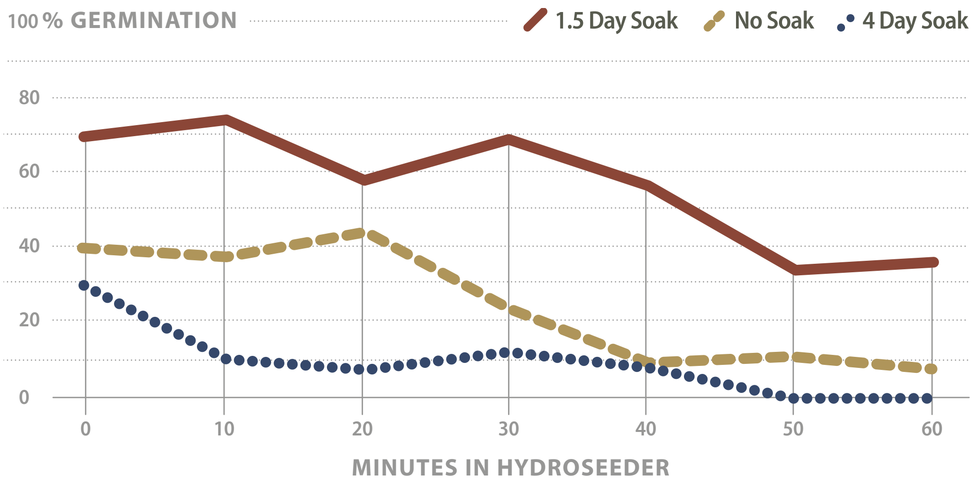


Figure 5-96 | **Duration inside hydroseeder can reduce germination of seed**

Using a centrifugal hydroseeding pump system, Kay and others (1977) found a reduction in germination of Bermudagrass (*Cynodon dactylon*) seeds after 20 minutes in the slurry tank. Seed germination improved when the seeds were soaked in water for 1.5 days prior to placing in a hydraulic seeder tank. However, soaking for longer than 1.5 days reduced germination more than if the seeds were not soaked (modified from Kay and others 1977).

vermiculite (although peat could be used as a substitute) and stored at cool temperatures for up to 10 days prior to hydroseeding.

Hydraulic Mulch—Hydroseeding without hydraulic mulch can increase seed damage (Kay 1972a, 1978). Using a minimum rate of 500 lb/ac hydraulic mulch is suggested for protecting seeds (Kay 1978).

Nozzle Type and Nozzle Position—Shooting slurry straight at the soil in close range can damage seeds. The impact at high speeds can cause seed coats to break. As one hydroseeding operator describes the action, "we just shove that seed right smack in the ground with a lot of force…the gun was slamming straight to it" (Brzozowski 2003). Describing this action to a Forest Service seed extractory specialist, his reaction was, "that can't be good for the seed" (Barnar 2007). In the seed production and seed extraction businesses, handling seeds carefully is a high priority. This attitude and practice should not stop with the seed producers, but follow through to the application of seeds. One application practice that could reduce seed damage is to aim nozzles so the slurry is not hitting the soil surface with full force at close range. Arching the slurry stream so the spray hits with lower force is more desirable. Using less pressure or lower pressure nozzles, such as fan nozzles, can also reduce seed damage (Figure 5-97). Some soils are very loose or powdery after construction, which can cushion the seeds, as opposed to very compacted surfaces. Seeds applied to these surfaces can be buried under the loose soil when the slurry is shot straight at the surface, offsetting the effects of seed breakage and increasing germination potential (Mast 2007).

Fertilizers—Adding fertilizer to the slurry can reduce germination of certain species due to the effects of fertilizer salts on seed imbibition, or uptake of water (Figure 5-98) (Brooks and Blaser 1964; Carr and Ballard 1979; Brown and others 1983). This is not just a problem when seeds and fertilizers are mixed together in the slurry tank; it can also negatively impact the seeds after they are applied to the soil surface and before the first rains dilute the surrounding salts. Effects of fertilizer salts are more detrimental on sites with low rainfall. Carr and Ballard (1979) found white clover (*Trifolium repens*) and, to a lesser degree, *Festuca* spp. had the greatest reduction in germination (Figure 5-6). They suggest white clover should be applied by hand, separate from the hydroseeding operation.

Assuming that most native seeds, especially legume species, are affected by fertilizer salts, it is important to understand what the effects of different types and rates of fertilizers will have on the salt concentrations in the slurry. Brooks and Blaser (1964), Carr and Ballard (1979). And Brown and others (1983) used inorganic, fast release fertilizers, which dissolve quickly in solution (Section 5.2.1). Organic and control release fertilizers, however, dissolve slowly and therefore should have lower salt levels in solution. Whichever fertilizers or rates are used, testing the slurry for soluble salts should be conducted to ensure that concentrations are not lethal (Section 3.8.4, see Salts).

Figure 5-97 | **Hydraulic seeder nozzles**

Hydraulic seeders are equipped with several types of nozzles. The nozzle shown in Photograph A shoots long, high pressure, streams, while the fan nozzle shown in Photograph B spreads the slurry out for closer applications.

Photo credit: David Steinfeld

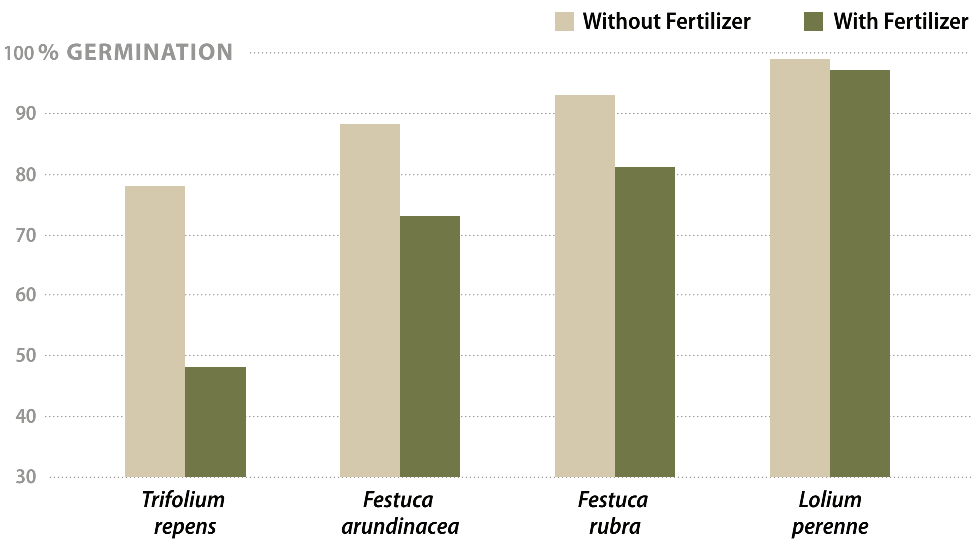


Figure 5-98 | **Fertilizer in hydroseeder mix**

Incorporating 10-30-10 fertilizer into hydroseed slurries can reduce the germination of some species (Carr and Ballard 1979).

The effect of hydroseeding operations on seed viability is an important issue and deserves more research attention. Monitoring information can be used to broaden understanding on how to properly use this important tool.

Select Hydraulic Mulch and Determine Rates

Hydraulic mulch is a low bulk density material applied through a hydraulic seeder to increase surface soil strength and reduce erosion. At high application rates, seeds are covered, thereby increasing the potential for increased seed germination. Commercial hydraulic mulches are derived from wood fiber, recycled paper (wood cellulose), sterilized grass straw synthetic fibers, mechanically treated wood fibers, or combinations of these. Wood fiber mulches are manufactured from wood chips thermally treated by a steam and high pressure shredding process; wood cellulose mulches are made from waste paper materials such as recycled newspaper and cardboard (Trotti 2000). Hydraulic mulches typically have very high water-holding capacities (over a 1,000 times their weight in water). A pound of wood fiber mulch, for example, absorbs between 1.5 to 2.5 gallons of water and, inversely, a gallon of water holds between 0.40 and 0.66 pound hydraulic mulch. This is important information to know when determining how much hydraulic mulch to add to a slurry tank. Most operators will not exceed a ratio of 0.4 to ensure they do not clog their system with a slurry that is too thick. At this proportion, a 1,000-gallon tank would hold 400 pounds of wood fiber mulch. Product specification sheets should indicate the ratio of hydraulic mulch to water for hydroseeding equipment.

The depth and cover of hydraulic mulch depends primarily on the quantity and properties of the mulch placed in the tank. Typical hydroseeding mulch manufacturer's application rates range in application rates from 1,000 to 3,000 lb/ac. At lower application rates (<1,000 lb/ac), wood cellulose (paper) fiber mulch will not cover the entire soil surface, leaving most seeds and much of the soil surface exposed. At the manufacturer's recommended application rates or higher (>3,000 lb/ac) the soil surface and seeds are usually completely covered (Figure 5-99). A class of higher strength mulches, purposefully manufactured with the tackifiers and tracer dye, called bonded fiber matrixes (BFM) are applied at rates above 3,000 lb/ac. Correctly applied this BFM can bond together to form a continuous mat given that fiber length is typically longer in these products. A BFM will stabilize seeds and control surface erosion up to a year after application depending on site conditions. Even more robust than BFM, High Performance Growth Media (HPGM) consists of engineered and mechanically kinked fibers that interlink when applied to soil. When applied correctly, sprayed from two different directions at the specified application rate, and achieving complete coverage, the HPGM becomes, in effect, a hydraulically applied erosion control matting as well as a growth media for seeds. Correctly applied wood fiber HPGM has a functional life of about a year and a coconut fiber HPGM has

Figure 5-99 | **Hydromulch as a bonded fiber matrix**

Hydraulic mulch applied at high rates and with specialized tackifiers will hold together as a sheet and is referred to as a "bonded fiber matrix," or BFM. The application rate of wood fiber mulch in this picture was 3,000 lb/ac.

Photo credit: David Steinfeld

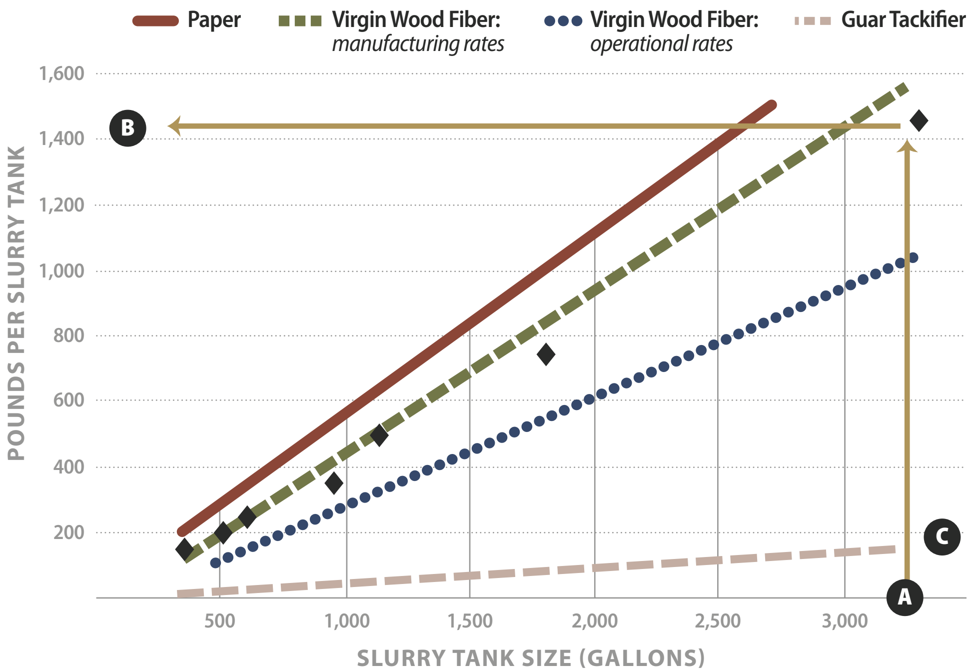


Figure 5-100 | **Slurry tank size and slurry composition**

The slurry tank can hold only so much material before the slurry becomes too thick to pump through the system. This graph provides a general relationship between the size of the slurry tank and the maximum amount of hydraulic mulch it can hold (modified from Bowie Industries). Because virgin wood fiber mulch holds more moisture than paper mulch, less virgin wood fiber mulch can be added to a slurry tank. For a project using a 3,200-gallon slurry tank (A), a maximum of 1,500 lb virgin wood fiber mulch (B) can be placed in the tank with 150 lb guar tackifier (C). Guar tackifier rates are based on a ratio of 1:10 guar to wood fiber mulch. At a prescribed rate of 1,000 lb/ac of wood fiber mulch, this slurry tank will cover approximately 1.5 ac. If the application rate is 3,000 lb/ac virgin wood fiber mulch, it will take two tanks.

a functional life of two years although fiber longevity will vary by site specific characteristics such as soil type or canopy cover.

The length of the wood or cellulose fibers is an important characteristic in creating a soil cover mulch that does not restrict seed germination or plant growth. Cellulose mulches have shorter fibers than wood fiber mulches and, therefore, these materials compact much easier when they are applied. Applying too much cellulose mulch can result in a soil surface that has the consistency of "paper mache." At application rates greater than 1,500 lb/ac cellulose mulch, there is a reduction in infiltration and air exchange, and seed germination and seedling establishment are decreased (Gassman 2001). Some manufacturers have overcome this problem by mixing straw, a long-fibered material, with paper mulch. Typically, cellulose mulch requires 20 to 40 percent more material to achieve the same uniformity of coverage as wood fiber mulch (Trotti 2000) (Figure 5-100). While recycled paper mulches are typically less expensive than wood fiber, the cost savings are partially offset by the increased amount of paper mulch used. Blended mulches (those with equal portions of wood fiber with recycled paper) are an effort to improve the characteristics of recycled paper by adding wood fiber.

Typically, paper a fiber or cellulose fiber mulches are the lightest duty mulches which are best used on flat or gently sloping surfaces. This mulch should be applied at the manufacturer's recommended application rate (1,000-2,000 lb/ac). This mulch has issues in that it provides little in the way of erosion control, it can form a paper mache like crust that some seeds cannot penetrate and it lays down in a dense layer with little pore space which when dry can wick moisture from the soil. Wood fiber and straw derived hydromulches provide little in the way of erosion control and should also be used on gently sloping surfaces. These mulches are installed at a manufacturer's recommended application rate of about 2,000 lb/ac. When correctly installed they have enough loft to allow seedlings to penetrate through the mulch. They hold some moisture which aids germination but provide little in the way of thermal regulation of the soil. The BFM and high performance growth media (HPGM) are manufactured to have long and short fibers that are mechanically treated so that they interlink with open pore space, when applied at the recommended application rate, which can be as high as 4,500 lb/ac. These products are generally packaged with tackifier and tracer dye for accurate use. They can provide excellent erosion control and can be used on slopes of 1:1 or steeper. It is recommended that these materials be used in a multi-step process with the seed and minimal mulch be sprayed on in the first pass, then the rest of the mulch cover the seed in two following passes from different directions so that the seed is in good contact with the soil and the mulch forms a contiguous layer covering the seed. These materials have good loft allowing seedling penetration, they have enough thickness to hold moisture help retain soil moisture and they provide a small measure of thermal regulation to the soil. BFMs and high performance growth media are the most expensive of the hydraulically applied mulches.

The use of hydraulic mulch for seed germination becomes less important on wetter sites, especially in climates where there is little soil drying during germination (Carr and Ballard 1980). These conditions are found from fall through early spring on many sites in the Coast Range and Cascade Mountains, as well as microsites that include north aspects and sites shaded by vegetation. On these sites, 1,000 lb/ac or less might be sufficient for seed germination but manufacturer's recommended application rates should be followed. In areas with high rainfall and erosive soils, a higher strength hydraulic mulch at higher application rates or even a bonded fiber matrix might be needed to keep seeds and soil in place until seeds have germinated and grown into established seedlings.

Select Tackifier

Tackifiers are sticking agents that bind soil particles together and protect the surface from wind and water erosion. When applied with hydraulic mulch, tackifiers increase the effectiveness of the mulch as a soil cover by binding the hydraulic mulch fibers and the surface soil particles together. Tackifiers create water-stable surfaces, which means they are capable of repeated wetting and drying and do not lose strength after a series of rainstorms. Hydraulic mulch and tackifiers can remain effective even through a winter with high precipitation (Figure 5-101).

Figure 5-101 | **Hydraulic mulch and tackifiers**

Hydraulic mulch with tackifiers remains effective for up to a year. This hydraulic mulch and tackifier slurry was applied nine months prior to this picture and was still partially effective.

Photo credit: David Steinfeld

Selecting a tackifier can be difficult. Numerous commercially available products are on the market from which to choose. Unless these products have been used side by side in the field, it is difficult to know the difference among them. A hydraulic seeder operator can offer advice on tackifiers and other hydraulic seeding products because they have tried a variety of products and usually have a good idea of their effectiveness. Many mulches are pre-packaged with the appropriate ratio of tackifier.

The two general types of tackifiers commonly used in hydroseeding are organic and synthetic. Organic tackifiers are derived from plant materials, which include guar, plantago, and other plant starches. Synthetic tackifiers are manufactured polymers and copolymers that include polyacrylamides (PAM), acrylic polymers and copolymers, methacrylates and acrylates, and hydro-colloid polymers. Organic tackifiers break down biologically and are typically effective for at least three months depending on site conditions and product type. Synthetic tackifiers are photo and chemically degradable and have somewhat greater longevity than organic tackifiers, lasting up to a year on many sites (CASQA 2003b).

Revegetation specialists and operators usually develop a preference for tackifier products based on ease of handling and storage, ease of application, toxicity to plants, environmental concerns, weather restrictions, and application rates.

Handling and Storage—Tackifiers are available as dry powder or liquid formulations. Most organic and some synthetic tackifiers are packaged as dry powders. These products are easy to handle and store because they weigh less and have less bulk than liquid containers. Liquid tackifiers should be stored in areas that will not freeze if stored over the winter. Handling and disposal of plastic containers are also a consideration when using liquid tackifiers.

Ease of Application—An important property of tackifiers is viscosity. Viscosity is the measure of the "stickiness" of a tackifier, or the propensity of the tackifier to hold a slurry together when it is applied. Tackifiers with high viscosity, such as guar-based tackifiers, will hold the slurry together as a fine stream when pumped from the nozzle (Figure 5-102A), and the stream of slurry will shoot farther. When a slurry with high viscosity hits the soil surface, it sticks and does not easily run off. A slurry with low viscosity, however, will separate as it is comes out of the nozzle and drift, especially if there is a breeze, resulting in uneven application (Figure

5-102B). If low viscosity slurries are applied at rates that are greater than the soil infiltration rates, the slurry will run off the surface. Not only will seeds be lost, but other materials in the slurry (including fertilizers) could enter surface drainage systems (Figure 5-102C).

Tackifiers act as lubricants and create less friction through the hydraulic equipment. With high viscosity tackifiers, equipment runs smoother and nozzles do not plug as frequently. This will enhance the overall performance and longevity of the equipment.

Toxicity to Plants—One reason organic tackifiers are sometimes preferred over synthetic tackifiers is the belief that these materials are better for seed germination and seedling establishment. They are organic substances that break down into non-toxic compounds. While organic tackifiers are sometimes advertised as being better for plant health, there is nothing in the scientific literature to indicate that synthetic tackifiers are any more harmful or toxic to plant establishment than organic tackifiers.

Environmental Concerns—There have been concerns about the use of polyacrylamides (PAM) on human health and the environment. Acrylamide, a known neurotoxin to humans, is the main ingredient of this polymer. Polyacrylamides alone have low toxicity—LD50 of 5,000/kg oral dosage (Peterson 2002). However, in the manufacturing of the polymer, some acrylamide is formed. The U.S. Food and Drug Administration has set a maximum allowable acrylamide content in PAM of 0.05 percent. While PAM does not appear to break down in the environment to acrylamide if released during decomposition, it is thought to be quickly decomposed by soil microbes (Peterson 2002). Furthermore, because PAM degrades slowly in the environment, there should not be an accumulation of acrylamide in the soil (Claassen and Hogan 1998). Evans (2006) cites reviews by Barvenic (1994) on health hazards and Goodrich and others (1991) on aquatic macrofauna, edaphic microorganisms, or crop species. When polyacrylamides were applied at recommended rates, the materials were found to be safe for the environment. The designer is referred to Barvenik (1994) for a comprehensive discussion of PAM in the environment.

As with all products used in revegetation, a Material Safety Data Sheet should be requested from the manufacturer of the product and reviewed for possible human effects and effects to the environment. Some states have regulations on the use synthetic polymers in landscaping. It is important to be abreast of the latest environmental regulations (Peterson 2002).

Weather Conditions—Tackifiers have limitations and conditions for proper application, including soils should be moistened prior to application; there should be a 1- to 3-day drying period after application; the site cannot freeze during or immediately after application; or they should be applied between a certain temperature range. It is important to understand which environmental restrictions apply to the tackifier being used and how it might affect the hydroseeding operations. A site that is expected to be wet in the fall, for example, will require a tackifier that needs a minimal curing period.

Tackifier Rates—When tackifiers are used with hydraulic mulches, they are applied at rates at 5 to 10 percent of the weight of the hydraulic mulch (CASQA 2003a). Refer to manufacturer labels for specific rates.

Select Other Slurry Components

The remaining components of the hydroseeding slurry can include dyes, fertilizers, biostimulants, and mycorrhizae.

Dyes—Dyes are used as markers for the applicator to indicate where the slurry has been applied. Most hydraulic mulches include dyes, so it is not usually necessary to include dyes in the slurry when using these mulches.

Fertilizers—Fertilizers are often applied through hydroseeders. Determining the type and amount of fertilizers to use is discussed in Section 5.2.1.

Biostimulants—Biostimulants are sometimes applied to the slurry.

Figure 5-102 | **High viscosity tackifiers**

High viscosity tackifiers, mixed at manufacturer recommended rates, keep the slurry together during application using a "stream" nozzle (A). Low viscosity tackifiers, or slurries with low concentrations of tackifiers, do not hold together when applied and will drift with wind (B) or run off slopes (C).

Photo credits: David Steinfeld

Mycorrhizae—Mycorrhizae are often included in the slurry (Section 5.2.7).

Locate Water Source

Hydroseeding cannot be conducted without a water source, yet a common mistake is to wait until the last minute to locate such a source. For many parts of the western United States, water sources can be long distances from the project site. It is important to establish where water will be obtained for hydroseeding early in the planning process. Considerations when selecting a water source include the following:

- **Distance**—On projects where the water source is a long distance from the hydroseeding site, large slurry tanks will increase the efficiency of the operation. Conservation of water should be a priority in these circumstances. Covering more area with each slurry tank is one way to reduce water needs. This can be accomplished by applying lower rates of hydraulic mulch and tackifier per acre.
- **Water quality**—The quality of the water for hydroseeding should be low in salts and other potentially toxic compounds. If in doubt, send a sample to a water quality lab for testing or, at minimum, run pH and conductivity measurements on a sample.
- **Water use permits**—Always check with the agency or landowner for permits to use their water.

Develop Hydroseeding Contract

Once a basic hydroseeding plan is developed, a contract is developed. The contract usually contains most of the following elements:

- **Site location and description**—A general description of the site, slope gradients, location, and time of year the hydroseeding will occur should be addressed.
- **Products and rates**—The hydroseeding products or equivalent products (hydraulic mulch, tackifiers, fertilizers, etc.) are identified, and the rates per acre for each product are stated for each hydroseeding mix or mixes. The total number of acres for each hydroseeding mix should be tabulated.
- **Water source**—The location and distance to each water source are described. The contract should indicate whether it is the responsibility of the contractor to obtain agreements from owners for use or any required water permits.
- **Storage area**—The contractor will need a site to store hydraulic mulches, tackifiers, fertilizers, and other materials associated with the hydroseeding operation. The site should be in close proximity to the hydroseeding areas and relatively safe from vandalism.
- **Equipment**—If specific types of hydraulic seeders are required for the job (large tank, or tracked equipment for example), they should be specified in the contract. Using hoses to access portions of the project site will often be necessary. The contract should specify how many feet of hose are needed and what percentage of the project will be applied by hose.
- **Cleaning equipment**—The contract should state that the tank and hoses will be cleaned from all previous hydroseeding or hydromulching projects. The equipment will be inspected and, if it does not pass inspection, the contractor will be required to clean equipment at an approved offsite location.
- **Weather conditions**—The weather conditions, based on manufacturer specifications, should be stated. The contract should specify acceptable temperature ranges and wind velocities. It should also state whether rain or freezing temperatures can occur within a specified period after application. A provision should be stated that applications will not occur on frozen ground. Some tackifiers also require that soils be moistened before application.

- **Mixing**—The contract should state that the seeds be mixed into the slurry immediately before application. It should further state that the slurry should be applied within 30 minutes after the seeds have been placed in the tank. When the seeds are in the slurry, it should be moderately agitated only enough to mix the seeds and keep the slurry from separating.
- **Application**—The slurry should be applied at the manufacturers recommended application rate. Anything less than 100 percent coverage of the soil surface is incorrect application of the material. Slurry should not run off the soil. If it does, adjustments to application speeds or nozzles should Figure 5-97 and Figure 5-98 show the spray pattern of two types of nozzles. Avoid applying slurry at a range that causes slurry to splash off the surface and soil to dislodge. A two-pass method is preferred to obtain good seed coverage. In the first pass, 50 percent or less of the slurry is applied, followed by the second pass that applies the remainder of the material. Each pass is applied in a different direction (bidirectionally), which reduces the "shadow effect" created by just one pass and may serve to better lock the matrix together (Bill Mast personal communication).
- **Traffic control**—The contract should state how traffic safety will be ensured during application. Will the contractor be required to supply signs, warning lights, or flaggers?

Keep Good Records

Hydroseeding is a complex task. Not only are several products being applied at different rates at one time, but they should be evenly applied over large complex areas. A skilled hydroseeding operator should be at the helm, and it is important to keep track of what is being applied and the acres on which it is being applied. This will ensure that the target amount is being applied and enable accurate payment to the contractor.

The records begin with the original hydroseeding prescription. These are the planned application rates of each hydroseeding material. It is not enough to know what is wanted as a finished product on the site; it should be understand how it will be accomplished. This means that the prescribed product quantities per acre are translated into how it will actually be applied. These calculations can be challenging, especially when the hydroseeding operation is in full swing. It is better to have some idea how this will work before arriving in the field. Inset 5-21 provides a guide through the process of determining how much of each hydroseeding material should go into a slurry tank. These calculations, along with the contract specification, become the operation plans.

During hydroseeding operations, the contract inspector should keep track of each slurry tank that is applied. This includes the time, amount of water, quantities of products, location, acreage, and weather conditions. Calculating the acreage of each slurry tank is important in the field to ensure that the rates of materials are being applied as prescribed. This can be accomplished using a method shown in Inset 5-21, Table 4.

When this information is collected, the actual applied rates of materials per acre can be made using the method shown in Inset 5-21, Table 6. This will show how close each slurry tank came to the prescribed rates. This is important feedback for the hydroseeder operator. If the application rates were off significantly, adjustments can be made quickly. These records can be summarized at the end of the project to determine total quantity of materials used and the number of acres covered. This information can be the basis for contract payment.

On projects with significant earthwork, cut or fill slopes can be longer than the distance a hydroseed spray can reach. Plan seed applications so that exposed soils are seeded while they are accessible. This may require multiple visits by the hydroseeding contractor.

Inset 5-21 | **Keeping track of the numbers**

Hydroseeding might look easy, but keeping track of the numbers is not. Most hydroseeding operators have learned to make calculations in their heads on the run. However, unless this type of work is conducted frequently, the designer will not be able to manage this along with the other requirements of being a contract inspector. As fast as this operation goes in the field, a good record-keeping system is essential. After all, it is the designer's responsibility to ensure that the contract is being fulfilled.

Planned Application Rates. A hydroseeding plan is developed during the preparation of the contract that locates hydroseeding areas and defines general rates of materials to be applied. Table 1 shows how planning information for hydroseeding can be displayed. In this example, three hydroseeding mixes are defined by different rates of tackifier, mulch, and seed mixes in a slurry unit. Hydro mix 1 will be applied on gentle slopes requiring only a light covering of mulch at 1,000 lb/ac. Hydro mix 2 is for steeper slopes and requires 2,000 lb/ac mulch and more tackifier. Hydro mix 3 is for very erosive slopes and requires 3,000 lb/ac mulch and a different seed mix. The hydro mix locations are designated on a road map. From this table, a total quantities list of materials for the project can be made by multiplying the per acre rates by the acres for each hydro mix.

Table 1

				Slurry Unit (per Acre Rates)			
				Seed	Tackifier	Mulch	Fertilizer
Hydro Mix	Reveg Units	Seedmix	Acres	Bags/ac	Buckets/ac	Bales/ac	Bags/ac
1	A2, B1	A	2.0	4	**100**	1,000	1,000
2	B1	A	5.0	4	200	2,000	1,000
3	D1, D2	B	3.5	4	200	3,000	1,000
Total quantities					**1,900**	**22,500**	**10,500**

Conversions to Product Units. When in the field, do not think in terms of pounds per acre because every product comes in packages. For example, mulch may be packaged in 45 pound bales. To make it a simple, all rates should be converted from pounds per acre to product units (Table 2).

Table 2

	Tackifier	Mulch	Fertilizer
Pounds per	**50**	45	50
Product unit	Bucket	Bale	Bags

Operational Plans. Table 3 converts the planned application rates to operational loading rates by converting "pounds per acre" to "product units per acre" and converting "product units per acre" to "product units per slurry tank." The key to these calculations is knowing approximately how many acres each slurry tank will cover. This is a function of the size of the slurry tank and the amount and type of mulch and other materials being mixed in each tank (**Section 5.4.2, see Select Hydraulic Mulch and Determine Rates**) for calculating acres per slurry tank). In this example, it was estimated that hydro mix 1 would cover approximately 1.5 acres. Hydro mix 2 would cover one-half the area (0.75 ac) because twice the hydromulch is being applied. Hydro mix 3 would cover one-third of the area as hydro mix 1. The math, using tackifier in hydro mix 1 as an example, is *100 (Table 1 grey cell) / 50 (Table 2 grey cell) * 1.5 (Table 3 grey cell) = 3 (Table 3 gold cell)* buckets per slurry tank. Notice the difference in some of the product unit rates, such as the fertilizer.

Table 3

				Per Slurry Tank			
				Seed	Tackifier	Mulch	Fertilizer
Hydro Mix	Tank Size	Ac/Tank	Seed-mix	Bags	Buckets	Bales	Bags
1	3,300	**15**	A	6	**3**	33	30
2	3,300	0.75	A	3	3	33	15
3	3,300	0.5	B	2	2.0	33	10

Operations Diary. Table 4 covers the minimum amount of information that should be collected during hydroseeding operations. It captures date, time, and quantity of product units placed in the slurry tank. It is also a record of the acres that were covered by each slurry tank (refer to Table 7 for a quick way to determine acreage). Notice that the application rates in this example (ac/tank) were variable, especially for Tank 2. This is not uncommon for hydroseeding projects. At the end of each day, Table 4 is used to summarize the amount of materials used and to track inventory. This table is the basis for contract payment.

Table 4

								Products			
								Seed	Tackifier	Mulch	Fertilizer
Tank	Map	Date	Start	Finish	ac/Tank	Water (gal)	Seed mix	Bags/ac	Buckets/ac	Bales/ac	Bags/ac
1	A2	10/18/07	9:15	9:50	1.20	3,300	Mix 1	6	2.0	33	30.0
2	A2	10/18/07	10:10	10:50	1.80	3,300	Mix 1	6	2.0	33	30.0
3	B1	10/18/07	11:20	11:55	0.70	3,300	Mix 1	3	5.0	33	15.0
4	B1	10/18/07	13:00	13:35	0.95	3,300	Mix 1	3	5.0	**33**	15.0
5	B1	10/19/07	14:15	15:15	0.80	3,300	Mix 1	3	5.0	33	15.0
							Total quantities	**21**	**19**	**165**	**105**

Actual Applied Rates. Tables 5 and 6 convert what was actually applied back to pounds per acre to compare what was originally planned from Table 1. For example, 33 bales of mulch were applied in Tank 4 (shaded cell in Table 4). It is converted to actual pounds per acre as follows:

*33 * 45 (shaded cell in Table 5) * 0.95 (shaded cell in Table 6) = 1,563 lbs/ac (circled cell in Table 6)*

Compared to the original plan, this was three-quarters of the planned rates because the slurry tank was applied over a greater area than originally planned. For seed rates, this means that a one-quarter fewer seeds were applied.

Table 5	Tackifier	Mulch	Fertilizer
Pounds per	50	**45**	50
Product unit	Bucket	Bale	Bags

Table 6

								Products			
								Seed	Tackifier	Mulch	Fertilizer
Tank	Map	Date	Start	Finish	ac/Tank	Water (gal)	Seed mix	Bags/ac	Buckets/ac	Bales/ac	Bags/ac
1	A2	10/18/07	9:15	9:50	1.20	3,300	Mix 1	5.0	83	1,238	1,250
2	A2	10/18/07	10:10	10:50	1.80	3,300	Mix 1	3.3	56	825	833
3	B1	10/18/07	11:20	11:55	0.70	3,300	Mix 1	4.3	357	2,121	1,071
4	B1	10/18/07	13:00	13:35	**0.95**	3,300	Mix 1	3.2	263	**1,563**	789
5	B1	10/19/07	14:15	15:15	0.80	3,300	Mix 1	3.8	313	1,856	938

Prior to hydroseeding, review the areas to be hydroseeded in the field (Table 7). For each road station (column C), the length of the slope (column D) that will be hydroseeded is measured (or estimated) and recorded. This information is placed in a spreadsheet as shown in this figure, and acreage for each station is made by multiplying slope length by distance between stations (column E) and converting to area units (columns F and G) (e.g., acres). During hydroseeding, the stations and percentage of area to be covered (column B) within the station are recorded for each slurry tank (column A). Partial station coverage is estimated and acreages adjusted, as shown in the last entry in this example. When the slurry is completed, the total acres for that slurry tank are summed.

Table 7

A	B	C	D	E	F	G
Tank	% Covered	Station	Slope Length (m)	Distance between stations (m)	Area (m^2)	Acres
4	100	20+1000	27	20	540	0.133
4	100	20+1020	24	20	480	0.119
4	100	20+1040	25	20	500	0.124
4	100	20+1060	24	20	480	0.119
4	100	20+1080	25	20	500	0.124
4	100	20+1100	27	20	540	0.133
4	100	20+1120	26	20	520	0.128
4	50	20+1140	28	20	560	~~0.138~~ **0.069**
		20+1160	23	20	460	0.114
		20+1180	21	20	420	0.104
		20+1200	26	20	520	0.128
		20+1220	22	20	440	0.109

Acres covered by Tank 4 = 0.95

5.4.3 INSTALLING CUTTINGS

Introduction

Live cuttings have a variety of uses in revegetation projects, from stream restoration to roadside stabilization. When live cuttings are used as slope reinforcement, barriers to soil movement, or integrated into retaining structures such as rock gabions, crib walls, or rock walls, they form the living component of a soil biotechnical engineering system (Sotir and Gray 1992). In slope reinforcement, live cuttings initially play a structural role by increasing soil strength and preventing surface erosion. As cuttings establish into plants, soils are stabilized through a dense network of interlocking root systems. Soils are further stabilized during the growing season as soils dry due to increased evapotranspiration and rainfall interception.

Soil biotechnical engineering techniques are well documented. Gray and Leister (1982), Sotir and Gray (1992), and Lewis (2000) are excellent sources on road and slope stabilization, and the designer should refer to Bentrup and Hoag (1998) for streamside stabilization. Section 5.3.2 described how to collect and evaluate live cutting quality; this section focuses on the care and installation of live cuttings to optimize the success of biotechnical engineering and other roadside revegetation projects. For simplicity, live cuttings are grouped by general application in biotechnical engineering projects as follows: live stakes, live brush layers, and live fascines.

Live Stakes

Live stakes are individual cuttings that are inserted into the slope to physically stabilize the soil and, with time, grow into individual plants with dense, interconnecting roots that further increase soil stability. Live stakes are used to repair small earth slips and slumps (Sotir and Gray 1992) and as pole plantings for stabilizing streambanks (Bentrup and Hoag 1998). Joint planting refers to live stakes inserted into voids or openings between large rocks. The live stakes can take root and revegetate rock riprap sites or portions of fractured bedrock (Sotir and Gray 1992). Live stakes are also used in live fascine installations and to anchor erosion mats to the soil (Lewis 2000). In gullies, draws, or intermittent streams, live stakes are placed in rows as live silt fences (Polster 1997) to slow water velocities and catch sediments and other debris. In saturated soil conditions, where excavation for brush layering or fascines is not feasible, live stakes can be densely stuck by hand.

Collection—Live stakes are collected from the main stems of donor plants located in the wild (Section 5.3.2) or from stooling beds in nurseries (Section 5.3.5). The optimum period to collect cuttings is during the dormant period after the plants have lost their leaves. If cuttings are collected outside this period, testing the viability of the cutting material is essential (Section 5.3.2, see Determine Rooting Potential). It is important to collect cuttings with several dormant buds because this is where shoots will originate (Figure 5-103).

When preparing stakes, all side branches are removed, leaving just the stem. Only stems with diameters between 1 and 3 inches are used. Stems are cut into lengths of 1 to 3 feet, depending on how the materials will be used. It is important to select the appropriate cutting length. Stems that are too short will affect the success of the project, and cuttings that are too long will increase the costs of the project. During collection, basal ends of the cuttings are always oriented in the same direction to ensure that the buds will be aligned. This will help avoid confusion later when the stakes are being installed. Finding the orientation of the buds is often difficult (Figure 5-103) and having to reorient in the field takes time. As individual stakes are made, the top of the stake is cut flat, while the basal end is cut at an angle (Figure 5-104). This makes the stake easier to insert into the soil and orients the live stake so the buds are facing up and away from the soil surface. If buds are facing down, the live stake will not root.

During collection, live stakes are wrapped in small bundles with twine. The size of the bundle should be light enough to be easily carried. Once the bundle size has been determined, the

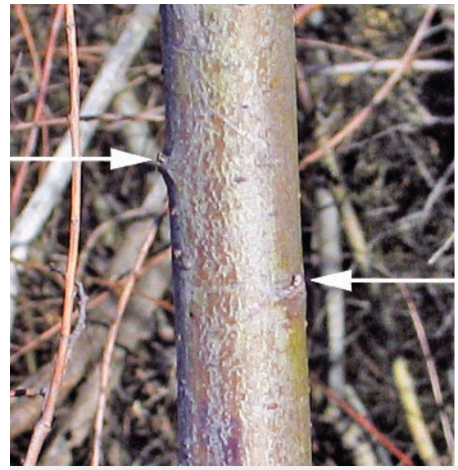


Figure 5-103 | **Bud orientation on cuttings**

The vertical orientation of buds on older willow (*Salix* spp.) stems can be visually difficult to discern (see arrows). Keeping track of the orientation of the bud from collection to installation is very important.

Photo credit: David Steinfeld

Figure 5-104 | **Live stake planting orientation**

Live stakes are cut at an angle on the basal end (circle) for easier installation and to ensure the stake is placed with buds facing up. Cuttings with buds installed upside down will not develop into plants.

numbers should not vary in order to track cutting quantities. Stakes can be cut from healthy donor plants. Stems that have obvious insect or disease damage should not be used. It is often easy to forget that live cuttings are plant materials, like seeds and seedlings, and should be handled and stored with care

Storage—It is recommended that live, dormant stakes be collected and installed the same day (Sotir and Gray 1992; Lewis 2000). This is not always possible in a road construction project. When it is not, temporary cold storage is an option. Temperatures in these facilities should be set below 40° F and, if humidifying equipment is available, it should be kept on high. For longer-term storage (over two weeks), cuttings should be wrapped in plastic or moist burlap to prevent the vegetative material from drying out and temperatures should be set just below freezing. Lower temperatures can result in damage and even death (Wearstler 2004). As a last resort, cuttings can be temporarily stored outside, provided daily temperatures are low (<50° F) and humidity is high, cuttings are completely wrapped in plastic, temperatures will not drop below 25° F, and the site is shaded from the sun.

Preparation—Studies of black willow (*Salix nigra*) have shown that soaking dormant cuttings prior to installation can increase survival (Schaff and others 2002; Martin and others 2005; Pezeshki and others 2005; Pezeshki and Shields 2006). Soaking for approximately 10 days appears to be the optimum period for black willow (Schaff and others 2002; Pezeshki and Shields 2006). Soaking non-dormant cuttings, however, appears to be detrimental to survival (Pezeshki and others 2005; Pezeshki and Shields 2006). Species native to the western United States might respond similarly to the black willow. The effects of soaking can be tested in other willow species using a method outlined in Section 5.3.2 (see Determine Rooting Potential). If live stakes are soaked in streams, it is important to be sure they are sufficiently protected from being swept downstream during high precipitation or snowmelt.

Installation—For most applications, live stakes are installed perpendicular to the soil surface. When installed, no more than one-quarter to one-fifth of the cutting is exposed (Sotir and Gray 1992; Darris and Williams 2001). Buds are always pointing up and away from the soil surface with at least two healthy buds above the soil surface. It is essential that soil be firmly packed around live stakes so there are no large air spaces surrounding the cutting. For successful sprouting the live stakes can be installed in locations and to a depth where soil moisture is consistently available. Live stakes can be installed using the techniques described in Section 5.4.4. These include a shovel, auger, or expandable stinger. In addition to these methods, several techniques are available specifically for live stake installation, which include a hammer, stinger, or Waterjet Stinger.

Hammer or Mallet—For best results a steel rod can be used to open a hole for the live stake and the stake inserted into the hole and the surrounding ground tamped to eliminate voids. Live stakes can be pounded into the ground using a hammer or mallet but this can abrade the bark, split the stake, and provide an opening to disease or fungus. If the stake is hammered the use of a dead blow hammer is recommended and the angled basal end of the stake is placed on soft soil surface and the top of the cutting is struck. A small 2 x 4 wood block can be placed on the top to absorb the impacts and reduce the risk of splintering the stake. If splintering does occur, the splintered ends can be cut (Lewis 2000). After cutting, there should still be several viable buds above the soil surface. Using a hammer or mallet works best when soils are loose and low in rock fragments. It becomes more difficult as rock content or compaction increases. Smaller stem diameters are often not sturdy enough for this installation method.

Stinger—The stinger is a good method for installing live stakes on rocky or compacted soils. A pilot hole is created by mechanically pushing a metal rod into the soil. A live stake is inserted into the hole and tamped to the bottom using a hammer or mallet, as described above. Some operators will create the hole with the stinger and, after placement of the stake, use the face of the excavator or backhoe bucket to push the stake farther into the soil. The hole created by the stinger is often larger than the diameter of the stake, and the soil should be tamped in around the cutting to reduce air space and create good soil contact. A stinger can be made by welding a long piece of rebar to the bucket of an excavator or backhoe. The stinger is limited by slope gradient and terrain accessibility.

Waterjet Stinger—The Waterjet Stinger hydraulically creates a hole for installing live stakes. A pump draws water from a stream, lake, or water truck for delivery through a hose to the stinger nozzle. As the tip of the nozzle is pushed into the ground, high-pressure water is injected into the soil, creating a slurry (Figure 5-105). When the Waterjet Stinger is removed, a stake is quickly pushed into the resulting slurry at the desired depth. As water drains from the slurry, soil settles around the cutting, resulting in good soil contact.

The advantages of using the Waterjet Stinger are that it is simple to operate and transport; little training is necessary to use it; production rates are high; holes are deep, ensuring that cuttings are planted directly into a wet environment; soils are saturated around the cutting for a long period of time; and the soil slurry settles around the cutting ensuring good soil to stem contact, eliminating air pockets in the rooting zone (Hoag and others 2001). The disadvantage of the Waterjet Stinger is that it requires a nearby source of water. If the project is not near a body of water, it can be brought in using a water truck or large water storage containers placed in the back of a truck (Figure 5-106). The Waterjet Stinger is also limited by the amount of rock present in the soil. This equipment does not work well in soils containing gravels, cobbles, and boulders that obstruct the downward movement of the probe (Hoag 2007). Sandy soils drain quickly, so installation of cuttings with the Waterjet Stinger should be done quickly and with a little more effort. Steep slope gradients and rough terrain also limit equipment and the transportation of water. For more information on the Waterjet Stinger, refer to Hoag and others (2001).

Expandable Stinger—The expandable stinger can install live stakes into all soil types and soil conditions, from rocky to compacted. It can plant long cuttings (> 4 ft) and stems of most diameters (including very small diameters). The stake is placed into the stinger, which is inserted into the soil and released, leaving the cutting at the desired depth (Section 5.4.4, see Select Planting Tools and Methods). This installation method can leave large air spaces around cuttings. It is therefore recommended that soils be tamped around the cutting after placement.

Hand-Sticking—Hand-sticking is appropriate in areas where soils are mucky or saturated, including recent landslides and wetlands, and cuttings can easily be inserted into the soil. Because this installation method can be done quickly, areas can be planted at very high densities (Figure 5-107).

Live Brush Layers

Live brush layers are cuttings that are spread on excavated benches and covered by soil (Figure 5-108). This practice is used in several biotechnical engineering applications, including brush layers and modified brush layers. Constructing brush layers is a three-step process in which contour benches are excavated, live branches are spread across the bench surface, and branches are covered with soil from constructed benches directly upslope. The process begins at the bottom of the slope and is repeated until the entire slope is installed with brush layers. In a modified brush layer system, the brush layers are resting on, and supported by, logs or live fascines (Sloan 2001).

Brush layers and modified brush layers increase slope stability and reduce erosion by breaking slope length, reinforcing soil, trapping sediment, increasing infiltration, acting as horizontal drains, and reinforcing soil as cuttings develop roots (Sotir and Gray 1992). Live brush layers can also be used to vegetate crib walls, rock gabions, green walls, and rock walls. In this application, live branches are placed on benches that are created as these structures are built. For crib walls (Inset 5-22), live layers are placed on the bench created behind each layer of logs; in rock gabions, live layers are placed on each layer of gabion baskets.

Collection—Materials for live layering are obtained from branched cuttings collected in the wild or from stooling beds. Stems up to 2 inches in diameter can be used (Sotir and Gray 1992). The basal end of the cuttings is always oriented in the same direction during collection

Figure 5-105 | **Waterjet stinger**

The Waterjet Stinger (A) injects high-pressure water into the soil, turning it to a slurry (B) into which a live stake can be inserted.

Photo credits: Chris Hoag

Figure 5-106 | **Water tank with pump**

A 250-gallon water tank with pump can be installed in the bed of a pickup truck to supply water for Waterjet Stinger sticking.

Photo credit: Chris Hoag

Figure 5-107 | **Hand-stuck cuttings**

Hand sticking cuttings at high densities is an option for saturated soils where the soils are too wet for installation of fascines or brush layers. This photograph shows leaves forming on cuttings several months after installation.

Photo credit: David Steinfeld

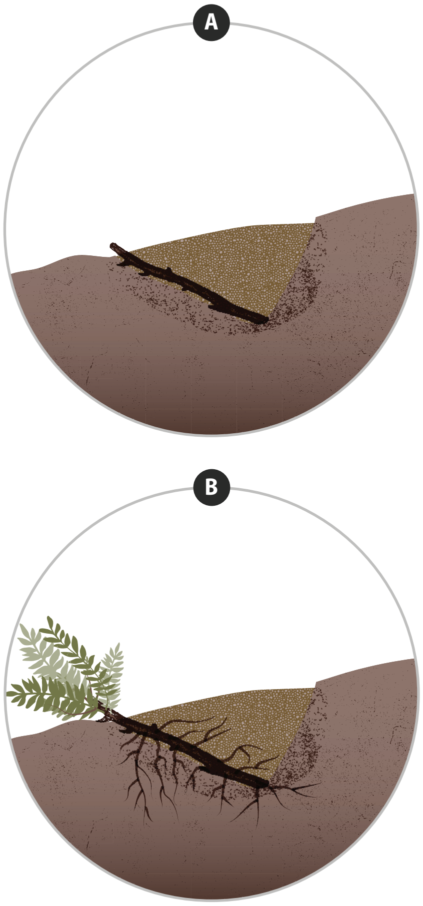


Figure 5-108 | **Live brush layers**

Live brush layers are cuttings that are placed on benches and covered with soil (A). The basal end of the cuttings should extend back to the base of the bench, and the growing tip should just show out of the soil. When placed on the contour and at regular intervals, live brush layers form a network of roots and vegetation that tie the slope together in a series of strips, increasing slope stability and reducing erosion.

and bundling. Cuttings for brush layers should be long enough that the growing tips are just exposed at the soil surface, while the basal portion of the cuttings reaches to the back of the bench (Sotir and Gray 1992). For rock gabions, rock walls, and crib walls, cuttings should be long enough to extend into soil or backfill behind the structures. During collection, cuttings are placed in bundles and secured with twine. Bundles should be light enough to carry. The optimum period to collect cuttings is during the dormant period when the plants have lost their leaves. If cuttings are collected outside of this period, then testing the viability of the cutting material is essential (Section 5.3.2, see Determine Rooting Potential). Fine branches dry out quickly if exposed to warm, dry temperatures. Cuttings should be protected during transportation, storage, and handling to avoid drying.

Storage—Refer to Section 5.4.3 (see Live Stakes).

Installation—Branched cuttings are laid out on benches so the basal end of the cutting reaches to the back of the bench and the growing tips extend just beyond the front. Soil is placed over the cuttings and tamped to ensure there are no large air spaces. Excessive compaction is unnecessary for plant establishment and is often detrimental for long-term plant growth (Section 3.8.2, see Soil Structure). The material used to cover live branches in or behind crib walls, rock gabions, and rock walls is often low in water-holding capacity, nutrients, and organic matter. Soil amendments, such as compost, can be incorporated into backfill material to improve water-holding capacity and to serve as a long-term source of nutrients and organic matter. These amendments can increase establishment and improve plant growth (Section 5.2.5). Waiting until after the construction of crib walls, rock gabions, and rock walls to amend the soil is not practical or feasible.

Live Fascines

Live fascines are cuttings bound together to form a long continuous bundle (Figure 5-109). When installed on the contour, live fascines slow runoff, increase infiltration rate, capture sediments, reduce slope length, and revegetate the site (Sotir and Gray 1992). Live fascines have a good potential for quick establishment because of the high density of buds near the

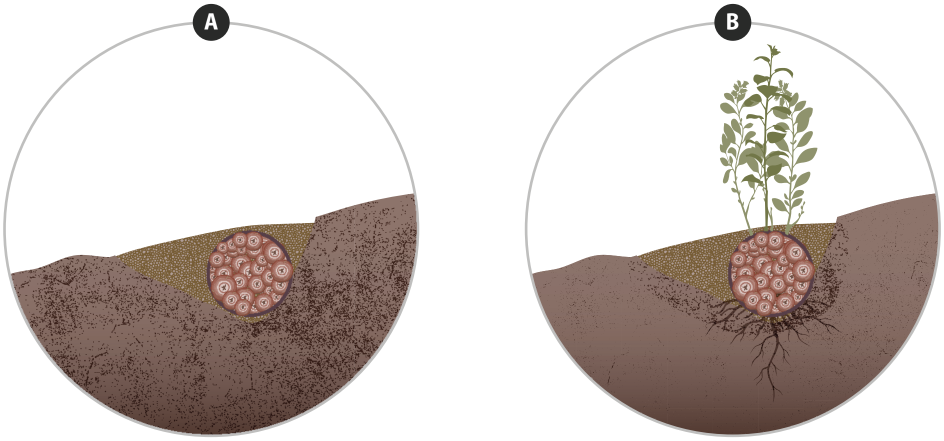


Figure 5-109 | **Live fascines**

Live fascines are long bundles of cuttings placed in trenches constructed perpendicular to the slope. The bundles are placed in contact with the soil, with the upper portion of the fascine covered by a thin layer of soil (A). Fascines initiate shoots and roots in the spring, and are established by early summer (B).

surface of the soil. Live fascines can quickly send out shoots and roots early in the growing season and become established before summer (Figure 5-109).

Fascines are used in the construction of live pole drains to drain saturated slopes, small slumps, or gullies (Polster 1997). Live pole drains are designed to intercept surface water from unstable slopes or seepage areas, and transmit it through a system of interconnecting bundles to more stable areas (Figure 3-70). The constant supply of intercepted water encourages vigorous growth of the cutting material into a continuous stand of vegetation. Fascines are also used as the base or support in the construction of modified brush layers. Live fascines have great potential for establishment because of the high density of buds just under the surface of the soil. These buds can emerge quickly in late winter and early spring. Because they are installed at the soil surface, live fascines are more prone to drying out than live brush layers or live stakes. For this reason, live fascines are more successful on moist sites or in conjunction with live brush layering or live staking.

Collection—Branches and stems up to 2 inches in diameter are collected from the wild or from stooling beds and gathered to form a long continuous bundle. Fascines vary in length from 5 to 30 feet, and from 6 to 8 inches in diameter. For large projects, construction of a series of sawhorse-type structures makes this operation easier and more efficient (Sotir and Gray 1992). At frequent intervals, bundles are secured with twine to hold the fascines together. Cuttings can be collected during the dormant season when the plants have lost their leaves. Fine branches dry out quickly if exposed to warm, dry temperatures and should be protected during transportation, storage, and handling

Storage—Refer to the discussion in Section 5.4.3 (see Live Stakes).

Installation—Prior to installation, trenches can be created at the proper depth so the top of the fascine is flush to the surface of the slope when installed. The shape of the trench should allow soil contact with all portions of the bundle. Soil is tamped down around the sides of the bundles to ensure soil contact, and the upper fifth of the bundle is covered by a thin layer (<1 inch) of soil. A very small portion of the fascine should be exposed, but not enough to dry the stems. If the fascine is buried too deeply, vegetative growth will be restricted.

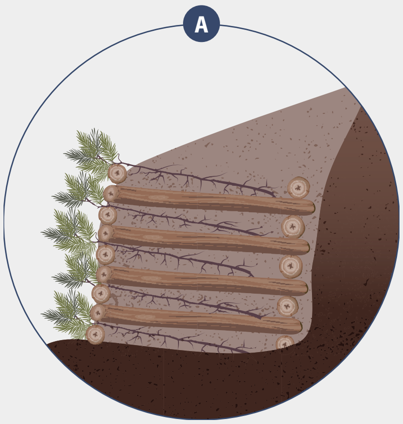
Inset 5-22 | **When should seedlings or rooted cuttings be substituted for live cuttings?**

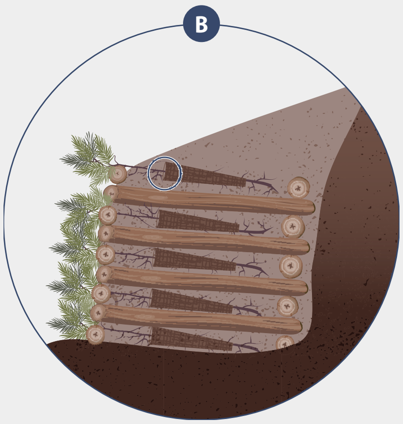
Live cuttings are widely used in biotechnical engineering projects. Sometimes, however, it is more practical to substitute rooted cuttings or seedlings in place of live cuttings. This is especially the case when the road project calls for cuttings to be planted in the summer or fall; when dormant, live cuttings are not available; or when live cutting material is not available in large enough quantities.

For example, a road near a designated Wild and Scenic River is being widened. Biotechnical engineering techniques using live willow cuttings are being planned for retaining walls to increase slope stability in areas adjacent to the river. The design looks good on paper (A). However, when discussing the details with a designer, questions arise: where will the cuttings be collected and what time of year will the willows be installed? Upon inventorying the willow stands on the district, they learn there is not a supply of willows large enough to meet the needs of the project. To obtain this volume and size of cuttings would require the establishment of stooling beds at a nursery (**Section 5.3.5**), which would take at least two years prior to project implementation.

More disturbing, they learn that the contract can only be implemented in the summer due to water quality and wildlife restrictions. While some cuttings installed in the summer would sprout, most would not, as was determined through rooting potential testing (**Section 5.3.2, see Determine Rooting Potential**). Referring back to the project objective, the design engineer and the designer realize that going ahead with the project, as designed, would compromise revegetation of the retaining wall. The decision was made to adopt an alternative design to install rooted cuttings grown in long tubes (at a nursery) instead of unrooted cuttings. The rooted cuttings would be planted at very high densities where the brush layers were to be installed (B). Because only a small amount of cuttings would be necessary to start rooted cuttings in containers at the nursery, there was no need to develop stooling beds, eliminating the extra time and costs to produce these plant materials.

The stems of the long-tube rooted cuttings can be set back several feet into the soil (circled in B) as long as a portion of the foliage is above ground. This will add length to the rooting area and the stems will initiate roots (C).





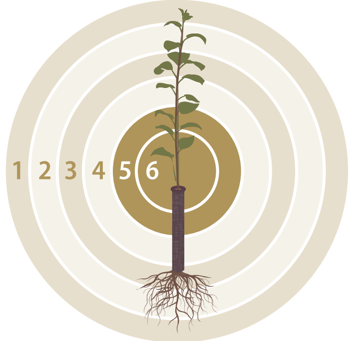
Introduction

Although a wealth of information exists about planting for reforestation, very little information has been published about planting nursery stock on roadsides. Several references can be found discussing harsh site reclamation. Ashby and Vogel (1993) is an excellent source for planting on restored minelands.

Before beginning a planting project, the revegetation plan and plant production contract can be reviewed carefully, as should the Target Seedling Concept (Figure 5-110) which was considered during the planning process (Section 3.13.1). The first four steps were covered when plants were ordered during the planning process. The timing of the outplanting window and planting tools should be considered at this time.

Timing of the Outplanting Window—The outplanting window is the period in which environmental conditions on the outplanting site are most favorable for survival and growth of nursery stock (Figure 5-111). The outplanting window is usually defined by limiting factors, and soil moisture and temperature are frequent constraints. In most of the continental United States, nursery stock is outplanted during the rains of winter or early spring when soil moisture is high and evapotranspirational losses are low. Fall outplanting is another option on some projects, especially when dormant and hardy plants can be installed just before the normal rainy season begins. Planting during the summer is usually discouraged because the nursery stock is not dormant and will experience severe transplant shock. If nursery stock is carefully handled and plants can be irrigated, then summer plantings are possible.

Planting Tools and Techniques—Nursery stocktype and the conditions on each outplanting site should be considered before planting begins. All too often, planters develop a preference for a particular planting implement because it has worked well in the past. However, no one tool will work for all types of nursery plants and under all site conditions. Size of nursery stock, in particular the depth and width of the root plug, is the critical consideration. Tall pots, for example, have an unusually deep root plug, which makes them difficult to plant properly with standard tools. For some types of plants and, especially, for large planting projects, it may be necessary to buy or rent specialized equipment, that can be secured in advance. The planting tools recommended for roadside revegetation projects are discussed in Section 5.4.4 (see Select Planting Tools and Methods).



1. Objectives of Outplanting Project
2. Type of Plant Material
3. Genetic Considerations
4. Limiting Factors on Outplanting Site
5. Timing of Outplanting Window
6. Outplanting Tools and Techniques

Figure 5-110 | **Target plant concept**

The final two steps of the Target Seedling Concept, the Outplanting Window and Planting Tools and Techniques, should be considered before initiating planting projects (adapted from Landis 2009).

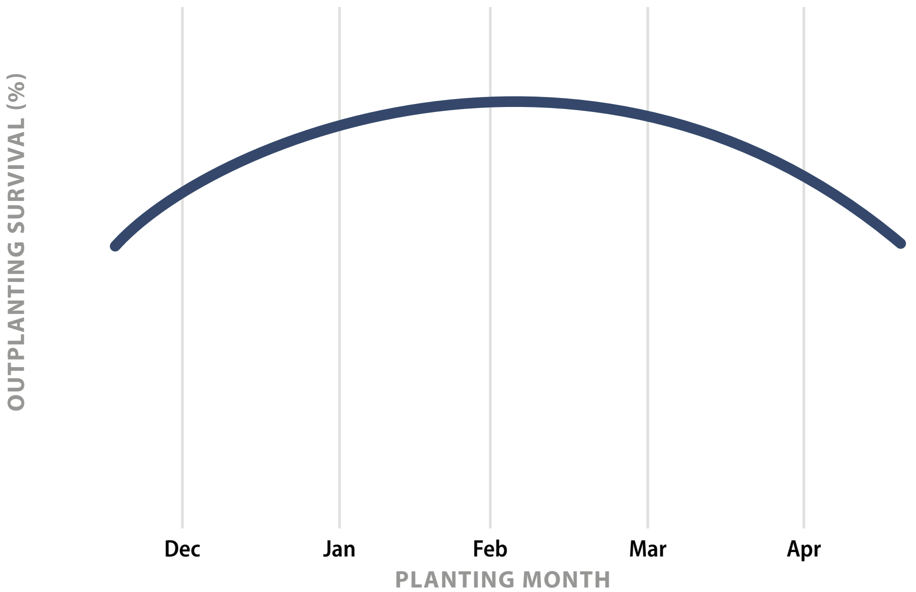


Figure 5-111 | **Outplanting window**

The best time to plant (referred to as the "outplanting window") will depend on local weather and soil moisture conditions. For example, on sites in the Pacific Northwest, where snowpack is uncommon, the outplanting window is typically from January through late February, when soil water content is high and atmospheric drying potential is low. Planting outside of these dates can lead to reduced seedling survival (modified from South and Mexal 1984).

Define Planting Areas

When construction is completed, the project site is assessed for planting. A detailed map showing the exact planting locations and conditions is developed by reviewing each location on the ground. Each area should be identified on a map and described in a spreadsheet by the following:

- Planting area acreage
- Planting patterns
- Plant spacing (density)
- Survival potential
- Species and stocktype mix

With this information, a planting strategy can be developed for each planting area using calculations similar to those shown in Figure 5-112.

Figure 5-112 | **Calculating number of plants needed**

This type of spreadsheet helps calculate how many plants of each species are needed and should be developed for each planting area. This example includes quaking aspen (POTR5), ponderosa pine (PIPO), and Saskatoon serviceberry (AMAL2), but can be extended to accommodate more species.

Revegetation Unit		Plant Species				
	2	PIPO	POTR5	AMAL2	Units	Definition
A	**Planting area**	0.75	0.75	0.75	acres	Area that will be displaced
B	**Target plant spacing**	9	14	20	feet	Desired distance between established plants
C	**Average surivial potential**	95	70	70	%	Percent of seedings that surive after one growing season
D	*(43,560 * A) / (B * B)*	403	167	82	plants	Desired number of established plants after one growing season
E	*D * (100 / C) =*	425	238	117	plants	Number of nursery plants that need to be planted

Size of Planting Areas—The first step is to measure the area of each planting unit. Although they could be calculated from Project plans or acquired from the electronic files, the true planting areas should be measured on-site. A practical method is described in Figure 5-113.

Planting Patterns—The pattern at which nursery stock is planted is critical for creating a more natural and visually pleasing roadside experience. Most planters have learned to install plants at uniform spacing and in rows (Figure 5-114A). Although uniform patterns ensure that all plants have equal growing space, it is not natural. Planting seedlings in groups (Figure 5-114B) or clumps (Figure 5-114C) is more visually appealing and more ecologically functional. Maintenance or roadsides can be considered in the location and spacing of plants. The operational right of way will include an obstruction free run-off area or "clear zone" next to the roadway. This clear zone would allow a driver to recover from an off-pavement event with potentially no or minor damage to the vehicle. The clear zone will also be kept in such a manner that

Figure 5-113 | **Calculating the planting unit area**

This spreadsheet is a practical way to calculate the area of each planting unit.

	A	B	C	D
1	Station	Slope length (m)	Distance Between Stations (m)	Area (m²)
2	2+1000	3	20	60
3	2+1020	4	20	80
4	2+1040	6	20	120
5	2+1060	7	20	140
6	2+1080	6	20	120
7	2+1100	4	20	80
8	2+1120	2	20	40
9				
10		Totals	**m²**	**640**
11			**ft²**	**6,888**
12			**acres**	**0.16**

D
= B2 * C2
= B3 * C3
= B4 * C4
= B5 * C5
= B6 * C6
= B7 * C7
= B8 * C8
= SUM (D2:D8)
= D10 * 10.76391
= D11 / 43,560

roadside vegetation does not provide cover to wildlife. The well designed planting pattern of vegetation beyond the clear zone will determine what maintenance practices are performed on this section of roadway and accommodate the required equipment's width and turning ability in the spacing and location of vegetation. Vegetation that benefits pollinators would include trees, shrubs and flowering forbs as well as native grasses. Plantings with all of these arranged in a foreground, middle-ground and back-ground design can be discussed with maintenance staff so that grasses and forbs that skirt the shrubs will be allowed to remain.

The revegetation specialist can meet with maintenance staff during the planning stage. Maintenance operations, especially mowing and herbicide use are significant reasons that limit roadsides as pollinator habitat. Mowing interrupts the life cycle of most wildflowers, preventing their blooming and subsequent reseeding, and over time effectively eliminating the plants from the roadside landscape. If the revegetation specialist is not able to agree on with maintenance personnel on practices that allow flowering plants to persist, then the expensive wildflower seeds can be removed from the proposed seed mix.

More specific considerations about planting patterns are based on project objectives and site characteristics. Topography and soil characteristics are two important site characteristics that can inform planting patterns. If one of the project objectives is to support wildlife, then topography can be used to design planting patterns that provide shelter (e.g., clumped trees at the bottom of a ravine) or migrations routes (e.g., trees planted as covering screens leading towards adjoining natural areas). Very sandy or serpentine soils may be avoided at a site and the spatial pattern of these soils will inform planting patters. A typical example would be to use plants to screen potentially unattractive areas, such as large cuts and fills

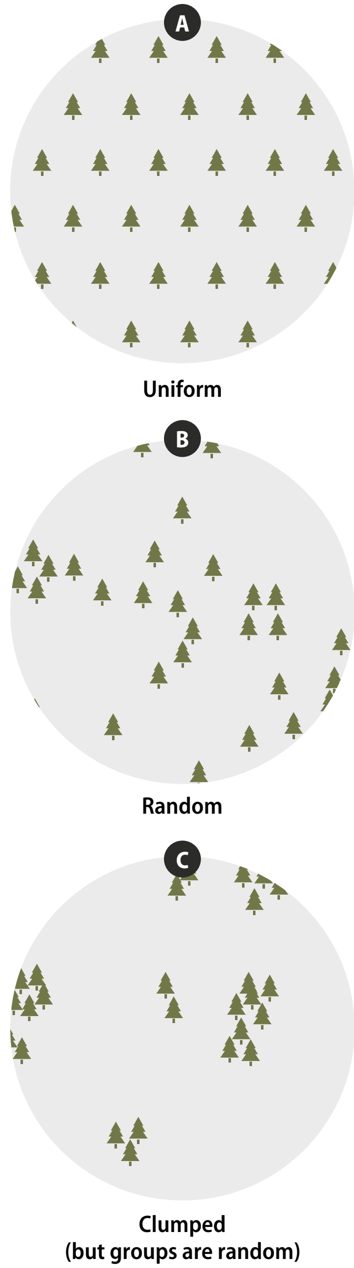


Figure 5-114 | **Planting patterns are based on project objectives**

The objectives of the outplanting project and desired appearance affect planting patterns. If the objective is rapid growth and quick site coverage, the plants can be regularly spaced (A). However, plants spaced in a more random pattern mimic natural conditions (B), and a random-clumped pattern where different species are planted in groups is often the most natural appearing (C) (adapted from Landis and Dumroese 2006).

or obliterated roads. Screen plantings can also be used to screen views of the roadway from adjacent properties. Plantings can frame and highlight attractive views. Locations of plants can be organized at intersections or points of interest to differentiate the location from the surrounding landscape. The potential to influence the road user's experience is very high. Long monotonous landscapes of homogeneous plantings can lull a driver to sleep and can be an unsafe distraction. A roadside that provides variety in form, color and use of materials can enliven the driver's experience. Landscape architects and designers using the many principles of design can exploit opportunities that may not be evident to a botanist or engineer. A thorough site analysis incorporating views from the road alignment (both directions) and views toward the road from adjacent properties is important in determining of where trees or shrubs should be planted to create views or screen views as the situation demands.

Plant Spacing—The planting spacing or density will determine how quickly an area will become screened by vegetation. The higher the density, the more plants are required. Selecting the appropriate density can be based on the existing vegetation density recorded at reference sites, as well as both short- and long-term project objectives. It can also be based on the expected survival rates of the planted stock, because not all planted stock will survive.

Survival Potential—Each planting area can be assessed for its unique site characteristics, such as rock content, soil depth, accessibility, steep slopes, and poor accessibility. These will determine the stocktype and species selection, method of planting, and the difficulty of transporting large plants to the site. The identified site limitations will determine the expected survival rates; target survival rates should be at least 70 percent to minimize the costs of site preparation and anticipated replanting.

Species Mix and Stocktype—Each planting area will have a different mix of species and stocktypes based on the site characteristics and project objectives defined during the planning stages. This is a refinement of those plans based on a site-specific evaluation of the area. Trees and other large woody plants are considered "keystone species" because of their sheer size and longevity. These structurally and functionally dominant plants play a pivotal role in restoration plantings because they generate physical structure and create ecological niches for many other species. This fosters the in-seeding of other plants, resulting in a more natural and visually appealing landscape. In the selection of flowering forbs to provide habitat to pollinators a variety of species should be selected. Besides being regionally endemic, species can be selected that have flowering periods overlap so that, from early spring through late fall, at least one or more species is flowering to provide nectar and pollen to insects.

Select Planting Tools and Methods

One planting method will rarely work for all planting areas and all species in a revegetation project. Roadside sites offer some serious challenges to planting nursery stock, most notably highly compacted soils and often a high percentage of rock. Road projects create the opportunity for unique situations, such as planting islands.

The most common type of planting method is manual planting using a shovel. Recent developments in mechanized planting equipment have increased the tools available. The most common types of planting tools for roadside revegetation sites are described below.

Shovel—The versatile "tile spade" shovel (Figure 5-115A) is the first choice for compacted soils and stocktypes used in roadside revegetation. Forestry supply companies sell a specialized planting shovel with a 14-by-5-inch blade, a welded reinforcement plate on the back of the blade (Figure 5-115B), and rubber padded footplates (Figure 5-115C). Shovels work well when planting both bareroot and container stock, as well as bulbs and other plant materials that do not require holes deeper than 1 foot. Working the shovel blade back and forth breaks up compacted soil and can create a planting hole for large container stock (Figure 5-115D). Sites should be accessible for hand planters, and the soils should not be too rocky or shallow. Very steep slopes (1:1 or greater) make shovel planting very slow and difficult.

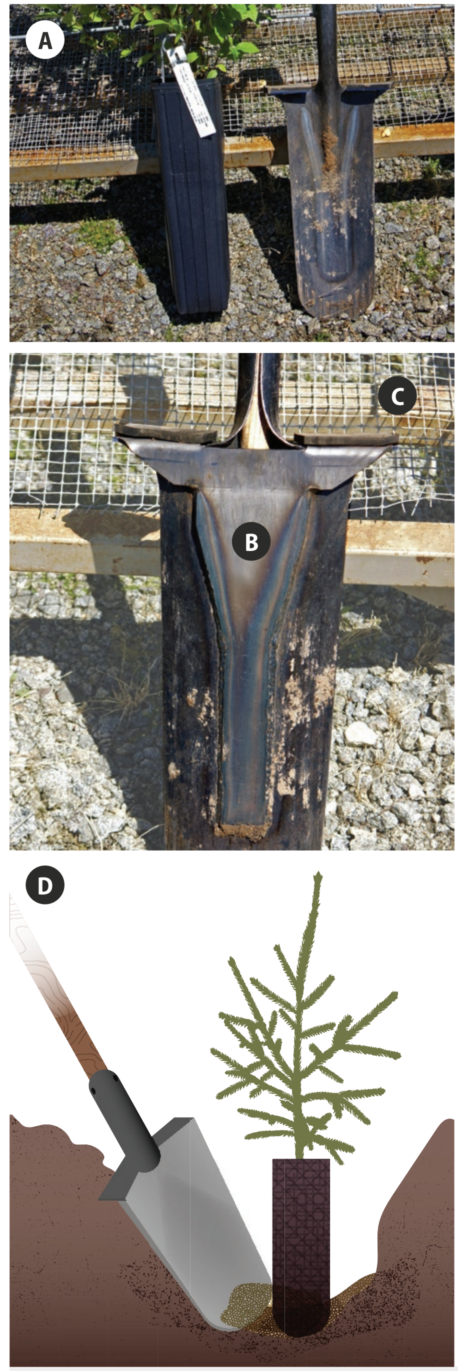


Figure 5-115 | **Tile spade shovels**

Specialized "tile spade" shovels are ideal for planting a wide variety of nursery stock on restoration sites (A). Commercial planting shovels feature a reinforced blade (B) and rubber-padded footplates (C). Working the long shovel blade back and forth breaks up compacted soil and creates planting holes deep enough for large container stock (D).

Photo credit: Thomas D. Landis

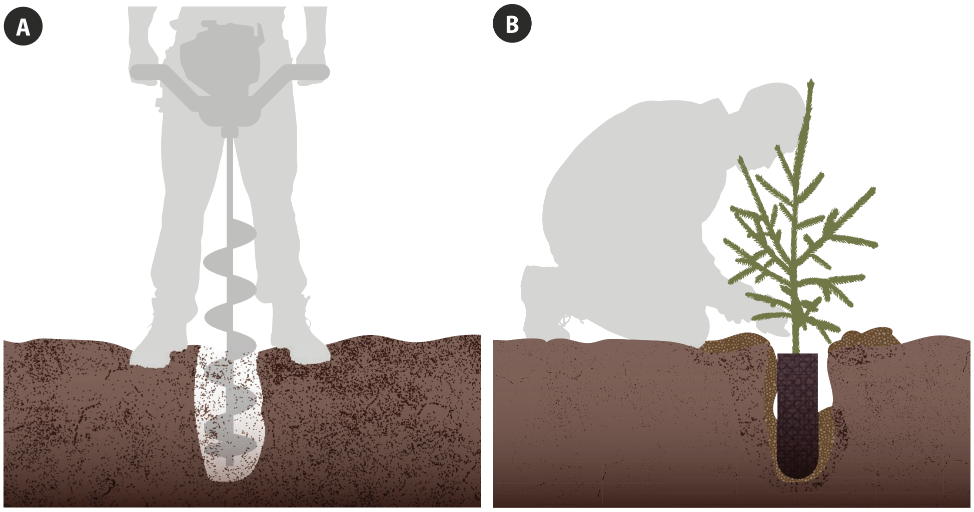


Figure 5-116 | **Power auger**

Power augers are effective because one trained operator determines the depth and spacing of the planting holes (A). Auger bits come in a variety of sizes to accommodate the large stocktypes favored in restoration plantings (B).

Power Auger—Power augers can be an excellent and efficient way to excavate holes for planting (Figure 5-116A). Many types of augers are available: one-person operated, two-person operated, and a chain saw modification. There are also larger augers that can be mounted on larger mobile equipment such skid steers. A wide variety of auger sizes means that this one implement can work for many stocktypes. Augers are particularly good for large container stock. For example, a 4-inch auger bit creates planting holes that will just fit the root plug of a "Tall Pot" container plant, ensuring good root-to-soil contact (Figure 5-116B). In a comprehensive review of planting tools, Kloetzel (2004) concluded that, when container size is larger than 336 ml (20 in^3), power augers will boost production under most soil conditions. It is most efficient to have one person operating the auger, with several people planting behind the operator. A down side of excavating with an auger is that when used in compacted soils the narrow planting pit can act as container that inhibits root growth beyond the limited area of backfill. Widening the hole and scarifying the sides can diminish this effect. Auger planting is effective on restoration sites because one person determines the location and pattern of the planting holes. Production rates are reduced with rocky or compacted soils, but a drill auger with a special bit has been developed for planting large container stock in rocky soils (St. Amour 1998).

Expandable Stinger—Specialized planting equipment is needed for the rocky and steep slopes that are often found along roadways. The original stinger was a pointed metal bar that was hydraulically forced into the soil to plant willow and cottonwood cuttings. The expandable stinger is a recently developed planting device attached to the arm of an excavator (Figure 5-117) that creates a hole and plants the seedling all in one operation. The planting head is composed of two parallel steel shafts, that are hinged in the middle to open and close in a scissor-like manner. Each shaft is constructed to create a long hollow chamber between them when closed. The opening and closing of the shafts are hydraulically driven. When the shafts are closed, the stinger comes to a point and is pushed into the soil by the force of the excavator arm. A long hardwood cutting or container plant is placed into the chamber. The expandable stinger is maneuvered to the planting spot, where the beak is inserted into the soil. When the beak opens, the seedling drops to the bottom of the hole leaving the seedling in place (Figure 5-117B and D).

At least two expandable stinger models are currently in use. The single-shot model inserts plants one at a time and averages between 50 to 80 seedlings per hour. The 50-shot model contains a rotary magazine that can hold 50 plants of up to three different species and can double the planting rate of the single-shot model (Kloetzel 2004).

The advantage of this equipment is that it can reach very steep cut-and-fill slopes—sites that are inaccessible by other planting methods. Smaller excavators can reach 25 feet, while larger machines extend planting up to a 50-foot radius, which is adequate for most cut-and-fill slopes.

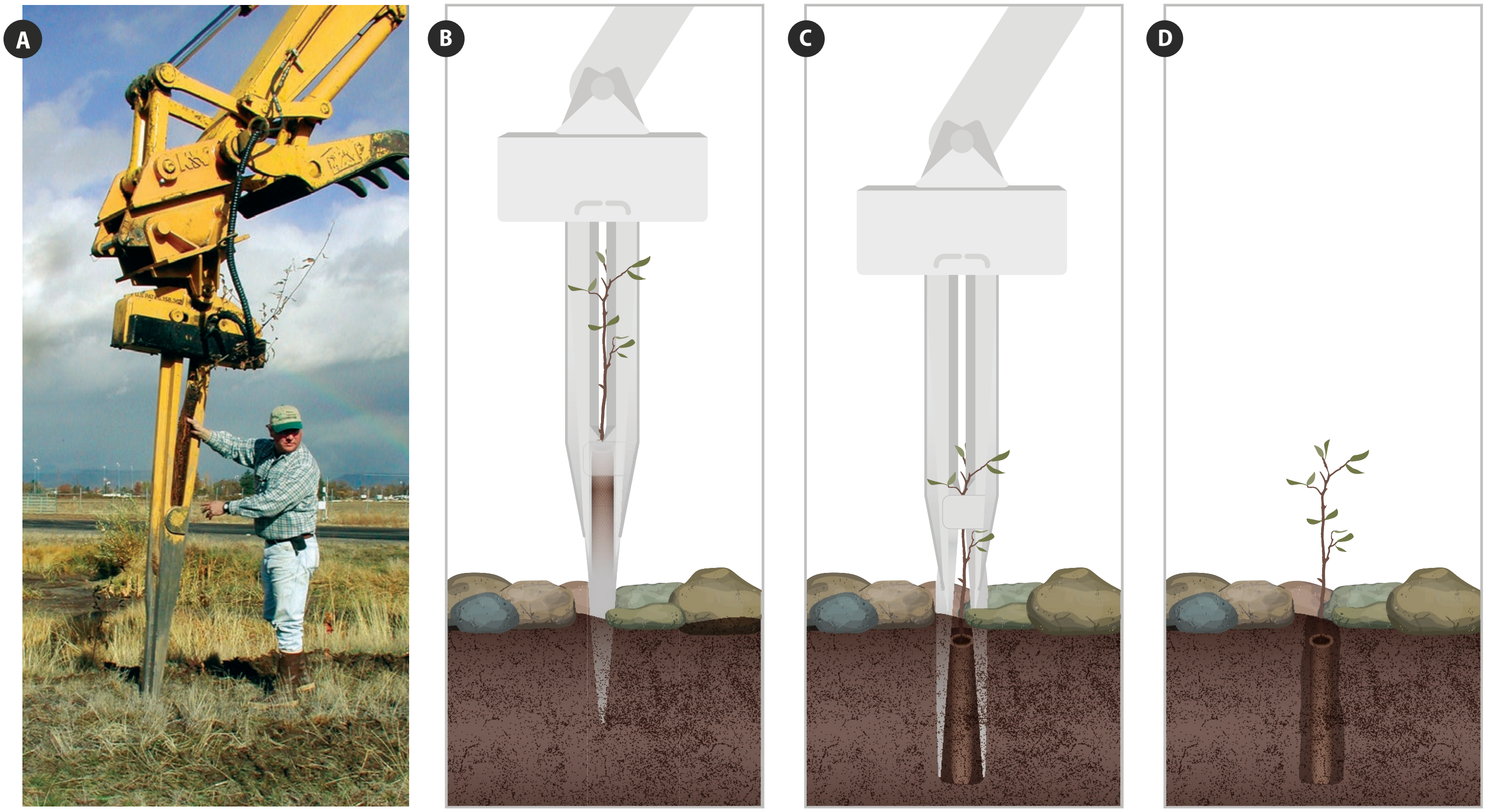


Figure 5-117 | **Expandable stinger**

The expandable stinger is operated by placing a long container or hardwood cutting into the chamber (A). The arm of the excavator pushes the point of the stinger into the soil to the appropriate planting depth for the root system (B) and the beak opens, shattering the soil (if it is compacted) and creating a hole (C). The stinger is removed and the plant remains in place as soil collapses around the sides of the plug (D).

Photo credit: David Steinfeld

This equipment can also plant in very rocky soil conditions, including riprap and gabions, and can insert plants up to 6 feet. With the typically compacted soils on roadside sites, the action of the beak of the expandable stinger breaks up the compaction around the planting hole. While soil typically falls back around the root plug after the expandable stinger has planted the seedling, it is still important to determine whether additional soil should be filled and tamped around the plant. Poor soil contact with the root system can reduce survival and growth during establishment.

The major drawback to the expandable stinger is the expense. Because of the high hourly rate of an operator and equipment, the expandable stinger should be working at full capacity at all times. Good planning is essential. This means that all the planting sites are laid out before the equipment arrives; there is a clear understanding of species mix and planting for each planting area; seedlings are on the site and ready for loading into the equipment; and there is enough personnel to keep the equipment going. In a well-planned operation, the expandable stinger can plant up to 200 seedlings in an hour. In addition to the hourly operating costs, the mobilization costs can be very high, especially if the excavator and expandable stinger are transported a long distance. These costs should be spread across all seedlings being planted for a true cost. The more seedlings that are planted by the expandable stinger at one construction site, the less it will cost per planted seedling. Larger planting projects (>1,500 seedlings) spread these costs over more seedlings and make expandable stinger projects economical.

Pot Planter—The pot planter is a modification of the Waterjet Stinger (Section 5.4.3) that creates planting holes large enough for container plants. As with the Waterjet Stinger, it draws water from a water source (e.g., a lake, stream, or water truck) and hydraulically creates a planting hole as the tip of the high pressure nozzle is pushed into the soil (Figure 5-118A). The pot planter has 3-inch vanes attached to the sides of the nozzle, which create holes large enough for containers up to 1 gallon (Figure 5-118B). The hole that is created by the pot planter is actually a soil slurry that is displaced when the root plug is pushed into it at the desired

Figure 5-118 | **Pot planter**

The pot planter creates a planting hole by injecting high-pressure water into the soil (A). Once the soil is liquefied, the container is pushed into the soil to the appropriate depth (B).

Photo credit: Chris Hoag

planting depth. Once the water drains from the slurry into the surrounding soil, the soil settles in around the root plug, ensuring good soil-to-root contact.

The advantages of using a pot planter are that the container plugs are thoroughly moistened at outplanting; there are fewer air pockets in the soil and better root-to-soil contact; and soil around the planting hole is moistened, allowing roots more time to move out of the plug and into the native soil. These advantages create the opportunity for earlier fall planting, even as early as late August to early September in some areas. The earlier the fall planting, the greater the chance for rooting to occur before winter sets in. This rooting will be in addition to the root growth that occurs the following spring and can make the difference in whether a seedling survives the first growing season. Large containers can be planted quickly at a rate of approximately one plant per minute (Hoag 2006). The pot planter is limited by the same factors as the Waterjet Stinger, which include steep slope gradients, inaccessibility, high soil rock content, and poor water source availability.

Planting into Engineered Structures—Occasionally seedlings will be planted as engineered structures are being built. These structures include vegetated gabion walls, other "green" walls (Inset 5-22). Planting should be well planned and integrated into the construction schedule. Because road construction often occurs in summer when plants are in full growth, special handling methods and irrigation should be implemented during installation to ensure optimum seedling establishment (Figure 5-119). The installation of plants into riprap, for example, requires good planning and integration into construction activities. Drawings and a set of planting instructions are essential. Seedlings are partially planted in the existing soil and partially in riprap. Riprap and soil are hand placed around the seedling plug to ensure good root-to-soil contact and that the seedlings are handled with care. The remainder of the riprap is placed and the seedlings are irrigated. Each vegetated engineered structure requires different sets of instructions and drawings that are specific to the objectives and environmental conditions of the site.

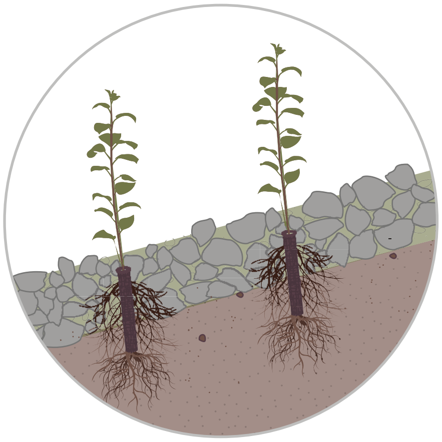


Figure 5-119 | **Plants integrated with engineered structures**

Engineered structures of gabions and riprap require tall nursery stock and special installation techniques. When properly installed, however, plants survive and grow well, greatly increasing the visual appearance of the structure.

Assess Plant Inventories

Depending on the size and scope of the project, many combinations of species, seedlots, and stocktypes may be grown at one or more nurseries. Seedling inventories from all nurseries where the stock is being grown should be consolidated into one list. Each nursery will supply a list of the quantity of seedlings in each seedlot that meet the contract specifications. This list may not exactly meet the original order. It is rare that the original seedling order ever gets filled

Figure 5-120 | **Managing plant inventories**

Spreadsheets are a good way to keep track of nursery orders and adjust plant inventories to planning needs.

Planned Seedling Needs

		Species and Stocktype				
		PIPO	POTR5	AMAL2	PUTR2	PREM
Planting Areas		2 Gal	1T18	1T12	1STP	1STP
A1		425	238	117		
A2		75	25	35	100	
B			275			50
A	Planned needs	500	538	152	100	50
B	Seedling inventory	400	435	200	125	75
C	Difference	-100	-103	48	25	25

Adjusted Seedling Needs

		Species and Stocktype				
		PIPO	POTR5	AMAL2	PUTR2	PREM
Planting Areas		1 Gal	1T18	1T12	STP	STP
A1		350	200	155		
A2		50	10	45	100	
B			255			50
A	Adjusted needs	400	435	200	100	50
B	Seedling inventory	400	435	200	125	75
C	Difference	0	0	0	25	25

exactly as requested. Some seedlots grow well, while others grow poorly, and this is reflected in the seedling inventory. There may be more seedlings in one seedlot and less in another.

Plant inventories do not always provide the full story about seedlots. Prior to putting together a planting plan, a visit to the nurseries will provide a full picture of the status of each seedlot. Stressed seedlings, poor roots, root-bound seedlings, disease, and other problems can only be realized by visiting the nursery months before plants are received. The visit to the nursery is not always a negative fact-finding mission. It should be approached as a problem-solving trip. For example, an inventory might indicate that certain seedlots do not meet size specifications. A closer review at the nursery may show that many of the seedlings that do not meet size specifications would be suitable in certain planting areas. If inventories are low, discussions with the nursery manager might bring up the possibilities of substituting surplus seedlots from other clients for the downfall in the inventory.

Match Inventories to Planting Area

At this point, the information developed during the location of planting units, including seedling density, species, and stocktype, can be reevaluated in light of the newest seedling inventory. In other words, the seedlings from the inventory should now be divided between planting areas in a manner that still meets the project objectives

Using the spreadsheet in Figure 5-120 is a simple way to reconcile the differences between the plants needed at each planting area and the plant inventory. In this example, three planting areas are defined (A1, A2, and B). For each planting area, the number of plants of each species/stocktype is listed. The planned needs are summarized in Line A. When the seedling inventory (Line B) is received, it is discovered that there will not be enough ponderosa pine (PIPO) or quaking aspen (POTR5) to meet the planned needs. The deficits are circled in Line C. In this example, seedlings can either be obtained from other sources or plant needs can be adjusted downward. In this example, the PIPO and POTR5 were adjusted downward because no substitute trees could be found to make up the difference. Saskatoon serviceberry (AMAL2) was adjusted upward as a partial substitution for the shortfall of tree seedlings. Plant spacing was recalculated from Figure 5-113 with a resulting increase of approximately 1 foot for both PIPO and POTR5. The extra antelope bitterbrush (PUTR2) and bitter cherry (PREM) were not planted (Line F) but rather surplused to a local landowner. Many more rows and columns can be added to this spreadsheet to accommodate more species and planting areas.

Transport Plants

The delivery of seedlings to the planting site is not generally the responsibility of the nursery. It can be an item in the seedling production contract, a separate transportation contract, or they can be transported by the designer. Whichever method is used, it is important that seedlings not be damaged during transportation by poor handling, hot temperatures, or drying conditions. Plants that have been packed in bags or boxes are protected from drying conditions and can be transported in most vehicles. If containers are transported in open pickups, they should be covered with a space blanket or special tarps to moderate temperatures and minimize the potential for desiccation (Figure 5-121). Specially constructed Mylar® tarps can be purchased from forestry or restoration supply companies.

Plants that have been kept in freezer storage can be thawed prior to transportation and planting. While small container stock has been shown to have satisfactory survival when planted frozen, there is no indication that large stock will perform the same. Once frozen seedlings have been thawed or cooler-stored seedlings have been allowed to warm, they can be planted immediately. Seedling viability will decrease if they are placed back into cold storage for more than a few days.

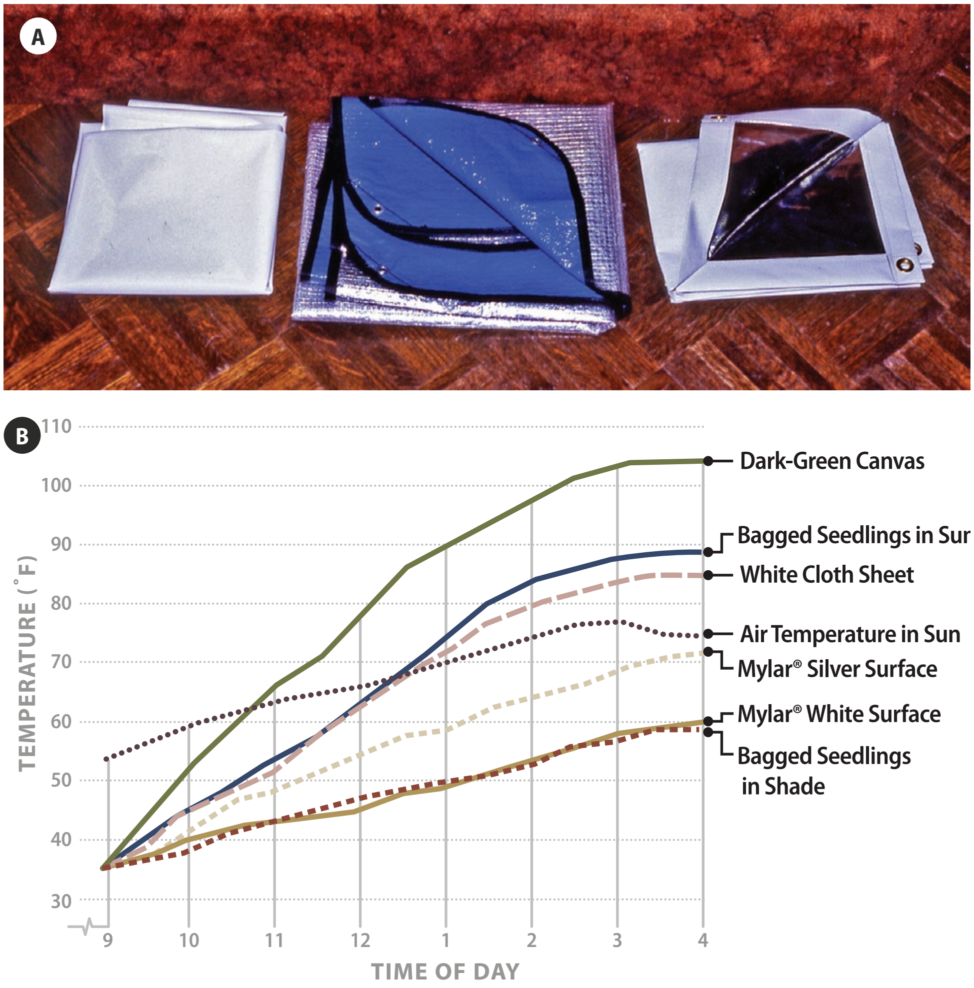


Figure 5-121 | **Protect nursery stock during transportation**

During transportation and onsite storage, nursery stock should be covered with special reflective tarps (A), which have been proven to reduce temperature buildup (B).

Photo credit: Thomas D. Landis

Plants that have not been packed in storage containers can be transported in enclosed units. Transporting plants in open vehicles, such as pickups, exposes foliage to strong, drying winds that can unduly stress the plants. Large container plants typically stand 2 to 4 feet tall (including the container) and require transportation with enough space to accommodate their size.

Develop Planting Contract

The following discussion outlines some of the basic components that should be addressed in a planting contract.

Location PREM—A map of the planting areas should be included in the contract.

Planting Quantities—The quantity of species, by stocktype, should be presented for each planting area.

Planting Method—There might be several planting methods that should be indicated for each stocktype and planting area.

Plant Spacing Requirements—For each planting area, describe or define the plant spacing at which each species will be planted. Calculations to determine the proper spacing between plants was presented in Figure 5-112. Approximate distance between plants can be determined graphically by knowing the target plants per acre, and, in reverse, the plants per acre can be determined by knowing the target spacing between plants (Figure 5-122). For example, if the plan calls for a density of 600 seedlings to be planted per acre, the spacing between plants would be around 8.5 feet (Line A in Figure 5-122). If the plan calls for 600 seedlings to be planted in planting pockets of three plants per pocket, there would be 200 planting pockets spaced approximately 15 feet apart (Line B in Figure 5-122). In another example, to determine the number of seedlings to order for a given area with a target spacing of 6 feet, the number of plants required would be just under 1,100 seedlings (Line C in Figure 5-122).

These spacing requirements are an average. Depending on the plantability of a site, the specified average spacing may vary up to 25 percent in any direction to find a suitable planting spot. Where an unplantable spot is encountered, the planter will plant in the closest plantable spot. Whenever possible, plants should be installed next to stumps, logs, or other obstacles that provide partial protection from sun, wind, and animals. If planting islands are designed into the planting areas, each island should be marked within the planting area by the contract inspector and the species mix should be stated in the contract.

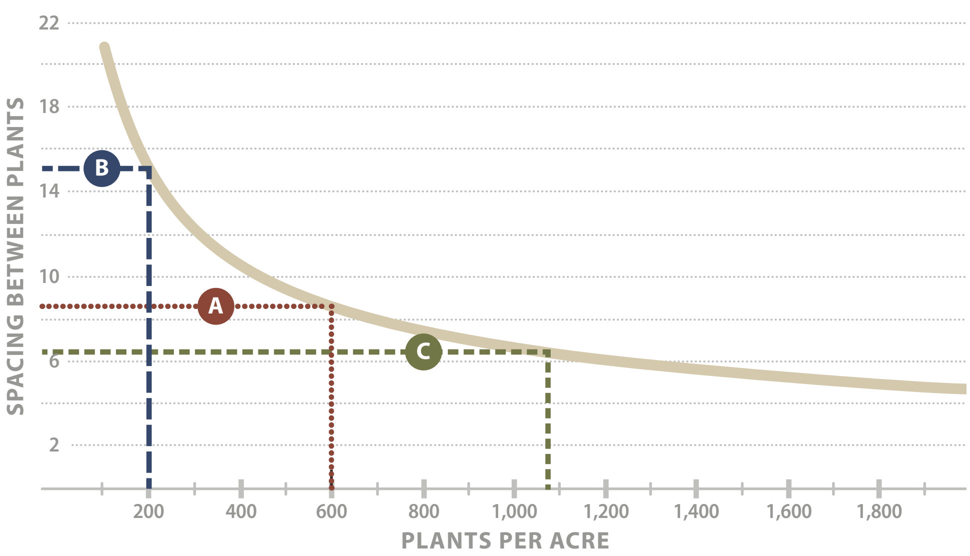


Figure 5-122 | **Estimating spacing between plants**

Approximate distance between plants can be determined from this graph by knowing the target plants per acre, and, in reverse, the plants per acre can be determined by knowing the target spacing between plants.

Figure 5-123 | **Healthy root structure is important**

Roots will circle and accumulate at the bottom of some container types (A), especially if the stock has been held too long. Pruning these roots at planting will ensure that new roots will promptly grow out into the surrounding soil (B).

Photo credits: Thomas D. Landis

Handling Care—Plants should be handled with care to prevent damage to roots and foliage. Seedlings should not be thrown, dropped, hit, or otherwise mechanically impacted. Extracting the root plug from the container can be done gently, avoiding excessive force when pulling the seedling from the container. Seedlings should not be removed from containers until the hole is excavated. The container is then removed, and the seedling is quickly planted. Excessive exposure of the root system to air will decrease seedling survival and growth (Greaves and Hermann 1978).

Root Pruning—The bottoms of some containers are poorly designed, causing roots to circle or build up at the bottom of the pot (Figure 5-123A). However, quality nurseries will typically not use these inferior containers. But if these containers are utilized, damaged roots can be cut prior to planting to prevent potential root strangling, especially for tap-rooted woody species (Figure 5-123B). Root pruning is best accomplished at the nursery, but this should be stated in the growing contract to cover the added expense. Pruning in the field is not recommended because of the increased root exposure. However, it may be necessary when nursery stock arrives with constricted roots.

Container Moisture—Root plugs that are dry should be thoroughly moistened prior to planting. Irrigating seedlings at the nursery several days before shipping and again on the day of shipping ensures that root plugs are completely wet. These instructions should be conveyed to the nursery manager prior to picking up the seedlings. Provisions can be included in the contract that addresses the need for wetting root systems should they be dry at the time of planting. Wetting rootplugs can be accomplished by dipping seedling containers into a large water container, such as a cattle trough or trash can, prior to planting. Planting seedlings using the pot planter ensures that the root plugs are wet at planting.

Temporary Storage—If container plants cannot be planted in one day, they can be stored in the field in a well-sheltered area protected from the sun and animals. Reflective tarps are recommended to keep plants cool and moist during on-site storage (Figure 5-121). If container plants are left out for several days, the root plug should not be allowed to dry out. If they do lose moisture, the containers should be irrigated prior to planting. Plants that have been extracted and placed in storage boxes or bags should not be left on-site but returned to a local cooler for storage.

Planting—Prior to preparing the planting hole, the planters should clear the surface of the planting spot of all limbs, logs, snow, duff, litter, rocks, and other loose debris. If sod, crowns of living plants, and roots are present, they should be scalped down to moist mineral soils.

Clearing and scalping dimensions should be stated in the contract. Planting holes should be located near the center of the prepared planting spot and be dug vertically rather than perpendicular to the ground surface. The planting hole should be 3 to 4 inches deeper than the total length of the root system or root plug, and wide enough to fully accommodate the width of the root system. Seedlings should be placed in the hole so that the cotyledon scar (the bump or constricted area on the seedling stem that is the transition from the root system to the stem) is 1 inch below the ground line. Species that can be rooted from cuttings can be planted deeper because portions of the stem will root when buried. The root plugs should not be forced into the planting hole, distorted, or broken during planting. After placing the plant in the hole, excavated soil is placed firmly around the root system so there is no loose soil or air pockets around the root plug. The root system should not be damaged during this operation. A small circular water-holding basin can be created around each seedling after planting to capture water or store irrigation water.

Administer Contract

The planting contract inspector should schedule the shipment of seedlings from the nursery, be certain that root plugs are moist and ready for planting, have the right quantities of plants at each planting area, and inspect the contract. In addition, if there are special planting patterns designed for the planting area, these may need to be marked on the site prior to planting.

The planting inspector should determine if the conditions are favorable for planting. Seedlings should not be planted into dry soil unless the planting spot is irrigated immediately after planting or the pot planter method is being used. Under certain circumstances, high moisture soils follow geomorphic features, such as creek or river terraces where high ground water brings moisture to the soil surface. These sites can be identified on the ground at the time of planting.

Monitor Planting Success

Valuable information can be obtained by monitoring nursery stock for several years after planting. The first few months are critical because nursery plants that die immediately after outplanting indicate a problem with nursery stock quality. Plants that survive initially, but gradually lose vigor, indicate poor planting or drought conditions. Therefore, plots can be monitored during and at the end of the first year for initial survival. Subsequent checks after three years will provide a good indication of plant growth potential (Figure 5-124). This performance information is then used to provide valuable feedback to the nursery manager, who can fine-tune the target specifications for the next crop.

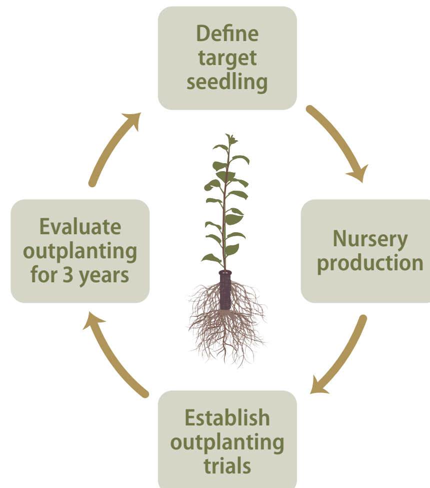


Figure 5-124 | **Monitoring outplanting results informs future decisions**

Monitoring the survival and growth of nursery stock for several years after planting provides valuable information for future projects.

5.5 POST-INSTALLATION CARE OF PLANT MATERIALS

The first year after plant materials are installed on a project site is typically the most critical period in a revegetation project because this is when plants become established. Applying the appropriate mitigation measures to improve the site and soil conditions prior to installation of plant materials greatly increases the chances of plant establishment. Sometimes even these measures are not enough to overcome limiting site factors. The implementation guides in this section cover several post-installation measures that can be conducted to increase the potential of plant establishment.

Establishing plants from nursery stock is often limited by animal browsing. Section 5.5.2 covers the methods available for protecting plants from different forms of animal damage. On hot, dry sites, plants need to be shaded from mid- to late afternoon solar radiation. The application of shade cards (Section 5.5.3) is one method for protecting young plants from heat stresses. Moderating the climate around plants from extreme temperatures and high evapotranspiration rates is sometimes accomplished through the use of tree shelters. Section 5.5.4 outlines when these structures are used, product types, and how they are applied. Some projects require supplemental irrigation for establishing seedlings on extremely dry sites. Section 5.5.5 discusses two types of irrigation used in revegetation projects: deep pot irrigation and drip irrigation.

5.5.1 INTRODUCTION

The first several years after the installation of seedlings are critical for the survival of healthy nursery plants. In the western United States, nursery plants die because of animal damage, high surface temperatures, high evapotranspiration rates, lack of soil moisture, and vegetative competition. This section describes certain steps to reduce these impacts. Where animal browsing is high, fencing, netting, and animal repellants are important to consider (Section 5.5.2). For high surface soil temperatures shade cards can be used to protect seedlings (Section 5.5.3). Reducing evapotranspiration rates is achieved using tree shelters (Section 5.5.4) and shade cards. Some high visibility projects require fast growth rates and low risk in plant establishment, in which case irrigation can be considered (Section 5.5.5). Additional measures that benefit seedling survival are covered in other sections. These include applying fertilizer, mulches, and beneficial organisms. (Section 5.2.1, Section 5.2.3 and Section 5.2.7).

5.5.2 ANIMAL PROTECTION

Planted seedlings can be damaged by a variety of animals, including cattle, deer, elk, gophers, and voles. While some damage by animals can be expected, excessive damage should be prevented. A variety of methods can be used to protect seedlings, including rigid and non-rigid netting, fencing, and animal repellents.

Netting

A common practice for protecting seedlings from browsing animals is to install a plastic netting over each seedling. The netting acts as a barrier to foraging of foliage, stems, and even root systems without impeding plant growth. It has been used to protect seedlings from deer, elk, gophers, and other ground-burrowing animals.

The two general types of netting are rigid and non-rigid. Non-rigid netting is a soft, fine-mesh plastic material. When installed on a seedling, it fits snuggly around the foliage like a sock. The rigid netting (Figure 5-125) has larger mesh openings and holds its form when installed. Rigid netting, while typically more expensive, is usually preferred over non-rigid because it is easier to install and seedling growth inside the netting is less restricted.

Netting should be installed as soon after planting as possible to ensure immediate protection. If installation occurs after bud break, care should be taken not to break or damage the terminal leaders or buds. Rigid netting is held in place with one or two bamboo stakes woven through the netting at three places and driven into the soil at a minimum depth of 8 inches. For deer and elk protection, netting is placed so the height of the netting is several inches or more above the terminal bud. Non-rigid netting is simply placed over the foliage like a sock and not secured with stakes. Rigid netting can offer some protection from gopher damage if the netting is installed more than several inches below the surface of the soil (Figure 5-125).

The effectiveness of netting decreases as the terminal leader grows out of the rigid netting and become susceptible to browsing. At this point, the netting can be repositioned upward to protect the terminal leader, which requires annual maintenance. At some point, netting should be removed entirely to avoid restricting seedling growth and ultimately killing the seedling. Some netting has been manufactured with photodegradable material that will break down within several years, eliminating the need for removal. Nevertheless, sites that have had any type of plastic netting installed on seedlings should be visited several years after planting to determine whether the plastic netting is degrading or needs to be removed.

Figure 5-125 | **Rigid netting**

Rigid netting can protect seedlings from deer, elk, and gopher damage. The netting in this picture was installed 3 inches below the ground line to protect the seedling from gophers while the foliage and terminal leader are protected from deer and elk browsing.

Photo credit: David Steinfeld

Fencing

Fencing is often used to protect planted or seeded areas from wild ungulate and livestock grazing or trampling. Each group of animals requires different fencing specifications. Fence height for wild ungulates requires 8 to 12 feet (Helgerson and others 1992), while fence height for livestock is 4 to 5 feet. Fences should be installed prior to seeding or planting to ensure optimal plant establishment.

Fencing entire planting or seeding areas is expensive to install and maintain. Maintenance should be given high priority because one break or opening in the fence will place the entire project at risk. It is recommended that fences be monitored and maintained at least weekly and up to three times per week during peak browse season (Greaves and others 1978). Fences can be designed with one or more gates to allow domestic or wild ungulates or other species to escape if they become trapped.

An alternative to fencing entire planting areas is to fence strategically located areas, such as planting islands. Fenced areas, called exclosures, range in diameter from 6 to 15 feet and are typically constructed with a 14-gauge, galvanized welded wire mesh (2- by 4-inch openings). Fence heights can be reduced around small diameter exclosures because wild ungulates are less likely to jump into small areas (Gobar 2006). In this strategy, the smaller size and greater number of exclosures reduce the risk of a failed project. After seedlings have grown high enough to withstand grazing and browsing pressures, small enclosures should be removed.

Animal Repellent

Browsing by deer and elk can be temporarily controlled by applying animal repellents to the foliage of seedlings. A variety of repellents are on the market with varying degrees of effectiveness. Trent and others (2001) tested 20 products for effectiveness in reducing deer browse on western red cedar (*Thuja plicata*) seedlings and found that products emitting sulfurous odors were the most effective. These products contain active ingredients such as "putrescent whole egg solids" or "meat meal." Less effective products were those causing pain or irritation, containing active ingredients such as capsaicin, garlic, and dlimonene. Of the products tested, the least effective repellents protected seedlings for a few weeks, while the most effective protected seedlings for up to three months. Because seedlings are generally more palatable after winter dormancy, deer repellents should be applied just before bud break (Helgerson and others 1992) and at several month intervals during the active growing period as needed. Animal repellents in a hydrophilic powder formulation are reported to adhere better and last longer in climates with high rainfall than liquid forms (Helgerson and others 1992). Additionally dyes can be incorporated to indicate the presence of these repellents which be useful to monitor application patterns.

5.5.3 SHADE CARDS

Because high soil surface temperatures can limit seedling survival and growth, it is important that the stem of the seedling (where heat buildup occurs and causes the most damage) is shaded from the sun (Childs and Flint 1987). Seedlings can be planted next to obstructions, such as logs, to utilize the shade these structures provide. Unless the placement of obstacles is planned into the project, construction sites will usually be free of material large enough to cast shadows. An alternative, but less effective, method of creating shade is using shade cards. Shade cards small, easy-to-install structures that shade the lower portions of the seedling from surface soil temperatures (Figure 5-126). Tesch and Helms (1992) reviewed numerous studies that evaluated the effects of shade cards on planted seedlings and found that, while the use of shade cards can significantly improve seedling survival, they should only be considered on sites where several revegetation conditions are suboptimal, including south-facing aspects, sites with high winds, or when planting small, poor quality stock.

Figure 5-126 | **Shade cards**

Shade cards are placed on the south side of the seedling so the shadow cast by the shelter protects the lower portion of the seedling. This photo was taken two years after shade card placement.

Photo credit: David Steinfeld

To be effective, shade cards should be installed in the spring after planting and before hot weather sets in. It is important to know where the shadow of the installed shade card will be cast in order to know where to place the card. The shadow should cast shade on the stem and lower portions of the seedling to protect these areas from high surface temperatures during the hottest portion of the day (Childs and Flint 1987). The length of the shadow is dependent on the longitude, date, time of day, slope angle, and height of the shade card. Improper installation of shade cards is a common mistake, which typically occurs when cards are placed on the wrong side of the seedling. Card installers should be aware of the cardinal directions at all times during the day, which can be difficult on cloudy days. For this reason, contractors and inspectors should use a compass when installing cards and inspecting contracts. Another common mistake is not placing the shade card close enough to shade the base of the seedling during the hottest time of the day. Shade cards are also used to protect seedlings from strong, drying winds that create high moisture stress for establishing seedlings. Typically, shade cards are placed on the windward side of the seedling to deflect the wind. It is important to know the direction of the strongest or hottest wind in order to properly install the shade cards. For example, on a site with strong, drying winds coming up-valley in the afternoon, two shade cards would be installed at a 90-degree angle to each other on the down-valley side to enclose the seedling.

Shade cards are made from shingles, cardboard, tarpaper, and polypropylene mesh. Selecting the appropriate shade card for the site can be based on how easy the shade card is to install, the weight, dimensions, life span, and costs. Drawbacks to the use of shade cards are the visual impact on the site and the fact that they should be removed after several years.

5.5.4 TREE SHELTERS

Tree shelters are translucent plastic tubes that are placed around seedlings after planting (Figure 5-127). They benefit seedling establishment by creating a favorable growing environment while shielding the seedling against animal damage. Tree shelters enhance plant growth by creating a microclimate similar to a mini-greenhouse, which has lower light intensities, higher temperatures, and higher relative humidities (Applegate and Bragg 1989; Jacobs and Steinbeck 2001). On high elevation sites, tree shelters increase above-ground temperatures and extend the growing season (Jacobs and Steinbeck 2001). Seedling survival and growth are enhanced by tree shelters on some sites because increased condensation on the inner shelter walls during the evening drips into the soil and increases soil moisture (Bergez and Cupraz 1997). On windy sites, tree shelters protect seedlings from wind damage and blowing sands (Bainbridge 1994). In addition, tree shelters protect seedlings from large game, gophers, rabbits, voles, and grasshoppers (Tuley 1985; McCreary and Tecklin 1997; Jacobs and Steinbeck 2001).

Where to Use—Tree shelters can be considered for sites where the potential for animal damage is extreme and seedling survival and rapid seedling growth are essential. These sites include, but are not limited to, sites with the following characteristics:

- Gopher or vole damage
- High elevation
- High winds
- Hot and dry
- High solar intensity
- Low water-holding capacity soils
- “One-shot” planting

Drawbacks—Tree shelters are not intended for all species or site conditions. Several studies have shown that, under certain climates, seedlings grown in tree shelters are more susceptible

Figure 5-127 | **Corrugated plastic tree shelter**

Corrugated plastic tree shelters create a microclimate around seedlings to enhance moisture and temperatures for seedling growth. In addition, they protect plants from animal browsing.

Photo credit: David Steinfeld

to low temperature extremes than those grown in the open (Svihra and others 1993; Kjelgren and others 1997). These conditions occur in the late winter and early spring on some sites when warmer daily temperatures in tree shelters induce earlier bud break and stem dehardening, leaving seedlings more susceptible to cold temperatures. Air temperatures can also be colder at night in tree shelters on some sites because tree shelters can potentially trap cold air near the ground surface (Swistock and others 1999). On the opposite extreme, extremely high temperatures in the summer can be reached inside the shelters during mid-day, which might be detrimental to seedling growth. For these reasons, installing tree shelters should be done with some understanding of the effects that the shelters will have on each species to be planted and the climate of the site. Small trials, prior to installation, can point out potential problems.

In visually sensitive areas, tree shelters do not blend well with natural backgrounds. Depending on the species and the site, tree shelters might have to remain around plants for up to five years. In addition, long-range planning for shelter removal is critical; without removal, the stem of the plant can be restricted.

Installation—Installing tree shelters may be done during or immediately after planting to protect seedlings from animal damage. Tree shelters are usually delivered in stacks of plastic sheets. They are assembled on site into cylinders that are placed over the seedling and held upright with a stake (Figure 5-127). The stake is driven into the soil so that the bottom of each cylinder is in direct contact with the soil surface. If burrowing animals are a problem, shelters can be installed several inches below the soil surface. This is an effective control of gophers and voles (McCreary and Tecklin 1997; Jacobs and Steinbeck 2001). Netting is sometimes placed over the opening of the shelter to prevent birds and lizards from becoming trapped (Bainbridge 1994). Rigid tubing can be placed over the top of the tree shelter to protect the emerging foliage from deer and elk browse (Figure 5-128). Tall tree shelters require very strong stakes anchored firmly in the soil to withstand strong winds. As the shelters are installed, care should be taken to avoid skinned bark, damaged buds, or broken leaders. Where moisture is a limiting factor, weeding the vegetation from around the shelters is essential. Seedlings competing with weeds are unlikely to take advantage of the water saved by a tree shelter (Bainbridge 1994; McCreary and Tecklin 1997).

Figure 5-128 | **Rigid tubing tree shelter**

Rigid tubing can be installed over the top of the tree shelter to protect seedlings from larger browsing animals.

Photo credit: David Steinfeld

Maintenance and Removal—Installed properly, tree shelters require little maintenance. Nevertheless, sites where tree shelters are installed should be inspected annually to assess seedling conditions in the tree shelter and determine if any maintenance is needed. Because yellow jackets and other animals create homes inside tree shelters, it is wise to be cautious when conducting inspections.

Tree shelters create growing conditions that favor seedling height growth over stem diameter growth (Figure 5-129). Because tree shelters physically support the seedlings while they are growing, the seedling directs more of its energy into growing up to the light and less into the stem. Tree shelters should not be removed until a portion of the seedling crown has grown out of the shelter. If the tree shelter is removed while it is still growing inside the shelter, the seedling will not be capable of supporting itself. Once the seedling has emerged from the shelter, stem diameters will continue to increase as the foliage acclimates.

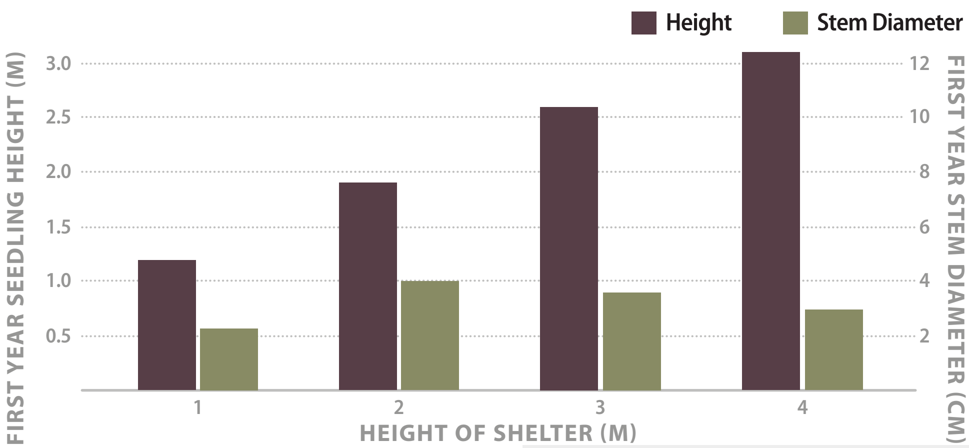


Figure 5-129 | **Effects of tree shelters**

A study conducted with Australian red cedar (*Toona australis*) on a warm, moist site in North Queensland showed that, as taller tree shelters are used, first-year shoot growth increases. Stem diameters, however, do not change (Applegate and Bragg 1989).

Available Products—Tree shelters are available in a variety of shapes, sizes, colors, and styles from companies that specialize in reforestation, restoration products, or grape growing.

Color—Color and translucency of the plastic are important characteristics for selecting a tree shelter. Brown-colored tree shelters greatly reduce solar radiation and, in one study on a high elevation site, were shown to drastically decrease seedling survival of Engelmann spruce (*Picea engelmannii*) (Jacobs and Steinbeck 2001). On hot, dry sites, however, reduced radiation might benefit seedlings. Oak seedlings (*Quercus* spp.) planted in a semi-arid environment performed best in short, brown-colored shelters because of reduced daily temperatures (Bellot and others 2002).

Lighter-colored tree shelters allow greater solar radiation to reach the seedling but can also heat up when they are exposed to direct sunlight. Highly translucent tree shelters can be considered where light is limiting. Low translucent shelters might be more appropriate for sites where solar radiation and mid-day temperatures are high in order to reduce the potential for overheating.

Material—Tree shelters are made from translucent plastic for light transmission and are built with different degrees of sturdiness. Corrugated tree shelters are the sturdiest and are used on sites with strong winds. Corrugated materials are also used in taller tree shelters for added support (Figure 5-127), and thin plastic can be used in shorter shelters. Tree shelters are typically designed to degrade in five years, but in many cases they do not. Many shelters can therefore be reused, which will reduce project costs.

Ventilation—Without ventilation, tree shelters will build up heat on warm days, especially if they are in direct solar radiation. Maximum daily summer temperature in shelters can be 8 to 16 degrees C (15 to 30 degrees F) higher than ambient air temperatures (Steinfeld 2005). Extreme temperatures can be reached on days where ambient air temperatures exceed 38° C (100° F). For these sites, shelters with some form of ventilation, such as holes, should be used. Ventilated tree shelters have been shown to reduce maximum daily shelter temperatures by 3° C (5° F) (Swistock and others 1999). Where ventilation is needed, taller shelters will require more ventilation than shorter shelters.

A ventilated tree shelter may restrict carbon dioxide in the area around the seedlings, which would be a further consideration for ventilation. Some studies have shown that carbon dioxide is very low in shelters (Dupraz and Bergez 1997). However, other studies that have shown higher levels of carbon dioxide within shelters than outside (Frearson and Weiss 1987).

Size—Selecting the size of the shelter should be based on the anticipated growth rates of the species planted and the anticipated animal damage. Shelter heights range from 1 to 9 feet and diameters up to 6 inches. To obtain the greatest benefit from tree shelters, the shelter height should not exceed the maximum seedling growth in the first year. Fast-growing species can have tall shelters; shorter shelters can be used for slow-growing species. Ideally, the shelter height should be greater than the browsing level of the foraging animal. For example, tree shelter heights in deer browse areas should be at least 4 feet tall so that new seedling growth from the top of the tube is not severely browsed back. Extending the protection of the tree shelter can be done by using a rigid netting placed over the top of the shelter. Large shelters can be cut into any height or diameter needed for the project. Very small shelters (less than 6 inches tall) can be used around germinating seeds to protect them from small animals and create a micro-climate for germination (Figure 5-130).

Costs—Tree shelters can be an expensive addition to a revegetation project. The high costs to purchase, assemble, install, maintain, and remove shelters should be considered against the benefit of increased survival and growth. On projects where smaller, less expensive seedlings are being planted, the cost savings from not planting larger stock can offset the installation of tree shelters. Assuming that tree shelters increase seedling survival, fewer seedlings would need to be planted, and these savings could offset the costs of installing tree shelters. Where quick establishment of vegetation is the objective, the use of tree shelters should be considered.

Figure 5-130 | **Tree shelters and germinating seeds**

Small tree shelters can be placed around germinating seeds to enhance germination and early seedling establishment, as shown in this photograph of an establishing California black oak (*Quercus kelloggii*) seedling in a tree shelter made out of xray film.

Photo credit: David Steinfeld

5.5.5 IRRIGATION

A wide range of irrigation methods and techniques are available to the designer, ranging from simple to elaborate, and from modestly priced to costly. Because irrigation is often a very expensive component for most revegetation projects, the decision to irrigate, and subsequently the selection and design, should be integrated into the objectives of the road project during the planning stages. The most common reason for irrigating in the western United States is to aid in seedling survival during the first several growing seasons. Those sites that have low soil water-holding capacities, high evapotranspiration rates, or low summer rainfall meet these criteria. Irrigation is also used when the project objectives call for a quick establishment of vegetation for visual screening, erosion control, or slope stabilization. Roadside irrigation is almost always a temporary measure, often spanning a maximum of three years. Therefore, elaborate or expensive irrigation systems are not often the best choice for these situations. Low-tech systems, requiring minimal maintenance, tend to be more appropriate for wildland restoration.

The challenge in wildland irrigation is the timing and placement of water in the soil. An irrigation system that delivers water when the plant is less likely to need it is wasteful and can be detrimental to the seedling. A system or schedule that applies water when the plant requires it for survival or growth is most cost effective and beneficial for seedling survival and growth.

Developing irrigation schedules based on plant needs is an essential part of using irrigation for establishing plants, and those needs change based on the species being established, nursery stocktype, soils, and climate. Supplemental irrigation strategies are tailored to the vegetation requiring irrigation. For example, during prolonged drought, areas seeded with forbs and grasses may require supplemental surface irrigation whereas tree seedlings may require deep watering. Within a lager revegetation project specific plantings may require supplemental irrigation because of site-specific characteristics such as topography. For example, plantings in fast-draining areas such as ridgelines or wares with shallow soils may require more irrigation than plantings in the bottom of swales were water naturally collects.

Placing the water in the soil profile where it can be directly accessed by much of the root system is critical for efficient use of an irrigation system. Some irrigation systems moisten more of the soil profile than will be accessible by the establishing root system, and water is consequently wasted. Other ineffective systems barely wet the soil surface, leaving the applicator satisfied but the roots without water. The objective of an efficient and effective irrigation system in wildland settings is to deliver only the amount of water needed, when and where it is needed for seedling survival and growth.

For the Designer
Shallow-rooted species such as grasses and forbs require water near the soil surface and irrigation practices should provide water to this shallow area.

Tree and shrub seedlings survive by growing roots down into the soil profile to access moisture at deeper portions of the soil profile than annual grasses and forbs. Deep placement of water for these species is far more important than surface soil moisture. In spite of this, many irrigation systems, such as drip, basin, and overhead sprinklers, deliver water through the surface, wetting soil where it is not needed and encouraging weeds and other competitive plants to establish and thrive. Furthermore, surface irrigation does not always ensure moisture will be evenly delivered to the deeper portions of the soil where the roots of trees and shrubs are growing. Soil structure and texture affect the wetting-front patterns of surface-applied irrigation water. If the soil is compacted, the amount of water that is delivered to the lower rooting zone can be reduced. A better method of water delivery to the root zone of trees and shrubs is to bypass the surface of the soil completely.

For the Designer
Deep-rooted species such as trees and shrubs require water well below the soil surface where the roots are growing. Successful approaches to irrigating these species delivery water deep under the soil surface (see below).

Deep Pot Irrigation

Several irrigation methods have been developed for arid land revegetation that bypass the soil surface and deliver water directly to the root zone. These systems include deep pot, porous hose, and wick irrigation methods (Bainbridge 2006a). Because these systems deliver water directly to the soil profile where roots are actively growing, far less water is required. Deep pot irrigation (Figure 5-131) appears to be the most effective and practical method for irrigating planted seedlings in arid environments (Bainbridge 2006b). This system has been found to be three times more effective at increasing seedling survival than surface irrigation using the same amount of water (Bainbridge and others 2001).

Deep pot irrigation delivers water to the root system through a pipe positioned next to the seedling (Figure 5-131). The pipe is either filled periodically by hand or through an installed drip irrigation system. The soil is moistened as water drains through both the bottom of the PVC pipe and the holes drilled in the sides. The amount of water delivered to the soil depends on the size of the pipe and how much water is applied. Deep pot irrigation pipes are typically made from PVC pipes, although most pipe or tubing material can be used. Pipe diameters range from 0.5 to 3 inches. Pipe lengths range from 8 to 18 inches, depending on the stocktype and water volume to be delivered. A seedling with a short root plug will require a shorter pipe, whereas a longer root plug will require a longer pipe. The bottom of the pipe should be positioned no deeper than the length of the root plug so the wetting front moves around the bottom and lower portions of the plug where it can be accessed by new, advancing roots. The top of the pipe is screened to prevent animal entry and is placed several inches above the level of the soil.

The diameter of the pipe will determine the quantity of water that can be delivered at any one irrigation (Figure 5-132). Given the same pipe lengths, a 2-inch-diameter pipe holds 4 times the amount of water as a 1-inch pipe, and a 3-inch-diameter pipe holds 8 times the amount of water. Because filling pipes is expensive, determining the proper diameter is important. Oversized pipes will deliver a wetting front that extends beyond where it can be accessed by the root system and water will be wasted. Pipes that are too small will not fully wet the area around the advancing rooting zone, requiring more frequent irrigations. Pipe size and irrigation frequencies depend on the factors described below.

Soil Type—Sandy or rocky soils have low water-holding capacities, causing wetting fronts to travel deeper and in a narrower band. Less water but more frequent irrigations are needed in these soils. Pipes should be placed closer to the root plug to ensure the wetting front reaches the root system. Finer textured soils, such as loams and clays, have a higher water-holding capacity and wider wetting fronts. More water can be applied in these soil types and at less frequent intervals than with sandy soils.

Stocktype—Large stocktypes have greater root volumes and greater above-ground vegetation to support than smaller stocktypes; therefore, they require more irrigation water. However, smaller stocktypes could require more frequent irrigation.

Seedling Quality—Healthy seedlings grow new roots quickly and can access deeper soil moisture. Poor quality seedlings are slow to initiate roots and therefore should be irrigated more frequently.

Competing Vegetation—Where undesirable vegetation is growing near planted seedlings, soil moisture is depleted sooner, requiring more frequent irrigation than if seedlings were free from competing vegetation.

Species—Every species has unique rooting patterns, growth rates, and water needs. Those that grow roots quickly and have a higher rate of water withdrawal require larger, deeper pipes and more frequent irrigation. These species include many fast-growing riparian species such as cottonwoods, willows, and maples. For more information, contact the nursery manager growing the species of interest. They are familiar with root growth and water needs by species.

The volume of the pipes and frequency of irrigation will determine the type of water delivery system to use. Sites that need frequent irrigation and high volumes of water per plant could require water delivery through a drip system (Section 5.5.5, see Drip Irrigation). For most projects, however, pipes can be economically watered by hand using backpack spray equipment or fire bladder bags. Bladder bags hold approximately 5 gallons of water and can be filled from water trucks or large water containers positioned in pickup beds. Assuming that an irrigator

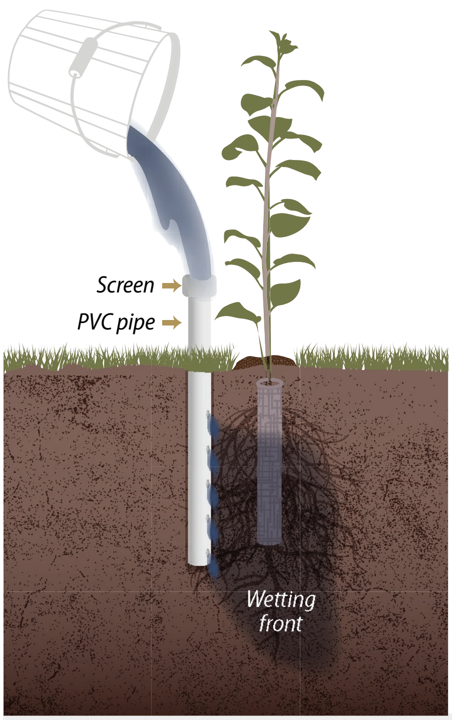


Figure 5-131 | **Deep pot irrigation**

Deep pot irrigation uses an open ended PVC pipe placed next to a planted seedling. Small holes (1 mm) are drilled 2 to 3 inches down the pipe and positioned toward the root system. A screen is placed over the top of the pipe to keep animals out. The size of the pipe and placement are designed to deliver the appropriate amount of water to actively growing roots (modified after Bainbridge 2006b).

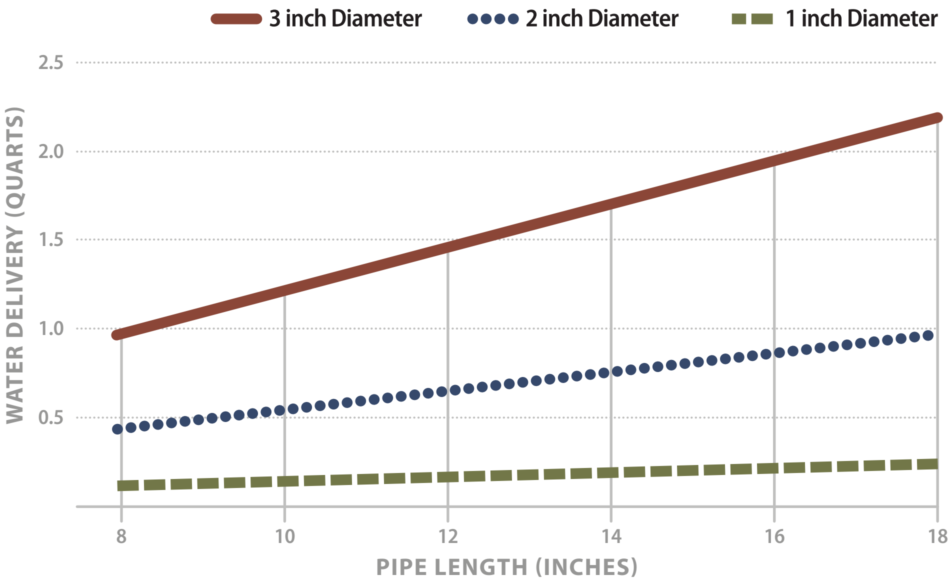


Figure 5-132 | **Water delivery**

The maximum amount of water that can be delivered to a root system in a single irrigation (y axis) is determined by the pipe length (x axis) and the diameter of the deep pot (lines). For example, a 14-inch pipe with a 1-inch diameter will hold approximately 0.15 quart of water; a 2-inch-diameter pipe will hold 0.75 quart; a 3-inch-diameter pipe will hold 1.7 quarts of water.

can carry 20 quarts of water at a time (5 gallons) and each plant in the project requires a quart of water, the applicator could irrigate 20 seedlings before returning for more water. If less water is required, more plants could be irrigated before refilling is necessary.

Deep pot irrigation allows for the introduction of soluble fertilizers (Section 5.2.1) and mycorrhizal fungi inoculum (Section 5.2.7) if seedlings require these treatments. Because soluble fertilizers are delivered directly to the roots bypassing the soil surface, weeds are not encouraged to grow. Care should be taken when determining fertilizer rates to avoid increasing soluble salts above levels that are toxic for root growth. Salt levels and pH of the irrigation water should be monitored to ensure that salts do not exceed toxicity levels for plant growth (Section 3.8.4, see Salts).

Determining when to irrigate can be based on the plant moisture stress (PMS). An accurate method for determining PMS is using a pressure chamber (Inset 5-23). This equipment reads plant stress (in negative bars) at the time of the readings. PMS readings should be made in the early morning, prior to sunrise, when diurnal PMS is at its lowest. Five seedlings should be collected in one area and averaged per site. If pre-dawn PMS readings are less than -15 bars, seedlings are under high moisture stress and should be irrigated soon to keep the seedlings from dying. If the objective of irrigation is for fast seedling growth, then PMS during plant growth (spring and fall) should be kept above -5 bars. PMS equipment is expensive to purchase. However, many USFS district offices use and maintain this equipment.

Drip Irrigation

Drip (or low pressure) irrigation is generally a temporary measure to help establish roadside plantings. It is typically used for one or two seasons to establish nursery-grown plants and then removed. Setting up drip irrigation might be considered extravagant. For projects where there is no tolerance for seedling failure, this can be a viable, economical alternative (Bean and others 2004).

Some advantages of using drip systems for roadsides are water efficiency, system flexibility, portability, and ease of application of soluble fertilizers. The main disadvantage is the high maintenance required to keep the system operational. Drip systems are composed of numerous points where failures can occur: storage tanks, burst end clamps, connectors, emitters, and hundreds of feet of pipe and drip irrigation tubing. For this reason, the system should be inspected and maintained regularly during the summer to ensure that all seedlings are being properly irrigated. This involves inspecting all emitters, pipes, tubing, and tanks. Emitters clog with sediment and insects (Bainbridge 2006c); animals gnaw through tubing when it is

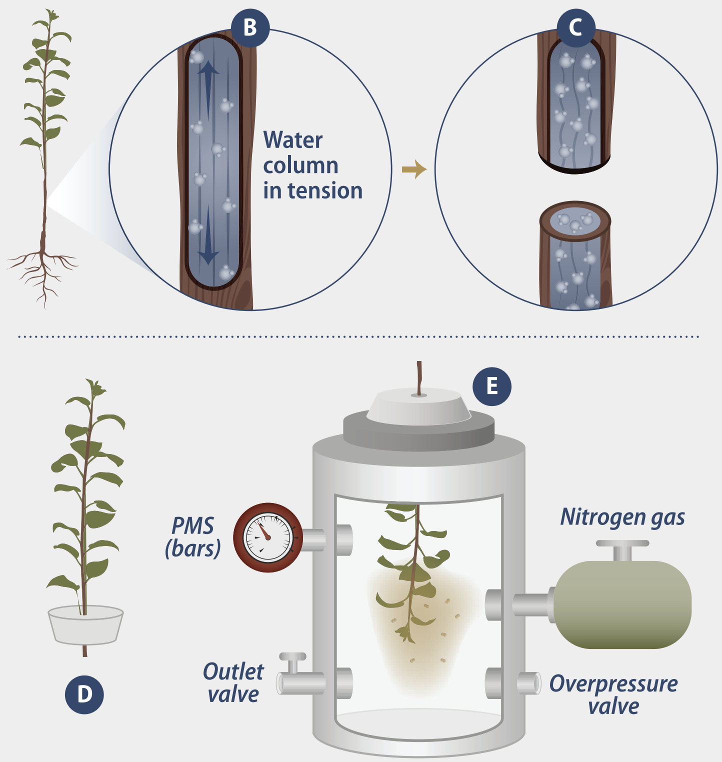
Inset 5-23 | **Measuring plant moisture stress**

Modified from McDonald 1984

Measuring plant moisture stress (PMS) with a PMS meter (A) is an accurate method to help determine the water needs and status of a plant. When a seedling is under moisture stress, it is pulling water from the soil through the stem. The water in the stem is under tension, much like a rubber band that is being stretched (B). When a small branch is cut, the tension in the stem is released and the water shrinks back from the cut surface (C). The further back the water shrinks, the more moisture stress the plant is under. The cut end of the stem is placed through a small hole in a stopper, with the end protruding from the lid (D). The foliage is placed in the steel chamber and tightened so it is airtight (E). Nitrogen gas is slowly applied into the chamber, exerting pressure through the stomata and pushing water through the stem toward the cut end. When the water just begins to emerge from the cut end, a pressure reading is made. This is the amount of suction or stress that the seedling is under at the time the sample was collected. Because PMS varies throughout a 24-hour period, seedling samples should be taken in the pre-dawn for consistency and comparison purposes.

PMS readings can be used to determine when to irrigate seedlings. If pre-dawn PMS readings are greater than -15 bars, seedlings are under high moisture stress and should be irrigated soon to keep the seedlings healthy. If the objective of irrigation is for fast seedling growth, then PMS during the plant growth (spring and fall) should be kept below -5 bars. PMS equipment is expensive to purchase; however, many USFS district offices use and maintain this equipment.

Photo credit: Thomas D. Landis



above ground; and plastic water tanks make great shooting targets. These types of damage to the system should be repaired before each irrigation cycle. Another disadvantage is that, on hilly sites, the system should be designed to maintain the correct pressure to each emitter.

In its simplest form, the drip irrigation system consists of a water source, mainline and side lateral pipes, and drip pipes and emitters. Frequently, drip irrigation systems will have pressure reducers that regulate head-gain pressure. The pressure reducers are inexpensive and are available in many sizes that can be matched to the system emitters. The system is under pressure during irrigation, which moves water from the water source, through the mainline and side laterals, to the emitters where seedlings are watered. The objective is to deliver equal amounts of water to each seedling. This is not a problem when the system is laid out on flat ground and pressures at any point in the system are equal, but flat terrain is seldom found on

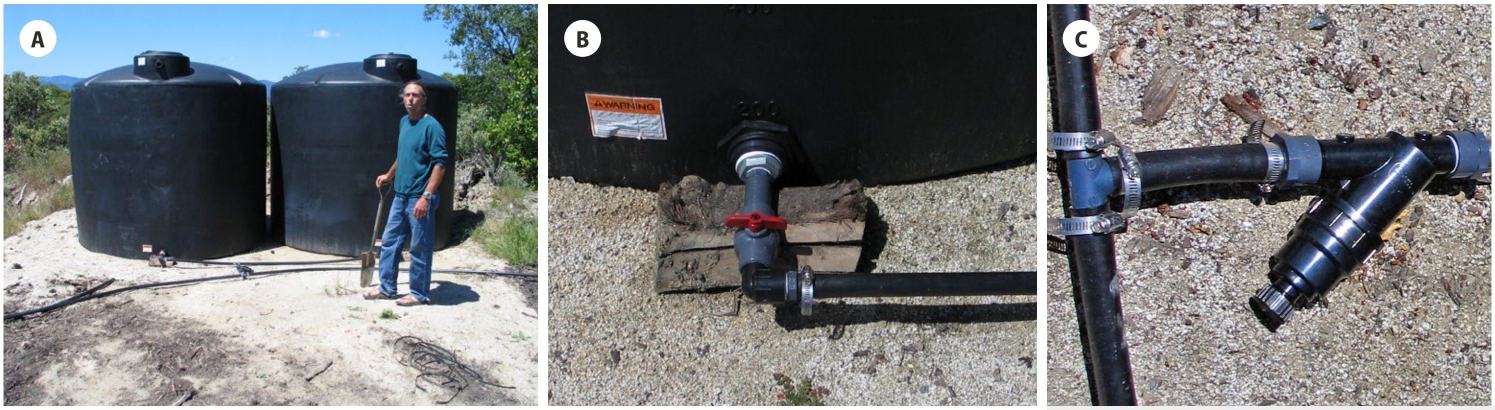


Figure 5-133 | **Large water holding tanks**

Large holding tanks are used for temporary drip irrigation systems (A). A simple on/off valve controls water to the gravity-feed system (B). Pressure release valves (C) are used to control water pressure on hilly sites.

Photo credits: David Steinfeld

highway projects. On projects that have any slope gradients, there will be changes in pressure depending on the elevation of the emitters. The pressure change occurs at a rate of 1 lb/in^2 (psi) per 2.31 feet elevation drop. This means that an emitter at an elevation that is 46 feet lower than the water source will have a psi of 20 (*46 / 2.31 = 20*), while an emitter at 92 feet lower than the water source will have a psi of 40 (*92 / 2.31 = 40*). Unless pressure-regulating techniques are used to reduce the pressure to the lower elevation emitters, the amount of water delivered to those emitters will be approximately twice that of the upper elevation emitters. Compensating for pressure changes is critical for delivering equal amounts of water to each seedling. Systems that do not compensate will have seedlings that receive too much water, while others will not receive enough during an irrigation cycle.

Water Source—The water source constitutes the beginning point of the drip system. It is typically the most uphill point because it should feed every emitter below. Water is typically trucked to the site and pumped directly into the mainline or stored in temporary, portable storage tanks (Figure 5-133). Water trucks range in capacity from 1,000 to 2,500 gallons. If there is a location for a portable water storage tank above the planting area, gravity feed can be used to pressurize the system. Operational water pressure for a drip system ranges from 20 to 40 psi. To achieve a minimum pressure of 20 psi with a gravity feed system requires a 46-foot elevation drop from the storage tank to the first line of emitters (*20 * 2.31 = 46*). If this drop does not exist, then a pump will be needed to augment the pressure.

Components of a temporary water tank system include filters, on-off valve, and an inline pressure-reducer (if the water source pressure is greater than 40 psi) (Stryker 2001). When planning water storage, ease of access is an important consideration. Sometimes water will need to be pumped a substantial distance to a water storage tank. In other cases, more than one tank will be required to reach all planting areas in complex terrain. Water from unknown sources should be sent to a qualified lab and analyzed for contaminants and impurities (Zoldoske 1998). Chances are that most water sources will have impurities that will clog very small drip emitter openings. Installing a 100 (150 micron) to 150 (100 micron) mesh filter is recommended (Stryker 2001).

Mainline and Laterals—The mainline delivers water from the water source to the lateral pipes. The layout of the mainline and laterals can compensate for pressure changes associated with hilly terrain. A series of parallel lateral lines can be laid out perpendicular to the slope gradient. Because each line is on the contour, there is no pressure difference between emitters within a line. Between lateral lines, however, there is change in pressure based on 1 psi per 2.31 feet of elevation drop. Placing a pressure regulator at the connection between the mainline and each lateral line can compensate for the pressure increase with elevation drop.

The drip tubing diameter determines the volume of water that can be carried in the lateral lines and the rate it will be delivered based on friction losses. A 2-inch pipe, for example, carries four times as much water as a 1-inch pipe, but the costs are correspondingly much higher. For long stretches, increased frictional losses inside narrow diameter pipes can cause inadequate water coverage. Increasing water pressures or increasing pipe diameters can compensate for this.

The carrying capacity is the amount of water that specific tubing can deliver under a specific line pressure. For example, 0.75-inch tubing has a carrying capacity of approximately 160 gallons per hour at a line pressure of 20 psi, whereas a 1-inch pipe has a carrying capacity of 370 gallons per hour at the same pressure. Charts are available that compare various tubing diameters, emitter outputs, and system pressures for determining the length of tubing. These charts should be referenced when designing an efficient drip system.

Emitters—From the laterals, water flows through a smaller diameter pipe to the emitter, which meters out water directly to the base of each plant. Emitters apply water to the soil surface without wasting water on the surrounding area, thus discouraging non-target species. When emitters are placed in a deep pot irrigation system, water efficiency is increased further because water is delivered directly to the roots. There are many types of emitters, but pressure compensating emitters work well on hilly topography because they are designed to discharge water at uniform rates under a range of water pressures. With pressure compensating emitters, a system at 15 psi would have the same emitter flow rate as a system at 45 psi (Stryker 2001).

These emitters are two to three times more expensive than non-compensating emitters. Emitters come in a range of flow rates, with the most common rates of 0.5 gallon/hour and 1.0 gallon/hour. Choosing the flow rate for the emitters should be based on soil texture, the water requirements of the plants, the water delivery capabilities of a system, and budget. Most designers agree that placing two emitters at each plant is better than one emitter with twice the output because the water distribution area will more closely match the rooting profile of the plant. Two emitters also offer backup should one of the emitters become clogged.

A good grasp of the soil drainage and water storage characteristics is necessary in choosing emitter capacity and duration of irrigations. Well-drained soils (e.g., sandy texture or high coarse fragments) require emitters with higher flow rates but shorter irrigation time. However, poorly drained soils (higher in clays or compacted) require lower output emitters and longer irrigations. The size of planting stock will influence the number of emitters and flow rates; the larger the planting stock, the longer the irrigation cycles and the more output emitters that are needed.

There are a limited number of emitters that can be installed on any one lateral line. For example, 0.75-inch pipe or tubing delivers approximately 160 gallons per hour. The number of emitters that can be installed on the line will vary by emitter output rates. Installing 0.5 gallon/hour emitters allows approximately 300 emitters (*600 / 2 = 300*) on the line. If two emitters were placed by each plant, 150 plants could be watered on a line. If the emitters were rated at 1.0 gallon/hour, then 75 plants could be watered.

Installation—The installation of a drip system involves placing pipe and inserting emitters. Tubing comes in rolls and is easiest to lay out like a wheel to keep kinks from developing in the line. Lateral tubing should be placed upslope from the plant, which will act like a stake should the tubing move downslope. Tubing migrates until it has been used for a while and may require periodic staking. When the main line and laterals are in their general locations, the system is filled with water to flush the pipes clean. The ends are clamped or plugged and then filled again. This will reveal whether there are any leaks or problems to fix before installing the tubing to the emitters. A pressure gauge should be used at this time to take readings across long runs within or between lateral lines to check consistency of pressures. If there are problems, they should be corrected at this time. Puncturing tubing for emitters can be done when the system is charged with water so that adequate emitter flows and problems are seen immediately. Some designers choose to bury emitters below the soil surface to reduce surface evaporation. Losing visual inspection, however, usually outweighs the benefits of this strategy (Zoldoske 1998).

Operation—Prior to operating the drip system, the system should be flushed to eliminate any dirt that got into the piping during construction and filters must be cleaned. Check salt levels and pH of the irrigation water using a pH/conductivity meter to ensure that salts do not exceed the toxicity levels for plant growth (Section 3.8.4, see pH). Once these measures have been taken, the system can be opened and lines and emitters can be inspected. If emitters need cleaning, repair, or repositioning, it is done at this time. Tools and spare parts for the system are brought along and used where needed. When to irrigate should be determined through PMS monitoring (Inset 5-23). Determining the duration of the irrigation cycle can be done once or twice during the growing season through a visual inspection of soil profiles dug below several emitters. The wetting front should be observed several hours after the system has been shut off because the wetting front will have stabilized at that time. The irrigation system can be used to train the plant to grow roots deep. Unless deep pot plants are used, new installations have plants with shallow roots and watering should begin by being frequent and shallow. Watering should transition to less frequent and longer duration so that water penetrates deeper into the soil. The surface soil will dry while deeper soil will remain wet and the plant roots will follow the water. The metering of the water is made easy with the use of inexpensive battery powered remote control valves and small and reuseable solar powered controllers.

6— Monitoring

6.1 **INTRODUCTION**

The goal of roadside revegetation is to establish plant communities along roadsides and other road-related disturbances that meet project objectives[1]. In practice, however, roadside revegetation projects rarely turn out exactly as planned. Therefore, regular visits to the project site to evaluate progress, and to intervene if necessary, are important parts of the revegetation process.

Monitoring is carried out for two reasons: (1) to correct, manage, and maintain the project effectively and (2) to learn what went right or wrong and apply this knowledge to future projects. Monitoring provides the answers to the following questions:

- Were revegetation goals and expectations met?
- Is native vegetation establishing appropriately or should corrective action be considered?
- Were desired future conditions (DFC) targets met?
- Are there differences in plant responses between different revegetation treatments?
- How are pollinators responding to revegetation treatments?
- Did revegetation result in a plant community capable of supporting a diverse pollinator population?
- Should the revegetation methods and techniques strategy be revised based upon monitoring data?

Answers to these questions may be obtained in a variety of ways depending on the purpose and needs of the project; however, a monitoring plan that can be applied to all revegetation projects does not exist. Instead, a monitoring plan is tailored to the objectives of each project and to the unique characteristics of the site. In developing a monitoring plan, it is important to determine the type and intensity of monitoring in advance. Simple field visits or photo point monitoring over time may provide sufficient information to determine whether objectives have been met, whereas statistically based procedures, outlined in Section 6.3, may help determine if specific targets were achieved. Regardless of the intensity of the strategy, consistency and a long-term commitment are keys to successfully implement an informative monitoring strategy.

Monitoring completes the project cycle by providing feedback regarding the success or failure of a revegetation project. This information can be used to adapt and improve other revegetation projects that are in the initiation, planning, or even implementation phases (Figure 6-1). Information collected during monitoring can help determine if corrective actions, such as adjusting seed mixes or follow-up management activities (e.g., reseeding or replanting), are appropriate. Monitoring results may also be used to improve revegetation techniques for future projects.

The monitoring phase may include the following steps:

- Determining what aspect of the project is to be monitored
- Developing a monitoring plan
- Collecting field data
- Analyzing field data
- Applying corrective measures
- Writing up findings

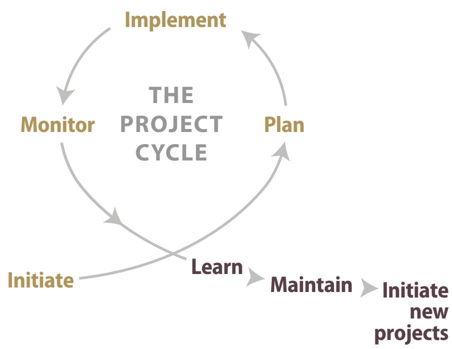


Figure 6-1 | **Monitoring and the project cycle**

Monitoring completes the project cycle and the results are used to guide future management and maintenance work. Monitoring can also provide insights for improving future projects.

1 This chapter uses abbreviated scientific names (plant symbols), from the PLANTS Database to conserve space in spreadsheets. The PLANTS Database includes scientific names, plant symbols, common names, distribution data, images, and species characteristics for vascular plants of the United States.

This chapter begins by describing monitoring plan development and moves through collecting, analyzing, and summarizing data in a monitoring report. A set of procedures are included that outline data collection for different plant, soil, and pollinator attributes.

6.2 DEVELOPING A MONITORING PLAN

Monitoring projects often fail because the purpose, goals, and monitoring methods are not clearly defined. The development of a monitoring plan is a process that clarifies what is to be considered prior to going into the field. Since field time is very expensive, development of a monitoring plan in the office can save valuable field time and improve the quality of the data being collected. The monitoring plan does not have to be lengthy; in fact, most can be written in a single page. The plan will be most useful if it addresses the following points (after Elzinga and others 1998):

- **Purpose**—Outlining the reason for monitoring, goals, and criteria for success
- **Intensity**—Determining the scope
- **Who**—Identifying expertise needed
- **What**—Determining parameters to monitor
- **When**—Determining frequency
- **Where**—Delineating where sampling will occur
- **How**—Selecting the monitoring procedures for data collection and analysis
- **Logistics**—Defining timeline, budget, data management, and equipment

These points become the backbone of the monitoring plan.

6.2.1 OUTLINING THE REASON FOR MONITORING (PURPOSE)

A common pitfall in many monitoring projects is the lack of clearly stated objectives or reasoning behind field visits and data collection. A good monitoring project is not defined by the amount of data collected, but whether the data adequately and effectively answered whether the objectives of the revegetation project were met. Successfully answering this question is only possible when the objectives for monitoring are clearly stated. Monitoring efforts not only link back to the original project objectives, but also to the specific DFCs developed in the planning phase (Section 3.2 and Section 3.7). Objectives and DFCs set the targets (sometimes referred to as "performance standards," "thresholds," "success criteria," or "indicators") against which the project is evaluated (Clewell 2004).

A monitoring plan begins with a statement of purpose or reason for monitoring. This is often a restatement of the objectives and DFCs of the revegetation project. If the objective of a revegetation project is to improve pollinator habitat by increasing the cover and diversity of native plants, then the monitoring plan would focus specifically on those elements pertaining to species diversity and plant cover and avoid collecting extraneous data. In addition, monitoring native bees and monarch butterflies would indicate how populations of insects have responded to the resulting plant composition. Time will be saved and the value of the data will be increased by streamlining data collection to include only the information needed to answer the question of whether the project met the objectives or DFCs stated in the plan.

DFCs are often stated in quantitative language. For example, the DFCs for a cut slope three years after construction could be stated in the revegetation plan as "less than 25 percent bare soil will be exposed" and "vegetative cover will be composed of greater than 70 percent native species." These DFCs are very specific and can be used as target values, or thresholds, for determining whether the project was successful. Monitoring methods, or procedures, are developed specifically around each of these DFC targets. When monitoring is approached in this manner, only the information needed to determine whether targets were met is collected. Expensive, superfluous data collection is avoided because the DFC targets are clearly defined. The monitoring plan defines how this information will be measured and evaluated. After field data is collected, the DFC target values can be used to evaluate success or failure and whether corrective action is needed.

6.2.2 DETERMINING THE INTENSITY (INTENSITY)

The scope of data collection will depend on the size and importance of a revegetation project. Not all revegetation projects will involve the same intensity of monitoring to meet project goals. Some portions of the revegetation project might entail only a field review and a series of photographs, while other areas within the project will involve a statistically designed monitoring procedure. At a minimum, most projects call for annual visits and recorded observations or qualitative assessments.

Portions of revegetation projects may benefit from statistically based monitoring procedures. For example, if a project has a water quality goal for sediment control that road sections near a high-value fishery have no greater than 20 percent bare soil for sediment control the first year after construction, the importance of this project to fisheries and water quality would underscore the importance of high confidence in the accuracy of the data. This could involve more intensive data collection and statistical analysis to ensure a higher level of certainty. Alternatively, road sections that do not affect the stream system may not involve the same level of effort. In such cases, qualitative assessments, such as photo point monitoring, may suffice (Section 6.5). In general, the scope of monitoring reflects the importance of the revegetation objective, ecological sensitivity of the project area, and budgetary constraints. The levels of monitoring intensities include the following:

- **Low**—Site visits, field notes, photographs
- **Moderate**—Photo point monitoring
- **High**—Statistically based data collection and analysis

6.2.3 IDENTIFYING THE NEEDED EXPERTISE (WHO)

For efficiency and safety, a minimum team of two people is recommended for revegetation monitoring. The team is typically composed of the designer, or someone familiar with the revegetation project, and a person trained in plant identification. If parameters, such as soil characteristics are being monitored, then a person with soils background would also be involved, or if pollinator surveys are being conducted, then the team would have a person knowledgeable in identifying pollinators.

It is important to have one person be responsible for all monitoring activities. This person develops and implements the monitoring plan, conducts data collection and analyses, and completes the final monitoring report. It is advantageous that the project designer or personnel who planned and implemented the revegetation project be involved with data collection and even be the person that oversees the monitoring activities. Monitoring is often delegated to others with less knowledge of the project, but a great opportunity for learning is lost when this occurs. Monitoring is the feedback loop for the designer and implementer to make improvements on the next project.

6.2.4 DETERMINING MONITORING FREQUENCY (WHEN)

Specifying the timing of data collection in terms of years following project completion is important in determining if DFC targets have been met. Monitoring that occurs within a year after project completion is conducted to assess whether some areas should be reseeded or replanted, and to determine efficacy of erosion-control devices (fabric, wattles, mulch, etc.). This low intensity monitoring is often conducted through site visits during which ocular estimates are made. Assessing the long-term success of a project is done three or more years after revegetation treatments have been completed. Some portions of a revegetation project may warrant more than one sampling visit. For example, a planting contract with a DFC of 400 live trees after the first year of planting and 300 trees alive after three years would be monitored the first and third years after planting.

Specifying the month or season when a project is monitored is also important. If the identification of individual plant species is the monitoring goal, monitoring is scheduled during the appropriate phenological window for plant identification. The bloom period is also the time when pollinators are sampled since this is when their populations are at their greatest. If outplanted stock is to be measured for survival or growth, the appropriate time to monitor is after seedlings have become established, which is typically 6 months to a year after planting. For climates with extended dry periods, common to the western United States, this monitoring is typically conducted in the fall. Alternatively, the collection of soil cover data for erosion control is done prior to intense rainstorm periods, which in New Mexico, Arizona, Colorado, Utah, and Texas is in the summer; for Gulf states, it is in the late summer and fall; and for the western United States, it is in fall and winter.

Bee populations vary seasonally and annually. For this reason, it is important for pollinator monitoring to sample a project more than once. For example, it may take several years for a newly seeded area to become established before there is an increase in pollinators. On these sites, monitoring pollinators the first year after seeding may not yield as much useful data as the second and third year, which may be the best years for monitoring. Pollinator surveys are best conducted when plants are flowering, which may warrant two or three surveys a year, especially if there is a variety of flowering species with different bloom times. Depending on the region, this can be in late spring/early summer, mid-summer, and late summer.

6.2.5 DELINEATING SAMPLING LOCATIONS (WHERE)

The sampling unit is the area in which a specific monitoring procedure will be used. Revegetation projects may be monitored as one sampling unit or several. A way to determine the locations of the sampling units is to revisit the revegetation unit map developed for the revegetation plan (Section 3.4). If the project is large or complex, some or all of the revegetation units may be treated as separate sampling units. Referring to the purpose for monitoring at the beginning of the monitoring plan helps identify the most important areas to monitor. For example, if the purpose for monitoring is to determine whether water quality objectives were met, only the areas adjacent to drainages and waterways would be delineated for high intensity monitoring, leaving the remainder of the project for low or moderate intensity monitoring. If the monitoring objective is to determine how well native plant species established, then setting up a sampling unit that would cover the entire revegetation project area may be appropriate. Comparing changes in plant or pollinator populations may benefit from locating and monitoring a nearby reference site.

6.2.6 DETERMINING PARAMETERS TO BE MONITORED (WHAT)

Clearly stating which essential data to collect will increase the quality of the monitoring data and minimize field time. Referring to the reason for monitoring, outlined at the beginning of the monitoring plan, helps narrow the parameters for data collection. These parameters are discussed in detail in Section 6.3.

6.2.7 SELECTING MONITORING PROCEDURES (HOW)

There are many vegetation and pollinator population monitoring methods, protocols, and procedures from which to select. Using an established set of monitoring procedures, tailored to the monitoring objectives, is important because they can save time and increase the quality of the data collected. The procedures outlined in this chapter were developed specifically for roadsides and road-related disturbances. A monitoring procedure, as defined in this report, provides information for conducting monitoring. These procedures are used for moderate and high intensity monitoring. Qualitative procedures, such as photo point monitoring, are used for moderate intensity monitoring. Statistically based procedures have been developed for high intensity monitoring.

For high intensity vegetation and pollinator monitoring, there are three sets of statistically based monitoring procedures that are used together. In the development of a monitoring plan, one procedure from each of the three procedure groups is selected for each sampling unit. These are discussed in Section 6.3.

6.2.8 LOGISTICS

The monitoring plan also includes a timeline that shows the periods and completion dates for field monitoring, data analysis, and the monitoring report. Included in this section are the specialists involved in monitoring, their expertise, and the estimated time involved. A budget can be developed from this information. Finally, a list of equipment can be attached to the monitoring plan.

6.3 PLANT AND SOIL MONITORING PROCEDURES

This section describes how to develop and implement a set of statistically based monitoring procedures specific to the revegetation project. It outlines methods to record, summarize, and analyze data. Monitoring personnel can obtain Excel® workbooks, which include field data forms and analysis spreadsheets for each procedure, from the Native Revegetation Resource Library. To obtain a list of Excel monitoring procedure workbooks referenced in this chapter, type "xls" in the Search field.

The following three questions are answered to develop a procedure for soil and plant monitoring for each sampling unit:

- What is the shape of the sampling unit?
- What are the monitoring objectives?
- What is being monitored?

The answer to these questions will lead the designer to draw from different sections of this chapter. Take, for example, a road cut that is being monitored to determine if soil cover targets conformed to the Storm Water Pollution Protection Plan. Using Figure 6-2, the Linear sampling area procedure would be used because the road cut is long and narrow. Since the objective is to determine if soil cover targets were met, the Compliance and the Soil Cover procedures would be used.

Sampling Unit Shape

The shape of the sampling area is important for determining how transects and quadrats are laid out in a sampling unit. For roadside monitoring, there are three main shape categories to choose from, each with a corresponding procedure:

What is the shape of the sampling area?	*Section to read:*
Linear	**6.3.6, Linear Areas**
Rectilinear	**6.3.6, Rectilinear Areas**
Dispersed	**6.3.6, Dispersed Areas**
What is being monitored?	
Soil Cover	**6.3.1**
Vegetative Cover	**6.3.2**
Species Presence	**6.3.3**
Plant Density	**6.3.4**
Plant Attributes	**6.3.5**
Pollinator Abundance	**6.4**
What is the objective for monitoring?	
Compliance	**6.3.7, Analysis of Compliance**
Treatment Differences	**6.3.7, Analysis of Treatment Differences**
Trends	**6.3.7, Analysis of Trends**

Figure 6-2 | **Quick guide to high intensity monitoring procedures**

For statistically based monitoring of plant and soil attributes, select a procedure that best answers each of these questions.

- **Linear**—This shape is long and narrow and is used to monitor cut slopes, fill slopes, and abandoned roads (Section 6.3.6)
- **Rectilinear**—These sampling areas are typical of staging areas, material stock piles, or large wide areas associated with road construction (Section 6.3.6)
- **Dispersed**—A series of discrete areas that include planting islands and planting pockets (Section 6.3.6, see Dispersed Areas)

Parameters to be Monitored

Parameters for monitoring revegetation projects may include the following, depending on monitoring objectives:

- **Soil cover**—The amount of exposed bare ground is used to determine if treatments produced adequate soil cover for erosion control (Section 6.3.1)
- **Species cover**—Used to determine the percentage of aerial or basal cover occupied by individuals or groups of species to quantify species prominence (Section 6.3.2)
- **Species presence**—Used to assess what species are on the site, how well species in a seed mix became established, or whether noxious, invasive, or undesirable species are present (Section 6.3.3)
- **Plant density**—Used to assess how many seedlings or cuttings became established after outplanting or how much mortality has occurred (Section 6.3.4)
- **Plant attributes**—Used to determine growth rates of outplanted seedlings or cuttings (Section 6.3.5)
- **Pollinator abundance**—Used to assess quantities of honey bees, native bees, and other pollinators (Section 6.4)

Monitoring Objectives

Monitoring objectives also guide how data are collected and statistically analyzed. Procedures have been developed for three basic types of monitoring objectives (Section 6.3.7):

- **Compliance**—This is often the main purpose for monitoring. It is used to determine if project objectives were met or simply to summarize monitoring data
- **Treatment differences**—This monitoring objective examines the differences between revegetation treatments or revegetation areas. It is useful to evaluate the effects of different revegetation treatments (seed mixes, fertilizers, soil amendments etc.) on plant establishment
- **Trends**—This objective evaluates changes in the revegetated plant community in the disturbed area over time. It is used when it is important to understand how plant communities evolve and change

6.3.1 SOIL COVER

Reestablishing a soil cover on disturbed sites is important for erosion control. The following soil cover procedures can be used to determine the amount and type of cover existing on the soil surface after slopes have been constructed. The quadrat is the unit of area monitored for soil cover. Exact measurements are based on recording the surface soil condition at data points within each quadrat. Quadrats can be read in the field using a fixed frame or read later in the office from digital photographs of the quadrat taken in the field.

Sampling Soil Cover Using a Fixed Frame

Soil cover is quantified at each quadrat based on readings from a 20-point fixed frame. This method is a point intercept method of estimating cover in a defined area (quadrat). Several types of frames have been developed. The most useful frames are lightweight, portable, and stable. One frame that meets these criteria uses a laser pointer to identify data points. The frame shown in Figure 6-3 has 20 slots to position a laser pointer. During monitoring, the laser pointer is moved to each of the 20 slots. Soil cover attributes are recorded where the laser hits the ground surface.

The fixed frame is located along the tape in a consistent manner throughout the sampling of a unit (Figure 6-4). For example, the frame might be placed on the right side of the tape with the lower corner of the frame at the predetermined distance on the tape. This procedure would be applied consistently across the entire sampling unit. The legs of the frame are positioned so that the surface of the frame is on the same plane as the ground surface.

Each data point is characterized from a set of predetermined label descriptors that include, but are not limited to, the following:

- Soil
- Gravel (2 mm to 3 inches)
- Rock (>3 inches)
- Applied mulch
- Live vegetation (grasses, forbs, lichens, mosses)
- Dead vegetation

Ideally, only cover in contact with the soil surface is considered effective ground cover for erosion control purposes; however, differentiating between plant leaves and stems that are in direct contact with the soil as opposed to simply in close proximity to the soil surface can be difficult and is not always feasible. In this procedure, the assumption is that if live or dead vegetation is within 1 inch of the soil surface, it is recorded as soil cover.

Vegetation often blocks the view of the soil surface and is therefore removed prior to data collection. When this is the case, the quadrat is clipped of standing vegetation (dead or alive) at a 1-inch height above the ground surface prior to taking the readings. The clipped vegetation is removed from the plot before the reading is made.

Data can be recorded on a field computer or field recording sheets. Field recording sheets bypass the need for electronic equipment in the field; however, data is entered into a spreadsheet at a later time for analysis. An Excel workbook with field entered forms and a data analysis package (see Figure 6-5) is available for this procedure in the Native Revegetation Resource Library.

Sampling Soil Cover using Digital Photographs and the Cover Monitoring Assistant (CMA) Program

Digital cameras are being used more frequently for monitoring plants and animal life. This technology allows the data recorder to spend most of the field time laying out transects and taking photographs of quadrats rather than collecting data, thereby reducing field time significantly. With recent developments in photo-imaging software, photographs can be assessed quickly in the office. Because these are permanently stored records, digital photographs have several advantages: photographs can be reviewed during the "off" season or "down time"; they are historical records that can be referenced years later; and they can be reviewed by supervisors for quality control. In addition, taking digital photographs of ground cover can be accomplished by one person, not two as is often used for fixed-frame monitoring. On steeper slopes, taking photographs to record quadrats is quicker and easier than reading attributes from a fixed frame.

Figure 6-3 | **Fixed frame for transect sampling**

A fixed frame can be adapted to allow for the positioning of a laser pointer at 20 points in the frame. Soil cover or plant cover attributes are recorded at each laser point. The frame in this example is 8 inches by 20 inches, with 2-inch spacing within rows and 4-inch spacing between rows. The laser is a Class IIIa red laser diode module that produces a 1-mm dot.

Photo credit: David Steinfeld

Figure 6-4 | **Fixed frame for measuring soil cover**

A fixed frame for measuring soil cover is placed at predetermined distances on a transect.

Photo credit: David Steinfeld

For the Designer

Find this and many other fillable spreadsheets in the Native Revegetation Resource Library by typing "xls" into the search field.

A2 fx Transect

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Sampling Area:												
2			Number of Points						% of Points				
3	Transect	Quadrat	Soil	Gravel	Mulch	Live Veg	Dead Veg	Total Points	Soil	Gravel	Mulch	Live Veg	Dead Veg
4	1	1	3	5	6	3	3	20	15	25	30	15	15
5	1	2	4	7	8	1	0	20	20	35	40	5	0
6	1	3	0	1	12	3	4	20	0	5	60	15	20
7	1	4	1	2	8	3	6	20	5	10	40	15	30
8	2	1	3	5	12	0	0	20	15	25	60	0	0
9	2	2	0	1	10	6	3	20	0	5	50	30	15

Figure 6-5 | **Data collection forms and statistical packages are available on the Native Revegetation Resource Library**

A data collection sheet and summary form spreadsheets, such as this one for soil cover, can be downloaded from the Native Revegetation Resource Library by typing in "xls" into the search field and selecting the appropriate workbook. Each section in this chapter has corresponding spreadsheets with instructions, field forms, and statistical packages.

Sampling by camera entails the same statistical design and plot layout as the fixed-frame method. The photograph is taken within a quadrat frame with 11-inch by 14-inch dimensions, covering approximately 1 square foot. In the office, digital photographs are catalogued electronically and a 20-point overlay is placed on the image that identifies the data points to be described (Figure 6-6). The data points are described in the same manner as for the fixed-frame method.

The Federal Highway Administration and the U.S. Forest Service have developed a computer program to evaluate digital photographs called Cover Monitoring Assistant (CMA). This program configures each digital photograph taken at a quadrat so it is easy to evaluate in the office. It randomly places 20 points on the photograph and navigates the user to each point where the soil cover attribute is recorded. The data for each photograph is summarized in spreadsheets for statistical analysis. The CMA program has reduced field time and increased data quality significantly. The CMA program information and the User's Guide are available in the Native Revegetation Resource Library.

6.3.2 SPECIES COVER

The species cover procedure is used to assess the above-ground abundance of plant species. This method is a point intercept method of estimating cover in a defined area (quadrat). This procedure can be used when DFC targets state that a certain percentage of vegetative cover be composed of native species. For example, a DFC target from the revegetation plan states that over 50 percent of the vegetative cover existing on the site two years after construction will be composed of native forb species for pollinator habitat and that this cover will consist of species that were in the seed mix. Monitoring vegetative cover with this procedure will determine whether this goal was achieved.

Another advantage of evaluating species cover is the elucidation of patterns of co-occurrences. Weedy species can occur in isolated patches, but often co-occur with other weeds and even among native species. Understanding these distributional patterns and the density of the species assemblages, as they change and develop with the project site, can help the designer select the most effective treatment methods, reduce redundant treatment costs, and prevent damage to the existing native plant community.

Because grass and forb cover changes during the growing season, the timing of species cover monitoring is important. It is ideal to monitor when most plants are flowering, typically mid-May through July for the western United States and July through August for the upper mid-western and eastern states. Bloom periods for forb species also coincide with the optimum period for monitoring pollinator species, so monitoring for species cover and pollinators can be done during the same field visit (Section 6.4).

This sampling procedure typically benefits from a botanists' knowledge to identify species and another person to help lay out the plots and record data. Sampling can be done either with a fixed frame or digital photographs using the CMA program.

Sampling Species Cover Using a Fixed Frame

Using the fixed frame discussed in Section 6.3.1, 20 points are identified in the quadrat frame. At each point, the species is identified and recorded in a ruggedized computer or on a field recording sheet. Species cover is quantified at each quadrat based on readings from a 20-point fixed frame. At each point, the species is recorded on a spreadsheet which is available on the Native Revegetation Resource Library.

Sampling Species Cover & Floral Density using Digital Photographs & CMA

The CMA program, discussed in Section 6.3.1, can also be used for determining species cover when plant species are easy to identify from digital photographs. These include species that are in bloom or with seed heads. Species of interest, such as those species used in a seed mix, may be the only species to identify for the analysis, requiring the recorder to know the appearance of just a few species. It may also be helpful to take a range of photographs of each species of interest for later reference when photographs are being analyzed. As with using CMA for determining soil cover, a 20-point grid is placed on each digital photograph and species cover points are evaluated (Figure 6-6).

Floral density can be quantified using the CMA program for describing the quality of pollinator foraging habitat while photographs are evaluated for species cover. In this analysis, the number of flowers of each species of interest are counted within the quadrat frame of each photograph (Figure 6-7). A spreadsheet for this procedure is available in the Native Revegetation Resource Library.

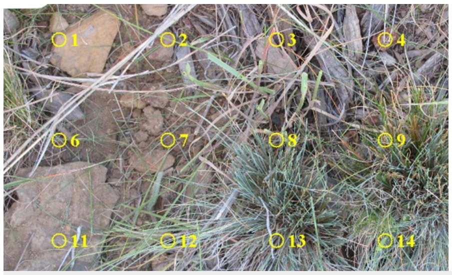


Figure 6-6 | **The CMA program reduces field time**

Using the CMA program for determining soil cover and/or species cover, each quadrat photo is overlain with a 20-point grid that is randomly placed. Beginning with the first point, the user determines that point lands on a rock and that cover code is entered. The program moves the recorder to the next point until all 20 points are entered. The cover codes are decided by the recorder. In this example, plant cover was detected along with soil, mulch, and rock cover codes. In this case, three plant species were identified (shown as the abbreviations BRCA, ELEL, and FEID) as discussed in Section 6.3.2.

Photo credit: David Steinfeld

6.3.3 SPECIES PRESENCE

The Species Presence procedure is an alternative to the Species Cover method of determining whether species are present on the site. While this method still necessitates a person knowledgeable in plant identification in the field, it takes far less time per quadrat because only the presence of a species is recorded. In this method, a fixed frame is placed on the surface of the soil at each quadrat location and the presence or absence a "species of interest" is recorded. Depending on the specific project's success criteria, only species of interest are recorded. Species of interest may include those species that have been seeded, important pollinator supporting species, and undesirable non-native plants. If ecological restoration is a project objective, then all species may be identified.

The size of the fixed frame is based on several factors, such as the growth pattern of the species of interest and the frequency that the species is present on the site. Large frames are not necessary for most grass and forb plant communities. The 1-square-foot frame used for the Soil Cover and Species Cover procedures may suffice (the tall grass prairie systems may be an exception, requiring larger frames). Larger native woody species and undesired weedy species are often measured in quadrats with an area of 1 square meter. This size of quadrat can accommodate the patchy distribution that weedy species frequently display and, when extrapolated, can create a fair representation of the plant species' frequency across the project site. An Excel workbook with field forms and a data analysis package is available in the Native Revegetation Resource Library for this procedure.

Figure 6-7 | **Floral density can be determined using CMA**

Floral density can be determined by counting the number of flowers for each species of interest in a quadrat, then evaluated. In this photograph, Oregon sunshine (*Eriophyllum lanatum*) is the main species that is counted.

Photo credit: David Steinfeld

6.3.4 PLANT DENSITY

Trees, shrubs, and wetland plants are typically established from containerized plants grown in nurseries and planted at a specified density depending on the project objectives. Monitoring the density of live plants after they are planted is important to determine how many plants have survived and whether the site will need to be replanted.

The quadrat in this procedure is a circular plot with a specified radius. For trees and shrubs, it is recommended a 1/100 acre plot be used, which has an 11.7-foot radius and covers 436 ft2. A staff is placed at the plot center and a tape or rope is stretched 11.7 feet. While one person holds the staff, the other walks the circumference of the plot and counts the number of plants of each species within the quadrat. This information is recorded on a spreadsheet, such as that shown in the form available in the Native Revegetation Resource Library. This spreadsheet summarizes the total plants per acre and the number of plants per acre by species. Note: for linear sampling areas, only one quadrat is placed randomly within the transect.

Plant density monitoring that is used to determine survival rates are called survival surveys and these are usually conducted six months to a year after planting. If the site is planted in fall or spring and monitoring occurs the following fall, the results are referred to as the "first year survival." Plant density monitoring thereafter is referred to as the years after planting (e.g., third year sampling is "third year survival").

6.3.5 PLANT ATTRIBUTES

This procedure can be used to assess plant growth responses to determine how well plants are growing or whether DFC targets pertaining to growth targets were met. Typically, only sensitive areas, such as visual corridors or wetlands, have stated growth targets. This procedure might have limited applicability to most revegetation projects.

Any part of a plant can be measured for growth, and the selection of an attribute is dependent on the species being sampled. Common attributes include the following:

- **Total height**—trees and most shrubs
- **Last season's leader length**—most trees
- **Stem diameter**—shrubs and trees
- **Crown cover**—shrubs, forbs, and grasses

Total height is typically measured from the ground surface to the top of the bud. If the plant has several leaders (or tops), the most dominant leader is used for measurement. Last season's leader growth can be observed in most tree species. For conifers, leader growth is measured from the last whorl of branches to the base of the bud. Comparing leader growth from year to year can indicate whether plants are healthy and actively growing.

Stem diameter is also used to measure trees and shrubs. In this method, the basal portion of the plant is measured with calipers at the ground surface. Another attribute is crown cover, which is more conducive to spreading plants, such as shrubs. A large frame with grids or points is placed over the plant to obtain an aerial coverage.

Attributes for shrub and tree species uses the sampling layout and design described for plant density (Section 6.3.4) and focuses only on those species of interest that have been identified in the revegetation plan. If there are many plants of a species of interest in a quadrat, only five plants are measured. An unbiased way to select which plants of each species to monitor is to sample those plants closest to the plot center. If there are not enough plants in the quadrat to sample, then the nearest plants outside of the quadrat are sampled. The measurement for each plant is recorded on a field data sheet, available in the Native Revegetation Resource Library. Note: for linear sampling areas, only one quadrat is placed randomly within the transect.

6.3.6 SAMPLING UNIT DESIGN

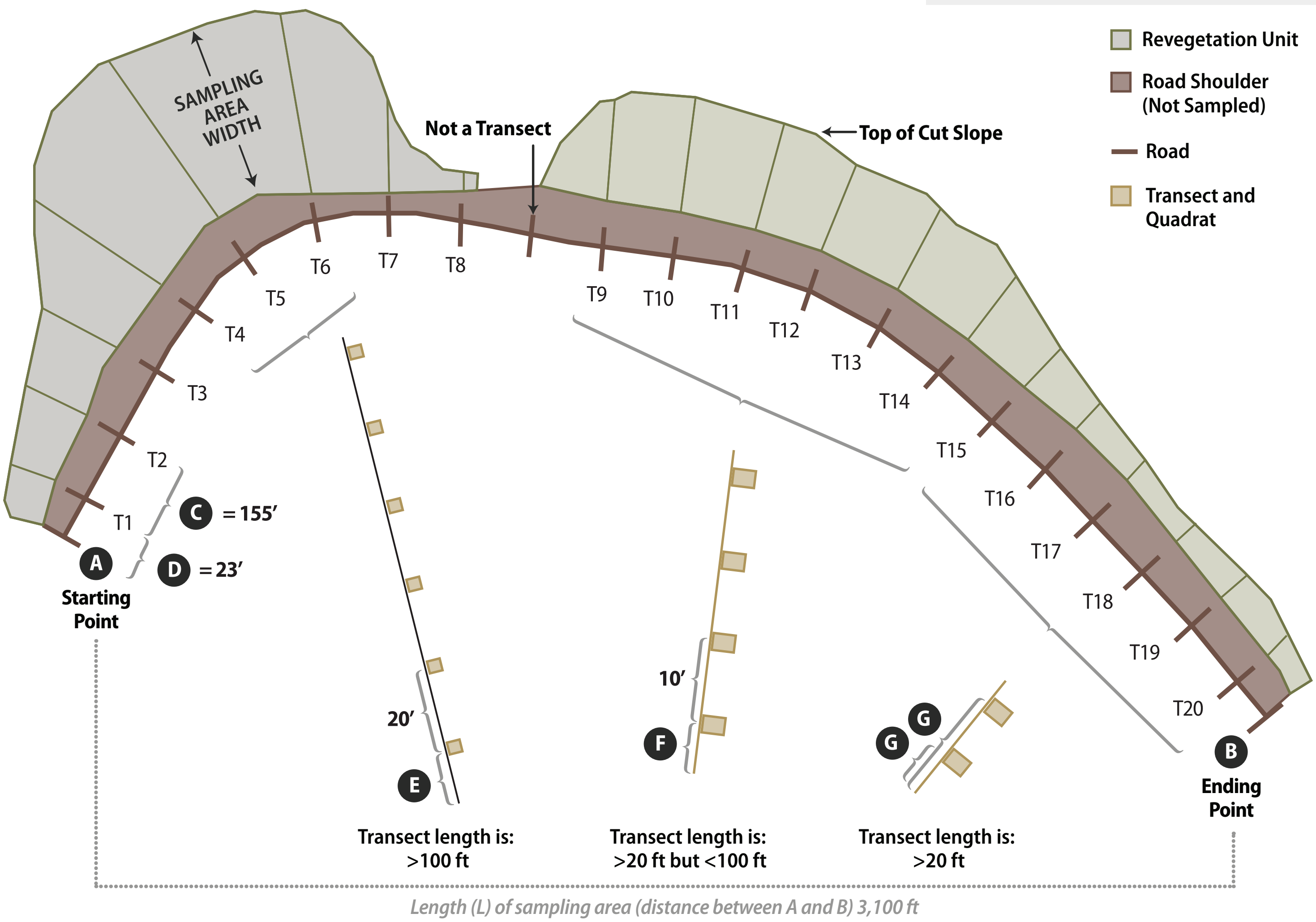
The shape of the sampling unit determines how quadrats are laid out. Procedures have been developed for linear sampling areas, such as long roadsides; rectilinear sampling areas for rectangular-shaped areas such as restored borrow areas; and dispersed sampling areas, which are revegetation areas that are in patches or clumps. These three sampling designs are described below, as well as how to calculate the minimum number of quadrats to obtain an accurate representation of the sampling unit.

Linear Areas

Linear areas, such as cut slopes, fill slopes, and abandoned roads, are sampled from equally spaced transects placed along the entire length of the sampling unit. Each transect has varying numbers of quadrats, depending on the length of the transect. When the sampling unit is uniform in width, each transect will have an approximately equal number of quadrats; when the width of the revegetation unit is variable, there will be an unequal number of quadrats per transect. In either case, each transect is treated as the primary experimental unit instead

Figure 6-8 | **Linear sampling areas**

Linear sampling areas are long units with varying widths. Road cuts, fills, and abandoned roads typically fit this sampling design. The design of linear sampling areas uses a series of equally spaced transects with uniformly spaced quadrats within each transect. The distance between quadrats varies by the length of the transect. Transects longer than 100 feet have 20 feet of spacing between quadrats (T4 through T6), transects between 20 and 100 feet have 10 feet between quadrats (T9 through T14), and transects less than 20 feet long have two randomly placed quadrats (T15 through T20).



n	C	D	E	F	G
Number of transects (20) calculated from pre-monitoring data	Distance between transects = length (L) / number (n) of transects = 3,100/20 = 155 ft	Distance to first transect = random number within the distance between transects (between 1 and 155 ft)	For >100 ft transect, a random number between 1 and 20	For >20 ft but <100 ft transect, a random number between 1 and 10	For <20 ft transect, two random numbers between 1 and 19

of the quadrat (the primary experimental unit in this report is either the transect, quadrat, or dispersed area and is the unit for which statistical analysis is conducted).

Figure 6-8 shows a typical sampling design for a linear area. In this example, the sampling unit included only those portions of the cut slope that were seeded; it did not include road shoulders or the ditch line. For statistical analysis, the number of transects (n) to collect was estimated to be 20 based on pre-monitoring data. Spacing the 20 transects equally along the sampling unit was calculated by dividing the total length of the sampling unit by the number of transects to obtain the distance between transects (3,100/20 = 155 feet). Locating the first transect is done in an unbiased way by generating a random number between 1 and 155. A random numbers table is available in the Native Revegetation Resource Library.

Transects are laid out by establishing a line, typically a measuring tape, perpendicular to the edge of the road. The transect begins at the edge of the road beyond the ditch line and where seeding or other treatments were conducted. Each transect contains a series of quadrats spaced as follows:

- **<20 foot transect length**—For transects where lengths are less than 20 feet, two quadrats are placed. Two random numbers are generated between the numbers 1 and 19. These numbers indicate the location of each transect.
- **>20 foot and <100 foot transect lengths**—For transects where lengths are between 20 and 100 feet, quadrats are placed at 10-foot intervals. The distance to the first quadrat is based on a random number between 1 and 10 feet.
- **>100 foot transect lengths**—Long transects have 20 feet between quadrats. The distance to the first quadrat is based on a random number between 1 and 20 feet.

Rectilinear Areas

When sampling units are more elliptical or rectangular in shape, or composed of several large irregular polygons, the sampling design is based on a rectangular grid of quadrats systematically located with a random starting point. Figure 6-9 illustrates an example of such a sampling design. Notice that this design is different from the linear sampling design in that there are no transects. The quadrat in this sampling design is the primary experimental unit, not the transect.

To determine the grid spacing (E) for the quadrat locations, the area of the sampling unit is calculated from maps, and the number of quadrats to be sampled (n) is determined from pre-monitoring data. The following equation gives the length of each side of a square grid (E):

$$E = \sqrt{\frac{\text{Area}}{n}}$$

For example, the sampling unit in Figure 6-9 covers 4,262 ft^2 and it has been determined from pre-monitoring data that approximately 20 quadrats are necessary to attain the statistical sampling requirements for this sampling unit. The equation indicates that each side (E) of the grid is 14.6 feet:

$$E = \sqrt{\frac{4{,}262}{20}} = 14.6 \text{ ft}$$

A starting point of the grid is arbitrarily located in any corner of the study area. To avoid biasing the placement of the quadrats, the corner of the grid is shifted by assigning random numbers to the x and the y coordinates, as shown in Figure 6-9. This is called a systematic design with a random start. It provides equal likelihood that any point in the study area is included in the sample unless there are obvious systematic patterns in the site, such as

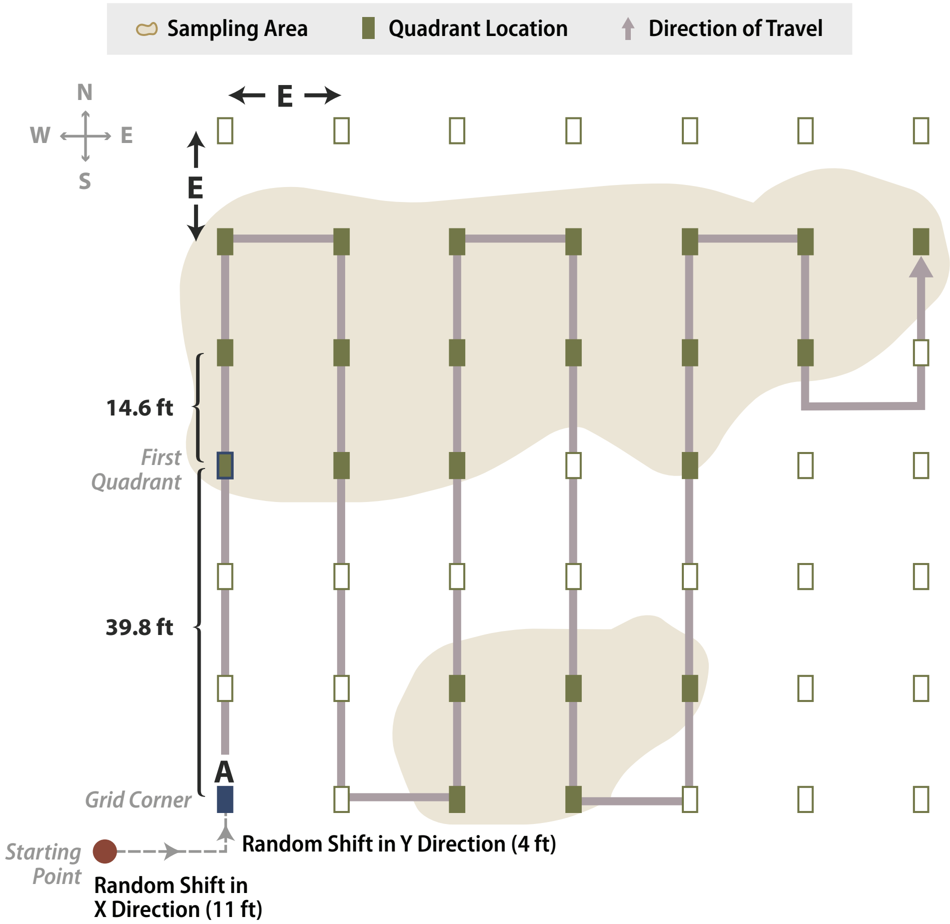


Figure 6-9 | **Rectilinear sampling areas**

For rectangular or elliptical sampling areas, a grid composed of quadrats is used. The length between grid cells (E) becomes the standard distance between quadrats for this sampling unit. In this example, E = 14.6 feet. To avoid bias, the x and y axes of the grid were randomly offset from the starting point by 11 and 4 feet to a new, random starting point (A). Then 39.8 feet was measured to the first quadrat. The monitoring team follows compass or GPS bearings to locate all quadrats.

planting rows. In this example, the random number shifts were 11 feet in the horizontal direction and 4 feet in the vertical direction.

The monitoring team locates the random starting point in the field and measures 39.8 feet (*10.6 + 14.6 + 14.6 = 39.8*) north to the first quadrat. From that quadrat, they measure 14.6 feet north to the second quadrat. After they collect data from the last quadrat in that line, they travel east 14.6 feet to locate the next plot. This system of sampling continues in this fashion until the entire area has been sampled.

Dispersed Areas

When sampling units occur as small, distinct areas, a two-stage sampling design is recommended. The first stage is to determine which dispersed areas to sample, and the second stage is to determine how to sample within each selected area. For the first sampling stage, it is suggested that a minimum of 20 dispersed areas be monitored within each revegetation unit. If there are 20 dispersed areas or fewer, then all dispersed areas are sampled. If there are more than 20 areas, then sampling is conducted with one of two sampling designs. For dispersed areas that are mapped, the systematic sampling design is used. If the dispersed areas are small or are not mapped, then a grid sampling design is used. Both sampling designs are described in more detail below. These areas include planting islands and planting pockets. In most cases, the grid sampling method is recommended.

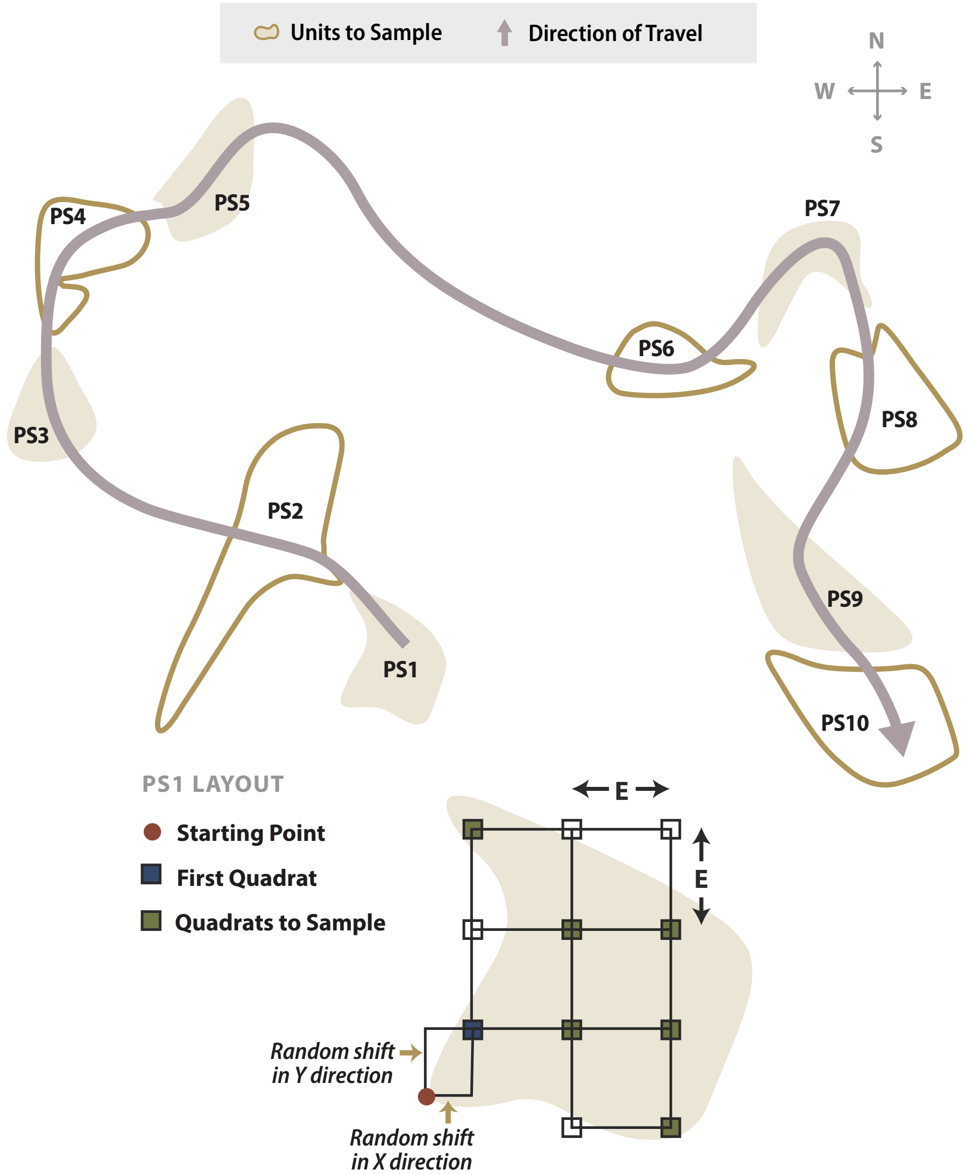


Figure 6-10 | **Systematic sampling of dispersed areas**

A systematic sample of dispersed areas, shown in this example, is based on 50 percent sampling (the pink areas). Alternating dispersed areas were sampled. Quadrats were located in each sampling unit by first locating a starting point and then measuring off random x and y offset coordinates to locate the first quadrat of the sampling grid.

Systematic Sampling of Dispersed Areas

First Stage

The systematic sampling method of dispersed areas assumes that the dispersed areas have been mapped. The dispersed area in this method is the experimental unit. In this approach, the dispersed areas are numbered sequentially by progressing from one dispersed area to the next closest dispersed area. Determination of the number (n) of dispersed areas to sample is presented in Section 6.3.6 (see Sample Size Determination). Odd or even-numbered dispersed areas are selected based on a random number using the RANDBETWEEN function. For example, if there were 40 dispersed areas (N) but only 20 dispersed areas needed to be sampled (n), then 50 percent of the dispersed areas would be sampled (n/N). A random number using RANDBETWEEN (1, 2) is used. If the function returns a "1," the odd-numbered dispersed areas are selected; if 2, then the even numbered areas are selected. Figure 6-10 provides a schematic depiction of such a design.

Second Stage

Once the dispersed areas have been selected, the layout of quadrats within each dispersed area is determined. A grid-based sampling design is used. To determine the grid spacing (E) for the quadrat locations, determine whether the size of the dispersed area is >1,600 ft^2 or

<1,600 ft^2 (1,600 ft^2 is a 40-by-40-foot area). Depending on the sample size, the number of quadrats will be as follows:

- **Less than 1,600 feet**—four quadrats
- **More than 1,600 feet**—eight quadrats

Using the following equation, the grid sides (E) are determined where n = 4 or 8 (depending on the size of the dispersed area) and the area is the estimated size of the dispersed area.

$$E = \sqrt{\frac{\text{Area}}{n}}$$

This calculation is made for each dispersed area. To avoid biasing the placement of quadrats, a predetermined starting point is made (e.g., the northwest corner of each dispersed area). Random x and y coordinates are generated for each dispersed area that is within the predetermined length of the square grid (E). The corner of the grid is placed at this point and oriented north. The location of the first quadrat is x and y feet from the starting point, as shown in Figure 6-10.

For the plant density and plant attribute procedures, only one quadrat is randomly located within each dispersed sampling area. The location is determined by assigning the RANDBETWEEN random number function to the number of quadrats determined for the dispersed area. The random number that is generated is the quadrat selected for sampling.

Grid Sampling of Dispersed Areas

First Stage

A grid sampling design is used on projects where dispersed areas have not been mapped and there are more than 30 areas. This sampling design is used on projects where dispersed areas are numerous and the sizes of the areas are small. In this sampling design, a grid is placed over the revegetation unit, as shown in Figure 6-11, and the dispersed area nearest to a grid

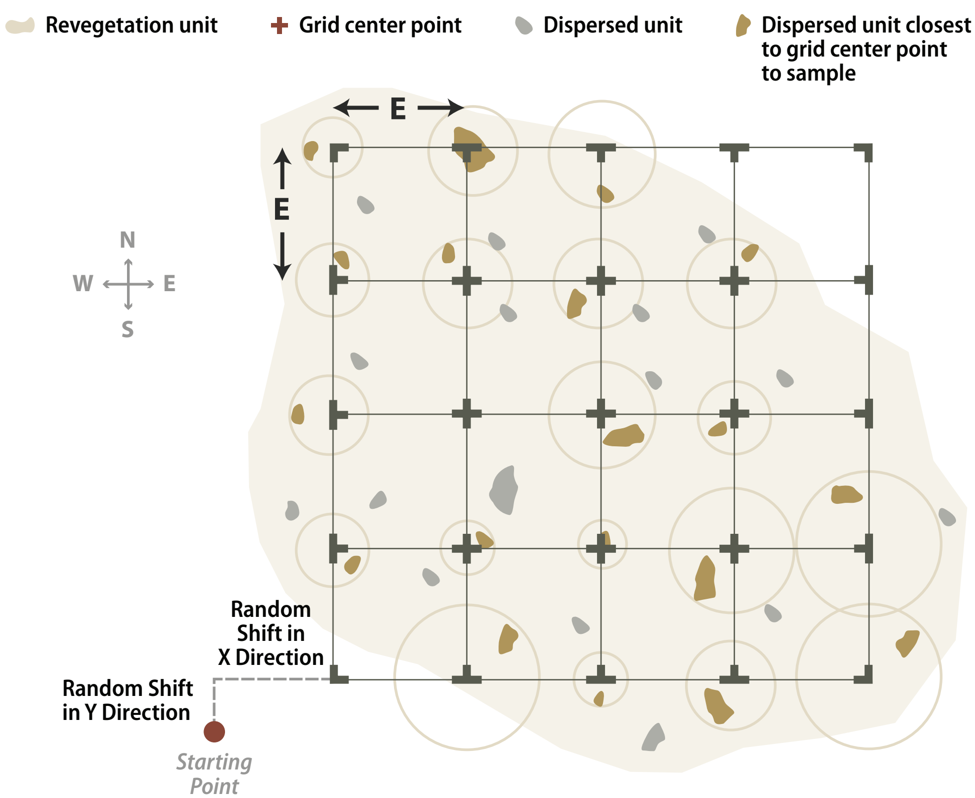


Figure 6-11 | **Sampling dispersed areas with an offset grid**

A systematic sample of dispersed areas, shown in this example, is based on 50 percent sampling (the pink areas). Alternating dispersed areas were sampled. Quadrats were located in each sampling unit by first locating a starting point and then measuring off random x and y offset coordinates to locate the first quadrat of the sampling grid.

crossing is selected for monitoring. One quadrat is randomly placed in each dispersed area and this becomes the experimental unit.

Determining the grid cell dimensions (E) is accomplished by using the following equation:

$$E = \sqrt{\frac{Area}{n}}$$

The grid is laid out in an unbiased manner by locating a starting point just outside the revegetation unit and assigning random numbers as offsets for the x and y coordinates. The corner of the grid is placed at the x and y offset point and oriented north. At each grid crossing, the closest dispersed area is selected for monitoring. If there are no dispersed areas found within half the distance between grid centers ($E / 2$), then the monitoring team moves on to the next grid center.

Second Stage

Since the dispersed areas are small (e.g., planting pockets, planting islands, benches), all measurements for seedling density and seedling attributes may be sampled within each dispersed area. For other procedures, such as soil cover, species cover, or species presence procedures, one quadrat is located randomly in the dispersed area.

Sample Size Determination

This section covers how to take pilot data to determine the number of experimental units (transects or quadrats) needed to statistically monitor a sampling unit. It is important to note that an alternative to taking pilot data is to simply to sample a minimum of 20 primary experimental units per sampling unit. For example, for a linear sampling area, 20 transects are laid out; for rectilinear areas—20 quadrats; and for a dispersed area sampling design—20 dispersed areas). Twenty primary experimental units will provide adequate data to accurately estimate means and confidence limits and to understand the uncertainty (i.e., width of confidence intervals). The risk is that, in some cases, the intervals may be too wide to provide meaningful estimates, which means that more samples would be needed, requiring revisiting of the sampling unit. Generally, if data are moderately variable and symmetrically distributed, 20 experimental units will often be adequate (personal communication: John Kern, Kern Statistical Services Inc., February 10, 2017). The following section is intended for projects where a more exact sample size, using pilot data, is desired to achieve the precision requirements of the monitoring plan.

Sample size determination methods are tailored to the monitoring objectives and sampling area design. This section outlines four sampling methods: (1) comparing means with DFC target for linear area sampling design, (2) comparing means with DFC targets for rectilinear sampling area design, (3) comparing means with DFC target for dispersed areas, and (4) determining sample size for comparing treatment areas.

Comparing Means with DFC Targets—Linear Sample Size Determination

To calculate the minimum sample size for linear sampling areas, the expected sample mean and the range in values are approximated. A visual estimate of the mean and the range of values may be adequate. For more precise estimates, four transects are sampled in the field to establish estimates of the mean and range of values.

The following is a quick method to determine the number of transects to sample based on pre-monitoring data collection:

- Driving the entire revegetation unit and noting extremes in vegetation
- Finding four areas that represent the extremes and laying out a transect in each area
- Randomly placing two quadrats within each transect to collect data on the attribute of interest (e.g., percent ground cover)

- For each transect, averaging the quadrat values (four averages)
- Calculating the average of the four transect averages and the range (difference between highest and lowest values of the four averages)
- Applying the range and the average to the following equation to obtain the minimum number of transects needed to monitor the revegetation unit (equation based on a sample size of 20 percent of the true population value with 90 percent confidence):

$$n = (0.838 * \text{Range})^2 / (0.2 * \bar{x})^2$$

The number of transects (n) obtained from this quick assessment is used to determine the layout of the monitoring design, as described in Section 6.3.5.

Example: Suppose that monitoring is to be conducted along a road cut to determine the percentage of soil cover. The monitoring objective is to estimate mean percent cover to within 20 percent of the true population value with 90 percent confidence. Four transects that represent a range in conditions are laid out within the revegetation unit. These transects do not need to be located randomly but rather can be sited to capture the range of values observed in the sampling unit. It is better to over-estimate the range of values, as this will tend to result in a conservative estimate of the sample size. The data set and equation are shown in Figure 6-12.

Using the equation presented above, an estimated 13 transects were calculated for a minimum sample size.

	QUADRAT		
Transect	**Q1**	**Q2**	**Averages**
T1	10	15	12.5
T2	12	22	17
T3	18	6	12
T4	32	21	26.5

Estimated Mean = **17**

Range (26.5 - 12.5) = **14.5**

$n = (0.838 * \mathbf{14.5})^2 / (0.2 * \mathbf{17.0})^2 = \mathbf{12.8}$ **transects**

Figure 6-12 | **Determining the number of transects using pilot data**

Example of how to calculate the number of transects needed, based on the pre-monitoring data set.

Comparing Means with DFC Targets—Rectilinear Sample Size Determination

When a grid of quadrats is to be implemented (Section 6.3.6), the sample size calculations use quadrat measurements as opposed to the transect averages that were used in linear sampling areas. The steps involved in calculating the number (n) of quadrats are as follows:

- Visiting the entire revegetation unit and noting extremes in revegetation
- Finding four areas that represent the extremes and laying out a transect in each area
- Randomly placing two to three quadrats within each transect to collect data on the variable of interest (e.g., percent ground cover)
- Averaging the quadrat values (eight quadrat values to average)
- Calculating the range of all eight samples (difference between highest and lowest values)
- Applying the range and the average to the following equation to obtain the minimum number (n) of transects needed to monitor the revegetation unit:

$$n = (0.838 * \text{Range})^2 / (0.2 * \bar{x})^2$$

Example: Using the data from the previous example (Figure 6-12), the eight quadrats would be averaged (instead of four transect averages being averaged). While the mean in this example remains 17, the range has spread to 26 (maximum 32 minus the minimum 6). The number of quadrats to sample would be 41:

$$n = (0.838 * 26)^2 / (0.2 * 17.0)^2 = 41.126$$

Comparing Means with DFC Targets—Dispersed Area Sample Size Determination

Systematic Sampling Method: The systematic sampling method is used when the dispersed areas are mapped (see Systematic Sampling of Dispersed Areas). The primary experimental unit in this design is the dispersed area. The number of quadrats to sample is estimated by following these steps:

- Finding four dispersed areas that represent the extremes of the attribute of interest

- Randomly placing two quadrats within each dispersed area to collect data on the attribute of interest (e.g., percent ground cover)
- For each dispersed area, calculating the average of the four dispersed areas' averages and the range
- Applying the range and the average to the following equation to obtain the minimum number of dispersed areas needed to monitor in a revegetation unit (equation based on a sample size of 20 percent of the true population value with 90 percent confidence):

$$n = (0.838 * \text{Range})^2 / (0.2 * \bar{x})^2$$

An example of the data set and equation are shown in Figure 6-12. Note: substitute "dispersed area" for "transect" in the first column heading.

Grid Sampling Method: The grid sampling method is used for revegetation units that have small dispersed areas that have not been mapped (see Grid Sampling of Dispersed Areas). Since only one quadrat is in a dispersed area, the quadrat becomes the primary experimental unit. The number of quadrats to sample is estimated by following these steps:

- Visiting a range of dispersed areas and selecting eight dispersed areas that represent extremes of the attribute of interest
- Randomly placing one quadrat in each dispersed area and collecting data on the attribute of interest (e.g., percent ground cover)
- Calculating the average and range in values
- Applying the range and the average to the following equation to obtain the minimum number (n) of dispersed areas to sample:

$$n = (0.838 * \text{Range})^2 / (0.2 * \bar{x})^2$$

Example: Using the data from the previous example (Figure 6-12), the eight quadrats would be averaged (instead of four transect averages being averaged). While the mean in this example remains 17, the range has spread to 26 (maximum 32 minus the minimum 6). The number of quadrats to sample would be 41:

$$n = (0.838 * \text{Range})^2 / (0.2 * \bar{x})^2$$

Comparing Means among Treatment Groups—Sample Size Determination

When determining the sample size for comparing treatment differences (Section 6.3.7), it is not necessary to differentiate between linear, rectilinear, or dispersed sampling area designs. Sample size determinations follow these steps:

- Reviewing each treatment area to be compared. These can be different revegetation units or different types of revegetation treatments.
- From each treatment area, collecting data from two transects with each transect consisting of two quadrats. These should represent a range of extremes for a total of four transects.
- Determining the range between the low and high quadrat values.
- Determining delta (also represented by **Δ**). Delta defines the level of significance that is needed for monitoring, or the meaningful difference in measurement output. For example, calculating bare soil at 1 percent difference in means would be unimportant, that is, the difference between 8 and 9 percent bare soil is too fine a distinction to make. A 5 percent difference might be important if the amount of data that is needed to be collected was not great. More than likely, a 10 percent difference (e.g., the difference between 10 and 20 percent bare soil) would be an acceptable delta value for bare soil

cover. It is important to note that the smaller the delta value, the more samples that need to be collected.

The number of transects (n) can be calculated using a simplified equation:

$$n = 15.68 / (\Delta * 2.059 / \text{Range})^2$$

The number of transects determined from these calculations are applied equally to the two (or more) areas being compared. This equation assumes that tests will be conducted at the delta level of significance and that there will be a difference detected at or greater than an 80 percent probability.

Example: A test was set up to determine whether a commercial product could increase plant cover by at least 10 percent one year after application, as advertised. In one area, the product was applied and in another similar area, it was not. To determine the number of transects to install in each area, a year after application, two transects were set up in the treated area and two transects in the untreated area. From the quadrat readings, the range in percent vegetative ground cover values was found to be 22. Assuming a delta level of significance of 10 percent (important to be able to detect a difference in 10 percent cover with at least 80 percent probability), the following number of transects required for each treatment area were determined to be 18:

$$n = 15.68 / (10 * 2.059 / 22)^2 = 17.9 \text{ transects}$$

In general, using the simple equation provided above, and possibly adding 10 to 20 percent additional samples as a level of conservatism, is a reasonable approach.

6.3.7 ANALYZE DATA

This section provides statistical methods for analyzing data collected for all monitoring procedures described in the previous section. There are three types of analysis based on the objective of the area being monitored:

- **Compliance**—Determine whether DFC targets were met
- **Treatment differences**—Determine whether there were differences between treatments or changes between years
- **Trends**—Determine the degree of vegetation or soil cover change over time

Only one of these procedures is selected for an analysis depending on the monitoring objective used. These procedures use confidence intervals to determine the statistical significance of the monitoring data set.

Analysis of Compliance

The objective behind most monitoring is to answer these three questions:

- Was the project successful?
- Were DFC targets met?
- Were the commitments made to the community and those described in planning and compliance documents and reports met in terms of protecting soil, reestablishing native vegetation, and maintaining or improving pollinator habitat?

To answer these questions, the means of the attribute data of interest (e.g., bare soil, species presence) are compared with the DFC targets. For example, a project has a DFC target of at least 70 percent soil cover on a road cut near a live stream one year after road construction.

Using the soil cover procedure, data are collected on 20 transects and a mean of 81 percent soil cover is determined. At this point, the designer might conclude that the targets were met. From a statistician's point of view, however, the data displayed in this context is inconclusive because the variability of the soil cover in the sampling unit is not known or cannot be accounted for. In other words, how good is the number? Is it really depicting what is happening on the site? If another person were to use the soil cover procedure in the same sampling unit but at a different spot, would the soil cover be exactly 81 percent? This is highly unlikely because of the high variability of soil cover.

Confidence intervals provide a means of predicting, at a chosen level of certainty, whether the soil cover value collected anywhere in the sampling unit will be within a stated range. Confidence intervals are an alternative to saying, "we think the soil cover at any point in the sampling unit will be around 81 percent." Using confidence intervals, it can be said instead that, "we are 90 percent confident that if data collection was repeated at this site 10 times, 9 out of 10 times the average soil cover estimate would be within our confidence limits." If a higher confidence level is desired (most scientists working in health fields want to be more certain), confidence intervals can be based on 95 percent or even 99 percent certainty. In this case, the confidence interval would be much wider.

The data sets from very different revegetation units are shown in Figure 6-13 to convey the concept of confidence intervals. While both data sets have the same mean of 81 percent soil cover, the confidence intervals are very different. Data set A was taken at a site with very uniform soil cover, while data set B had much more variability. For both data sets, a 90 percent confidence interval is desired. Notice that the confidence interval for data set B is much wider than data set A since it has greater variability.

With confidence intervals, it can be said with greater certainty whether the DFC target or threshold of 70 percent soil cover was met. It can be stated with 90 percent confidence that data set A met the target because the lower confidence limit (73 percent) is above the target of 70 percent. Alternatively, data set B poses some problems. It cannot be said with 90 percent confidence that the average is above the threshold of 70 percent because the lower confidence limit of data set B is 66 percent, or 4 percent below the threshold. The designer might argue that, because the mean is above the target, the target was met. To statisticians, however, the fact that the lower confidence interval is below the stated target indicates a fair amount of uncertainty. They would have to obtain more data or change how confident the prediction is before they could be certain the DFC target was met.

Calculating Confidence Intervals

Workbooks are available in the Native Revegetation Resource Library website to calculate confidence intervals depending on the sampling unit design (Section 6.3.6):

- **Linear sampling design**—Select this Excel workbook for linear sampling designs.
- **Rectilinear sampling design**—Select this Excel workbook for rectilinear sampling designs.
- **Dispersed sampling design**—For this sampling design, there are two workbooks to choose from. If a grid sampling design was used, this Excel workbook is used, and if a systematic sampling design was used, this workbook is used.

Interpreting Confidence Intervals for Compliance

Confidence intervals, as stated previously, are used to evaluate the success of a revegetation project relative to a specified DFC target. For example, an objective of a revegetation project was to establish at least 65 percent total cover over the soil to protect against surface erosion. Or stated another way, the objective was that no more than 35 percent bare soil would be exposed one year after revegetation treatments were applied. During monitoring, it was found that the lower confidence level was 23.8 and the upper confidence level was 30.8, both below the target of 35 percent. It could be said with a 90 percent level of confidence

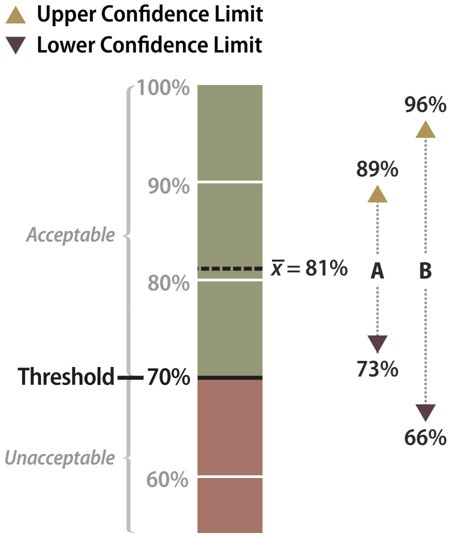


Figure 6-13 | **Example data analysis results**

Data set A has an upper confidence limit of 89 percent and a lower confidence limit of 73 percent. Since the lower confidence limit is above the target, or threshold, of 70 percent, it can be stated with 90 percent confidence that the target was met. Data set B has a wider confidence interval and a lower confidence limit of 66 percent, which is below the target. In this case, there is uncertainty at the 90 percent confidence limit that the target was met.

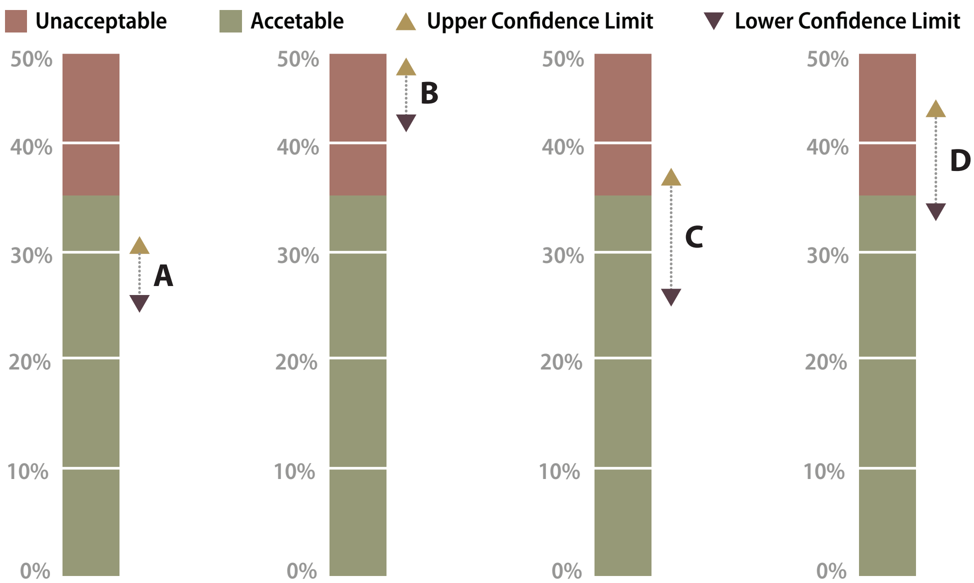


Figure 6-14 | **Possible scenarios when comparing targets to confidence intervals**

Four possible scenarios that can be encountered when comparing targets to confidence intervals. Confidence interval A is clearly acceptable, whereas confidence interval B is clearly unacceptable. Uncertainty arises when the lower confidence limit is acceptable but the upper confidence limit is unacceptable. This is shown in cases where the mean is in the acceptable range (C) and in the unacceptable range (D).

that the objectives were met. But what if the confidence interval was either above the target or straddled the target?

Figure 6-14 shows four possible scenarios for confidence intervals that may be encountered. Scenario A is a case in which the data supports the conclusion at 90 percent confidence that the project met the target. Scenario B did not meet the target because the lower confidence limit was above 35 percent bare soil.

Scenario C is a case where the mean meets the target, but the upper confidence limit is above the target. It cannot be said with 90 percent confidence that the targets were met. At this point it might be asked how important it is to know whether the target was met. If the site directly influences a live stream, it might be very important. However, if there are no streams nearby, it might suffice to report that there was some uncertainty whether the target was met. If it is determined that more certainty is needed, more data must be collected.

Scenario D is a case where the mean does not meet the target, but the lower confidence limit is below the target of 35 percent bare soil. One might state that this project did not meet the target, but this still could not be stated with 90 percent confidence. In this scenario, more transects could be taken to narrow the confidence interval and hope that the results do not straddle the target.

Another option for Scenarios C and D might be to implement measures to decrease the amount of bare soil. This could include more seeding or application of mulch. The site would be resampled after an interval of time to determine whether the DFC target had been met.

Analysis of Treatment Differences

There may be opportunities to compare the effects of different revegetation products or methods on plant establishment and growth using monitoring data. Some of these opportunities will be planned (e.g., trying a new product), and some will be mistakes (e.g., inadvertently doubling the rate of mulch application). Planned or unplanned, when different revegetation activities have occurred within a revegetation unit, monitoring can be designed to assess whether there is a different vegetative response between those activities or treatments. The monitoring design outlined in this section will not replace a well-designed study or experiment; it is suggested that if more conclusive results of treatment differences are desired, a study would be designed with statistical oversight. An Excel workbook is available in the Native Revegetation Resource Library for this analysis.

The confidence interval concept is applied in this subsection to determine differences between new revegetation treatments (new treatments) and routine revegetation methods (standard treatments). Three possible outcomes are possible when new treatments are compared to standard methods: (1) the new treatment results in a favorable increase in the measured parameters over the standard treatment (positive difference), (2) the new treatment results in a decrease (negative difference), or (3) there is no positive or negative difference (no difference). Using confidence intervals, it is possible to determine which of these outcomes is statistically supported for any monitoring data set. In this method, the means and variance of means are calculated for both the new treatment and standard treatment and a confidence interval is calculated for the certainty of the treatment differences.

The following example demonstrates how a confidence interval is determined and how it can be used to interpret two data sets. During a hydroseeding operation, it is discovered that fertilizer was mistakenly applied at twice the normal rate in one area. This area was staked in the field when the realization was made and visited by the project team a year later. Some on the team believed that there was more vegetative ground cover where fertilizer was doubled; others felt that there was less. One or two on the team did not believe they could make either call. Since monitoring was going to occur a few weeks later, they decided to design a monitoring procedure to answer the question, "Was there a positive, negative, or no response of vegetative ground cover to the application of additional fertilizer?"

Within the framework of monitoring that was already scheduled for this revegetation unit, a monitoring strategy was developed. The species cover procedure was used (Section 6.3.2) along with the linear sampling design since this was a road cut (Section 6.3.6). Each treatment area was considered a separate sampling unit, and monitoring of each treatment area took place independently of the others. The data from each treatment area was recorded in the Species Cover spreadsheet (see Species Cover Monitoring Procedure workbook) to obtain means and variance of means. These values were then entered into the Comparing Treatment Differences Monitoring Procedure spreadsheet to obtain confidence intervals.

The results of this analysis showed that the standard rates of fertilizer had an average vegetative ground cover of 33 percent as compared to 62 percent for double the fertilizer rate. While this looks like an obvious difference, how certain could the team be? In this example, the confidence interval (at 90 percent confidence) showed that additional fertilizer significantly increased vegetative ground cover. This can be shown graphically in Figure 6-15. The doubled fertilizer treatment increased ground cover a minimum of 16 percent (lower confidence interval) over the standard treatment to as much as 42 percent ground cover (upper confidence limit).

The team accepted these results and commented that fertilizer rates should be increased for future projects. One member posed the question, "We might have achieved better vegetative cover on this site during the first year, but how did additional fertilizer affect the native species cover?" Since the monitoring team was still on the project site, they resampled the two areas using the species cover procedure (Section 6.3.2). In this procedure, native and non-native annuals and perennials were recorded at each quadrat. Confidence intervals were determined for each treatment for native perennial cover and they learned, in this case, that additional fertilizer had a negative effect on the establishment of native perennial cover (Figure 6-15). But what if the upper confidence interval in this example had been positive and the lower confidence interval had been negative? In this case, it would have to be concluded that there was no difference between treatments at 90 percent confidence.

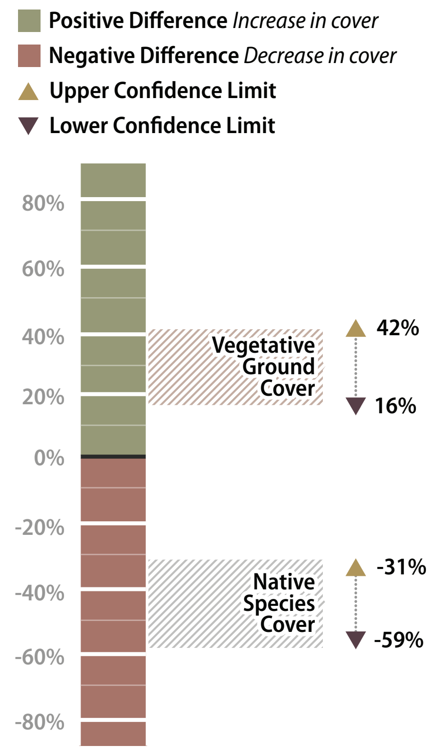


Figure 6-15 | **Interpreting results with confidence intervals**

In the example presented in the text, confidence intervals are used to answer: (1) how vegetative ground cover responds to 2X the fertilizer rate, and (2) how native species cover responds to 2X the fertilizer rates. The confidence interval collected for the first question was found to be positive, indicating that vegetative ground cover responds positively to twice the fertilizer. The confidence interval for the data set collected for the second question was negative, indicating that native species cover responded negatively to more fertilizer.

Analysis of Trends

The last of the three objectives for roadside monitoring is assessing trends, or the degree that attributes, such as vegetative or soil cover, change over time. One of the main reasons to perform this type of monitoring is to understand how plant growth or successional patterns change. Many monitoring procedures employ permanent monitoring plots or transects that can be repeatedly and accurately revisited for sampling. This approach does not work as well for roadside monitoring however, because of the hazards to road maintenance personnel and to the public of placing permanent stakes in road corridors. In addition, permanent markers are often hard to relocate years later or can move due to the instability of steep cut and fill slopes. In this section, a statistical analysis that does not entail locating and resurveying of exact quadrats is offered. An Excel workbook is available in the Native Revegetation Resource Library for this procedure.

The confidence interval approach is applied in this section to determine if there are differences in attributes from one sampling date to another. Three outcomes are possible when comparing data from one sampling date to the next: (1) attributes have increased since the last sampling period (positive difference), (2) attributes have decreased since the last sampling period (negative difference), or (3) either there was no change in attributes or the number of samples was inadequate to detect the amount of change that occurred. Using confidence intervals, it is possible to make statistically valid statements regarding the observed outcomes.

The following example demonstrates how confidence intervals are determined and how they are used to interpret data collected on different sampling dates. Members of the project team believed that California brome (*Bromus carinatus*; BRCA5) was a short-lived species; that it established well after seeding but by the fifth year it had very little presence on most sites. They also believed that Idaho fescue (*Festuca idahoensis*; FEID) started out slowly but gained dominance over time. The team felt that by understanding these trends they might develop a better seed mix for sites like the ones they were monitoring. The question they posed was: "Is there a positive, negative, or no difference in the cover of California brome and Idaho fescue from the first year to the fifth year after seeding?"

This question necessitated the use of the Species Cover procedure (Section 6.3.2) since dominance was being expressed as percent crown cover for each species. Linear Sampling Design was used for both monitoring dates because the sampling unit was a long cut slope. The data from each sampling date for California brome and Idaho fescue was entered into the spreadsheet shown in the Species Cover spreadsheet (see Species Cover Monitoring Procedure workbook) to obtain means and variance of means. These values were then entered into the spreadsheet shown in the Analyzing Trends Monitoring Procedure workbook to produce confidence intervals for comparison. Data entry was also conducted in the same manner for Idaho fescue.

The results of this analysis showed that California brome had an average crown cover of 35 percent in 2001 but decreased to 27 percent in 2006, five years later. Was this a statistically significantly difference? Using confidence intervals, it was determined that the means were not statistically different at 90 percent confidence. This can be shown graphically in Figure 6-16. Because the upper confidence limit was positive and the lower was negative, the team could be 90 percent confident that crown cover did not increase from 2001 to 2006. Alternatively, Idaho fescue did show an increase in mean crown cover from 2001 to 2006. This increase was found to be significant because both the upper and lower confidence limits were positive. The team could be 90 percent confident that there was a true increase in crown cover.

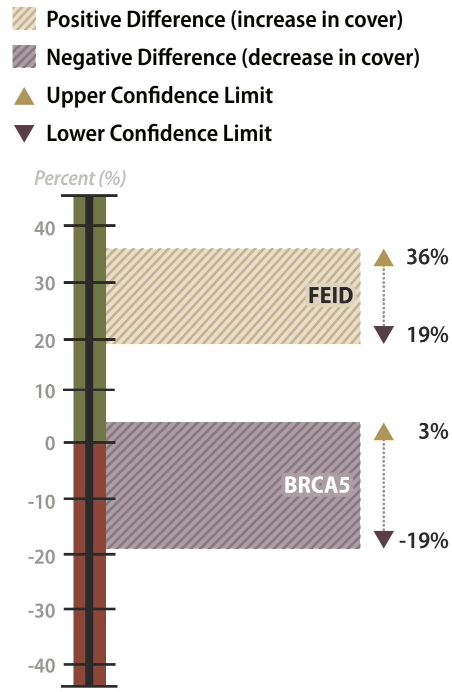


Figure 6-16 | **Example results with confidence intervals**

In the example, confidence intervals were used to determine whether California brome (BRCA5) and Idaho fescue (FEID) increased, decreased, or stayed the same from 2001 to 2006. The percent crown cover of California brome was found not to have changed during this period because the lower confidence limit was negative and the upper confidence limit was positive. The confidence interval for the Idaho fescue showed an increase between 2001 and 2006. Since the upper and lower confidence limits were positive, the differences in the means between sampling dates were significant at 90 percent confidence.

6.4 POLLINATOR MONITORING PROCEDURES

The monitoring procedures presented in this section provide instructions for monitoring bees, butterflies, and monarch butterflies to assess the quality of revegetated roadsides as pollinator habitat. The data collected from these procedures will allow the project designer to determine if the revegetation project successfully addressed pollinator-specific DFCs. These procedures can be used to assess roadside habitat in a number of ways, such as determining (1) whether revegetation efforts have increased pollinator richness and abundance (by including nearby non-revegetated roadsides in samples as reference sites), (2) if pollinator richness and abundance change over time, (3) the effects of different roadside management strategies or seed mixes on pollinators, and (4) habitat quality and survival rates for monarch butterflies.

Three monitoring procedures are presented in this section.

- **Bee abundance procedure**—This is a standardized, streamlined monitoring procedure that provides estimates of bee abundance and involves minimal time and training. It involves establishing transects in the project and conducting timed assessment to observe and count the abundance of bees on flowers. This procedure can be used to statistically compare the quality of sites or seed mixes for pollinators and assess changes in pollinator populations over time. This procedure can be conducted on the same transects as those established for soil and plant monitoring (Section 6.3).
- **Bee and butterfly diversity procedure**—This procedure provides methods for measuring morphogroups of bee and butterfly species along transects in the project. While it involves some training and practice, this procedure generates robust data that is useful for detecting community-level changes in bee or butterfly abundance and richness.
- **Monarch butterfly reproduction and habitat procedure**—This procedure outlines methods to measure the abundance of host plants for monarch butterflies and the density of monarch eggs and larvae. Obtaining this data entails a moderate amount of time and expertise, but they can be used to quantify host plant availability and survival rates of monarchs.

In all of these procedures, it is important to standardize the sampling effort and weather conditions. Weather conditions strongly influences pollinator behavior. Pollinators are uncommon during cold, windy, or overcast weather, so it is best to monitor under optimal and consistent conditions when monitoring adult bees or butterflies. Optimal conditions for sampling pollinators include sampling between 10 a.m. and 4 p.m. on days with air temperatures over 60° F, wind speeds less than 10 miles per hour, and skies mostly clear. If sampling over time, monitoring is conducted using the same procedure over the same area at roughly the same phenology stage or the same weeks and months every year and under similar weather conditions.

It is important to note that counting individual European honey bees alone cannot provide a measure of the value of habitat for native bees or other pollinators because the number of individual honey bees visiting habitat is primarily determined by the number of managed hives in the vicinity. Although the presence of honey bees does indicate that the vegetation supports bees, it does not demonstrate how well the vegetation increases abundance and diversity of unmanaged bees and other pollinators.

Pollinator populations vary over the course of the growing season and from year to year. If a species of interest is to be targeted using monitoring (e.g. monarch butterflies), it is useful to schedule monitoring according to their flight period. Pollinator populations also vary annually, increasing as plants become established and mature, which may take several years after seeding or planting. For this reason, monitoring procedures are conducted for multiple years after a revegetation project has been completed.

6.4.1 BEE ABUNDANCE MONITORING PROCEDURE

Overview of procedure

- **What the procedure will measure**—Wild bee and honey bee abundance
- **Sampling design**—Transects within the project area
- **Sampling frequency**—Two visits per growing season (at minimum)
- **Sampling timing**—Warm, sunny, and calm days, between 10 a.m. and 4 p.m.

- **Level of identification needed**—Distinguish bees from all flower visitors; distinguish native bees from European honey bees
- **Equipment needed**—Stopwatch or clock, data sheets, clipboard and pencils, long measuring tape (100 meters), flags/stakes to mark transects, GPS device, this procedure and pollinator identification guide
- **Personnel needed**—Can be conducted by a single person, but easier with two
- **Workbooks**—Bee Abundance Monitoring Procedure workbook

This streamlined monitoring procedure provides a quantitative measurement of bee abundance and can be conducted with minimal time and training. The surveyor must be able to recognize bees from other insects visiting flowers, and distinguish honey bees from native bees (see **Native Revegetation Resource Library guide** for more information about this level of identification). Two separate visits are made in a growing season to conduct a timed assessment to observe and count bees on flowers. During each visit, observations are made along transects. Surveys are conducted in the middle of the growing season, at least one month apart. In California, for example, May through July is the ideal survey window, while in the Upper Midwest or Northeast, July through August is preferred. Monitoring is conducted only when weather conditions are warm, sunny, and calm, with air temperatures over 60° F, wind speeds less than 10 miles per hour, and skies mostly clear. Pollinators are most active between 10 a.m. and 4 p.m.

Figure 6-17 | **Two-person monitoring teams**

With a two-person monitoring team, one person counts pollinators and the other records the data and tracks time.

Photo credit: Michael Kent, Cape Atlantic Conservation District

This procedure can be implemented with one person, but it is easier with a two-person team (Figure 6-17). When using two people, one person observes and counts bees while the other records the data and tracks the time and weather conditions. A field data and analysis form in the Bee Abundance Monitoring procedure workbook can be downloaded here.

Bee counts are made along multiple transects perpendicular to the road across the entire length of a roadside sampling area, as described in Section 6.3.6. The bee counts can be conducted on the same transects and at the same time that Soil Cover, Species Cover, and Species Presence procedures (Section 6.3.1, Section 6.3.2 and Section 6.3.3) are conducted. However, the bee abundance monitoring is conducted prior to the Soil Cover, Species Cover, or Species Presence procedures to reduce disturbance that could disrupt bee activity.

For each transect, a measuring tape is laid out from the edge of the road shoulder to the outer roadside edge (Figure 6-18). The length of each transect determines the time spent counting bees on each transect. Plan on spending approximately one minute counting bees for every 10 feet of transect. For example, if the transect length is 35 feet, then time spent counting bees for that transect would be 3.5 minutes. To reduce the disturbance to bees prior to sampling,

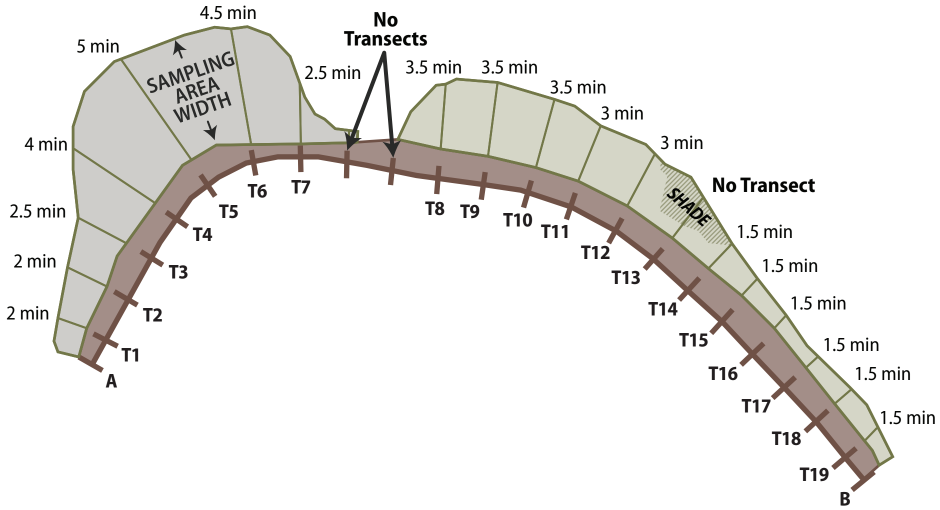


Figure 6-18 | **Transect layout on roadsides for Bee Abundance monitoring procedures**

Multiple transects for pollinator surveys are laid out similarly to those described in Section 6.3.6 for each roadside sampling area. In this example, survey times are based on 1 minute per 10 feet of transect. Transects that are shaded from the sun are not sampled, nor are transects that are less than 10 feet.

only one person lays out the measuring tape and then stays clear of the tape while walking back to the beginning of the transect.

Transects typically start from the road and end at the outer edge of the roadside. In situations where the shadow of the surveyor is directly in front of the direction of travel, the transect recording begins at the outer edge of the roadside and travels to the road. If the entire transect is shaded, then this is noted on the data sheet. Bee activity declines in shaded areas.

At the start of each transect, the data recorder starts the stopwatch and the observer begins to count bees, covering about 10 feet of the transect per minute. The observer chooses the side of the transect with the least shadow and observes the flowers within 3 feet of the transect line. While walking transects, each bee that lands on the reproductive structures of the flower is recorded. Bees that are perching on leaves or petals are not counted. If performing the monitoring with just one person, a timer is used and the timer is paused as needed to record a bee. The timer is restarted when observations resume.

While moving along the transect, a tally of the number of native bees and honey bees is recorded. The same individual bee is not counted twice, even if it visits multiple flowers, because the overall goal is to count the number of individuals using the site rather than the rate of floral visitation.

At the end of each transect, the recorder tallies the number of pollinators, the travel time, time of day, the length of transect, transect number, and weather conditions. If other monitoring procedures (e.g., Soil Cover, Species Cover, and Species Presence) are to be conducted, the team returns to the beginning of the transect and conducts these procedures.

Records of roadside sampling areas also include the site name, sampling area designation, date, name of the sampler, weather conditions, time of visit to the site, and any pertinent notes about the site. It is also valuable to record the plants that are blooming along the transect at the time of the survey, as well as to collect data on the floral associations of the bees at the site. The data sheet is available at the website mentioned previously. This procedure was adapted from a procedure developed by researchers with the University of California, Davis; Rutgers University; Michigan State University; and The Xerces Society (Ward and others 2014).

Data Analysis

To determine overall abundance per roadside sampling area, the number of individual bees observed during each monitoring event is tallied. Then, the monitoring events per year are averaged. To determine the number of honey bees and the number of native bees per transect-foot, the total number of bee counts of all transects in a field visit is summarized and divided by the total transect distance. This number can be can be used to compare with other field monitoring visits.

A second analysis method is based on the statistical methods outlined in Section 6.3.7. Using this method, field data is entered into the Bee Abundance Monitoring procedure workbook, which calculates mean and confidence intervals for honey bees and native bees for each sampling area. Confidence intervals can be used to determine if there are significant changes in populations between sampling areas or dates. This analysis can also be used to correlate findings from Soil Cover, Species Cover, and Species Presence procedures. For example, using data from each transect, a regression analysis of bee populations to floral density (Section 6.3.2) could be analyzed. Other regressions could include percent bare soil, specific plant species, and species richness.

The number of native bees counted through this monitoring procedure correlates positively with the overall diversity of native bees at a site; therefore, if a large abundance of individuals is present, that indicates higher diversity (Ward and others 2014). If multiple roadside sampling areas are surveyed, the differences observed in native bee abundance reflect differences in habitat quality among sites. Native bee counts can be used to rank the quality of sites or the quality of seed mixes, or can be used over time to assess changes at a site. Note that honey bee abundance cannot provide a measure of the value of habitat for native bees or other pollinators because the number of individual honey bees visiting habitat is determined by the number of managed hives in the vicinity.

6.4.2 BEE AND BUTTERFLY DIVERSITY PROCEDURE

Overview of procedure

- **What the procedure will measure**—Abundance and richness of bees and butterflies
- **Sampling design**—Transects within the project area
- **Sampling frequency**—Three visits per growing season, at a minimum—late spring, mid-summer, late summer
- **Sampling timing**—Warm, sunny, and calm days, between 10 a.m. and 4 p.m.
- **Level of identification needed**—Identify morphological groups (morphogroups) of bees and groups of butterflies
- **Personnel needed**—Two people: one person to identify pollinators, one to keep time and record data
- **Equipment needed**—Stopwatch or clock, data sheets, clipboard and pencils, long measuring tape (100 meters), flags/stakes to mark transects, GPS device, this procedure and pollinator identification guide, and plant lists and plant identification guide (see Native Revegetation Resource Library)
- **Workbooks**—Bee and Butterfly Diversity Monitoring Procedure workbook (see Native Revegetation Resource Library)

Procedure Details

This procedure provides measurements of bee and butterfly abundance, as well as the number of bee species (richness). It can be challenging to identify pollinators. For example, most native bee species can only be identified to species by examining pinned specimens under the microscope and obtaining confirmation from experts. In fact, standard pollinator monitoring techniques typically employ destructive sampling, with specimens collected with nests or traps, pinned, and then identified by a taxonomist. While these collection techniques provide the most robust data, they can be labor intensive, time consuming, and expensive. Collecting observational data on pollinators is an economical and effective alternative to monitoring pollinators, as long as the observers have had some training and practice in order to recognize and monitor pollinators. This procedure can be used to collect consistent observational data on bee and butterfly communities. The procedure is based on a standardized method designed by researchers and practitioners (Kremen and others 2011; Minnerath and others 2016).

The goal of this procedure is to identify specific associations between pollinators and their habitat. Monitoring takes place along transects, which are located within sampling units that have relatively uniform vegetation and site characteristics (Figure 6-19). If the project is large or composed of several different plant communities, then several sampling units may be delineated and sampled separately. The number of transects placed in a sampling unit depends on the size of the unit and topographic relief:

- **<2 acres – no relief**—establish one 400 feet transect through the middle of the area outside of the clear zone, running parallel to the road (Figure 6-19A)
- **<2 acres – with relief**—orient multiple transects of equal length that add up to a total of 400 ft. running perpendicular to road (for ease of walking the transect) and spaced apart evenly. Figure 6-19B shows a sampling area where 10 transects averaging 40 feet in length were laid out for a total of 400 feet.

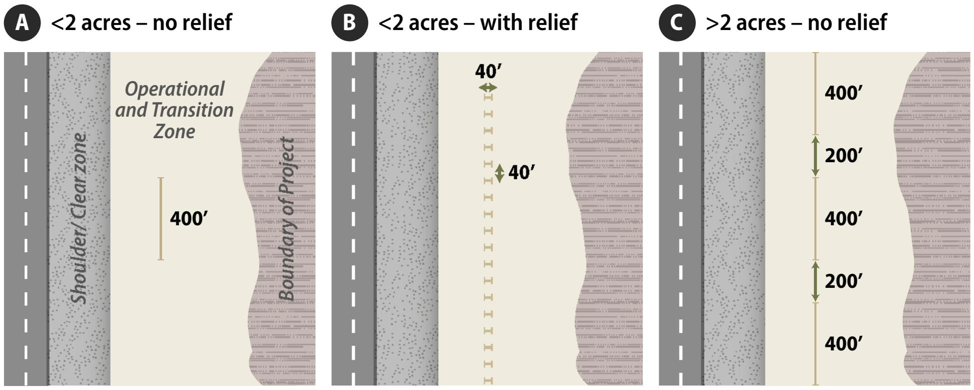


Figure 6-19 | **Transect layout on roadsides for Bee and Butterfly Diversity monitoring procedures**

- **>2 acres – no relief**—establish three 400 feet transect through the middle of the area outside of the clear zone, running parallel to the road separated evenly (Figure 6-19C)
- **>2 acres – with relief**—orient multiple transects of equal length that add up to a total of 1,200 ft. running perpendicular to road (for ease of walking the transect) and spaced apart evenly.

If making comparisons between sites, it is best to keep the individual transect length and the distances between transects constant. For sites that are greater than 2 acres in size, three 400-foot-long transects are used that are spaced evenly throughout the site. Transects are located in full sun where possible (or notations are made on data sheets when in shade) because pollinator activity declines in shade. GPS coordinates are taken to allow others to monitor the area in the future.

Monitoring is conducted at least three times a growing season, ideally monthly. This is because many bee and butterfly species fly for a limited number of weeks each growing season, and the communities may differ greatly between samplings. It is important to be consistent from year to year in the frequency of monitoring so that comparisons between years can be made.

Weather conditions strongly influence bee and butterfly behavior. Bees avoid activity on cold, windy, or overcast days, so monitoring is optimal when sampling on days with air temperatures over 60° F, wind speeds less than 10 miles per hour, and skies mostly clear. Standardizing the time of day that sampling occurs is also important. Pollinators are most active between 10 a.m. and 4 p.m.

These procedures can be implemented by observers working on their own or in pairs, with one person to act as an observer and the other to record observations and data. It is easiest to conduct observations of bees and butterflies on separate walks of the transects to help focus identification.

When making observations of floral visitors in a transect:

- Insects should be observed carefully and only identified to a level at which the surveyor is confident.
- Insects visiting flowers should not be disturbed before an observation can be made. The surveyor should walk slowly and avoid sudden movements. Insects will respond to shadows passing overhead, so the surveyor should walk so as not to cast a shadow where observations are to be made.

Bee Monitoring

The transect is walked at a steady pace, such as 10 feet per minute; expect each 400-foot-transect to take 40 to 60 minutes. The surveyor walks slowly, not spending more than a couple of observational minutes at any flower or group of flowers. The time spent walking transects should be consistent so that the data is collected with the same level of effort to allow for comparisons between samples.

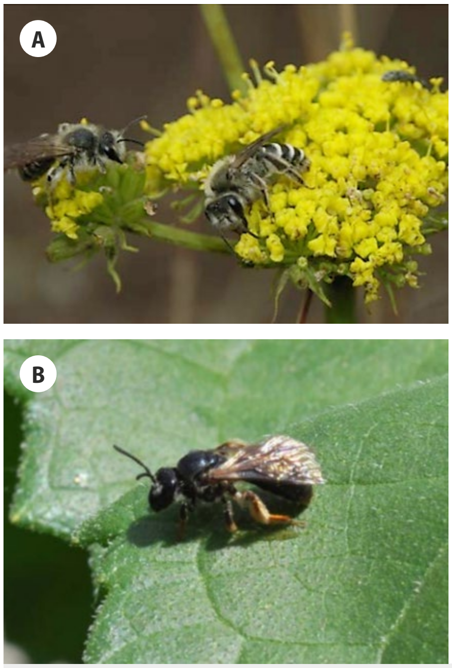


Figure 6-20 | **Recording bee visits**

When recording bee visits, only bees present on reproductive parts of flowering plants (A) but not on leaves, petals, or in flight (B) are recorded.

Photo credit: Mace Vaughan, Xerces Society (A), Sara Morris, Xerces Society (B)

Only bees that are on the reproductive parts of the flower are identified and recorded (Figure 6-20). Bees sitting on petals, leaves, or in flight are not recorded. When a bee is visiting a flower, the bee is observed and identified using the identification guides presented in the Native Revegetation Resource Library. It can also be helpful to note other floral visitors beyond bees, and the species of the flower on which the bees are observed. If more than one floral visitor is observed on a single flower, the number of visitors is noted first and then they are identified. After the bee data is collected, each additional flower species that is in bloom but did not have floral visitors during the survey is noted.

Butterfly Monitoring

This monitoring procedure is based on the standardized Pollard Walk (Pollard and others 1975) and can be used to collect observational data on the abundance and richness of butterflies. The objective of this procedure is not to count all butterflies present at the entire site or within the habitat being monitored, but to count those individuals that occur in, or move through, the transect' s sampling area while the surveyor is walking a steady pace of 10 feet per minute. The surveyor identifies and counts butterflies on flowers or in flight if they occur within approximately 15 feet on each side of the transect or overhead of the surveyor. Butterflies that fly in from behind the surveyor are not counted to avoid counting the same individual twice. Butterflies are identified to the level most comfortable to the surveyor (refer to butterfly identification guide) and recorded as whether the butterfly was observed in flight or nectaring on a flower. If the butterfly is nectaring, it can be helpful to record the species of the plant on which the butterfly was feeding.

Considerations include:

- It is important to be consistent, using the same level of effort with each time transect.
- The time spent walking the transect is recorded each time.
- It is recommended that records of observations include the site name, date, name of the sampler, weather conditions, time of visit to the site, and any pertinent notes about the site.
- It is also valuable to record the plants that are blooming along the transect at the time of the survey, as well as to collect data on the floral associations of the pollinators at the site.

Data Analysis

To draw meaningful conclusions about the effects of roadside habitat on bees and butterflies, data is collected consistently over time in the same areas. To determine changes in abundance over time, the number of individuals observed during each monitoring event is tallied (transects can be combined if multiple transects are sampled). These numbers can be averaged for each year (e.g., the results from late spring, mid-summer, and late summer can be averaged) and plotted on a graph or table to show changes between years. The numbers of individuals can also be totaled for each monitoring event and evaluated separately. Honey bee counts may be excluded in some analysis because the placement of hives influences their abundance.

To calculate species richness for each sampling period or each year, the total number of bee morphogroups and butterfly groups that were observed are tallied. Richness can then be plotted to record changes over time, whether comparing the average or total number of groups observed across all sample periods for each year, or comparing the total number of groups observed during a certain sampling period from year to year.

As noted before, pollinator populations vary over the course of the growing season and from year to year, so it is important to schedule monitoring accordingly. Pollinator populations also vary annually, increasing as plants become established and mature, which may take several years after seeding or planting. For this reason, monitoring is conducted for several years or more after the project has been completed, ideally 3 to 5 years. The longer sites are surveyed, the more meaningful the results.

6.4.3 MONARCH BUTTERFLY REPRODUCTION AND HABITAT PROCEDURE

Overview of Procedure

- **What the procedure will measure**—abundance of milkweed plants, abundance of nectar plants in bloom, abundance of monarch eggs and larvae
- **Sampling design**—Transects within the project area, with uniformly spaced quadrats along each transect
- **Sampling frequency**—Once a growing season during the breeding season of monarchs, at a minimum
- **Sampling timing**—Warm, sunny, and calm days between 10 a.m. and 4 p.m.
- **Level of identification needed**—Recognize monarch butterfly eggs and larvae, identify milkweed species, identify target nectar plants
- **Personnel needed**—Two people: one person to identify plants, one to search for monarch eggs and larvae
- **Equipment needed**—Stopwatch or clock, data sheets, clipboard and pencils, long measuring tape (100 meters), flags/stakes to mark transects, GPS device, 1m x 1m quadrat, this procedure and monarch egg and larval identification guides, and plant lists and plant identification guide (see Native Revegetation Resource Library)
- **Workbooks**—Monarch Butterfly Monitoring Procedure (see Native Revegetation Resource Library)

Procedure Details

Monarch butterfly populations have recently declined to dangerously low levels and are being considered for listing under the Endangered Species Act. If the project area is within the distribution of the monarch butterfly, it may be important to conduct monarch monitoring. Monarch butterflies have a range that extends across most the United States (exceptions include western Washington and parts of western Oregon where their host plants do not occur) and into southern Canada and northern Mexico.

This procedure outlines how to measure (1) abundance of milkweed, (2) abundance of nectar plants, and (3) density of monarch eggs and larvae. Measurements are made along multiple transects perpendicular to the road across the entire length of a roadside, as described in Section 6.3.6 (see Linear Areas) and as shown in Figure 6-18. This procedure can be conducted on the same transects and at the same time that Soil Cover (Section 6.3.1), Species Cover (Section 6.3.2), and Species Presence procedures (Section 6.3.3) are conducted. However, the monarch egg and larval monitoring is conducted prior to the Soil Cover, Species Cover, or Species Presence procedures to reduce disturbance that could dislodge caterpillars from milkweed plants.

For each transect, a measuring tape is laid out from the edge of the road shoulder to the outer roadside edge. Vegetation is sampled at quadrats spaced every 20 feet along the transects. Milkweeds, nectar sources, and monarch eggs and larvae are sampled within each quadrat. A 1m x 1m quadrat frame is constructed with PVC pipe and corner connectors.

A workbook that contains data forms for milkweed abundance, nectar plant abundance, and monarch eggs and larvae density is available in the Native Revegetation Resource Library.

Milkweed Abundance

The number of plants and stems of milkweed species that are rooted within the quadrat are recorded. A milkweed plant is defined as all above-ground stems originating from a single identifiable common point in the ground. One milkweed plant may be composed of one or multiple stems, depending on the species. For example, green antelopehorn milkweed plants (*Asclepias viridis*), butterfly milkweed (*A. tuberosa*), or swamp milkweed (*A. incarnata*) may grow multiple stems per plant. When these plants are found, each cluster of stems originating from a single point is counted as a single plant (Figure 6-21). Multiple stalks from a single point are recorded as a single plant with multiple stems. Some species, such as common milkweed (*A. syriaca*) or whorled milkweed (*A. verticillata*), grow multiple stalks, and it is impossible to discern if the stalks are from the same plant without excavating the roots. Each individual stalk that does not originate from a central point and is separated by soil is therefore counted as a separate plant. Data on the number of plants, as well as the number of stems per plant, is recorded to determine milkweed density per area.

Figure 6-21 | **Milkweeds may have multiple stems from one plant**

Milkweeds with multiple stems are recorded as a one plant.

Nectar Plant Abundance

Within each quadrat, the species with blooming flowers and the number of plants is recorded. After monitoring is completed, at the end of the growing season, gaps in bloom or times when species diversity was low can be identified.

Density of Monarch Eggs and Larvae

To determine the monarch density per plant, monarch butterflies are recorded within each quadrat and within a 10-foot swath between quadrats. Each milkweed that is encountered within a quadrat is examined for monarch eggs and larvae. The numbers of eggs and larvae are recorded for each quadrat. For plants within the 10-foot swath between quadrats, the number of milkweed plants and stems by species and the number of eggs and larvae observed on these stems are recorded separately (e.g., quadrat 3—quadrat 4). The collected data is used to determine the monarch density at the site, calculated as a proportion of milkweed plants with monarchs.

All parts of the milkweed plant are carefully examined, including the bottoms of the leaves, the area within the small leaves at the top of the plant, and buds and flowers if they are present. Eggs are very tiny, about 1 mm wide, and are cream colored (Figure 6-22). Early instars of caterpillars are also very small, 2-6 mm in length . Monarch caterpillars leave clues such as chew marks on the leaves that indicate their presence (Figure 6-23). It is important to handle the plants carefully to avoid dislodging any larvae. Photographs of the egg and caterpillar are helpful to distinguish monarchs from other insects. Monarch eggs and larvae can be hard to find.

These procedures were adapted and modified from the Monarch Conservation Science Partnership Monarch Monitoring Trial Protocol, the Monarch Larva Monitoring Protocol, and the Prairie Reconstruction Initiative Retrospective Research protocol (personal communications: Laura Lukens, University of Minnesota, January 3, 2017; Diane Larson, United States Geological Survey, January 6, 2017).

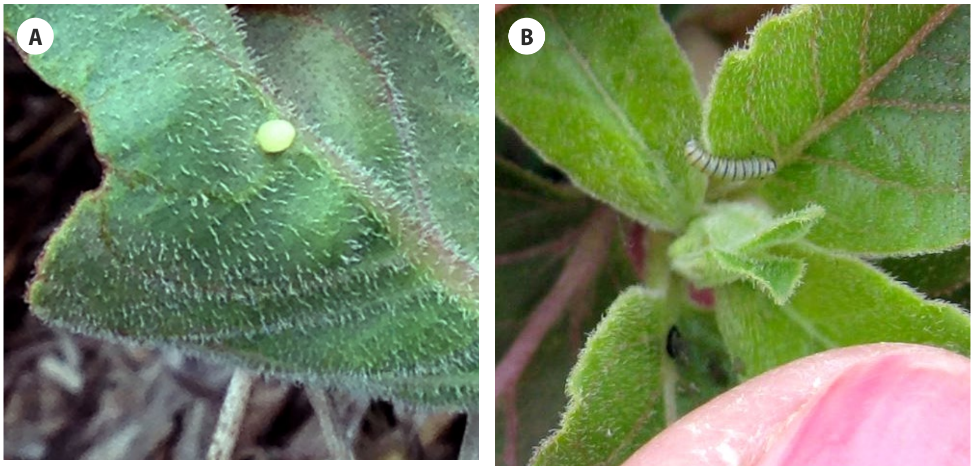


Figure 6-22 | **Monarch butterfly eggs and caterpillars**

Monarch eggs are often deposited singly on the underside of milkweed leaves (A), and early instar caterpillars can be found on milkweed vegetation or on flowers (B).

Photo credits: Stephanie McKnight/Xerces Society (A); Anne Stine/Xerces Society (B)

6.4.4 POLLINATOR PLANT MONITORING

Monitoring plant species found on a project site is a method of assessing potential pollinator habitat. This involves collecting and evaluating data from any or all plant monitoring procedures outlined in Section 6.3. To do this, plant species recorded during these surveys are categorized as to whether they are pollen or nectar producers, flowering times, plant structure, or any other characteristics important for pollinator habitat. Some of these plant characteristics are available on the ERA.

DFC targets developed during planning can be referred to for grouping plant species. For example, a DFC target may be "50 percent of the plant cover will be composed of flowering species." Using the Species Cover monitoring procedure (Section 6.3.2), plant species are grouped as "flowering" and "non-flowering," and the percent cover for each group is summarized. Using the analysis procedures described in Section 6.3.7 it could be determined statistically whether the DFC target was achieved.

DFC targets can also include overlapping bloom time throughout the growing season so that flowering species are available sequentially for pollinators.

Figure 6-23 | **Chew marks on milkweed leaves indicate the presence of monarch butterflies**

An indication of the presence of monarch butterflies is the chew marks on milkweed leaves.

Photo credit: Jennifer Hopwood, Xerces Society

6.5 PHOTO POINT MONITORING PROCEDURES

Photo point monitoring is a method of recording landscape changes in vegetation over time and showing the success or failure of a revegetation project. Photo monitoring can be established for long-term monitoring where a permanent point has not been established and subsequent photographs are taken (Section 6.5.1) or where permanent locations have not been located from historic photographs or photo monitoring can be reconstructed from historic photographs (Section 6.5.2).

Landscape images from photo point monitoring, in conjunction with data collected from other monitoring methods, can be a powerful way to describe the results of a revegetation project. *Hall's Photo Point Monitoring Handbook* (2002a, 2002b) provides a thorough coverage of this subject.

6.5.1 ESTABLISHING PHOTO POINTS FOR LONG-TERM MONITORING

Locating Photo Points

The first step in establishing a long-term photo-monitoring point is to determine where the photo will be taken. The locations of the photo point are often based on the objectives of the revegetation project. For example, if the objectives for revegetation are visual enhancement, photo points are located where motorists view the vegetation of interest from the road. With time, small shrub and tree seedlings planted along roadsides will fill in the entire picture frame, obscuring any long-distance views. If it is important to photograph long-distance views, then the location and direction of the camera are placed where the foreground is free of potentially tall growing vegetation.

Photo point locations are recorded with GPS coordinates and described in detail so they can easily be found years later by other personnel. Permanent structures that can be easily described and located by others make good reference points for photo locations. These include large boulders, culvert inlet and outlet, concrete headwalls, drain inlet frames or concrete aprons, topographical features, guardrail posts, permanent survey markers, mile post markers, road signs, road intersections, railroad lines, telephone poles, and other types of utility structures. Since these features are not always permanent, it is important to locate more than one structure in the field.

The photograph is either taken from a permanent structure or from a measured distance and direction from the structure. For example, a photographer might decide to take a picture on the fog line directly above a culvert outlet. This spot would be easy to describe and locate in the field by another person several years later. A photographer might also locate a photo point using a sign post as a permanent reference. In this case, an azimuth reading and measured distance from the sign post would be recorded in the notes.

A common method for locating a photo point is to drive a stake (rebar) at the spot. This method works in some cases but has drawbacks: the stake may interfere with maintenance activities, such as mowing or traffic safety if it is not set back far enough from the roadway; the stake is driven several feet into the soil, which is difficult on most cut slopes and some fill slopes; and the stake is identified with a tag that must be readable over time. One problem associated with poorly placed stakes is that they are often displaced through active soil movement, animal traffic, vandalism, or road maintenance activities. Using a more permanent feature of the roadside, such as a concrete structure, guardrail, or signpost, is generally a better alternative.

The Camera

When using a digital camera for photo point monitoring, the highest resolution is used. Using cameras with good lens quality is also essential for optimum photographs. The camera is situated so that the zoom lens does not have to be used. The zoom lens can pose problems in reproducing the original photograph (Hall 2002b) and also result in lower picture resolution.

Taking the First Picture

The camera is set on a tripod over the identified photo point location and the image is previewed on the LCD screen or through the lens. With a compass aligned to the side of the camera, an azimuth reading is taken. Using a clinometer on the top of the camera, the degrees from horizontal are recorded. A log or electronic document is kept that includes the following information about each photograph:

- Project name
- Photograph ID
- Date
- Time
- Photographer
- GPS location
- Location on plan map
- Location description
- Azimuth of camera

- Angle of camera
- Manufacturer and model of camera
- Large imported jpeg image of photograph

Taking Subsequent Photographs

At later dates, the photo point is relocated using the map, GPS point, and/or and location description. The camera azimuth and vertical angle are set, and the image is viewed through the LCD screen or lens and compared to the print of the original photograph. If the original spot cannot be located, then relocating the photo point can be attempted using the procedures outlined in the following section.

6.5.2 ESTABLISHING PHOTO POINTS FROM HISTORIC PHOTOGRAPHS

If no records exist for the original photo locations, then a close approximation can be determined (after Hall 2002a). Prior to monitoring, all historic photographs of interest are printed out in large format. The general locations along the road corridor where these photographs may have been taken are located. Based on the photograph, permanent features, such as guardrails, culverts, trees, shrubs, road cuts, and fills, are found. The general area is walked while comparing the large photograph with the surrounding area. Finding several permanent reference points in the distance, such as mature trees or large rocks, and moving until all features are positioned similar to the photograph is a quick means of establishing a general location for the original photograph. Figure 6-24 shows how a photo point was located using guardrails and a culvert as reference points.

6.6 DEVELOPING A MONITORING REPORT

The purpose of a monitoring report is to document how well a revegetation plan was implemented. This report is written and shared so that corrective measures can be made and that the lessons learned from implementing the revegetation project can be applied to future projects. Most projects fail to deliver a monitoring report for the following reasons:

- The monitoring plan was too complicated (massive amounts of extraneous data were generated)
- The monitoring was not designed in a meaningful or statistical manner
- The monitoring objectives were poorly stated
- Insufficient data were collected to draw any meaningful conclusions
- Data were lost

More than likely, the main reasons were that “there wasn’t enough time” or “there were more important things to get done.” In other words, writing a monitoring report often is not completed because it does not seem important at the time. It stands to reason, however, if time was taken to collect field data, time should be given to analyze and present the findings.

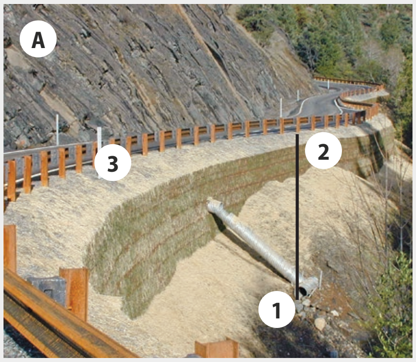
The value of a monitoring report is that it is often the only record of what was done on a revegetation project and how well it was executed. It is a statement to management as to whether revegetation objectives were met. Monitoring reports are often a required component of regulatory permits, such as when wetland construction is involved. It can also guide revegetation specialists and road managers to improve revegetation methods and reduce costs on future projects. In addition, monitoring reports can be referenced later to assess the effectiveness of species mixes and revegetation techniques in response to climate change.

The monitoring report does not have to be long. In fact, a two- to three-page report summarizing the important findings is often sufficient for most projects. That is also the appropriate length

Figure 6-24 | **Establishing photo point locations from historic photographs**

To relocate the photo point from the original photograph (A), a large print was made and taken to the general location in the field. Since the original photograph was taken from the paved road surface on the inside of the guardrail, there was little doubt that the elevation of the second photograph (B) would be approximately the same.

Locating the original photo point along the guardrail was accomplished by establishing a relatively vertical centerline connecting two identifiable reference points on both the original photograph (A) and the photograph to be taken (B). In this example, the centerline is drawn from the left side of the culvert (1) to the 12th post of the guardrail (2) from the reflector stake (3). Picture B is a close approximation to the photo point location of photo A, but notice that the centerline is not quite in the same direction as in photo A. To find the more exact location, the photographer would move to the right along the inside of the guardrail until the centerline lines up in the same direction as in photograph A.



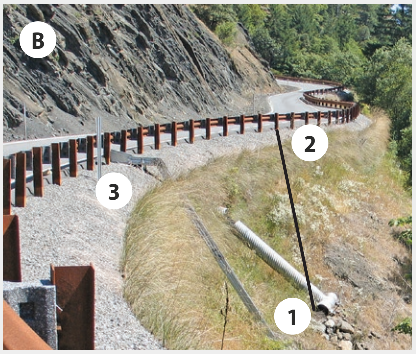


Photo credits: David Steinfeld

of a report that most people have time to read. The details of the data collection and analysis can be included in an appendix. Examples of several monitoring reports can be found in the Resource Library by entering "Plans and Reports" in the Report Type dropdown menu and "Monitoring" in the Topic Type dropdown menu.

Every monitoring report will be different, but most reports address the following questions in some form:

- Who did the monitoring?
- When did monitoring occur?
- Where in the project was monitoring conducted?
- What was monitored?
- How was it monitored?
- How was it analyzed?

The above questions were addressed in the monitoring plan, so they should be easy to document. The report then answers these questions:

- Were the objectives met?
- Are corrective actions needed?
- What lessons were learned?
- Is there further monitoring that needs to occur?

Many monitoring reports are followed by appendices that contain some or all of the following:

- Maps
- Data analysis
- Photo point monitoring
- Project diaries—A detailed account of all activities that took place during the project
- A summary of the revegetation treatments or activities that occurred on the project

Revegetating highly disturbed sites with native plants to maintain or increase pollinator habitat is a relatively new field of study. Well-designed and executed monitoring projects can provide useful information to a wider audience of practitioners, designers, scientists, and managers working in this field. Conferences, societies, newsletters, journals, and trade publications are some venues to share this knowledge. The small-scale trials that were tested during implementation of a revegetation plan (e.g., different rates of fertilizer, tackifier, seeds, and hydromulch) are likely of great interest to other designers. By taking the time to share monitoring results, the science and practice of revegetating highly disturbed sites can be advanced and future revegetation projects can be improved.

7— Operations & Maintenance

7.1 INTRODUCTION

Roadside maintenance is the final step in the revegetation timeline. It occurs when the revegetation efforts and responsibilities are transferred to the road maintenance staff for the long-term management of roadside vegetation. If the transfer is successful, revegetation objectives are carried out for many years with good results. The intended audience for this chapter is maintenance staff. In handing off a roadside revegetation project, it is helpful if the objectives and reasoning behind the revegetation plan are understood by maintenance staff. This may have occurred if maintenance staff were included during the planning phases of the revegetation plan. In such instances, maintenance staff can provide insights into the development of a vegetation management strategy (Section 3.2) and bring to the discussion a thorough understanding of how vegetation responds to various management activities specific to the project environment.

Many state departments of transportation have a statewide Integrated Vegetation Management (IVM) plan or an Integrated Roadside Vegetation Management (IRVM) plan. Some states have more detailed IVM plans for regions within the state. IVM plans are typically updated annually based on monitoring of the previous year's work.

The IRVM is "an approach to right-of-way maintenance that combines an array of management techniques with sound ecological principles to establish and maintain safe, healthy and functional roadsides" (Brant and others 2015). It applies many of the Integrated Pest Management concepts developed for agriculture, horticulture, and forestry to roadside vegetation management. IVM plans typically include sections on preventing the introduction of unwanted vegetation, protecting rare plants, preserving natural areas, and developing a decision-making process for treating vegetation.

For the Designer
To ensure that revegetation objectives are carried through during the maintenance phase, maintenance staff should be informed of these objectives and how they relate to maintenance activities.

7.2 DECISION PROCESS FOR TREATING UNWANTED VEGETATION

Most states have a decision-making process within the IVM for treating unwanted vegetation. The process includes some or all the steps outlined in Figure 7-1. An IVM decision-making process can be used to evaluate the control of an individual target weed species (e.g., noxious weed control) or control the vegetation on an entire section of roadside. In this process, roadsides are inventoried and objectives are set for unwanted vegetation. All methods for treating unwanted vegetation are considered, including no action, mowing, herbicide application, manual removal, prescribed burns, grazing, and biological control. A treatment plan is developed based on a thorough understanding of a species or plant community. Treatment plans often outline the "action threshold" or "tolerance level" that, when exceeded, constitutes the implementation of a vegetation treatment. The effectiveness of the treatment is determined based on monitoring. If the treatment is ineffective, then the treatment options are reviewed and updated, if appropriate. If the treatments are effective, then no action is taken and monitoring continues.

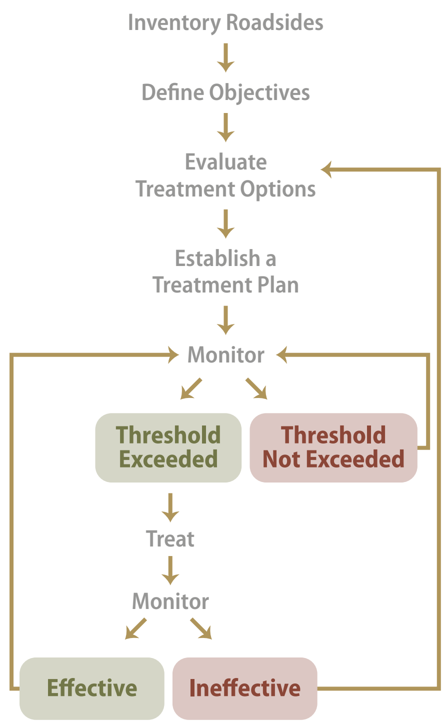


Figure 7-1 | **Components of a decision-making process for treating unwanted vegetation**

7.2.1 INVENTORY OF ROADSIDES

Roadsides are inventoried for weeds or unwanted vegetation. For some states, invasive and noxious weeds are reported using GPS equipment and GIS mapping technology. The associated maps often prioritize sections of road that require some form of vegetation control. Roadside inventories can also show areas of desirable vegetation, rare plants, threatened species or populations, natural areas, pollinator habitat, and vegetative types. Vegetation assessments conducted during the planning stages of a revegetation plan may be useful in inventorying roadside vegetation by identifying target weed species and prioritizing roadsides for treatment (Section 3.6.1).

7.2.2 DEFINING ROADSIDE OBJECTIVES

The backbone of a treatment plan is composed of clearly stated road maintenance objectives. These include objectives for road safety as well as roadside resources. Objectives are set at a statewide level in the IVM plan or at the local or regional level within a state.

Many states assign maintenance objectives to roadside zones similar to those shown in Figure 3.88. Oregon and Washington, for example, identify three roadside zones (WSDOT 2016, ODOT 2013):

- **Zone 1**—This zone borders the roadway pavement with vegetative objectives of preventing pavement breakup, preventing noxious weeds, facilitating a "soft return" to the travel lane should a driver accidentally veer, and maintaining maximum visibility.
- **Zone 2**—This zone is spatially located between zone 1 and zone 3, and the vegetative objectives are to maintain low growing vegetation for maximum sight distance, enhance visual qualities, and maintain hydraulically functioning ditches. Pollinator habitat can also be an objective.
- **Zone 3**—This zone is farthest from the roadway and has fewer restrictions for maintaining low-growing vegetation for sight distance. These areas may contain shrubs and trees, and can serve as pollinator habitat.

Each of these zones is treated differently and may have separate action thresholds, treatment plans, monitoring activities, and maintenance schedules.

Roadside objectives are also developed for the important resources associated with roadsides. These resources include pollinator habitat, water, natural areas, and visual resources. These objectives are brought forth from the prevention and protection portions of the plan (Section 7.3 and Section 7.4) of the IVM. It is important that resources, safety, and road maintenance objectives are clearly stated so that treatment options can be developed accordingly.

It is important to note that state departments of transportation manage areas that are not roadway or right-of-way. These areas include rest areas, "back 40" property, stockpile lots, maintenance yards, office grounds, bike paths, scenic viewpoints, and points of interest pull-outs. Management objectives for these areas may integrate well with creating or improving pollinator habitats because alternative uses are unlikely to conflict with maintenance activities or expose people (maintenance staff or volunteers) to the dangers of the roadside.

7.2.3 EVALUATING TREATMENT OPTIONS

In this step of the decision-making process, all possible treatments are evaluated for how each best meets the road objectives. The details of each vegetation treatment are described in Section 7.3. In evaluating each treatment, it is important to consider how well each treatment meets the roadside safety, maintenance, and resource objectives. If there are conflicts, how can the treatment be modified?

To evaluate treatments, a working knowledge of the target weed species or plant community of concern is needed. It is important to understand how a weed species or an entire plant community changes over time through succession, how they respond to various disturbances, how they can be controlled or maintained, and how treatments change the direction and rate of plant succession (Figure 3-9). Some of this information can be obtained from the vegetation management strategy outlined in the revegetation plan or from the designers of the revegetation plan (Section 3.2). Adjacent maintenance departments, land owners, and local agricultural extension specialists are good contacts to discuss the best controls for the target weed species present on the project site. Plant Guides located on the profile page of the USDA PLANTS database provide control treatments for many weed species. Other resources include a publication by Harper-Lore and others (2013) that describes how to control 40 common weed species in the U.S.

In evaluating treatments, it is also important to understand how each treatment affects roadside resources. Pollinators are affected by most vegetation treatment methods, and a knowledge of the important pollinators on the roadsides, their life history, and their habitat requirements can help in developing the appropriate treatments. Water quality can be affected by vegetation maintenance, especially where bare soil is created near drainages and stream courses. Reviewing the Storm Water Pollution Prevention Plan for the project area or road corridor, if it is available, can help the designer identify appropriate treatments.

7.2.4 ESTABLISHING A VEGETATION TREATMENT PLAN

The vegetation treatment plan prioritizes the treatments that best meet the road objectives. It addresses the action threshold for treatment implementation to control a target weed species or a plant community on a section of roadside. The action thresholds may be based on the phenological condition of the vegetation (e.g., treat when average grass height is 2 feet), presences of a noxious weed (e.g., control all noxious weeds no later than flowering stage), and safety threat (e.g., trim or remove trees when they are considered hazardous to road or neighboring property). When the action threshold is exceeded, the plan details the treatment that will be used (e.g., timing, rates, equipment, personnel).

The treatment plan prioritizes the areas to be treated and sets site limitations (e.g., distance from streams or bodies of water, slope steepness, saturated soils). It also addresses the effects of the treatment on other roadside resources and options for mitigating negative effects. For example, the effects of mowing on pollinators and pollinator habitat can be minimized if mowing is done outside the flowering period of most forb species.

7.2.5 MONITORING TREATMENTS

The treatment plan outlines how roadsides will be monitored. Setting up monitoring for operations and maintenance is similar to the steps outlined for vegetation monitoring (Section 6.2). Monitoring in an IVM plan addresses the following:

- **Purpose**—Determines if the action threshold was exceeded, treatments were applied as prescribed, treatments were effective, or other resources were negatively affected
- **Who**—Identifies personnel or expertise needed
- **What**—Determines what is being monitored (e.g., noxious weed presence, vegetation height)
- **When**—Defines frequency and time of year
- **Where**—Delineates sections of road to be monitored
- **How**—Determines intensity and methodology
- **Logistics**—Timeline, budget, and equipment

Monitoring is the feedback loop for effectively controlling unwanted vegetation over time. As outlined in Figure 7-1, monitoring is conducted to determine if an "action threshold" is exceeded. If it is not, then monitoring continues as scheduled and no treatments are made.

If an action threshold is exceeded, then a treatment is applied according to the treatment plan. Implementation monitoring during treatment application records whether the treatment was applied as prescribed or if changes were made based on equipment or site factors. Post-treatment monitoring evaluates the effectiveness of the treatment and whether the treatment affected other resources (e.g., pollinator, water quality, visual resources). If the treatment was not effective in controlling unwanted vegetation or other resources were adversely affected, then a reevaluation of the treatment is made and, if necessary, the treatment plan is changed.

7.3 VEGETATION TREATMENT OPTIONS

When developing a vegetation treatment plan, it is important that the target vegetation and the objectives outlined in the IRVM plan are understood. In addition, it is important to understand the resources of value that may be affected with a vegetation treatment. These include water quality, wildlife habitat, visual resources, and pollinators. This section describes common vegetation treatments and how they affect these resources, with an emphasis on enhancing pollinators and pollinator habitat.

Because pollinator species can be strongly affected by weed control treatments, it is important to know the important pollinator species that inhabit the area during maintenance activities and develop weed treatments that minimize the negative effects on their populations and habitat. This section outlines vegetation management practices that can control target vegetation while supporting pollinators. Additional details are provided in two recent publications from the U.S. Department of Transportation (Hopwood and others 2015, Hopwood and others 2016), which review the best management practices (BMPs) for controlling roadside vegetation while optimizing pollinator habitat and reducing pollinator mortality. In addition, a review of Section 3.11.6, which covers control of unwanted vegetation before and during construction, may be useful.

Given the complexity of developing treatments that control target vegetation while maintaining or improving pollinator habitat, some general pollinator strategies may aid in designing vegetation treatments specific to a project environment. These are outlined in Figure 7-2.

7.3.1 NO ACTION

While not taking an action to control vegetation is not a treatment, it is included in this section as a reminder that there are times when vegetation does not need to be treated. Reviewing vegetation management objectives in the IRVM plan, especially how treatments may affect resource objectives such as water quality and pollinator health, may provide justification for the “no action” treatment. On roadsides where rare plant species or at-risk pollinator species are present, taking no-action may be the most prudent approach to protecting species.

7.3.2 MOWING

Mowing is frequently used to maintain roadside vegetation by reducing invasive weeds and woody plants, improving driver sight lines, allowing vehicle pull off, and reducing the risk of wildfires. Typically, vegetation in the clear zone, a band of vegetation directly adjacent to the pavement or shoulder, is mowed regularly to keep the vegetation short for drivers who need to regain control of their vehicle and to lower the fuel level for spread of fires. Periodic mowing within the clear zone creates a habitat that is not typically used by pollinators. However, roadside vegetation beyond the clear zone can support pollinators.

Mowing at certain times can directly kill pollinator eggs or larvae present on the vegetation. It can also indirectly affect adult pollinators by temporarily removing host and flowering plants (e.g., food sources). For these reasons, it is important to carefully time or limit mowing during the growing season. This is especially true if the habitat supports endangered or rare and sensitive pollinator species. Higher mowing frequencies reduce native plant growth, plant diversity (Parr and Way 1988), and the ability of forbs to compete with grasses (Williams et al. 2007), and decrease the amount of nectar and pollen present on the roadside. More frequent mowing can also increase the roadkill of pollinators, especially butterflies (Skorka

Figure 7-2 | **Considerations for developing a vegetation treatment sensitive to pollinators**

Timing and Frequency	Treatments are timed to avoid or minimize effects on flowering plants or treatments are timed to maximize plant diversity
	The number of treatments are kept to a minimum to reduce the impacts on pollinators
	Treatments are timed to avoid detrimental effects on breeding or nesting of at-risk pollinators
	Treatments are avoided during periods when floral resources are scarce
	Prescribed fire and grazing are timed carefully to avoid negatively affecting life cycles of imperiled or sensitive pollinators
	Avoiding mowing, non-targeted herbicide applications, burning, and grazing during adult flight periods or when butterfly or moth larvae are feeding on host plants
	Treating perennial weeds with herbicides in late summer and fall when it is most effective
	Applying herbicides when they are most effective — early plant stages
	Applying herbicides when pollinators are least active — before sunrise, after sunset, cool temperatures
	Rotational burns, conducted 3 to 5 years apart, will allow time for pollinator populations to recover
	Varying the timing of broadcast burns from year to year
Effect	Treatments maintain some undisturbed vegetation
	Using of herbicides beyond the safety strip is targeted to noxious and non-native plants
	Grazing is conducted to have minimal trampling impacts that may affect nesting habitat
	Haying is done at the end of the growing season
	Selecting herbicides that are selective to target weeds minimizes the impacts to non-target plants species
	Applying non-selective herbicides when desirable vegetation is dormant
	Using herbicides with low toxicity to pollinators
	Using appropriate equipment and weather conditions to avoid herbicide drift
	Selecting grazers that can be controlled
	Where appropriate, leaving snags and trees with cavities, and down wood for nesting habitat
	Setting mower blades at 12 to 16" will reduce the impact to vegetation structure
Scale	Distance from edge is less than 50 feet - pollinators have places to go for habitat and food during treatments
	Leaving untreated adjacent areas within 100 feet of center of treated area
	Treatments are patchy - <50 percent of the area is treated
	Brush removal is used to soften forest edges and to maintain stems or other sites for tunnel nesting bees
	Leaving sections of the road corridor unburned

and others 2013). Therefore, minimizing the number of times a roadside is mowed benefits many pollinator species.

Reducing routine mowing of the entire right-of-way (fence to fence) benefits pollinators by allowing wildflowers to bloom and thereby supply nectar and pollen as food. It is best to restrict routine mowing to the clear zone as much as possible, and mow beyond the clear zone only when there are well-defined objectives, such as reducing brush or maintaining lines of sight. Reducing mowing beyond the clear zone to two or fewer times a growing season is best for wildflowers and pollinators. In some regions, mowing can be reduced to once a year per site, every other year, or even every two to three years, depending on the regional intervals of mowing needed to control woody plant encroachment or to reinvigorate populations of wildflowers.

When timed appropriately, mowing can reduce the effects on pollinators and promote plant diversity. It is optimal to delay mowing until autumn or after the first frost if regional constraints allow. When mowing is delayed, butterflies and other pollinators with larvae that reside on vegetation are able to complete their full life cycles, and flowering plants are able to bloom and provide pollen and nectar to pollinators uninterrupted throughout the growing season. If mowing must occur during the growing season, consider selecting a time to mow that balances vegetation management needs (e.g., noxious weed control) with the resource needs of pollinators (e.g., presence of flowers and host plants). For example, mowing at a time that promotes the growth of wildflowers benefits pollinators in the long term. Timing will vary with region. Wildflower growth is promoted by a mid-summer mow in some regions, while in others mowing after spring bloom might be optimal. It is also worth considering varying the season when mowing occurs every few years to increase plant diversity. Mowing consistently at the same time every year will select some plants over others. Plant diversity can be maintained by occasionally varying the timing of mowing, which will favor different plants and prevent certain plants from dominating.

For the Designer
The timing and frequency of mowing can have large effects on pollinators and the vegetation they rely upon and be carefully considered by maintenance staff.

It is important to time mowing to avoid vulnerable stages of the life cycle of any rare or declining species that are present. For example, in Texas, to reduce harm to monarch butterflies, it is best to avoid mowing before March and between May and August, time periods during which monarchs are breeding in the region. Finally, it is helpful to adjust the height of the mower. By mowing vegetation at a height of 12 to 16 inches, vegetation recovers more quickly and plant stress is reduced, particularly during dry periods or drought. Mowing also leaves a greater depth of vegetation for pollinators to use.

There may be a public perception that by reducing mowing, road departments are not taking care of roadsides, which can be an obstacle to implementing mowing strategies that benefit pollinators. Public education may change this perception with time as the public becomes more aware of the benefits of roadsides to pollinator populations and health.

7.3.3 MANUAL REMOVAL

Hand-pulling weeds can be the most exhaustive and complete method of controlling specific weeds because it is highly targeted. Hand-weeding is well suited for removal of weeds that occur in low numbers or that are scattered throughout a site. Hand-weeding is often the least intrusive method of removing weedy species as it has the least effect on pollinators.

Tools that help with hand-weeding include hoes, picks or pulaski axes, trowels, and shovels. The Extractigator ® or the Pullerbear™ are designed to provide grip and leverage for removing deep-rooted species such as scotch broom. It is important to target weeds during their active growth stages before the weeds have flowered and set seed. For perennial and rhizomatous species, it is best to remove as much of the root material as possible because many plants can re-sprout from root fragments.

One strategy for hand-pulling is the Bradley Method (Brock 2016) which prioritizes the areas to be weeded, beginning in undisturbed areas first, and then working out toward more heavily infested areas. When pulling weeds by hand or with tools, it is useful to minimize soil disturbance so that weeds do not become established. It is also important to dispose of weeds in designated areas. If weed removal results in large patches of bare soil, re-colonization by unwanted species can be reduced by seeding with desirable species.

7.3.4 HERBICIDES

Herbicides are used to control woody vegetation as well as target weed species on roadsides. The use of herbicides can benefit pollinators by suppressing undesirable plants and encouraging the valuable native plants that provide them with food or shelter. However, used indiscriminately, herbicides can reduce the quality of roadside habitat by removing floral resources and host plants, and may be directly toxic to some pollinators (Mader and others 2010; Russell and Schultz 2010; LaBar and Schultz 2012). Overuse of herbicides can also weaken stands of vegetation, making them more vulnerable to weed invasions, which also indirectly affect pollinators (Inset 7-1). By using herbicides as efficiently as possible, maintenance staff can reduce both the amount applied and the effect on plants that benefit pollinators. Using products selectively, timing applications carefully, and following label directions can increase the effectiveness of herbicide use and decrease impacts to pollinators and other resources.

Inset 7-1 | **Weeds and Pollinators**

Some weeds can provide resources for pollinators (e.g., Harmon-Threatt and Kremen 2015). However, nonnative plants typically only support a subset of the overall pollinator community (e.g., Tallamy and Shropshire 2009). Additionally, noxious weeds reduce overall plant diversity, which also reduces pollinator diversity (Memmott and Wasser 2002; Zuefle and others 2008). When noxious and invasive weeds are removed and plant diversity recovers, pollinator abundance and diversity rebounds as well (e.g., Hanula and Horn 2011; Fiedler and others 2012).

It is important to use the appropriate products and application rates that are effective in controlling the target weed species yet have minimal effects on non-target plant species. Whenever possible, the use of selective herbicides—those formulated to control specific weeds or groups of weeds—can reduce damage to nontarget plants. Nonselective herbicides—those that are broad-spectrum and kill or damage all plants—can also be used selectively to reduce effects on nontarget plants. For example, nonselective herbicides can be used selectively by applying them on weeds when desirable native plants are dormant and by using directed or targeted applications (e.g., spot spraying). In addition, understanding how quickly the herbicide being applied degrades on the site ensures that seed germination and restoration planting are not negatively affected. Herbicide labels include information about selectivity and persistence.

Applications can be timed to be most effective based on the herbicide's mode of action and the application technique. For example, when using a systemic herbicide (absorbed by the plant and transported throughout the plant by the vascular system), perennial weeds can be treated in late summer and fall. During this period, perennials begin to move sugars down to their roots, and the herbicide is translocated to vegetative reproductive structures where it is most effective at controlling the plant. Applications of herbicides at the stage of growth when the weed is most vulnerable can make applications most successful. For many weeds, this is the seedling or rosette stage.

Reducing off-site movement of herbicides and the use of nonselective broadcast applications can help avoid damage to non-target plants that provide pollinators with food or shelter. Referring to road inventories of unwanted vegetation (Section 7.2.1), conducting training in weed identification, and using plant identification reference materials to recognize noxious and invasive weeds will help distinguish these species from similar non-target species. In order to avoid weakening non-target species, weeds can be targeted using spot treatment applications made with a backpack sprayer, weed wiper, or similarly appropriate technology. Using highly targeted applications on cut stems, stumps, or under bark can also reduce unnecessary effects to desirable plants. Broadcast treatments or pellet dispersal are recommended only for dense infestations of weeds or for clear zone or guardrail treatments.

The off-site movement of herbicides can be reduced by selecting appropriate spray equipment, periodically calibrating equipment, and adhering to the pesticide label. Nozzles that produce larger droplets are less likely to cause herbicides to drift off target. Equipment that is calibrated regularly limits over and under applications. It is best to avoid applications when wind speeds are greater than 15 mph and during a temperature inversion (when warmer air above traps cooler air near the ground) when herbicides and other pesticides can linger in the air and move long distances offsite with air movement.

To reduce direct contact exposure to pollinators, herbicides can be applied during a time of day when pollinators are less active. Many pollinators (but not all) are less active before the sun rises or after the sun sets, and are also less active at cooler temperatures (below 50 degrees Fahrenheit). Additionally, avoiding broadcast applications of systemic herbicides and herbicides with long residuals reduces exposure to butterfly and moth caterpillars that can be poisoned by consuming contaminated vegetation.

7.3.5 GRAZING

Grazing is used to limit tree and shrub invasion, provide structural diversity, and encourage the growth of nectar-rich plants. However, livestock grazing is only beneficial to plant diversity, and in turn, pollinators, at low to moderate levels during short periods of time separated by long recovery periods (Hopwood and others 2016). Grazing can negatively affect insect communities by changing the plant community structure and diversity (Kruess and Tscharntke 2002). Insufficient forage from grazing can decrease bumble bee populations (Carell 2002; Hatfield and LeBuhn 2007) and destroy potential nest sites through trampling (Sugden 1985). Intensive grazing can also affect butterfly populations through trampling (Warren 1993) and altering plant community composition (Stoner and Joern 2004).

Development of a grazing plan that includes careful consideration of the type of grazer, its food preference, and how well the grazer can be managed is important for managing invasive species and compatibility with pollinator health and other resources. For example, goats and sheep can be controlled through herding when they are brought onto a site and when they are removed, bracketing periods of time when pollinators and pollinator habitat are least affected. Goats and sheep preferentially eat broadleaf plants and are therefore the preferred grazers for sites where broadleaf weeds are an issue. At specific densities and duration, goats and sheep can control large infestations of invasive weeds. In addition, they can be controlled in areas near water, thereby reducing effects on water quality, and can be effective in inaccessible spots, such as steep slopes.

It is best to introduce grazers at a time when they preferentially feed on the target weed species. Grazing is most effective, for example, when target weeds are palatable; however, this period may be detrimental to pollinators. If rare or imperiled pollinators are present, timing grazing so as to avoid breeding and foraging periods is best. Avoiding grazing during the adult flight period or when imperiled butterfly or moth larvae are feeding on host plants reduces the effect on pollinators. It is also important to avoid grazing during periods when floral resources are already scarce, as grazing during such times can eliminate pollinators from sites over time. Lastly, the stocking density of grazers can help to determine the duration of grazing. If stocking density is high, it is best to keep the duration relatively short so that desirable vegetation is not affected.

7.3.6 FIRE

Prescribed fire is used to manage roadside vegetation and rejuvenate plant diversity in some regions of the United States that have a history of natural fires. Prescribed fire can benefit pollinators through restoration or maintenance of suitable habitat (e.g., Huntzinger 2003), but it can also be harmful when not applied appropriately and have long-term effects on the populations of some species (e.g., Ne'eman and others 2000). For example, burns during the growing season destroy eggs, caterpillars, and above-ground nests and remove vegetation at a time when pollinators need floral resources, host plants, and nesting materials, while winter burns destroy species that overwinter in leaf litter or stems. The scale of the prescribed fire can also affect pollinators. For example, an extremely large and expansive fire may kill pollinators overwintering in above-ground biomass, and such fires during the growing season may eliminate all floral resources in a given area. Smaller, dispersed fires, on the other hand, conserve floral resources and support pollinators in the area by providing refuges.

Burns that are timed so as to have the least effect on pollinators and limiting the scale and frequency of each burn are important pollinator-friendly practices. It is best to use prescribed burning on sections of the roadside corridor rather than the entire corridor. By leaving unburned roadside habitat, enough pollinators remain to recolonize the burned areas. Rotational burning, such as burns conducted three to five or more years apart, allow time for pollinator populations to recover. Rotational burning can provide the benefits of prescribed fire without irreparably damaging the local pollinator community (Black and others 2011). Varying the timing of prescribed burns can also reduce harm to pollinators by avoiding continuously affecting certain pollinators and components of the roadside plant community. Burns affect pollinators no matter when the burn occurs, so altering the timing of burns can reduce negative effects to a particular group or suite of pollinators.

7.3.7 BIOLOGICAL CONTROL

Biological control is the process of introducing natural enemies of the target weed that occur in the geographic region of the weed. Introductions are highly regulated by the U.S. Department of Agriculture and are monitored by government scientists, university researchers, and state agencies. Although biological weed control is not currently widely implemented by state departments of transportation, several have released natural enemies to such weeds as purple loosestrife (*Lythrum salicaria*), leafy spurge (*Euphorbia esula*) (Johnson 2000), yellow star thistle (*Centaurea solstitialis*), and Russian thistle (*Salsola kali*) (Harper-Lore and others 2013). Biological control can be an effective and focused approach to weed control. However, there are ecological and economic risks associated with introducing a species outside of its natural range, including unpredictable and irreversible consequences (Simberloff and Stiling 1996). The Eurasian weevil (*Rhinocyllus conicus*), for example, was introduced to control musk thistle (*Carduus nutans*), but expanded its host plants to include native thistles after introduction, including several rare thistle species (Louda et al. 1997). The loss of native thistles or other native species affects the wildlife that depend upon the plants, including pollinators that visit the plants for pollen and nectar or use the plants as hosts for their caterpillars.

It is best to avoid using natural enemies that have expanded their hosts to include native plants. Coordinating with state agencies, keeping records about locations of releases, and monitoring the target weed populations and potential non-target native species can be used to evaluate the potential impacts of biocontrol agents.

7.3.8 MECHANICAL REMOVAL

Weed populations can be opportunistically removed during road construction. Removal of populations is accomplished by excavating soils within the populations at least a foot deep and transporting the weed-contaminated material offsite to an approved storage area.

Brush may also be removed from roadsides. Brush removal can benefit pollinator health when brush and trees that pose no risk to motorists are left on site and by opening up the canopy along forest edges. Mechanical trimming to remove problematic shrubs or trees and selective trimming to partially remove woody vegetation can benefit pollinators by creating opportunities for wildflowers to grow. However, complete removal of trees and shrubs is not always beneficial because many butterflies and moths use woody native plants as hosts and to roost during the flight period, and some tunnel-nesting bees use the stems of some shrubs as nesting sites.

Removal of any brush or trees that could be hazardous to motorists is important. This includes plants that could impede sight distance, become dangerous fixed objects, fall onto the highway, or shade the road in winter creating patches of ice. When possible, consider leaving snags or trees with cavities in areas where they are set back from the road and pose no safety risk. Snags can provide nesting habitat for some bees, as well as habitat for birds and bats.

Transitional areas between forest and grass can be created by using brush removal to feather or soften forest edges adjacent to clear zones. Edge feathering involves thinning portions of the forest canopy along the edge next to grassy areas and removing undesirable or unhealthy trees. Periodic cutting to maintain healthy growth and an open canopy benefits remnant patches of savanna, forest, or other habitat dominated by woody vegetation, improves the quality of the habitat for pollinators and many birds, and is aesthetically pleasing.

7.3.9 HAYING

In some states, landowners are permitted to cut and remove roadside vegetation for animal fodder. States might grant emergency hay permits under drought conditions, for example, or allow annual haying by adjacent landowners on certain roads throughout the growing season. Haying is not a tool typically used by roadside maintenance staff, although it does affect roadside vegetation and thus pollinators by the abrupt removal of flowers and host plants from a site. In general, haying once in the middle of the growing season can favor wildflowers and cool-season grasses that are often suppressed by dominant warm-season grasses. However, too-frequent haying in a growing season can reduce roadside revegetation over time (Jacobsen et al. 1990), thereby reducing floral resources for pollinators. A poorly timed haying may have severe consequences for rare or endemic pollinator species. When possible, maintenance staff who communicate with landowners can suggest they hay a portion of the entire site at a time, leaving a refuge for pollinators. Additionally, setting the mower blades at 12 to 16 inches reduces the effect on vegetation structure that provides nesting and overwintering habitat, and allows vegetation to recover and bloom more quickly.

7.4 PREVENTION

Ideally, when maintenance staff takes over a roadside revegetation project, the site is weed-resistant (Section 3.11.4). Maintaining a healthy native plant community thereafter greatly reduces the possibility for future weed invasion. The role of maintenance then, is to prevent or minimize unwanted vegetation from becoming established in a weed-free revegetation project. Prevention is the first line of defense in vegetation management and it is accomplished by maintaining a weed-resistant roadside environment, quickly treating disturbances, and protecting natural areas.

7.4.1 MAINTAINING A WEED-RESISTANT ROADSIDE ENVIRONMENT

Roadside vegetation changes over time through successional processes and land uses. If the revegetation project is implemented successfully, the roadside vegetation should continue to be weed-resistant. That can change, however, if the vegetation is disturbed, creating bare soil where weeds can become established. Some practices to maintain a weed-resistant roadside environment are described below.

Minimizing Ground Disturbance

Maintaining a roadside free of ground disturbance is not always possible, but minimizing the amount of disturbance can reduce the area affected. Ground disturbances, and potential solutions, include the following:

- Rutting from vehicle run-offs (repairing roadsides soon after crashes)
- Mowing slopes that exceed 3(H):1(V) often cause rutting and erosion from equipment
- Mowing when soils are too wet, compacting vegetation and soil, and causing erosion
- Landslides (maintaining stable cut and fill slopes)
- Gullies and rills from road runoff (improving road drainage, soil structure, and groundcover)
- Ditch cleaning (limiting ditch cleaning or maintaining a groundcover with occasional mowing)
- Unauthorized trails and off-road vehicle disturbances (controlling access)
- Grazing (controlling animals)
- Vegetation maintenance (performing maintenance activities to prevent soil exposure)

Disposal of Soil in Designated Areas

Road maintenance often necessitates the disposal of soil that comes from maintaining the road. Material from landslides, ditch cleaning, and winter gravelling operations is sometimes pushed over the roadsides or deposited in areas along the roadside, potentially covering roadside vegetation with exposed soils. It is important that excavated soils be removed and deposited in designated areas that have been reviewed for their offsite effects on water quality and other resources.

Controlling Noxious Weeds

If there are no sources of weed seeds, then exposed soils revegetate from the seeds that are sown by the maintenance staff. It is important to reduce or eliminate unwanted seed sources by controlling noxious weeds prior to disturbances (Section 7.3).

Retaining Shade

Many weeds require full or partial sunlight to thrive (Penny and Neal 2003); therefore, retaining shade from existing native vegetation is one strategy to control some weed species. Cutting trees and shrubs or mowing vegetation can increase light and space for invasive weeds (Schooler and others 2010).

Mulching of Woody Material On Site

Maintenance activities that produce material from processed slash or excess vegetation from right-of-way clearing can be shredded and spread over the roadsides as mulch, especially on areas that have bare soils. Strategic placement of this material can reduce the potential for weed establishment.

7.4.2 TREATING DISTURBANCES FOR QUICK RECOVERY

When ground disturbances do occur, a quick response by maintenance staff to treat these areas can ensure that unwanted vegetation does not become established, as described below.

Limiting or Controlling the Activity Causing the Disturbance

The first response is to assess the activity that caused the disturbance and to fix it before proceeding to revegetate the site. For example, if runoff from a road surface causes erosion on a fill slope, then it is important to fix the drainage before restoring the vegetation. If a large vehicle run-off creates rutting of the roadside, it is recommended that soil filling and regrading of the area occur prior to reseeding. If off-road vehicle use creates bare soil, then access to the area would be limited prior to revegetating the site.

Having an Appropriate Seed Mix Readily Available

Having an appropriate seed mix available prior to a disturbance is important because locating the appropriate seed mixes at the quantities needed can be difficult on short notice. Seed mixes may be available commercially or from the designer of the revegetation project. At a minimum, a list of appropriate plant species in a seed mix can be obtained from the revegetation plan or using the ERA tool. If a seed mix is maintained for these disturbances, keeping the mix in favorable long-term storage environments maintains its viability (Section 5.3.4, see Seed Storage). The disturbance may need to be stabilized until it is favorable to seed.

Improving Soils

Sites that have been disturbed often have poor soils because the topsoil has been removed or mixed with the subsoil (e.g., landslide scars, gullies). Compost blankets are a quick way of covering bare soils and increasing the soil productivity at the same time (Section 5.2.3, see Seed Covering).

Oversowing Seeds

On disturbed sites, environmental conditions for seed germination are often poor for many native grass and forb species. Applying seeds at excessive rates increases the probability of greater plant establishment. It is important to understand the site's environmental conditions that facilitate seed germination and establishment, as all sites have a maximum seed load they are able to support. If seeding is conducted above this rate, a net gain may not be realized.

For the Designer
Seeding at excessive rates can benefit the project to a point. Understanding conditions that contribute to, or limit, seed establishment will help determine maximum seeding rates.

Applying a Weed-free Mulch

After seeds are sown on a disturbed area, applying a mulch over the seeds ensures that soil erosion is kept to a minimum and seeds have a favorable germination environment. Most seeds can germinate through mulches applied ½ to 1 inch thick on top of the seed. A variety of mulches are available that include wood fiber, hydromulch, straw, hay, erosion mats, and manufactured wood strands (Section 5.2.3). It is important to obtain weed-free mulches so the introduction of unwanted vegetation is kept to a minimum. Having weed-free sources available prior to disturbances expedites a quick recovery.

Using Clean Equipment

Inspecting and cleaning vehicles and equipment that will apply seeds and mulch ensures that unwanted vegetation is not brought onto the site. The equipment is typically pre-washed by the contractor at an approved off-site facility. Washing with high-powered, high-temperature water (steam cleaning) is effective. After cleaning, equipment can be inspected at the wash site or another agreed upon location prior to arriving at the project site. Overlooked areas to inspect are the hoppers and hoses of hydroseeding equipment.

Avoiding Nitrogen Fertilizer the First Year

Consider applying a slow-release fertilizer (instead of fast-release fertilizers) after native plants have established to reduce the nitrogen levels available for annual weed establishment (Section 3.11.4).

7.5 PROTECTION

Roadsides may contain unique plant communities and rare plants that may need protection. These areas are identified in the planning process but are managed during the operations and maintenance phase of the project. Many states have programs to protect listed species, species of interest, or remnant plant communities (AASHTO 2013a) on roadsides. They are called by a variety of names, including Special Management Areas (SMAs), natural heritage remnants, wildflower research areas, and Biological Management Areas (BMAs). These areas have some or all of the following features in common (adapted from AASHTO 2013a):

- **Collaboration**—Most states with established management areas in right-of-way have accomplished this through collaboration with maintenance staff; conservation groups; and federal, state, and local agencies.
- **GIS**—Many states use GIS to identify rare plant populations and remnant habitats. Known locations of rare species are obtained from state departments of natural resources, the U.S. Fish and Wildlife Service, the U.S. Forest Service, the Bureau of Land Management, counties, local environmental groups, and individuals.
- **Management plans and BMPs**—Most special management areas have plans or BMPs for how to preserve remnant sites or species of interest. These practices include how vegetation control treatments, such as mowing, herbicides, prescribed burns, and grazing, will be used to preserve and enhance remnant areas or species of interest. Maintenance treatments that support species of interest, such as minimizing shading from trees or competition from surrounding vegetation, can be a part of the BMPs. In areas where species of interest require full sunlight for survival, trees and shrubs around these plants may be removed. Where competing vegetation or noxious plant species threaten species of interest, herbicide may be applied or manual removal of vegetation around these species may occur. In areas where potential soil erosion and landsides threaten species of interest or remnant areas, soil stabilization measures may be taken. Public access may be curtailed if it affects plant survival.
- **Signage**—Some states place special signs along the boundaries of the management areas and have instructions on the signs indicating what maintenance activities are allowed.
- **Training**—Some states have developed training programs for maintenance staff specific to managing rare species. This training covers the identification of species of interest, habitat, and preferred management options.

8— Case Studies

Chapter 8 provides five case studies to highlight successful pollinator-friendly practices and strategies in various roadside projects from multiple parts of the country. Several of these case studies are a subset of those found in Hopwood and others 2016a.

8.1 I-35 CORRIDOR (AKA "THE MONARCH HIGHWAY") CASE STUDIES

In 2014, President Obama released a Presidential Memorandum that tasked federal agencies with identifying strategies to promote the health of pollinators in order to reverse pollinator declines. The 2015 "National Strategy to Promote the Health of Honey Bees and Other Pollinators" was a direct outcome of the memorandum, and that strategy called for a multi-state partnership called the "Monarch Highway" along the I-35 corridor. Running through Minnesota, Iowa, Missouri, Kansas, Oklahoma, and Texas, the I-35 highway spans the central flyway monarch butterflies take during their annual migration. The "Monarch Highway" effort hopes to serve as a national model of cooperation to enhance pollinator habitat along transportation rights-of-way. The six states involved in the strategy have agreed to coordinate efforts to establish best practices and promote monarch butterfly and pollinator conservation. A list of I-35 plant species and their pollinator attributes is available in the Native Revegetation Resource Library.

The two following case studies highlight successful projects from Iowa, one of the six states that comprise the I-35 corridor where agencies are focused on restoring habitat to support the imperiled Monarch butterfly and other pollinators.

8.1.1 BRINGING PRAIRIE BACK TO IOWA: IOWA'S INTEGRATED ROADSIDE VEGETATION MANAGEMENT PROGRAM AND LIVING ROADWAY TRUST FUND

Prairie once dominated Iowa's landscape, covering more than 85 percent of the state. With less than 0.1 percent of virgin prairie remaining, and more than 95 percent of Iowa's original wetlands destroyed, Iowa has the nation's most altered landscape. Prior to the mid-1980s, roadside weed control in Iowa relied heavily on blanket spraying, putting large amounts of herbicide into the environment with undesirable consequences. Recognizing Iowa's lost heritage and the need to protect groundwater and surface waters, Iowa roadside managers began making some changes. For example, they began using native prairie grasses and wildflowers for erosion control and reintroduced "a little wildness," according to Kirk Henderson, retired State IRVM Specialist from the Native Roadside Vegetation Center at the University of Northern Iowa.

Butterfly milkweed and prairie coneflower flourish along an Iowa roadside.

Photo credit: Iowa Living Roadway Trust Fund

In 1989, the Iowa legislature passed IRVM legislation to promote an ecologically integrated approach to roadside management while maintaining a safe travel environment (Code of Iowa, Section 314). The legislation emphasized the establishment and protection of native vegetation as well as judicious use of herbicides, mowing, prescribed burning, and other management tools. Iowa is widely seen as a leader in IRVM, in large part because of this legislation. The bill also established the Living Roadway Trust Fund, an annual competitive grant program administered by the Iowa DOT that provides funding for school, city, county, and state projects, as well as research projects involving IRVM.

Iowa's road use tax, along with several other sources, funds the Living Roadway Trust Fund. Roadside managers can submit applications to obtain resources to help implement IRVM, including vegetation inventories, purchasing native seed, equipment for burns or plant establishment, GPS units, signage, workshops, and more. Roadsides are seeded with mixes of species that are appropriate for a particular site, including many wildflowers that are attractive to pollinators. Seed mixes also contain species that bloom at different times throughout the growing season, which helps support pollinators all season long. The targeted vegetation management practiced by Iowa's roadside managers also benefits pollinators (Ries and others 2001).

Research projects have also been supported by the Living Roadway Trust Fund, including studies of restoration techniques, as well as studies of the impact of roadside habitat on butterflies (Ries and others 2001) and bees (Hopwood and others 2010). Since the bill, more than 100,000 acres of Iowa's nearly 600,000 acres of state and county roadsides have been planted to native vegetation (Brandt and others 2015). In the process, Iowa has fostered the development of experienced roadside managers who are equipped to collaborate with other land managers around the state and bring habitat and wildlife, such as pollinators, back to Iowa's landscape.

Photo credits: Kirk Henderson

8.1.2 IOWA'S NATURAL SELECTIONS PROGRAM INCREASES IOWA NATIVE SEED

The Natural Selections program was formed to build the native seed industry in Iowa to meet the demands for high quality, regionally adapted, and genetically diverse sources of native seed for prairie restorations, including roadside restorations. For native regional seed to be priced to compete with cultivars, it has to be produced in commercial quantities. The Natural Selections program is a collaboration between state and federal agencies, as well as private corporations. Past or present partners include the Iowa Crop Improvement Association, the Living Roadway Trust Fund administered by Iowa DOT, USDA Natural Resources Conservation Service Elsberry Plant Materials Center, the University of Northern Iowa, and independent seed producers. Seed is collected by hand from remnant populations by the project manager and by volunteers throughout the state. Seed is collected from remnant roadsides, natural areas, and private land in three regional zones within Iowa. Iowa's Natural Selections program uses provenance zones large enough to support a market but narrow enough to retain regional distinctiveness. Collectors do not collect seed to intentionally select for certain traits. Foundation seed plots at the University of Northern Iowa amplify the seed, which is then further increased. Once seed has been increased, it is released to qualified native seed growers with production certified by the Iowa Crop Improvement Association. About 6 to 8 years after the initial collection, enough seed is available to sell to the public.

Successes of the project include increasing seed of 70 species, with nearly 120 ecotypes of 60 species released for commercial production and 180,000 to 200,000 pounds of ecotype source-identified seed produced annually. More information can be found at the Tall Prairie website.

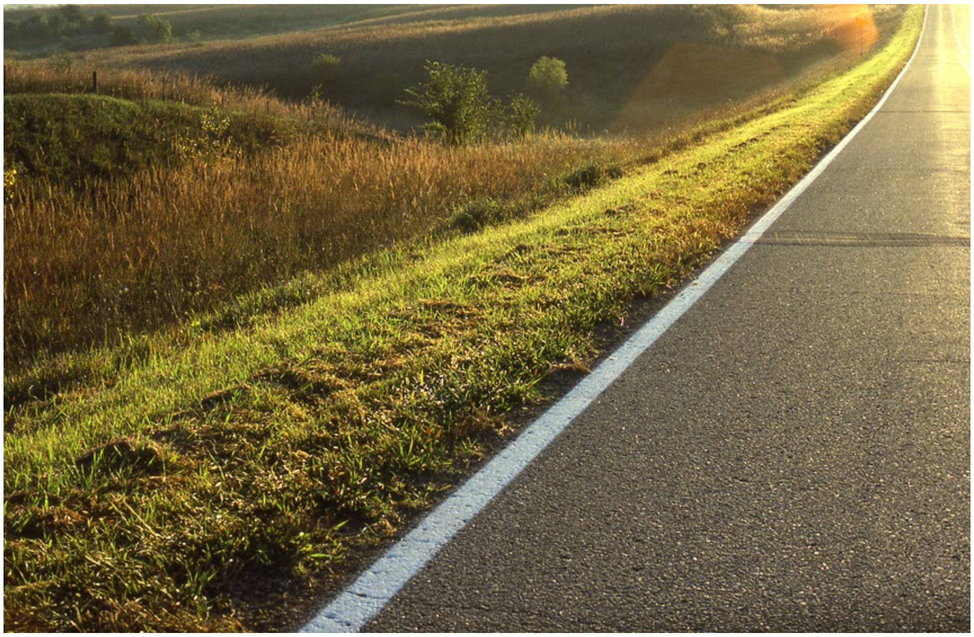


Photo credit: Carl Kurtz

8.2 FLORIDA RESOLVES TO PROTECT WILDFLOWERS ON ROADSIDES

The following case study from Florida highlights a unique citizen-based effort to protect pollinator habitat through county policy resolutions that were subsequently supported by pollinator-friendly management plans.

Florida, home to a great diversity of plants and animals, was once dubbed the "land of flowers" by a Spanish explorer in 1513. Many of these wildflowers can be found on Florida's 200,000 acres of roadsides. However, wildflower proliferation along roadsides can be limited by the frequency of mowing. Roadside mowing can be very intensive in some parts of Florida, particularly in urban areas. When showy stands of wildflowers were mowed during bloom when pollinators were present, concerned citizens contacted Florida DOT. Jeff Caster, State Transportation Landscape Architect with Florida DOT, describes the situation: "There would be butterflies on the side of the road feasting on the native vegetation and we would come in and mow it all down and we would get people naturally upset with us. Environmentally conscious citizens called us to complain that we were mowing down wildflowers and butterfly habitat."

Florida DOT isn't able to alter their management plans based on direct requests from a garden club or an individual that wants less roadside mowing. But citizens in Wakulla County found another way. They worked with their county commissioners to draft a resolution that made it county policy to preserve existing stands of roadside wildflowers. Then, county staff worked with Florida DOT to develop a roadside management plan to accommodate the resolution.

Recognizing the cultural, historical, and environmental significance of native wildflowers, 27 out of Florida's 67 counties have moved to adopt similar wildflower resolutions. These counties "make a commitment to saying they want to enjoy the visibility of wildflowers for whatever reason, some do it to attract nature-based tourism, some doing it to help their farms," Caster says. A model resolution can be found on the Florida Wildflower Foundation's website.

Florida's unique grassroots approach to protecting wildflowers at the county level has great potential for pollinator conservation.

Photo credits: Maria Urice

Native wildflowers along a Florida turnpike.

Photo credit: Jeff Norcini

This interchange, in the heart of Washington's grape and hops growing region, is undergoing integrated management to reduce the dominant invasive species kochia and cereal rye. Native milkweed occurs naturally at this site, serving as potential breeding habitat for monarch butterflies.

Photo credit: Washington State Department of Transportation

8.3 MAPPING AND PLANNING BENEFIT WASHINGTON STATE POLLINATORS

Washington State Department of Transportation (WSDOT) maintains about 100,000 acres of roadside. WSDOT has been implementing integrated vegetation management for many years with the overarching goal of reducing undesirable vegetation while encouraging desirable vegetation. Many of their practices and policies to manage vegetation also promote pollinator habitat.

Whenever possible, WSDOT preserves existing native habitat that can provide food, host plants, shelter, and nesting for pollinators. WSDOT also identifies roadsides for "managed succession" (WSDOT 2003). These are areas that have desirable vegetation that could flourish under a strategy that allows natural plant succession to proceed to a stable plant community. Outside of the clear zone or lines of sight where repeated mowing still occurs, roadsides managed for natural succession have multi-year treatment strategies that employ a variety of vegetation management tools, including reduced mowing and targeted herbicide use. Managed succession allows native vegetation to emerge and flourish, with sagebrush (Artemisia tridentata), greasewood (Sarcobatus vermiculatus), and native grasses taking hold in prairie regions, and understory shrubs that are attractive to pollinators like snowberry (Symphoricarpos albus), Oregon grape (Mahonia nervosa), and spirea (Spiraea sp) in other regions.

When roadside revegetation is needed, WSDOT prioritizes the use of native plants, including a diversity of native wildflowers and flowering shrubs and trees. Landscape designers focus on native plants that can establish with minimal input and compete with weeds. Key considerations for pollinators during the planning process include sequential bloom periods of flowering plants and high plant diversity. Maintenance staff are included in the planning process to provide input on long-lived plants that can be managed minimally.

Mapping and planning are key elements of Washington DOT's approach to roadside revegetation and maintenance. Vegetation inventories help to identify areas with weed infestations as well as areas that are conducive to managed succession. All maintenance staff have tablets, used to record data and view maps and aerial images.

WSDOT uses the best available science to inform their actions, and also undertake their own research to determine the right methods for their management needs. For example, experimental plots are used for testing seed mixes and planting methods. WSDOT also monitors the effectiveness of maintenance techniques on vegetation and pollinators. More information about the actions Washington Department of Transportation is taking to protect pollinators and promote pollinator health can be found at their website.

A site identified through GIS analysis as a priority location for managed succession to replace nonnative species with desirable native species. Careful planning and management for a number of years has increased native plants such as camas, snowberry, serviceberry, and Oregon grape, but invasive scotch broom still remains and requires selective treatment with herbicides.

Photo credit: Washington State Department of Transportation

8.4 ESTABLISHING NATIVE PLANTS IN ARIZONA

In 1992, Arizona DOT began to use native species in all roadside revegetation efforts. This was implemented by drafting a plant list from State maps of biotic communities grouped by eco-regions. From this list, they identified species that were available commercially. Over the years, available plant mixes included a diversity of 15 to 25 species, composed of annual, biennial, perennial wildflowers, shrubs, and 3 to 5 species of native grasses. After observing that grasses out-competed flowers and even shrubs over time in plantings composed of 50 percent grass and 50 percent wildflowers/shrubs, Arizona DOT scaled back the proportion of grasses to 25 percent. The availability of plant materials, particularly seeds of native species, has increased greatly since 1992.

Arizona is one of the only States to include noxious and invasive species control in construction specifications. In practice, this specification means that noxious and invasive weeds are controlled before, during, and after road construction. By proactively controlling problematic weeds that can outcompete beneficial plants, this practice helps the desired species establish quickly and maintain the long-term integrity of the planting.

Native wildflowers along Arizona's Interstate 10.

Photo credits: Arizona Department of Transportation

REFERENCES

Ahmad M. 2013. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere. In Press.

Alaux C, Ducloz, F, Crauser D, Le Conte, Y. 2010. Diet effects on honeybee immunocompetence. Biology Letters: rsbl20090986.

Alexander R. 2003a. A composting update: the way we were, and where we're going. Municipal Stormwater Management 13(1). 7 p.

Alexander R. 2003b. Developing and implementing national erosion/sediment control specifications for composted products. Durham (NH): Recycled Materials Resource Center.

Allen EB, Espejel C, Sigüenza C. 1997. Role of mycorrhizae in restoration of marginal and derelict land and ecosystem sustainability. In: Palm ME, Capela IH, editors. Mycology in sustainable development: expanding concepts, vanishing borders. Boone (NC): Parkway Publishers Inc. p. 147-159.

Amaranthus M, Steinfeld D. 2003. A symbiotic relationship [online]. Erosion Control, Sept/Oct. 4 p.

Amaranthus M, Steinfeld D. 2005. Arbuscular mycorrhizal inoculation following biocide treatment improves *Calocedrus decurrens* survival and growth in nursery and outplanting sites. In: Riley LE, Dumroese RK, Landis TD, technical coordinators. National proceedings: forest and conservation nursery associations–2004. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. RMRS-P-35. p 103-108.

Amaranthus MP, Perry DA. 1987. The effect of soil transfer on ectomycorrhiza formation and the survival and growth of conifer seedlings on old, nonreforested clearcuts. Canadian Journal of Forest Research 17:944–950.

Amaranthus MP, Steinfeld DE. 1997. Soil compaction after yarding of small-diameter Douglas-fir with a small tractor in southwest Oregon. Portland (OR): USDA Forest Service, Pacific Northwest Research Station. Research Paper PNW-RP-504. 7 p.

Amaranthus MP. 2002. Declaration of interdependence: mycorrhizal fungi are the 'tiny little secrets' for planting success. Oregon Association of Nurserymen Digger. 46(4):48-53.

Ament R, Begley J, Powell S, Stoy P. 2014. Roadside Vegetation and Soils on Federal Lands – Evaluation of the Potential for Increasing Carbon Capture and Storage and Decreasing Carbon Emissions. FHA Report. 47 p. Report for the Federal Highway Administration, # DTFH68-07-E-00045.

Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 113-120.

Anderson NP, Hart JM, Sullivan DM, Christensen NW, Hornectk DA, Pirelli GJ. 2013. Applying lime to raise soil pH for crop production (western Oregon). Oregon State University Extension Service. EM 9057.

Andrus CW, Froehlich HA. 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. Corvallis (OR): Forest Research Laboratory. Research Bulletin 45. 12 p.

Anonymous. [nd]. Mycorrhizae and revegetation of disturbed lands. Bozeman (MT): Montana State University.

Araratyan, LA, Zakbaryan, SA. 1988. On the contamination of snow along main highways. Biologicheskii Zhurnal Armenii 41: 511-519

Archuleta JG, Baxter ES. 2008. Subsoiling promotes native plant establishment on compacted forest sites. Native Plants Journal. 9:2 17-122.

Applegate GB, Bragg AL. 1989. Improved growth rates of red cedar (*Toona australis* (F. Muell.) Harms) seedlings in grow tubes in north Queensland. Australian Forestry Journal 52(4):293-297.

Ashby WC, Vogel WG. 1993. Tree planting on mined lands in the Midwest: a handbook. Carbondale (IL): Southern Illinois University, Coal Research Center. 115 p.

American Association of State Highway and Transportation Officials [AASHTO]. 2013. Chapter 8 Winter Operations and Salt, Sand, and Chemical Management.

AASHTO. 2013a. Chapter 9.1 Inventory of and management for rare species and sensitive resources in the ROW.

Association of Official Seed Analysts [AOSA]. 2002. Rules for testing seeds. Stillwater (OK): Association of Official Seed Analysts. 166 p.

Aubry C, Shoal R, Erickson V. 2005. Grass cultivars: their origins, development, and use on national forests and grasslands in the Pacific Northwest. Portland (OR): USDA Forest Service. 41 p.

Bainbridge D, Tisler J, MacAller R, Allen MF. 2001. Irrigation and mulch effects on desert shrub transplant establishment. Native Plants Journal 2(1):25-29.

Bainbridge DA. 1994. Tree shelters improve establishment on dry sites. Tree Planters' Notes 45(1):13-16.

Bainbridge DA. 2006a. Beyond drip irrigation–hyper-efficient irrigation. In: American Society of Agricultural and Biological Engineers Annual International Meeting; 2006 July 9-12; Portland, OR. St Joseph (MI): American Society of Agricultural and Biological Engineers. Paper 062071. 10 p.

Bainbridge DA. 2006b. Deep pipe irrigation. Holualoa (HI): Agroforestry Net Inc. 8p.

Bainbridge DA. 2006c. Irrigation for remote sites. San Diego (CA): San Diego State University, Soil Ecology and Restoration Group. Restoration Bulletin 6. 20 p.

Ballard TM. 1981. Physical properties and physical behavior of forest soils. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washtington State University Cooperative Extension Service. P. 113-120.

Barnar J. 2007. Personal communication. Bend (OR): USDA Forest Service, Bend Seed Extractory. Manager.

Barnum, S.A. 2003. Identifying the best locations to provide safe highway crossing opportunities for wildlife. In 2003 Proceedings of the International Conference on Ecology and Transportation, edited by C. Leroy Irwin, Paul Garrett, and K.P. McDermott. Raleigh, NC: Center for Transportation and the Environment, North Carolina State University, 2003. 246-252.

Barnum, S., K. Rinehart, and M. Elbroch. 2007. Habitat, highway features, and animal-vehicle collision locations as indicators of wildlife crossing. In Proceedings of the 2007 International Conference on Ecology and Transportation, edited by C. Leroy Irwin, Debra Nelson, and K.P. McDermott. Raleigh, NC: Center for Transportation and the Environment, North Carolina State University, 2007. 511-518.

Barvenik FW. 1994. Polyacrylamide characteristics related to soil applications. Soil Science 158(4): 235-243.

Basey AC, Fant JB, Kramer AT. 2015. Producing native plant materials for restoration: 10 rules to collect and maintain genetic diversity. Native Plants Journal 16(1):37-52.

Baskin JM, Baskin CC. 1989. Seasonal changes in the germination responses of buried seeds of Barbarea vulgaris. Canadian Journal of Botany 67:2131-2134.

Baxter E, Stephan E. 2011. Using biosolids to establish native grasses on timber haul roads. Learning Summary.

Bean TM, Smith SE, Karpiscak MM. 2004. Intensive revegetation in Arizona's hot desert–the advantages of container stock. Native Plants Journal 5(2):173-180.

Bedrossian TL. 1983. Watershed mapping in northern California. Californian Geology 36:140-147.

Beesley L, Moreno-Jimenez E, Gomex-Eyles, Harris E, Robinson B, Sizmur T. 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental Pollution. 159 (2011) 3269-3282.

Bellot J, Ortiz De Urbina JM, Bonet A, Sanchez JR. 2002. The effects of tree shelters on the growth of Quercus coccifera L. seedlings in a semiarid environment. Forestry 75(1):89-106.

Bentrup G, Hoag JC. 1998. The practical streambank bioengineering guide. Aberdeen (ID): USDA Natural Resources Conservation Service, Plant Materials Center. 150 p.

Berger RL. 2005. Integrated roadside vegetation management. Washington (DC): Transportation Research Board. 80 p.

Bergez JE, Cupraz C. 1997. Transpiration rate of Prunus avium L. seedlings inside an unventilated treeshelter. Forest Ecology and Management 97:255-264.

Black SH, Shepherd M, Vaughan M. 2011. Rangeland management for pollinators. Rangelands 33(3):9-13.

Black SH, Fallon C, Hatfield R, Mazzacano, C. 2014. Controlled Burning and Mardon Skipper: Summary of Mardon Skipper Coon Mountain Burn Site Occupancy Study Data from 2009 to 2013. Report to the U.S. Forest Service, Oregon Zoo, and U.S. Fish and Wildlife Service: 29.

Bloomfield HE, Handley JF, Bradshaw AD. 1982. Nutrient deficiencies and the aftercare of reclaimed derelict land. Journal of Applied Ecology 19:151-158.

Bogemams J, Nicrinck L, Stassart, JM. 1989. Effect of deicing chloride salts on ion accumulation in spruce *(Picea abies* (L.) sp.). Plant and Soil 113:3-11.

Bollen WB. 1974. Soil microbes. In: Cramer O, editor. Environmental effects of forest residues management in the Pacific Northwest. Portland (OR): USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. General Technical Report PNW-24. p B1-B41.

Blomqvist G, Johansson EL, 1999. "Airborne spreading and deposition of deicing salt case study", Science of the Total Environment, 235, 161-168.

Bonar R. 1995. The northern pocket gopher–most of what you thought you might want to know, but hesitated to look up. Missoula (MT): USDA Forest Service, Technology and Development Program. Technical Services, Reforestation TE02E11. 61 p.

Borland J. 1990. Mulch–examining the facts and fallacies behind the uses and benefits of mulch. American Nurseryman 172(4):132-141.

Bouchard NR, Osmond DL, Winston RJ, Hunt WF. 2013. The capacity of roadside vegetated filter strips and swales to sequester carbon. Ecological Engineering. Vol 54:227-232.

Bower AD, St. Clair JB, Erickson V. 2014. Generalized provisional seed zones for native plants. Ecological Applications, 24(5), pp:913-919.

Bowman D, Cramer G, Devitt D. 2006. Effect of Salinity and Nitrogen Status on Nitrogen Uptake by Tall Fescue Turf. Journal of Plant Nutrition 29:1481-1490.

Bradshaw AD, Marrs RH, Roberts RD, Skeffington RA. 1982. The creation of nitrogen cycles in derelict land. Philosophical Transactions of the Royal Society of London. Series B, Biological 296:557-561.

Bradshaw AD. 1992. The reclamation of derelict land and the ecology of ecosystems. In: Jordan WR, Gilpin ME, Aber JD, editors. Restoration ecology: a synthetic approach to ecological restoration. Cambridge (England): Cambridge University Press. p. 53-74.

Brandle JR and Nickerson HD. 2017. Windbreaks for snow management. 4p.

Brant J, Henderson K, Uthe J. 2015. Integrated roadside vegetation management - technical manual. USDA Natural Resource Conservation Service and Iowa DOT's Living Roadway Trust Fund. 105 p.

Breed M, Stead M, Ottewell K, Gardner M, and Lowe A. 2013. Which provenance and where? Seed sourcing strategies for revegetation in a changing environment. Conservation Genetics. Vol 14:1-10.

Brejda JJ, Yocom DH, Moser LE, Waller SS. 1993. Dependence of 3 Nebraska Sandhills warm-season grasses on vesicular-arbuscular mycorrhizae. Journal of Range Management 46(1):14-20.

Brock TD. 2016. The Bradley method for control of invasive plants.

Brooks CR, Blaser RE. 1964. Effect of fertilizer slurries used with hydroseeding on seed viability. Washington (DC): Highway Research Board. Highway Research Record 53:30-34.

Brown JD. 2016. A field study of biochar amended soils: water retention and nutrient removal from stormwater runoff. Presented at 2016 US Biochar Initiative Conference. Corvallis OR. 29p.

Brown JE, Maddox JB, Splittstoesser WE. 1983. The effect of fertilizer and strip mine spoil on germination and growth of legumes. In: Graves DH, editor. Proceedings 1983 symposium on surface mining, hydrology, sedimentology and reclamation. Lexington (KY): University of Kentucky. p 419-422.

Brown MB, Wolf DD, Morse RD, Neal JL. 1982. Survival of rhizobium inoculum in hydroseeding slurries. In: Graves DH, editor. Proceedings 1982 symposium on surface mining, hydrology, sedimentology and reclamation. Lexington (KY): University of Kentucky. p. 681-685.

Brown R, Amacher M. 1999. Selecting plant species for ecological restoration: a perspective for land managers. In: Holzworth LK, Brown R, compilers. Revegetation with native species: Proceedings, 1997 Society for Ecological Restoration annual meeting; 1997 November 12- 15; Ft Lauderdale, FL. Ogden (UT): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-8. p. 1-16.

Brown RN, Gores JH. 2011. The use of soil amendments to improve survival of roadside grasses. HortScience 46(10): 1404-1410.

Brunsden D, Prior DB. 1984. Slope instability. Chichester (UK): John Wiley and Sons Ltd. 620 p.

Brunzel S, Elligsen H, Frankl R. 2004. Distribution of the Cinnabar moth *Tyria jacobaeae* L. at landscape scale: use of linear landscape structures in egg laying on larval hostplant exposures. Landscape Ecology 19(1), 21-27.

Bryson GM, Barker AV. 2002. Sodium accumulation in soils and plants along Massachusetts roadsides. Communications in Soil Science and Plant Analysis 33(1-2), 67-78.

Brzozowski C. 2003. Carpets of grass [online]. Santa Barbara (CA): Forester Communications Inc, Erosion Control.

Brzozowski C. 2004. Hydroseeding: a versatile alternative [online]. Santa Barbara (CA): Forester Communications Inc, Erosion Control.

Burghardt KT, Tallamy DW, Shriver, WG. 2009. Impact of native plants on bird and butterfly biodiversity in suburban landscapes. Conservation Biology 23:219–224.

Burroughs Jr ER, King JG. 1989. Reduction of soil erosion on forest roads. Ogden (UT): USDA Forest Service, Intermountain Research Station. General Technical Report INT-264. 22 p.

Busse M. 2000. Ecological significance of nitrogen fixation by actinorrhizal shrubs in interior forests of California and Oregon. In: Powers RF, Hauxwell DL, Nakamura GM, technical coordinators. Proceedings of the California Forest Soils Council conference on forest soils biology and forest management. Albany (CA): USDA Forest Service, Pacific Southwest Research Station. General Technical Report GTR-PSW-178. p. 23-41.

Calderone NW. 2012. Insect pollinated crops, insect pollinators and US agriculture: trend analysis of aggregate data for the period 1992-2009. PLoS ONE 7(5) e37235.

California Department of Transportation [Caltrans]. 2003. Caltrans erosion control new technology report. Sacramento (CA): California Department of Transportation. CTSW-RT-03-049. 463 p.

California Stormwater Quality Association [CASQA]. 2003a. EC-3 Hydraulic mulch. In: Construction Handbook [online]. Menlo Park (CA): California Stormwater Quality Association. 3 p.

California Stormwater Quality Association [CASQA]. 2003b. EC-5 Soil binders. In: Construction Handbook [online]. Menlo Park (CA): California Stormwater Quality Association. 7 p.

Cane JH. 1991. Soils of ground-nesting bees (Hymenoptera: Apoidea): texture, moisture, cell depth and climate. Journal of the Kansas Entomological Society: 64(4): 406-413.

Campbell KB, Helgested E, Shaw EJ, Hawkes GR. 1980. Western fertilizer handbook. Sacramento (CA): California Fertilizer Association. 269 p.

Campbell RK. 1986. Mapped genetic variation of Douglas fir to guide seed transfer in southwest Oregon. Silvae Genetica 35:85-96.

Casement B and Timmermans J. 2007. Field shelterbelts for soil conservation. Agdex 277/20-3. 8p.

Carr WW, Ballard TM. 1979. Effects of fertilizer salt concentration on viability of seed and Rhizobium used for hydroseeding. Canadian Journal of Botany 57(7):701-704.

Carr WW, Ballard TM. 1980. Hydroseeding forest roadsides in British Columbia for erosion control. Journal of Soil and Water Conservation 35(1):33-35.

Carson MA, Kirkby MJ. 1972. Hillslope form and process. London (UK): Cambridge University Press. 475 p.

Carvell C. 2002. Habitat use and conservation of bumble bees (*Bombus* spp.) under different grassland management regimes. Biological Conservation 103:33–49.

Center for Invasive Plant Management [CIPM]. nd. Chapter 8: Invasive plant prevention. In: Invasive plant management: CIPM online textbook. Bozeman (MT): Montana State University, Department of Land Resources and Environmental Sciences, Center for Invasive Plant Management

Chaplin-Kramer R, Tuxen-Bettman K, Kremen C. 2011. Value of wildland habitat for supplying pollination services to Californian agriculture. Rangelands 33(3):33-41.

Charvat I, Tallaksen J, White J, Agwa H, Raley M, Slack S, Hebberger J, Gould E. 2000. Mycorrhizal/ plant factors involved in roadside reclamation. St Paul (MN): Minnesota Department of Transportation. Final Report - MN/RC-2000-30. 131 p.

Childs SW, Flint LE. 1987. Effect of shadecards, shelterwoods, and clearcuts on temperature and moisture environments. Forest Ecology and Management 18:205-217.

Claassen VP, Carey JL. 2004. Regeneration of nitrogen fertility in disturbed soils using composts. Compost Science and Utilization 12(2):145-152.

Claassen VP, Hogan MP. 1998. Generation of water-stable soil aggregates for improved erosion control and revegetation success. Sacramento (CA): California Department of Transportation. Research Technical Agreement 53X461. 111 p.

Claassen VP, Hogan MP. 2002. Soil nitrogen pools associated with revegetation of disturbed sites in the Lake Tahoe area. Restoration Ecology 10(2):195-203.

Claassen VP, Marler MM. 1998. Annual and perennial grass growth on nitrogen-depleted decomposed granite. Restoration Ecology 6(2):175-180.

Claassen VP, Zasoski RJ, Southard RJ. 1995. Soil conditions and mycorrhizal infection associated with revegetation of decomposed granite slopes. Sacramento (CA): California Department of Transportation. Technical Report FHWA-CA-TL 96/1. 151 p.

Claassen VP, Zasoski RJ. 1994. The effects of topsoil reapplication on vegetation reestablishment. Sacramento (CA): California Department of Transportation. Technical Report FHWA-CA-TL- 94/18. 52 p.

Claassen VP, Zasoski RJ. 1998. A comparison of plant available nutrients on decomposed granite cut slopes and adjacent natural soils. Land Degradation and Development 9:35-46.

Claassen VP. 2006. Soil resource evaluation. Sacramento (CA): California Department of Transportation.

Clark TW, Stevenson M, Ziegelmayer K, Rutherford M, editors. 2001. Species and ecosystem conservation: an interdisciplinary approach. New Haven (CT): Yale University Press.

Cleary BD, Greaves RD, Hermann RK, editors. 1988. Regenerating Oregon forests, a guide for the regeneration forester. 5th printing. Corvallis (OR): Oregon State University Extension Service. 287 p.

Clevenger, Anthony P., and Marcel P. Huijser. Wildlife Crossing Structure Handbook Design and Evaluation in North America. Lakewood Co.: U.S. Federal Highway Administration Central Federal Lands Highway Division, 2011. Print

Clevenger, A.P. and N. Waltho. 2000. Factors influencing the effectiveness of wildlife underpasses in Banff National Park, Alberta, Canada. Conservation Biology, 14(1), 47-56.

Clevenger, A.P. and N. Waltho. 2005. Performance indices to identify attributes of highway crossing structures facilitating movement of large mammals. Biological Conservation 121:453-464.

Clewell A, Rieger J, Munro J. 2005. Guidelines for developing and managing ecological restoration projects. 2nd ed. Tuscon (AZ): Society for Ecologicial Restoration International.

Cole DW, Johnson D. 1981. The cycling of elements within forests. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 185-198.

Composting Council Research and Education Foundation, United States Composting Council [CCREF and USCC]. 2006. Compost use on state highway applications. Harrisburg (PA): Composting Council Research and Education Foundation, United States Composting Council. 15 p.

Cook DF, Nelson SD. 1986. Effect of polyacrylamide on seedling emergence in crust-forming soil. Soil Science 141:328-333.

Corkiki L, Allen EB, Merhaut D, Allen MF, Downer J, Bohn J, Evans M. 2005. Effectiveness of commercial mycorrhizal inoculants on the growth of *Liquidambar styraciflua* in plant nursery conditions. Journal of Environmental Horticulture 23(2):72-96.

Cox TS, Glover JD, Van Tassel DL, Cox CM, DeHaan LR. 2006. Prospects for Developing Perennial Grain Crops. BioScience. Vol. 56 No.8. August 2006.

Crémieux, L, Bischoff A, Müller-Schärer H, Steinger T. 2010. Gene flow from foreign provenances into local plant populations: fitness consequences and implications for biodiversity restoration. American Journal of Botany. 97(1): 94–100.

Crowder W, Darris D. 1999. Producing Pacific Northwest native trees and shrubs in hardwood cutting blocks or stooling beds. Portland (OR): USDA Natural Resources Conservation Service. Technical Notes–Plant Materials No 24. 13 p.

Croxton PJ, Hann JP, Greatorex-Davis JN, Sparks TH. 2005. Linear hotspots? The floral and butterfly diversity of green lanes. Biological Conservation 121:579–584.

Curtis MJ, Claassen VP. 2005. Compost incorporation increases plant available water in a drastically disturbed serpentine soil. Soil Science 170(12):13.

Dancer WS, Handley JF, Bradshaw AD. 1977. Nitrogen accumulation in kaolin mining wastes in Cornwall. I. Natural communities. Plant and Soil 48:153-167.

Dancer WS. 1975. Leaching losses of ammonium and nitrate in the reclamation of sand spoils in Cornwall. Journal of Environmental Quality 4(4):499-504.

Darboux F, Huang C. 2005. Does soil roughness increase or decrease water and particle transfer? Soil Science Society of America Journal 69:748-756.

Darris DC, Williams D. 2001. Native shrubs as a supplement to the use of willows as live stakes and facines in western Oregon and western Washington. In: Haase DL, Rose R, editors. Proceedings of the conference: native plant propagation and restoration strategies; 2001 Dec 12-13; Eugene, OR. Corvallis (OR): Oregon State University, Nursery Technology Cooperative. p. 112-120.

Darris DC. 2002. Native shrubs as a supplement to the use of willows as live stakes and facines in western Oregon and western Washington. Portland (OR): USDA Natural Resources Conservation Service. Technical Notes–Plant Materials No 31. 10 p.

Daugovish O, Downer J, Faber B, McGiffen M. 2006. Weed survival in yard waste mulch. Weed Technology 21(1):59-65.

Davies RJ. 1988a. Sheet mulching as an aid to broadleaved tree establishment. I. The effectiveness of various synthetic sheets compared. Forestry 61(2):89-105.

Davies RJ. 1988b. Sheet mulching as an aid to broadleaved tree establishment II. Comparison of various sizes of black polythene mulches and herbicide treated spot. Forestry 61(2):107-124.

DeByle NV. 1969. Black polyethylene mulch increases survival and growth of a Jeffrey pine plantation. Tree Planters' Notes 19(4):7-11.

Deere DU, Deere DW. 1988. The rock quality designation (RQD) index in practice. In: Kirkaldie L, editor. Rock classification systems for engineering purposes. Philadelphia (PA): American Society of Testing Materials. ASTM Special Publication 984. p. 91-101.

Denning C, Prellwitz R, Reneria R, Rose E. 1994. Parameters for stability analysis. In: Hall DE, Long MT, Remboldt MD, editors. Slope stability reference guide for national forests in the United States. Volume II. Washington (DC): USDA Forest Service, Engineering Staff. EM 7170-13. p. 327-721.

DePuit EJ, Coenenberg JG. 1979. Responses of revegetated coal strip mine spoils to variable fertilization rates, longevity of fertilization program, and season of seeding. Bozeman (MT): Montana State University, Montana Agricultural Experiment Station. Research Report 150. 81 p.

Di Pasquale G, Salignon M, Le Conte Y, Belzunces LP, Decourtye A, Kretzschmar A, Suchail S, Brunet J-L, Alaux C. 2013. Influence of pollen nutrition on honey bee health: do pollen quality and diversity matter. PLOS One 8(8): e72016.

Dirig R, Cryan JF. 1991. The status of silvery blue subspecies (*Glaucopsyche lygdamus lygdamus and G. l. couperi: Lycaenidae*) in New York. Journal of the Lepidopterists' Society 45(4):272-290.

Dixon RM, Carr AB. 2001a. Land imprinting specifications for ecological restoration and sustainable agriculture. In: Ascough JC II, Flanagan DC, editors. Soil erosion research for the 21st Century, proceedings of an international symposium; 2001 Jan 3-5; Honolulu, HI. St Joseph (MI): American Society of Agricultural Engineers. ASAE.701P0007. p. 195-197.

Dixon RM, Carr AB. 2001b. Preferential flow control: key to sustainable land management. In: Bosch D, King K, editors. Preferential flow water: movement and chemical transport in the environment, proceedings of the 2nd international symposium; 2001 Jan 3-5; Honolulu, HI. St Joseph (MI): American Society of Agricultural Engineers. ASAE.701P0006. p. 287-289.

Dixon RM, Simanton JR. 1977. A land imprinter for revegetation of barren land areas through infiltration control. IN Hydrology and water resources in Arizona and the southwester. Vol 7, p 79-88.

Dorner J. 2002. An introduction to using native plants in restoration projects. Seattle (WA): Plant Conservation Alliance and Environmental Protection Agency. 66 p.

Dreesen DR, Harrington JT. 1997. Propagation of native plants for restoration projects in the southwestern US–preliminary investigations. In: Landis TD, Thompson JR, technical coordinators. National proceedings, forest and conservation nursery associations. Portland (OR): USDA Forest Service, Pacific Northwest Research Station. General Technical Report PNW-GTR-419. p. 77-88.

Dumroese RK, Jacobs DF, Landis TD. 2005. Successful stock production for forest regeneration: what foresters should ask nursery managers about their crops (and vice versa). In: Colombo SJ, editor. The thin green line: a symposium on the state-of-the-art in reforestation, proceedings; 2005 July 26-28; Thunder Bay, Ontario. Sault Ste Marie (Ontario): Ontario Ministry of Natural Resources, Forest Research Information Paper 160:14-20.

Dumroese RK, Stumph T, Wenny DL. 1998. Revetating Idaho's Henry's Fork: a case study. In: Rose R, Haase DL, editors. Native plants: propagation and planting; 1998 Dec 9-10; Corvallis, OR. Corvallis (OR): Oregon State University, Nursery Technology Cooperative. p. 108-112.

Dumroese RK., Landis TD; Barnett JP; Burch F. 2005. Forest Service Nurseries: 100 years of ecosystem restoration. Journal of Forestry: 241-247

Dumroese RK. 2006. Personal communication. Moscow (ID): USDA Forest Service, Southern Research Station. Research Plant Physiologist.

Dupraz C, Bergez JE. 1997. Carbon dioxide limitation of the photosynthesis of *Prunus avium* L. seedlings inside an unventilated treeshelter. Forest Ecology and Management 119(1):89-97.

Dyer K, Curtis L, Willie R, Crews JT. 1984. Response of vegetation to various mulches used in surface mine reclamation in Alabama and Kentucky–7-year case history. Broomhall (PA): USDA Forest Service, Northeastern Forest Experiment Station. General Technical Report NE-93. 11 p.

Eilers EJ, Kremen C, Greenleaf SS, Garber AK, Klein AM. 2011. Contribution of pollinator-mediated crops to nutrients in the human food supply. PLoS one 6(6)e21363.

Elzinga, CL, Salzer DW, Willoughby JW. 1998. Measuring and monitoring plant populations. Denver (CO): USDI Bureau of Land Management. BLM Technical Reference 1730-1. 492 p.

Environmental Protection Agency [EPA]. 1994. A plain English guide to the EPA Part 503 Biosolids Rule. EPA/832/H-93/003. EPA Office of Waste Management. 183p.

Environmental Protection Agency [EPA]. 1995. Process design manual - land application of sewage sludge and domestic septage. EPA/625/R-95/001. 301 p.

Environmental Protection Agency [EPA]. 2006. Environmental Protection Agency (EPA) National Pollutant Discharge Elimination System (NPDES) Glossary Terms: "Final Stabilization." Washington (DC): US EPA, Office of Wastewater Management.

Epstein E. 1997. The science of composting. Boca Raton (FL): CRC Press LLC. 487 p.

Epstein E. 2002. Land application of sewage sludge and biosolids. Boca Raton (FL): CRC Press LLC. 201 p.

Erickson VJ, Mandel NL, Sorensen FC. 2004. Landscape pattern of phenotypic variation and population structuring in a selfing grass, *Elymus glaucus* (blue wildrye). Canadian Journal of Botany 82:1776-1789.

Erickson VJ, Wood J, Riley SA. 2003. Guidelines for revegetation of invasive weed sites and other disturbed areas on national forests and grasslands in the Pacific Northwest. Portland (OR): USDA Forest Service, Pacific Northwest Region. 80 p.

Erickson VJ. 2008. Developing native plant germplasm for national forests and grasslands in the Pacific Northwest. Native Plants Journal 9:255–266.

Evans RG. 2006. Review of the application of polyacrylamides for soil erosion reduction through sprinklers. Sidney (MT): USDA Agricultural Research Service. 4 p.

Fava EM. 2015. Biosolids as a roadside soil amendment. Dissertations and Master's Theses (Campus Access) at the University of Rhode Island DigitalCommons@URI.

Feber RE, Smith H, Macdonald DW. 1996. The effects on butterfly abundance of the management of uncropped edges of arable fields. Journal of Applied Ecology 33:1191–1205.

Federal Highway Administration [FHWA]. 1992. Drainable pavement systems - participant notebook. (Demonstration Project 87). Publication No. FHWA-SA-92-008. Federal Highway Administration, Washington, DC.

Federal Highway Administration [FHWA]. 2005. Project development and design manual (PDDM). Washington (DC): US Department of Transportation, Federal Highway Administration. Publication Number FHWA-DF-88-003.

Federal Highway Administration [FHWA]. 2008. 2008 Status of the Nation's highways, bridges, and transit: conditions and performance. FHWA, Washington DC.

Federal Highway Administration [FHWA]. 2008(B). Vegetation Control for Safety – A guide for Local Highway and Street Maintenance Personnel. FHWA, Washington DC.

Federal Highway Administration [FHWA]. 2010. Carbon Sequestration Pilot Program, estimated land available for carbon sequestration in the National Highway System. 24 p.

Federal Highway Administration [FHWA]. 2012. Road Weather Management Program, Snow and Ice. Website updated November 2012.

Federal Highway Administration [FHWA]. 2017. Clear Zones.

Federal Register [FR]. 2006. Rules and regulations. Federal Register 71(102). 2 p.

Federal Register [FR]. 2014. Presidential Memorandum – Creating a Federal Strategy to Promote the Health of Honey Bees and Other Pollinators, The White House, Washington, D.C., June 20, 2014, Filed 6-23-14; 11:15 am, Federal Register Doc. 2014-14946.

Ferrick MG, Gatto LW. 2004. Quantifying the effect of a freeze-thaw cycle on soil erosion: laboratory experiments. Hanover (NH): US Army Corps of Engineers, Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory. Letter Report A670134. 47 p.

Fidelibus MW, Bainbridge DA. 2006. Microcatchment water harvesting for desert revegetation [online]. San Diego (CA): San Diego State University, Soil Ecology and Restoration Group. Restoration Bulletin 5. 12 p.

Fiedler AK, Landis DA, Arduser M. 2012. Rapid shift in pollinator communities following invasive species removal. Restoration Ecology 20(5):593–602.

Fisher PR, Argo WR. 2005. Electrical conductivity of growing media: why is it important? Greenhouse Management and Production 25(5):54-58. Scoggins HL, Nelson PV, Bailey DA. 2000. Development of the press extraction method for plug substrate analysis: effects of variable extraction force on pH, electrical conductivity, and nutrient analysis. HortTechnology 10(2):367-36.

Flint AL. 1983. Soil physical properties and available water capacity of southwest Oregon forest soils [MS thesis]. Corvallis (OR): Oregon State University. 61 p.

Flint LE, Childs SW. 1984. Seedling responses to heat and moisture environments in clearcuts and shelterwoods. Forestry Intensified Research Report 6(2):3-4.

Foltz RB, Dooley JH. 2003. Comparison of erosion reduction between wood strands and agricultural straw. Transactions of the American Society of Agricultural Engineers 46(5):1389-1396.

Foltz, R.B.; Wagenbrenner, N.S. 2010. An evaluation of three wood shred blends for post-fire erosion control using indoor rain events on small plots. Catena. 80: 86-94. doi:10.1016/j.catena.2009.09.00.

Forman RTT, Alexander LE. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29: 207-231.

Forman RTT, editor. 2003. Road ecology: science and solutions. Washington (DC): Island Press. 481 p.

Frankie GW, Thorp GW, Schindler MH, Ertter B, Przybylski M. 2002. Bees in Berkeley? Fremontia 30(3-4):50–58.

Frearson K, Weiss ND. 1987. Improved growth rates within tree shelters. Quarterly Journal of Forestry 81:184-187.

Fredricksen RL, Harr RD. 1981. Soil, vegetation, and watershed management. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 231-260.

Fifield JS. 2004. Designing for effective sediment and erosion control on construction sites - 2nd edition. Forester Press.

Fritzsche CJ. 1992. Calcium magnesium acetate deicer: An effective alternative for salt-sensitive areas. Water Environ Tech WAETEJ. 4(1), 44-51.

Froehlich HA, McNabb D. 1984. Minimizing soil compaction in the Pacific Northwest forests. In: Stone EL, editor. Forest soils and treatment impacts. Proceedings of the 6th North American Forest Soil Conference; 1983 June 19-23; Knoxville, TN. Knoxville (TN): University of Tennessee, Department of Forestry. p. 159-192.

Froehlich HA, Miles DWR. 1984. Winged subsoiler tills compacted forest soil. Forest Industries 111(2):42-43.

Froehlich HA, Robbins RW, Miles DWR, Lyons JK. 1983. Monitoring recovery of compacted skid trails in central Idaho. Contract 43-0256-2-543 [Special report for Payette National Forest]. Located at: Payette National Forest, McCall, ID.

Froese JC, Cruse RM, Ghaffarzadeh M. 1999. Erosion mechanics of soils with an impermeable subsurface layer. Soil Science Society of America Journal 63:1836-1841.

Fryrear DW and Skidmore EL. 1985. Chapter 24. Methods for controlling wind erosion. In Soil Erosion and Crop Productivity. ASA-CSSA-SSSA. P 443-457.

Fulbright TE. 1988. Effects of temperature, water potential, and sodium chloride on Indiangrass germination. J. Range Manage. 41:207-210.

Gade K.J. 2013. Freeways as Corridors for Plant Dispersal: A Case Study from Central Arizona. Proceedings of the 2013 International Conference on Ecology and Transportation.

Gallai N, Salles J-M, Settele J, Vaissière BE. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecological Economics 68: 810-821.

Gassman S. 2001. Hydraulic seeding: it's all in the slurry. Overland Park (KS): Grounds Maintenance.

Gatto LW, Ferrick MG, White KD. 2004. Inclusion of freeze-thaw-induced soil and bank erosion in CoE planning, engineering, O&M, and model development. Hanover (NH): US Army Corps of Engineers, Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory. Technical Note 04-2. 5 p.

Gedney DS, Weber WG. 1978. Design and construction of soil slopes. In: Schuster RL, Krizek R, editors. Landslides, analysis and control. Washington (DC): National Research Council, Transportation Research Board Commission on Sociotechnical Systems. Special Report 176. p. 172-191.

Gelbard JL, Belnap J. 2003. Roads as conduits for exotic plant invasions in a semiarid landscape. Conservation Biology 17(2):420–432.

Ghazoul J. 2006. Floral diversity and the facilitation of pollination. Journal of Ecology 94:295–304.

Gibson DL and Carrington ME. 2007. Road salt germination inhibition of native plants used in roadside plantings. Transactions of the Illinois State Academy of Science. Vol. 101, #1&2, p13-22.

Gifford GF. 1975. Beneficial and detrimental effects on range improvement practices on runoff and erosion. In: Watershed management, proceedings of a symposium conducted by the irrigation and drainage division of the American Society of Civil Engineers; 11-13 Aug 1975; Logan, UT. Reston (VA): American Society of Civil Engineers. p. 216-248.

Gjessing E, Lygren E, Berglind L, Gulbrandsen T, Skanne R. 1984. Effect of highway runoff on lake water quality. Science of the Total Environment 33:247-257.

Gobar C. 2006. Personal communication. Albuquerque (NM): USDA Forest Service. Forest Wildlife Biologist.

Goheen D. 2005. Personal communication. Medford (OR): USDA Forest Service. Zone Pathologist.

Goodrich, MS, Dulak LH, Freidman MA, Lech JJ. 1991. Acute and long-term toxicity of water- soluble cationic polymers to rainbow trout (*Oncorhynchus mykus*) and the modification of toxicity by humic acid. Environmental Toxicology and Chemistry 10:509-551.

Gray DH, Leiser AT. 1982. Biotechnical slope protection and erosion control. Malabar (FL): Robert E Krieger Publishing Co. 271 p.

Greaves RD, Black HC, Hooven EF, Hansen EM. 1978. Plantation maintenance. In: Cleary BD, Greaves RD, Hermann RK, editors. Regenerating Oregon forests, a guide for the regeneration forester. 5th printing. Corvallis (OR): Oregon State University Extension Service. p. 187-203.

Greaves RD, Hermann RK. 1978. Planting and seeding. In: Cleary BD, Greaves RD, Hermann RK, editors. Regenerating Oregon forests, a guide for the regeneration forester. 5th printing. Corvallis (OR): Oregon State University Extension Service. p. 131-161.

Grismer ME, Hogan MP. 2004. Simulated rainfall evaluation of revegetation/mulch erosion control in the Lake Tahoe Basin - 1: method assessment. Land Degradation Development 15:1-16.

Grismer ME, Hogan MP. 2007. Simulated rainfall evaluation at Sunriver and Mt Bachelor Highways, Oregon. Report to WF-HLD. 8 p.

Grismer ME, Hogan MP, Steinfeld DE. 2011. Highway 35 treatment slopes and bio-retention steps monitoring plan: 1 laboratory column analyses. Integrated Environmental Restoration Services. 18 p.

Grubb B. 2007. Personal communication. Fort Collins (CO): Colorado State Forest Service Nursery. Nursery Grower.

Grubb PJ. 1977. The maintenance of species richness in plant communities and the importance of the regeneration niche. Biological Reviews 52:107-145.

Guinon M. 1993. Promoting gene conservation through seed and plant procurement. In: Landis TD, editor. Proceedings, Western Forest Nursery Association; 1992 Sept 14-18; Fallen Leaf Lake, CA. Fort Collins (CO): USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. General Technical Report RM-221. p. 38-46.

Gustafson DJ, Gibson DJ, Nickrent DL. 2005. Using local seeds in prairie restoration – data support the paradigm. Native Plant Journal 6(1):25-28.

Habte M, Osorio NW. 2001. Arbuscular mycorrhizas: producing and applying arbuscular mycorrhizal inoculum. Honolulu (HI): University of Hawaii, College of Tropical Agriculture and Human Resources. 48 p.

Haddad NM. 1999. Corridor and distance effects on interpatch movements: a landscape experiment with butterflies. Ecological Applications 9:612–622.

Haddad NM, Baum KA. 1999. An experimental test of corridor effects on butterfly densities. Ecological Applications 9:623–633.

Haferkamp MR, Miller RF, Sneva FA. 1985. Seeding rangelands with a land imprinter and rangeland drill in the Palouse vegetative prairie and sagebrush-bunchgrass zone. In: 39th annual report, vegetative rehabilitation and equipment workshop; 1985 February 10-11; Salt Lake City, UT. Missoula (MT): USDA Forest Service, Missoula Equipment Development Center. p. 19-22.

Halbritter DA, Daniels, JC, Whitaker DC, Huang L. 2015. Reducing mowing frequency increases floral resource and butterfly (Lepidoptera: Hesperioidea and Papilionoidea) abundance in managed roadside margins. Florida Entomologist 98(4): 1081-1092.

Hall DE, Long MT, Remboldt MD, editors. 1994. Slope stability reference guide for National Forests in the United States, Volume II. Moscow (ID): USDA Forest Service, Rocky Mountain Research Station. EM-7170-13.

Hall FC. 2002a. Photo point monitoring handbook: part A - field procedures. Portland (OR): USDA Forest Service, Pacific Northwest Research Station. General Technical Report PNW-GTR- 526. p. 1-48.

Hall FC. 2002b. Photo point monitoring handbook: part B - concepts and analysis. Portland (OR): USDA Forest Service, Pacific Northwest Research Station. General Technical Report PNW-GTR- 526. p. 49-134.

Hamm PB, Campbell SJ, Hansen EM, editors. 1990. Growing healthy seedlings: identification and management of pests in northwest forest nurseries. Corvallis (OR): Oregon State University, Forest Research Laboratory. Special Publication 19. 110 p.

Hansen MJ, Clevenger AP. 2005. The influence of disturbance and habitat on the presence of non-native plant species along transport corridors. Biological Conservation 125(2): 249–259.

Hanula JL, Horn S. 2011. Removing an invasive shrub (Chinese privet) increases native bee diversity and abundance in riparian forests of the southeastern United States. Insect Conservation and Diversity 4(4):275–283.

Harmon-Threatt AN, Kremen C. 2015. Bumble bees selectively use native and exotic species to maintain nutritional intake across highly variable and invaded local floral resource pools. Ecological Entomology: 4: 471-478.

Harper-Lore BL, Johnson M, and Ostrum WF. 2013. Vegetation Management: An Ecoregional approach. U.S. Department of Transportation Federal Highway Administration.

Harrington JA, Meikle T. 1992. Road salt effects on the germination of eight select prairie species. Proceedings of the thirteenth North American prairie conference. Department of Parks and Recreation, Windsor, Ontario, Canada, 183-192.

Harper-Lore BL, Wilson M, editors. 2000. Roadside use of native plants. Washington (DC): Island Press. 665 p.

Hatchett B, Hogan M, Grismer M. 2006. Mechanical mastication thins Lake Tahoe forest with few adverse impacts. California Agriculture 60(2):77-82.

Hatfield RG, Jepsen S, Mader E, Black SH, Shepherd M. 2012. Conserving Bumble Bees, Guidelines for Creating and Managing Habitat for America's Declining Pollinators. 32 pp. Portland, OR: The Xerces Society for Invertebrate Conservation.

Hatfield RG and LeBuhn G. 2007. Patch and landscape factors shape community assemblage of bumble bees, *Bombus* spp. (Hymenoptera: Apidae), in montane meadows. Biological Conservation 139:150–158.

Hatfield RG, Colla SR, Jepsen S, Richardson LL, Thorp RW. 2015. International Union for the Conservation of Nature (IUCN) Assessments for North American *Bombus* spp. for the North American IUCN Bumble Bee Specialist Group. The Xerces Society for Invertebrate Conservation, Portland, OR.

Havens K, Vitt P, Still S, Kramer A, Fant J, Schatz K. 2015. Seed sourcing for restoration in an era of climate change. Nature Areas Journal 35:122-133.

Havlin JL, Beaton JD, Tisdale SL, Nelson WL. 1999. Soil fertility and fertilizers, an introduction to nutrient management. 6th edition. Upper Saddle River (NJ): Prentice-Hall Inc., 499 p.

Herrera CM. 1989. Pollinator abundance, morphology, and flower visitation rate: analysis of the "quantity" component in a plant-pollinator system. Oecologia, 80: 241-248.

Heilman P. 1981. Minerals, chemical properties, and fertility of forest soils. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 121-136.

Helgerson OT, Newton M, deCalesta D, Schowalter T, Hansen E. 1992. Protecting young regeneration. In: Hobbs SD, Tesch SD, Owston PW, Stewart RE, Tappener II JC, Wells GE, editors. Reforestation practices in southwestern Oregon and northern California. Corvallis (OR): Oregon State University, Forest Research Laboratory. p. 384-420.

Helgerson OT. 1990. Heat damage in tree seedlings and its prevention. New Forests 3:17-42.

Henderson K. 2000. Integrating all the management tools: integrated roadside vegetation management. In: Harper-Lore BL, Wilson M, editors. Roadside use of native plants. Washington (DC): Island Press. p. 30-31.

Herrick JE, Van Zee JW, Havstad KM, Burkett LM, Whitford WG. 2005a. Monitoring manual for grassland, shrubland and savanna ecosystems, vol I: quick start. Las Cruces (NM): USDA Agricultural Research Service, Jornada Experimental Range. 36 p.

Herrick JE, Van Zee JW, Havstad KM, Burkett LM, Whitford WG. 2005b. Monitoring manual for grassland, shrubland and savanna ecosystems, vol II: design, supplementary methods and interpretation. Las Cruces (NM): USDA Agricultural Research Service, Jornada Experimental Range. 200 p.

Hoag JC, Simonson B, Cornforth B, St John L. 2001. Waterjet Stinger: a tool for planting dormant nonrooted cuttings. Native Plants Journal 2:84-89.

Hoag JC. 2003. Willow clump plantings. Boise (ID): USDA Natural Resources Conservation Service. Plant Materials Technical Note No. 42. 8 p.

Hoag JC. 2006a. Personal communication. Aberdeen (ID): USDA Natural Resources Conservation Service, Aberdeen Plant Materials Center. Plant Ecologist and Wetland Specialist.

Hoag JC. 2006b. The pot planter: a new attachment for the Waterjet Stinger. Native Plants Journal 7(1): 100-101.

Hoag JC. 2007. Personal communication. Aberdeen (ID): USDA National Resource Conservation Service, Aberdeen Plant Materials Center. Plant Ecologist and Wetland Specialist.

Hobbs SD. 1982. Performance of artificially shaded container-grown Douglas-fir seedlings on skeletal soils. Corvallis (OR): Oregon State University, Forest Research Laboratory. Research Note 71. 5 p.

Hogan MP. 2007. Personal communication. Tahoe City (CA): Integrated Environmental Restoration Services. Consultant in revegetation.

Hopwood J, Black SH, Fleury S. 2016a. Pollinators and Roadsides: Best Management Practices for Managers and Decision Makers. 96 pp. Washington, D.C.: Federal Highway Administration.

Hopwood J, Black SH, Fleury S. 2016b. Roadside Best Management Practices that Benefit Pollinators: Handbook for Supporting Pollinators through Roadside Maintenance and Landscape Design. 88 pp. Washington, D.C.: Federal Highway Administration.

Hopwood J, Black SH, Lee-Mäder E, Charlap A. Preston R, Mozumder K, Fleury S. 2015. Literature Review: Pollinator Habitat Enhancement and Best Management Practices in Highway Rights-of-Way. 68 pp. Washington, D.C.: Federal Highway Administration.

Hopwood JL, Winkler L, Deal B, Chivvis M. 2010. Use of roadside prairie plantings by native bees. Iowa Living Roadway Trust Fund Final Report 90-00-LRTF-011

Hopwood JL. 2008. The contribution of roadside grassland restorations to native bee conservation. Biological Conservation 141:2632-2640.

Horneck DA, Hart JM, Topper K, Koepsell B. 1989. Methods of soil analysis used in the soil testing laboratory at Oregon State University. Corvallis (OR): Oregon State University, Agricultural Experiment Station. SM 89:4. 21 p.

Horning ME, McGovern TR, Darris DC, Mandel NL, Johnson R. 2010. Genecology of *Holodiscus discolor* (Rosaceae) in the Pacific Northwest, U.S.A. Restoration Ecology 18(2): 235-243.

Houseal G, Smith D. 2000. Source-identified seed: The Iowa roadside experience. Ecological Restoration 18(3):173-183.

Hufford KM, Mazer SJ. 2003. Plant ecotypes: genetic differentiation n the age of ecological restoration. Trends in Ecology and Evolution 18:147-155.

Huijser, Marcel P. Wildlife-vehicle Collision Reduction Study: Report to Congress. McLean, VA: U.S. Dept. of Transportation, Federal Highway Administration, 2008. Print.

Huijser, Marcel P., Angela C. Kociolek, Tiffany D.H. Allen, Patrick McGowen, Patricia C. Cramer, and Marie Venner. 2015. Construction Guidelines for Wildlife Fencing and Associated Escape and Lateral Access Control Measures. NCHRP 25-25 Task 84.

Humbert J-Y, Ghazoul J, Sauter GJ, Walter T. 2010. Impact of different meadow mowing techniques on field invertebrates. Journal of Applied Entomology 134(7):592–599.

Huntzinger M. 2003. Effects of fire management practices on butterfly diversity in the forested western United States. Biological Conservation 113(1):1–12.

Indiana Department of Transportation, 2008. The Indiana Procedural Manual for Preparing Environmental Documents, Section II.B.3.f Context Sensitive Solutions, Indiana Department of Transportation (Bloomington, IN: Indiana Department of Transportation, 2008).

International Seed Testing Association [ISTA]. 1976. International rules for seed testing. Seed Science and Technology 4:4-180.

Jablonski B, Koltowsk Zi, Marcinkowski J, Rybak-Chmielewska H, Szczesna T, Warakomska Z. 1995. Zawartosc metali ciezkich [Pb, Cd, i Cu] w nektarze, miodzie i pylku pochodzacym z roslin rosnacych przy szlakach komunikacyjnych [The content of heavy metals (Pb, Cd and Cu) in the nectar, honey and pollen collected from roadside plants]. Pszczelnicze Zeszyty Naukowe 39:129–144.

Jackson LE, Strauss RB, Bartolome JW. 1988. Plant and soil dynamics in California annual grassland. Plant and Soil 110:9-17.

Jacobs DF, Rose R, Haase DL, Alzugaray PO. 2004. Fertilization at planting impairs root system development and drought avoidance of Douglas-fir seedlings. Annals of Forest Science 61:643-651.

Jacobs DF, Steinbeck K. 2001. Tree shelters improve the survival and growth of planted Engelmann spruce seedlings in southwestern Colorado. Western Journal of Applied Forestry 16(3):114-120.

Jacobsen RL, Albrecht NJ, Bolin KE. 1990. Wildflower Routes: Benefits of a Management Program for Minnesota Right-of-Way Prairies. Proceedings of the Twelfth North American Prairie Conference 153-158.

Jasper DA, Roson AD, Aboot LK. 1979. Phosphorus and the formation of vesicular arbuscular mycorrhizas. Soil Biology and Biochemistry 11:501-505.

Jenny H. 1980. The soil resource origin and behavior. Ecological Studies 37. 1st edition. New York (NY): Springer-Verlag Inc. 377 p.

Jepsen S, Schweitzer DF, Young B, Sears N, Ormes M, Black SH. 2015. Conservation status and ecology of Monarchs in the United States. 36 pp. NatureServe, Arlington, Virginia, and the Xerces Society for Invertebrate Conservation, Portland, Oregon.

Johnson GR, Stritch L, Olwell P, Lambert S, Horning ME, Cronn R. 2010. What are the best seed sources for ecosystem restoration on BLM and USFS lands? Native Plants Journal 11:117–131.

Johnson RC, Hellier BC, Vance-Borland KW. 2013. Genecology and seed zones for tapertip onion in the US Great Basin. Botany 91(10):686-694.

Johnson, AM. 2000. Best Practices Handbook on Roadside Vegetation Management. Minnesota Department of Transportation, Report # 2000-19, p. 78, University of Minnesota 132 p.

Johst, K., Drechsler M, Thomas J, Settele J. 2006. Influence of mowing on the persistence of two endangered large blue butterfly species. Journal of Applied Ecology 43(2):333–342.

Jones PH, Jeffrey BA, Watler PK, Hutchon H. 1992. Environmental Impact of Road Salting. In F. M. D'Itri (Ed.), Chemical deicers and the environment (pp. 1-116). Lewis Publishers, Boca Raton, FL. P 1-116.

Kay BL, Evans RA, Young JA. 1977. Soaking procedures and hydroseeder damage to common bermudagrass seeds. Agronomy Journal 69(4):555-557.

Kay BL. 1972a. Hydro-seeding limitations and alternatives. Davis (CA): University of California Davis, Agronomy and Range Science. Agronomy Progress Report #43. 3 p.

Kay BL. 1972b. Revegetation of ski slopes and other disturbed mountain sites in California. Davis (CA): University of California Davis, Agronomy and Range Science. Agronomy Progress Report #42.

Kay BL. 1974. Erosion control treatments on coarse decomposed granite. Davis (CA): University of California Davis, Agronomy and Range Science. Agronomy Progress Report #60. 7 p.

Kay BL. 1978. Mulch and chemical stabilizers for land reclamation in dry regions. In: Schaller F, editor. Reclamation of drastically disturbed lands. Madison (WI): American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. p. 467-483.

Kay BL.1983. Straw as an erosion control mulch. Davis (CA): University of California Davis, Agronomy and Range Science. Agronomy Progress Report #140. 11 p.

Kearns CA, Inouye DA, Waser NM. 1998. Endangered mutualisms: the conservation of plant–pollinator interactions. Annual Review of Ecology & Systematics 29:83–113.

Keller G, Sherar J. 2003. Low-volume roads engineering: best management practices field guide. US AID and USDA Forest Service. 158 p.

Kemp PJ. 2006. Erosion control product acceptability lists for multi-modal applications. April 2006 edition. Madison (WI): Wisconsin Department of Transportation. 36 p.

Kerr JT, Pindar A, Galpern P, Packer L, Potts SG, Roberts, SM, Rasmont P, Schweiger P, Colla SR, Richardson LL, Wagner DL, Gall LF, Sikes DS, Pantoja A. 2015. Climate change impacts on bumblebees converge across continents. Science. 349(6244): 177-180.

Ketcheson GL, Megahan WF, King JG. 1999. "R1-R4" and "BIOSED" sediment prediction model tests using forest roads in granitics. Journal of the American Water Resources Association 35(1):83-98.

Ketcheson GL, Megahan WF. 1996. Sediment production and downslope sediment transport from forest roads in granitic watersheds. Ogden (UT): USDA Forest Service, Intermountain Research Station. Research Paper INT-RP-486. 12 p.

Kill DL, Foote LE. 1971. Comparison of long and short-fibered mulches. Transactions of the American Society of Agricultural Engineers 14:942.

Kjelgren R, Montague DT, Rupp LA. 1997. Establishment in treeshelters. II. Effect of shelter color on gas exchange and hardiness. HortScience 32(7):1284-1287.

Klein, A. M., Vaissiere, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society of London B: Biological Sciences, 274(1608):303-313.

Klock GO. 1981. Some engineering aspects of forest soils. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 269-277.

Kloetzel S. 2004. Revegetation and restoration planting tools: an in-the-field perspective. Native Plants Journal 5(1):34-42.

Knapp EE, Rice KJ. 1994. Starting from seed: genetic issues in using native grasses for restoration. Restoration and Management Notes 12:40-45.

Kramer AT, Havens K. 2014. Plant conservation genetics in a changing world. Trends in Plant Science 14(11):599-607.

Kramer AT, Larkin DJ, Fant JB. 2015. Assessing potential seed transfer zones for five forb species from the Great Basin floristic region, USA. Natural Areas Journal. 35: 174–188.

Kruess A and Tscharntke T. 2002. Contrasting responses of plant and insect diversity to variation in grazing intensity. Biological Conservation 106(3):293–302.

Kruess A, Tscharntke T. 2002. Grazing intensity and the diversity of grasshoppers, butterflies, and trap-nesting bees and wasps. Conservation Biology 16:1570–80.Landis TD, 2009. The target plant concept. In: Dumroese RK, Luna T, Landis TD, editors. Nursery manual for native plants: A guide for tribal nurseries – Volume 1: Nursery Management. Washington (DC): USDA Forest Service. P. 15-31.

LaBar CC, Schultz CB. 2012. Investigating the role of herbicides in controlling invasive grasses in prairie habitats: effects on non-target butterflies. Natural Areas Journal 32(2):177–189.

Landis, TD, Dumroese RK. 2006. Monitoring Electrical Conductivity in Soils and Growing Media. Forest Nursery Notes, Summer 2006. R6-CP-TP-04-2006. USDA-Forest Service, Pacific Northwest Region:6-10.

Landis TD. 2011. Using organic fertilizers in forest and native plant nurseries. Forest Nursery Notes 31(2): 1-17.

Landis T, Tinus RW, McDonald SE, Barnett JP. 1989. The biological component: nursery pests and mycorrhizae. The container tree nursery manual. Vol 5. Washington (DC): USDA Forest Service. Agricultural Handbook 674. 171 p.

Landis T, Tinus RW, McDonald SE, Barnett JP. 1994. Nursery planning, development, and management. The container tree nursery manual. Vol 1. Washington (DC): USDA Forest Service. Agricultural Handbook 674. 188 p.

Landis TD, Dumroese RK, Haase D. 2010. Seedling processing, storage and outplanting, volume 7, the container tree nursery manual In: Luna T, Dumroese RK, editors. Nursery manual for native plants: a guide for tribal nurseries. Washington (DC): USDA Agricultural Handbook. 199 p.

Landis TD, Steinfeld D, Watson R. 2002. The long tube stocktype and expandable stinger. Forest Nursery Notes R6-CP-TP-06-01. p. 15-17.

Landis TD, Steinfeld DE. 1990. Salt injury. In: Hamm PB, Campbell SJ, Hansen EM, editors. Growing healthy seedlings: identification and management of pests in northwest forest nurseries. Corvallis (OR): Oregon State University, Forest Research Laboratory. p. 83-86.

Landis TD. 1981. Irrigation water quality in tree nurseries in the inland west. In: Huber RF, editor. Proceedings of the 1981 Intermountain Nurserymen's Association meeting; 1981 Aug 11-13; Edmonton, Alberta. Edmonton (Alberta): Canadian Forestry Service, Northern Forest Research Centre. Information Report NOR-X-241. p. 60-67.

Landis TL, Dreesen DR, Dumroese RK. 2003. Sex and the single Salix: considerations for riparian restoration. Native Plants Journal 4(2):111-117.

Lavelle M. 2014. Hitting the road this summer? Take a closer look at the blur of the roadside shrubbery and grass. It soaks up a lot of carbon. With better management, it could soak up a lot more. The Daily Climate - July 25, 2014.

Laycock WA, Richardson BZ. 1975. Long-term effects of pocket gopher control on vegetation and soils of a subalpine grassland. Journal of Range Management 28(6):458-462.

Leger, E. A. 2008. The adaptive value of remnant native plants in invaded communities: an example from the Great Basin. *Ecological Applications* 18: 1226-1235.

Leharne S, Charesworth D, Chowdhry B. 1992. A survey of metal levels in street dusts in an inner London neighbourhood. Environment International 18:263-270.

Lesica, P., Allendorf.FW. 1999. Ecological genetics and the restoration of plant communities: mix or match? Restoration Ecology 7:42–50.

Lewis L. 2000. Soil bioengineering, an alternative for roadside management–a practical guide. San Dimas (CA): USDA Forest Service, San Dimas Technology and Development Center. Technical Report 0077 1801 - SDTDC. 44 p.

Ley TW, Stevens RG, Topielec RR, Neibling WH. 1994. Soil water monitoring and measurement [online]. Pullman (WA): Washington State University. Pacific Northwest Publication PNW0475.

Linhart YB. 1995. Restoration, revegetation, and the importance of genetic and evolutionary perspectives. In: Roundy BA, McArthur ED, Haley JS, Mann DK, editors. Proceedings, Wildland shrub and arid land restoration symposium, 1993 October 19-21; Las Vegas, NV. USDA Forest Service, General Technical Report. INT-GTR-315. p. 271-287.

Linsley EG. 1958. The ecology of solitary bees. Hilgardia 27:543-599.

Louda SM, Kendall C, Connor J, Simberloff D. 1997. Ecological effects of an insect introduced for the biological control of weeds. Science 277:1088–1090.

Louis Berger Group. 2011. Implementing Measures to Reduce Highway Impacts on Habitat Fragmentation. NCHRP 25-25 Task 68.

Lövei GL, Macleod A, Hickman JM. 1998. Dispersal and effects of barriers on the movement of the New Zealand hover fly *Melanostoma fasciatum* (Dipt., Syrphidae) on cultivated land. Journal of Applied Entomology 122(1-5), 115-120.

Lowenstein H, Ptikin FH. 1970. Ponderosa pine transplants aided by black plastic mulch in Idaho plantation. Tree Planters' Notes 21(4):23-24.

Luce CH. 1997. Effectiveness of road ripping in restoring infiltration capacity of forest roads. Restoration Ecology 5(3):265-270.

Lyles L, Krauss RK. 1971. Threshold velocities and initial particle motion as influenced by air turbulence. Tans. ASAE 14:563-566.

Mackay DB. 1972. The measurement of viability. In: Roberts EH, editor. Viability of seeds. Syracuse (NY): Syracuse University Press. p. 172-208.

Mader E, Spivak M, Evans E. 2010. Managing Alternative Pollinators: A Handbook for Beekeepers, Growers, and Conservationists. Sustainable Agriculture Research and Education, Handbook 11. College Park, MD: University of Maryland, Sustainable Agriculture Research and Extension and Ithaca, NY: Cornell University, Natural Resource, Agriculture, and Engineering Service.

Mallams K. 2006. Personal communication. Central Point (OR): USDA Forest Service, J Herbert Stone Nursery. Zone pathologist.

Margulis L, Sagan D, Thomas L. 1997. Microcosmos: four billion years of evolution from our microbial ancestors. Berkeley (CA): University of California Press. 304 p.

Martin L, Pezeshki SR, Shields Jr FD. 2005. Soaking treatment increases survival of black willow posts in a large-scale field study. Ecological Restoration 23(2):95-98.

Massu L. 2005. Common control measures for invasive plants of the Pacific Northwest. In: USDA Forest Service. Pacific Northwest Region invasive plant program: preventing and managing invasive plants. Final Environmental Impact Statement. Portland (OR): USDA Forest Service, Pacific Northwest Region. R6-NR-FHP-PR-02-05.

Mast B. 2007. Personal communication. Richland (WA): Wildlands Inc. President.

Maxwell WG, Ward FR. 1976a. Photo series for quantifying forest residues in the coastal Douglas-fir-hemlock type and coastal Douglas-fir-hardwood type. Portland (OR): USDA Forest Service, Pacific Northwest Research Station. General Technical Report PNW-51. 103 p.

Maxwell WG, Ward FR. 1976b. Photo series for quantifying forest residues in the ponderosa pine type, ponderosa pine and associated species type, lodgepole pine type. Portland (OR): USDA Forest Service, Pacific Northwest Research Station. General Technical Report PNW-52. 73 p.

Maxwell WG, Ward FR. 1979. Photo series for quantifying forest residues in the Sierra mixed conifer type, Sierra true fir type. Portland (OR): USDA Forest Service, Pacific Northwest Research Station. General Technical Report PNW-95. 79 p.

McCreary DD, Tecklin J. 1997. Effects of seedling protectors and weed control on blue oak growth and survival. In: Pillsbury NH, Verner J, Tietje WD, technical coordinators. Proceedings of a symposium on oak woodlands: ecology, management, and urban interface issues; 1996 March 19-22; San Luis Obispo, CA. Albany (CA): USDA Forest Service, Pacific Southwest Research Station. General Technical Report PSW-GTR-160.

McDonald PM, Helgerson OT. 1991. Mulches aid in regenerating California and Oregon forests: past present and future. Berkeley (CA): USDA Forest Service, Pacific Southwest Forest and Range Experiment Station. General Technical Report PSW-123. 19 p.

McDonald SE. 1984. Irrigation in forest-tree nurseries: monitoring and effects on seedling growth. In: Duryea ML, Landis TD, editors. Forest nursery manual: production of bareroot seedlings. Boston (MA): Martinus Nijhoff/Dr E Junk Publishers. p. 107-121.

McElroy GH, Dawson WM. 1986. Biomass from short-rotation coppic willow on marginal land. Biomass 10:255-240.

McFrederick QS, Kathilankal JC, Fuentes JD. 2008. Air pollution modifies floral scent trails. Atmospheric Environment 42(10):2336-2348.

McGinnies WJ, Crofts KA. 1986. Effects of N and P fertilizer placement on establishment of seeded species on redistributed mine topsoil. Journal of Range Management 39:118-121.

McGregor SE. 1976. Insect pollination of cultivated crop plants. USDA Agriculture Handbook No. 496.

McKay JK, Christian CE, Harrison S, Rice KJ. 2005. “How local is local?” – A review of practical and conceptual issues in the genetics of restoration. Restoration Ecology. 13:432–440.

McLean EO. 1973. Testing soils for pH and lime requirement. In: Walsh LM, Beaton JD, editors. Soil testing and plant analysis. Madison (WI): Soil Science Society of America. p. 77-95.

McKenna DD, McKenna KM, Malcom SB, Berenbaum MR. 2001. Mortality of Lepidoptera along roadways in central Illinois. Journal of the Lepidopterists Society 55(2):63–68.

McLendon T, Redente EF. 1992. Effects of nitrogen limitation on species replacement dynamics during early succession on a semiarid sagebrush site. Oecologia 91:312-317.

Megahan WF. 1974. Deep-rooted plants for erosion control on granitic road fills in the Idaho Batholith. Ogden (UT): USDA Forest Service, Intermountain Research Station. Research Paper INT-161. 18 p.

Memmott J, Waser NM. 2002. Integration of alien plants into a native flower–pollinator visitation web. Proceedings of the Royal Society of London Series B: Biological Sciences 269:2395–2399.

Menz MH, Phillips RD, Winfree R, Kremen C, Aizen MA, Johnson SD, Dixon KW. 2011. Reconnecting plants and pollinators: challenges in the restoration of pollination mutualisms. Trends in Plant Science 16(1):4-12.

Meyer LD, Wischmeier WH, Daniel WH. 1971. Erosion, runoff, and revegetation of denuded construction sites. Transactions of the American Society of Agricultural Engineers 14:138-141.

Mijnsbruggea KV, Bischoff A, Smith B. 2010. A question of origin: Where and how to collect seed for ecological restoration. Basic and Applied Ecology. 11(4): 300-311.

Michener CD. 2007. The Bees of the World, 2nd Ed. 992 pp. Baltimore: John Hopkins University Press.

Millar CI, Libby WJ. 1989. Disneyland or native ecosystem: genetics and the restorationist. Restoration and Management Notes 7(1):18-24.

Miller RM, Jastrow JD. 1992. The application of VA mycorrhizae to ecosystem restoration and reclamation. In: Allen MF, editor. Mycorrhizal functioning: an integrative plant-fungal process. New York (NY): Chapman and Hall. p. 438-467.

Miller RM, May SW. 1979. Below-ground ecosystems project. In: Land Reclamation Program: annual report 1978. Argonne (IL): Argonne National Laboratory. ANL/LRP 5. p. 64-70.

Minnerath A, Vaughan M, Lee-Mader E. 2016. Maritime Northwest citizen science monitoring guide native bees & butterflies. Xerces Society. 60p.

Minore D. 1971. Shade benefits Douglas-fir in southwestern Oregon cutover area. Tree Planters' Notes 22(1):22-23.

Mok, J-H. Landphair, H.C., and Naderi, J.R., Landscape Improvement Impacts on Roadside Safety in Texas, Landscape and Urban Planning, Vol. 78, 2006, pp. 263-274.

Monsen SB, Stevens R. 2004. Seedbed preparation and seeding practices. In: Monsen SB, Stevens R, Shaw NL, compilers. Restoring western ranges and wildlands. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-136 - volume 1. p. 121-154.

Montalvo AM, Williams SL, Rice KJ, Buchmann SL, Cory C, Handel SN, Nabhan GP, Primack R, Robichaux RH. 1997. Restoration biology: a population biology perspective. Restoration Ecology 5: 277–290.

Morgan JP. 1994. Soil impoverishment: a little-known technique holds potential for establishing prairie. Restoration and Management Notes 12:55-56.

Morandin LA, Kremen C. 2013a. Bee preference for native versus exotic plants in restored agricultural hedgerows. Restoration Ecology 21(1):26–32.

Morandin LA, Kremen C. 2013b. Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. Ecological Applications 23(4):829-839.

Morgenson G. 2007. Personal communication. Bismark (ND): Lincoln-Oakes Nurseries. Nursery Manager.

Moroń D, Szentgyorgyi H, Grześ I, Wantuch M, Rozej E, Laskowski R, Woyciechowski M. 2010. The effect of heavy metal pollution on development of wild bees. Atlas of Biodiversity Risks – From Europe to the Globe, From Stories to Maps (eds Settele J, Penev LD, Georgiev TA, Grabaum R, Grobelnik V, Hammen V et al.), pp. 224–225. Pensoft, Sofia & Moscow.

Mulder C, Aldenberg T, de Zwart D, van Wijnen HJ, Breure AM. 2005. Evaluating the impact of pollution on plant-Lepidoptera relations. Environmetrics 16:357–373.

Munguira ML, Thomas JA. 1992. Use of road verges by butterfly and burnet populations, and the effect of roads on adult dispersal and mortality. Journal of Applied Ecology 29:316–329.

Munshower FF. 1994. Practical handbook of disturbed land revegetation. Boca Raton (FL): CRC Press. 265 p.

National Research Council [NRC]. 2005. Assessing and managing the ecological impacts of paved roads. Washington (DC): National Academies Press. 294 p.

National Research Council [NRC]. 2007. Status of pollinators in North America. Washington, D.C.: National Academies Press. 312 p.

[NRCS] USDA Natural Resources Conservation Service. 1994. Planning and design manual for the control of erosion, sediment, and stormwater. 1st edition [online]. Mississippi State (MS): Mississippi State University, Agricultural and Biological Engineering.

National Roadside Vegetation Management Association [NRVMA]. 1997. How to develop and implement an integrated roadside vegetation management program - a guide for township, city, county, parish, state, turnpike and other roadside authorities. 48 p.

Ne'eman GA, Dafni A, Potts SG. 2000. The effect of fire on flower visitation rate and fruit set in four core-species in east Mediterranean scrubland. Plant Ecology 146:97–104.

Neufeld J, Davison J. 2000. Practical considerations when selecting a soil testing laboratory for an educational program [online]. Journal of Extension 38(4). 9 p.

Nieminen MN, Nuorteva P, Tulisalo E. 2001. The effect of metals on the mortality of *Parnassius apollo* larvae (Lepidoptera: Papilionidae). Journal of Insect Conservation 5(1):1–7.

Nitrogen-Fixing Tree Association Staff [NFTA]. 1986. Actinorrhizal trees useful in cool to cold regions. In: NFT Highlights: a quick guide to useful nitrogen-fixing trees from around the world. Morrilton (AR): Winrock International.

Norcini JG, Thetford M, Klock-Moore KA, Bell ML, Harbaugh BK, and Aldrich JH. 2001. Growth, Flowering, and Survival of Black-eyed Susan from Different Regional Seed Sources. HortTechnology 11(1): 26-30.

Norland MR. 2000. Use of mulches and soil stabilizers for land reclamation. In: Barnhisel RI, Darmody RG, Daniels WL, editors. Reclamation of drastically disturbed lands. Madison (WI): American Society of Agronomy. Agronomy Monograph 41. p. 645-666.

Nursery Technical Cooperative [NTC]. 2004. Nursery Technical Cooperative 2003-2004 Annual Report. Corvallis (OR): Oregon State University, Department of Forest Science.

Oberts GL. 1986. Pollutants associated with sand and silt applied to roads in Minnesota. Water Resources Bulletin 22:479-483.

Odum EP. 1971. Fundamentals of ecology. Philadelphia (PA): WB Saunders Co. 574 p.

Ollerton J, Winfree R, Tarrant S. 2011. How many flowering plants are pollinated by animals? Oikos 120:321-326

Onstad CA, Wolfe ML, Larson CL, Slack DC. 1984. Tilled soil subsidence during repeated wetting. Transactions of the American Society of Agricultural Engineers 27:733-736.

Oregon Department of Transportation [ODOT]. 2013. ODOT Integrated Vegetation Management Statewide Plan. 12p.

Ottewell KM, Donnellan SC, Lowe AJ, Paton DC. 2009. Predicting reproductive success of insect-versus bird-pollinated scattered trees in agricultural landscapes. Biological Conservation 142(4):888-898.

Ouin, A., S. Aviron, J. Dover, and F. Burel. 2004. Complementation/supplementation of resources for butterflies in agricultural landscapes. Agriculture, Ecosystems & Environment 103:473-479.

Ozores-Hampton M, Obreza TA, Stoffella PJ, Fitzpatrick G. 2002. Immature compost suppresses weed growth under greenhouse conditions. Compost Science & Utilization 10(2):105-113.

Ozores-Hampton M. 1998. Compost as an alternative weed control method. HortScience 33(6):938-940.

Page HN, Bork EW. 2005. Effect of planting season, bunchgrass species, and neighbor control on the success of transplants for grassland restoration. Restoration Ecology 13(4):651–658.

Page I. 1977. Improving the efficiency of ripping. Rotorua (New Zealand): Forest Industries Review. Forest Research Institute. p. 7- 13.

Palmer JP. 1990. Nutrient cycling: the key to reclamation success. In: Chambers JD, Wade GL, editors. Evaluating reclamation success: the ecological consideration–proceedings of a symposium; 1990 Apr 23-26; Charleston, WV. Radnor (PA): USDA Forest Service, Northeastern Forest Experiment Station. General Technical Report NE-164. p. 27-36.

Palumbo AV, McCarthy JF, Amonette JE, Fisher LS, Wullschleger SD, Daniels WL. 2004. Prospects for enhancing carbon sequestration and reclamation of degraded lands with fossil-fuel combustion by-products. Advances in Environmental Research. 8:425-438.

Parent V, Koenig R. 2003. Solutions to soil problems. I. High salinity (soluble salts). Logan (UT): Utah State University Extension. AG/Soils/2003-01. 2 p.

Parmesan C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution, and Systematics. Vol 37:637-669.

Parmesan C. 2007. Influences of species, latitudes and methodologies on estimates of phenological response to global warming. Global Change Biology. 13:1860-1872.

Parmesan C and Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature. Vol 421:37-42.

Parr TW and Way JM. 1988. Management of roadside vegetation: the long-term effects of cutting. Journal of Applied Ecology 25:1073-1087.

Parsons Brinckerhoff, 2014. Appendix U Illiana Corridor Sustainability and Context Sensitive Solutions Technical Report, Illinois Department of Transportation and Indiana Department of Transportation, June 2014, pp.44.

Pellett NE, Heleba DA. 1995. Chopped newspaper for weed control in nursery crops. Environmental Horticulture 13(2):77-81.

Penny GM, Neal JC. 2003. Light, temperature, seed burial, and mulch effects on mulberry weed (*Fatoua villosa*) seed germination. Weed Technology 17(2):213-218.

Perugini M, Manera M, Grotta L, Cesarina Abete M, Tarasco R, Amorena M. 2011. Heavy metal (Hg, Cr, Cd, and Pb) contamination in urban areas and wildlife reserves: honeybees as bioindicators. Biological Trace Element Research 140(2):170–176.

Peterson, D. 2002. Hydrophilic polymers - effects and uses in the landscape. Restoration and Reclamation Review. Vol 7S. 16 p.

Pezeshki SR, Brown CE, Elcan JM, Shields Jr FD. 2005. Responses of non-dormant black willow (*Salix nigra*) cuttings to pre-planting soaking and soil moisture. Restoration Ecology 13:1-7.

Pezeshki SR, Shields FD. 2006. Black willow cutting survival in streambank plantings, southeastern United States. Journal of the American Water Resources Association 42(1):191-200.

Pill WG, Frett JJ, Williams IH. 1997. Matric priming of Kentucky bluegrass and tall fescue seeds benefits seedling emergence. HortSci 32:1061-1063.

Pill WG, Nesnow DS. 1999. Germination of hydro-seeded Kentucky bluegrass (*Poa pratensis L.*) and perennial ryegrass (*Lolium perenne L.*) in response to seed agitation in the tank. Journal of Turfgrass Management 3(2):59-67.

Poff RJ. 1996. Effects of silvicultural practices and wildfire on productivity of forest soils. In: Sierra Nevada Ecosystem Project: Final report to Congress. Vol II. Assessments and scientific basis for management options. Davis (CA): University of California, Centers for Water and Wildland Resources. p. 477-493.

Polster DF. 1997. Restoration of landslides and unstable slopes: considerations for bioengineering in interior locations. In: Proceedings of the 21st Annual British Columbia Mine reclamation symposium; 1997 Sept 22-25; Cranbrook, BC. Victoria (BC): British Columbia Technical Research Committee on Reclamation. p. 153-166.

Ponisio LC, M'Gonigle LK, Kremen C. 2015. On-farm habitat restoration counters biotic homogenization in intensively managed agriculture. Global Change Biology 22(2): 704-715.

Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. 2010. Global pollinator declines: trends, impacts and drivers. Trends in Ecology and Evolution. 25(6): 345-353.

Potts SG, Vulliamy B, Dafni A, Ne'eman G, Willmer PG. 2003. Linking bees and flowers: how do floral communities structure pollinator communities? Ecology 84:2628–2642.

Potts SG, Vulliamy B, Roberts S, O'Toole C, Dafni A, Ne'eman G, Willmer PG. 2005. Role of nesting resources in organizing diverse bee communities in a Mediterranean landscape. Ecological Entomology 30(1):78–85.

Powell D, Urban C, Johnson C. 1998. Personal communication. Baker City (OR): USDA Forest Service. Forest Silviculturist, Forest Botanist, Area Ecologist.

Preiadjati A, Smits WTM, Tolkamp GW. 2001. Vegetative propagation to assure a continuous supply of plant material for forest rehabilitation. In: Hillegers PJM, de Longh HH. The balance between biodiversity conservation and sustainable use of tropical rain forests: workshop proceedings; 1999 Dec 6-8; Balikpapan, Kalimantan, Indonesia. p. 19-30.

Proudfoot J, Ponder D, Tindall D, Wysocki D. 2015. Guidebook for Designing and Managing Rights-of-Way for Carbon Sequestration and Biomass Generation. National Cooperative Highway Research Program. Report 804. 55p.

Quarles III HD, Hanawalt RB, Odum WE. 1974. Lead in small mammals, plants, and soil at varying distances from a highway. Journal of Applied Ecology: 937-949.

Racey GD, Raitanen E. 1983. Seedling development as affected by fibre and straw mulching at midhurst Nursery. Ottawa (Ontario): Ontario Ministry of Natural Resources, Forest Resources Branch. Nursery Notes 94. 5 p.

Rauch N. 2006. Personal communication. Bend (OR): USDA Forest Service Bend Seed Extractory, Seed Extractory Assistant Manager.

Rauzi F, Tresler RL. 1978. A preliminary report on herbage yields, stand evaluation, soils, and chemical content of selected grasses and a legume grown on topsoil, White River and Wind River geologic materials. Laramie (WY): University of Wyoming, Wyoming Agricultural Experiment Station. Research Journal 124.

Reeder JD, Sabey B. 1987. Nitrogen. In: Williams RD, Schuman GE, editors. Reclaiming mine soils and overburden in the Western United States. Ankeny (IA): Soil and Water Conservation Society. p. 155-184.

Rehfeldt, GE. 1994. Evolutionary genetics, the biological species, and the ecology of the Interior cedar-hemlock forests. Pages 93–100 in: Proceedings of the interior cedar–hemlock–white pine forests: ecology and management. 1993 March 2–4; Spokane, WA. Department of Natural Resource Sciences, Washington State University, Pullman, Washington, USA.

Resource Efficient Agricultural Production Canada [REAP Canada]. 1991. Effects of carbon addition on nitrogen fixation and P nutrition of hairy vetch and following crops. In: Abboud A, Patriquin DG. Processes involved in mobilization of P in different farming systems in Southwestern Ontario: nutrient levels in plant tissues and soils. Harrow (ON): Agriculture Canada Ecological Services for Planning. Report to Canada-Ontario SWEEP (Soil and Water Enhancement Program), SWEEP Report #23 from REAP-Canada. p. 22-24.

Re-Sourcing Associates, Inc, CPM Consultants Inc. 1997. Wood waste recovery: size reduction technology study. EPA Report No. CDL-97-3. 66 p.

Reuter JE, Jassby AD, Marjanovic P, Heyvaert Heyvaert AC, Goldman CR. 1998. Preliminary phosphorus and nitrogen budgets for Lake Tahoe. In: Annual Progress Report 1998, Lake Clarity and Watershed Modelling, Presidential Deliverable for Lake Tahoe, USEPA Water and Watershed Grant; 1998 July 18; Tahoe Research Group, Department of Civil and Environmental Engineering. Davis (CA): University of California, John Muir Institute for the Environment.

Robichaud PR, Ashmun LE, Foltz RB, Showers CG, Groenier JS, Kesler J, DeLeo C, Moore M. 2013. Production and aerial application of wood shreds as a post-fire hillslope erosion mitigation treatment. Gen. Tech. Rep. RMRS-GTR-307. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 31 p.

Rice RM. 1982. Sedimentation in the chaparral: How do you handle unusual events?, in: Sediment Budgets and Routing in Forested Drainage Basins, edited by F. J. Swanson and others. Forest Service, U.S. Dep. Agric., Washington, D. C. pp 39-49.

Ries L, Debinski DM, Wieland ML. 2001. Conservation value of roadside prairie restoration to butterfly communities. Conservation Biology 15:401–411.

Riley L, Steinfeld D, Riley S. 2013. Effects of polyacrylamide crystals on seedling establishment and growth of native species when applied to soils of highly disturbed sites. Internal report to WFHLD. 24 p.

Riley S. 1999. Proposal to cage shrubs [Internal memo Umatilla National Forest]. Located at: Umatilla National Forest, Pendleton, OR. 10 p.

Ritchie GA. 1985. Root growth potential: principles, procedures and predictive ability. In: Duryea ML, editor. Proceedings - evaluating seedling quality: principles, procedures and predictive ability of major tests; 1984 Oct 16-18; Corvallis, OR. Corvallis (OR): Oregon State University, Forest Research Laboratory. p. 93-104.

Robidoux PY, Delisle CE. 2001. Ecotoxicological evaluation of three deicers (NaCl, NaFo, CMA)-effect on terrestrial organisms. Ecotoxicology and Environmental Safety. 48(2), 128-139.

Rose R, Haase DL, Boyer D. 1995. Organic matter management in forest nurseries: theory and practice. Corvallis (OR): Oregon State University, Nursery Technology Cooperative. 65 p.

Rose R. 2002. Slow release fertilizers 101. In: Dumroese RK, Riley LE, Landis TD, technical coordinators. National proceedings: forest and conservation nursery associations–1999, 2000, and 2001. Ogden (UT): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-24. p. 304-308.

Rose R. 2004. Comparison among soil and tissue testing laboratories. In: Nursery Technology Cooperative, 2003-2004 Annual Report. Corvallis (OR): Oregon State University, Department of Forest Science. p. 39-47.

Ross DJ, Cairns A. 1981. Nitrogen availability and microbial biomass in stockpiled topsoils in Southland. New Zealand Journal of Science 24:137.

Rossi P. 1999. Length of cuttings in establishment and production of short-rotation plantations of *Salix aquatica*. New Forests 18:161-177.

Roulston TAH, Goodell K. 2011. The role of resources and risks in regulating wild bee populations. Annual Review of Entomology 56: 293-312.

Russell C, Schultz CB. 2010. Investigating the use of herbicides to control invasive grasses: effects on at-risk butterflies. Journal of Insect Conservation 14(1):53-63.

Saarinen K, Valtonen A, Jantunen J, Saarnio S. 2005. Butterflies and diurnal moths along road verges: Does road type affect diversity and abundance? Biological Conservation 123:403-412.

Salt Institute. 2007. The Snowfighters Handbook. The Salt Institute, Alexandria, Virginia. 27p.

Samways MJ, Caldwell PM, Osborn R. 1996. Ground-living invertebrate assemblages in native, planted and invasive vegetation in South Africa. Agriculture, Ecosystems & Environment 59:19–32.

Sardinas HS, Kremen C. 2014. Evaluating nesting microhabitat for ground-nesting bees using emergence traps. Basic and Applied Ecology: 15(2): 61-168.

Savolainen O, Pyhäľärvi T, Knürr T. 2007. Gene flow and local adaptation in trees. Annual Review of Ecology, Evolution, and Systematics 38:595-619.

Schaff SD, Pezeshki SR, Shields FD. 2002. Effects of pre-planting soaking on growth and survival of black willow cuttings. Restoration Ecology 10(2):267-274.

Saunders DA, Hobbs RJ, Margules CR. 1991. Biological consequences of ecosystem fragmentation – a review. Conservation Biology 5:18–32.

Schaffers AP, Raemakers IP, Sykora KV. 2012. Successful overwintering of arthropods in roadside verges. Journal of Insect Conservation 16(4):511–522.

Schmidt L. 2000. Guide to handling of tropical and subtropical forest seed. Humlebaek (Denmark): Danida Forest Seed Centre.

Schooler SS, Cook T, Prichard P, Yeates AG. 2010. Disturbance-mediated Competition: The Interacting Roles of Inundation Regime and Mechanical and Herbicidal Control in Determining Native and Invasive Plant Abundance. Biological Invasions, Vol. 12. p 3289–3298.

Schröder R, Schröder R., Prasse, R. 2013. From nursery into nature: a study on performance of cultivated varieties of native plants used in re-vegetation, their wild relatives and evolving wild × cultivar hybrids. Ecological Engineering. 60: 428-437. [SER]

Society for Ecological Restoration. 2004. The SER international primer on ecological restoration. Tuscon (AZ): Society for Ecological Restoration, International Science and Policy Working Group.

Settele J, Bishop J, and Potts S. 2016. Climate change impacts on pollination. Nature Plants. Vol 2:1-3.

Shaw N. 2004. Production and use of planting stock. In: Monsen SB, Stevens R, Shaw NL. Restoring western ranges and wildlands. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-136 - volumes 1-3. p. 745-768.

Sheley R. 2005. Personal communication. Madras (OR): USDA Forest Service, Crooked River National Grassland.

Simberloff D, Stiling P. 1996. How risky is biological control? Ecology 77(7):1965-1974.

Skórka P, Lenda M, Moroń D, Kalarus K, and Tryjanowski P. 2013. Factors affecting road mortality and the suitability of road verges for butterflies. Biological Conservation 159:148-157.

Slick BM, Curtis WR. 1985. A guide for the use of organic materials as mulches in reclamation of coal minesoils in the Eastern United States. Broomall (PA): USDA Forest Service, Northeastern Forest Experimental Station. General Technical Report NE-98. 144 p.

Sloan R. 2001. Modified brush layers and live pole drains for landslide reclamation [online]. Santa Barbara (CA): Erosion Control.

Smallidge PJ, Leopold DJ. 1997. Vegetation management for the maintenance and conservation of butterfly habitats in temperate human-dominated habitats. Landscape and Urban Planning 38:259–280.

Smith MR, Charvat I, Jacobson RL. 1998. Arbuscular mycorrhizae promote establishment of prairie species in a tallgrass prairie restoration. Canadian Journal of Botany 76(11):1947-1954.

Snell-Rood EC, Espeset A, Boser CJ, White WA, Smykalski R. 2014. Anthropogenic changes in sodium affect neural and muscle development in butterflies. Proceedings of the National Academy of Sciences, 111(28): 10221-10226.

Sobek AA, Skousen JG, Fisher Jr SE. 2000. Chemical and physical properties of overburdens and minesoils. In: Barnhisel RI, Darmody RG, Daniels WL, editors. Reclamation of drastically disturbed lands. Madison (WI): American Society of Agronomy. Agronomy Monograph 41. p. 77-104.

Soderstrom B, Hedblom M. 2007. Comparing movement of four butterfly species in experimental grassland strips. Journal of Insect Conservation 11(4):333–342.

Soil Survey Staff. 1975. Soil Taxonomy. Washington (DC): USDA Soil Conservation Service. Agricultural Handbook. 436 p.

Sotir RB, Gray DH. 1992. Soil bioengineering for upland slope protection and erosion reduction. In: Engineering Field Handbook. Washington (DC): USDA Natural Resources Conservation Service. EFH- 210. 61 p.

South DB, Mexal JG. 1984. Growing the “best” seedling for reforestation success. Auburn (AL): Auburn University. Forestry Department Series 12. 11 p.

South Dakota Department of Agriculture. 2006. Windbreaks and snow management. 2 p.

Spangler MG, Handy RL. 1973. Soil engineering. 3rd edition. New York (NY): Intext Educational Publishers. 748 p.

Spellerberg I. 1998. Ecological Effects of Roads and Traffic: A Literature Review. Global Ecology and Biogeography Letters 7(5):317-333.

Spira TP. 2001. Plant-pollinator interactions: a threatened mutualism with implications for the ecology and management of rare plants. Natural Areas Journal 21(1):78–88.

Spokas KA, Cantrell KB, Novak JM, Archer DW, Ippolitor JA, Collins HP, Akwasi AA, Boateng AA, Lima IM, Lamb MC, McAloon AJ, Lentz RD, Nichols KA. 2012. Journal of Environmental Quality. P 973-989.

St. John L, Ogle DG, Scianna J, Winslow S, Holzworth LK. 2003. Plant materials collection guide. Boise (ID): USDA Natural Resources Conservation Service. Plant Materials Technical Note No 1. 12 p.

St. John T. 1995. Specially-modified land imprinter inoculates soil with mycorrhizal fungi (California). Restoration and Management Notes 14(1):84.

St. John T. 1999. Nitrate immobilization of the mycorrhizal network for control of exotic ruderals. CalEPPC News 7(1):4-11.

St. Clair JB, Kilkenny FF, Johsnon RC, Shaw NL, Weaver G. 2013. Genetic variation in adaptive traits and seed transfer zones for Pseudoroegneria spicata (*bluebunch wheatgrass*) in the northwestern United States. Evolutionary Applications 6:933-938.

St. Clair B, Johnson R. 2003. Structure of genetic variation and implications for the management of seed and planting stock. In: Riley LE, Dumroese RK, Landis TD, technical coordinators. National proceedings: Forest and Conservation Nursery Associations–2003; 2003 June 9–12; Coeur d’Alene, ID; and 2003 July 14–17; Springfield, IL. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-33. p. 64-71.

St. Clair JB, Mandel NL, Vance-Borland KW. 2005. Genecology of Douglas fir in western Oregon and Washington. Annals of Botany 96:1199-1214.

St. Amour, M. 1998. Evaluation of a powered auger for planting large container seedlings. Pointe-Claire (Quebec): Forest Engineering Research Institute of Canada. Field Note No. Silviculture-107. 2 p.

State of Illinois General Assembly-a, 2013. “Statute 605 ILCS 5/ Illinois Highway Code, Article 4 Division 2 State Highways, Section 4-219 Context Sensitivity”, (Springfield, IL: Legislative Information System, 2013).

Steed JE, DeWald LE. 2003. Transplanting sedges (*Carex spp.*) in southwestern riparian meadows. Restoration Ecology 11(2):247-256.

Steinbrenner EC. 1981. Forest soil productivity relationships. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 199-229.

Steinfeld D, Amaranthus MP, Cazares E. 2003. Survival of ponderosa pine (*Pinus ponderosa* Doug. ex Laws.) seedlings outplanted with Rhizopogon mycorrhizae inoculated with spores at the nursery [online]. Journal of Arboriculture 29(4).

Steinfeld D. 2002. Blaine Road project: findings - willow seedlings and cuttings trials [Internal memo]. Located at: Ashland Ranger District, Rogue River National Forest, Ashland, OR. 7 p.

Steinfeld D. 2004. Soil temperatures under mulch and no mulch on the Chiloquin Highway revegetation project [personal files]. Located at: USDA Forest Service, Ashland Ranger District, Rogue River National Forest, Ashland, OR.

Steinfeld D. 2005. Summary of tree shelter temperature recordings in and outside of tree shelters at the Canyonville planting pocket site [personal files]. Located at: USDA Forest Service, Ashland Ranger District, Rogue River National Forest, Ashland, OR.

Steinfeld DE, Landis TD. 1990. Soil compaction. In: Hamm PB, Campbell SJ, Hansen EM, editors. Growing healthy seedlings. Corvallis (OR): Oregon State University, Forest Research Laboratory. p. 87-91.

Stevens R, Monsen SB. 2004. Mechanical plant control. In: Monsen SB, Stevens R, Shaw NL, compilers. Restoring western ranges and wildlands. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-136 - vol 1. p. 65-87.

Stevens R, Van Epps GA. 1984. Seeding techniques to improve establishment of forage kocia (*Kocia prostrate* [L.] Schrad.) and fourwing saltbush (*Atriplex canescens* [Pursh.] Nutt.). In: Tiedemann AR, McArthur ED, Stutz HC, Stevens R, Johnson KL, compilers. Proceedings- symposium on the biology of Atriplex and related chenopods; 1983 May 2-6; Provo, UT. Ogden (UT): USDA Forest Service, Intermountain Forest and Range Experiment Station. General Technical Report INT-172. p. 269-272.

Stoner KJL and Joern A. 2004. Landscape vs. local habitat scale influences to insect communities from tallgrass prairie remnants. Ecological Applications 14:1306–1320.

Strauss, S. Y, J. A. Lau, & S. P. Carroll. 2006. Evolutionary responses of natives to introduced species: what do introductions tell us about natural communities? *Ecology Letters* 9: 357-374.

Stryker J. 2001. Irrigation tutorials.

Sucoff E. 1975. Effects of deicing salts on woody vegetation along Minnesota roads. Minn. Agr. Expt. Sta. Tech. Bul. 303.

Sugden EA. 1985. Pollinators of *Astragalus monoensis* Barneby (Fabaceae): new host records; potential impact of sheep grazing. Great Basin Naturalist 45:299–312.

Sullivan DM, Cogger CG, Bary AI. 2007. Fertilizing with Biosolids. PNW 508-E. 18p.

Svensson B, Lagerlöf J, Svensson BG. 2000. Habitat preferences of nest-seeking bumble bees (Hymenoptera: Apidae) in an agricultural landscape. Agriculture, Ecosystems & Environment 77(3):247-255.

Svihra P, Burger D, Harris R. 1993. Treeshelters for nursery plants may increase growth and be cost effective. California Agriculture 47(4):13-16.

Swaileh KM, Hussein RM, Abu-Elhaj S. 2004. Assessment of heavy metal contamination in roadside surface soil and vegetation from the West Bank. Archives of Environmental Contamination and Toxicology 47(1):23–30.

Swistock BR, Mecum KA, Sharpe WE. 1999. Summer temperatures inside ventilated and unventilated brown plastic treeshelters in Pennsylvania. Northern Journal of Applied Forestry 16(1):7-10.

Tallamy DW, Shropshire KJ. 2009. Ranking lepidopteran use of native versus introduced plants. Conservation Biology 23(4):941–947.

Tanaka Y. 1984. Assuring seed quality for seedling production: cone collection and seed processing, testing, storage, and stratification. In: Duryea ML, Landis TD, editors. Forest nursery manual: production of bareroot seedlings. Boston (MA): Martinus Nijhoff/Dr W Junk Publishers. p. 27-40.

Teidemann AR, Lopez CF. 2004. Assessing soil factors in wildland improvement programs. In: Monsen SB, Stevens R, Shaw NL, compilers. Restoring western ranges and wildlands. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. General Technical Report RMRS-GTR-136 - vol 1. p. 39-56.

Tesch SD, Helms JA. 1992. Regeneration methods. In: Hobbs SD, Tesch SD, Owston PW, Stewart RE, Tappener II JC, Wells GE, editors. Reforestation practices in southwestern Oregon and northern California. Corvallis (OR): Oregon State University, Forest Research Laboratory. p 166-201.

Tewksbury JJ, Levey DJ, Haddad NM, Sargent S, Orrock JL, Weldon A, Danielson BJ, Brinkerhoff J, Damschen EI, Townsend P. 2002. Corridors affect plants, animals, and their interactions in fragmented landscapes. Proceedings of the National Academy of Sciences 99(20): 12923-12926.

Therrell L, Cole D, Claassen V, Ryan C, Davies MA. 2006. Wilderness and backcountry site restoration guide. Missoula (MT): USDA Forest Service, Missoula Technology and Development Center. Pub # 0623 2815. 394 p.

Thomas GW. 1967. Problems encountered in soil testing methods. In: Soil testing and plant analysis. Part 1. Madison (WI): Soil Science Society of America. SSSA Special Publication Series No. 2. p. 37-54.

Thorup RM. 1984. Ortho agronomy handbook - a practical guide to soil fertility and fertilizer use. San Francisco (CA): Chevron Chemical Company. 454 p.

Tisdale SL, Nelson WL. 1975. Soil fertility and fertilizers. New York (NY): Macmillan Publishing Co. 694 p.

Trahan NA, Peterson CM. 2008. Impacts of magnesium chloride-based deicers on roadside vegetation. In: In: Transportation Research Board (Ed.), Proc. 6th Intl. Symposium on Snow Removal and Ice Control Technology. Transportation Research Circular E-C126. SNOW08-050, 171-186.

Trappe JM, Bollen WB. 1981. Forest soil biology. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 145-155.

Trent A, Nolte D, Wagner K. 2001. Comparison of commercial deer repellents. Missoula (MT): USDA Forest Service, Missoula Technology and Development Center. Technology Tip 0124- 2331-MTDC. 6 p.

Trombulak SC, Frissell CA. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology 14(1):18-30.

Trotti J. 2000. Hydraulic seeding and stabilization [online]. Erosion control 7(8).10 p.

Tuley G. 1985. The growth of young oak trees in shelters. Forestry 58:181-195.

Tuttle RW, Wenberg RD, Sotir RB. 1996. Chapter 16. Streambank and shoreline protection. In: Engineering Field Handbook. Washington (DC): USDA Natural Resources Conservation Service. EFH- 210, Part 650. 88 p.

Tyser RW, Worley CA. 1992. Alien flora in grasslands adjacent to road and trail corridors in Glacier National Park, Montana (USA). Conservation Biology 6(2):253–262.

Ungar IA. 1992. The effect of salinity and temperature on seed germination and growth of Hordeum jubatum. Can. J. Bot. 52:1357-1362.

University of Minnesota Extension Service [UMES]. 2004. Soluble Salts. St Paul (MN): University of Minnesota Extension Service. BU-01731. 3 p.

University of Nevada. 2009. Effects of de-icing salts on vegetation in the Lake Tahoe Basin.

USDA Agricultural Research Service. 2012. Plant hardiness zone map. [USFS] USDA Forest Service. 1991. J Herbert Stone Nursery Annual Report. Central Point (OR): USDA Forest Service, J Herbert Stone Nursery.

USDA Forest Service [USFS]. 2003. BAER Manual–FSM 2523. In: USDA Forest Service. Forest Service manual FSM 2500–watershed and air management. Washington (DC): USDA Forest Service National Headquarters. 44 p.

USDA Forest Service [USFS]. 2004. National strategy and implementation plan for invasive species management.

USDA Forest Service [USFS]. 2005. FSM 2070–native plant materials.

USDA Forest Service [USFS]. 2006. Interior Columbia Basin ecosystem management project.

USDA Forest Service [USFS]. 2007. Invasive plant prevention. In: Center for Invasive Plant Management. Invasive plant management: CIPM online textbook. Bozeman (MT): Montana State University.

USDA Forest Service, USDI Bureau of Land Management [USDA/USDI]. 2005. Revegetation equipment catalog. Boise (ID): Rangeland Technology Equipment Council.

Varnes DJ. 1978. Slope movement types and processes. In: Schuster RL, Krize RJ, editors. Landslides- analysis and control. Washington (DC): National Academy of Sciences, Transportation Research Board. Special Report 176. p. 12-33.

USDA Forest Service, USDI Bureau of Land Management [USFS/USDI]. 1994. Record of decision for the final supplemental environmental impact statement on management of habitat for late- successional and old growth forest related species within the range of the northern spotted owl. Portland (OR): USDA Forest Service. 475 p.

USDA Forest Service, USDI Bureau of Land Management [USFS/USDI]. 2001. A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy.

USDA Natural Resources Conservation Service [NRCS]. 1997. Collecting plant materials. Brooksville (FL): USDA Natural Resources Conservation Service, Brooksville Plant Materials Center. Technical Note No. 35. 4 p.

Valtonen A, Saarinen K. 2005. A highway intersection as an alternative habitat for a meadow butterfly: effect of mowing, habitat geometry and roads on the ringlet (Aphantopus hyperantus). Annales Zoologici Fennici 42(5):545-556.

Valtonen A, Saarinen K, Jantunen J. 2006. Effect of different mowing regimes on butterflies and diurnal moths on road verges. Animal Biodiversity and Conservation 29:133–148.

Visser S, Fujikawa J, Griffiths CL, Parkinson D. 1984. Effect of topsoil storage on microbial activity, primary production and decomposition potential. Plant and Soil 82(1):41-50.

Visser S, Griffiths CL, Parkinson D. 1984. Topsoil storage effects on primary production and rates of vesicular-arbuscular mycorrhizal development in Agropyron trachycaulum. Plant and Soil 82(1):51-60.

Von der Lippe M, Kowarik I. 2007. Long-Distance Dispersal of Plants by Vehicles as a Driver of Plant Invasions. Conservation Biology 21(4):986–996.

Walker RF. 2002. Responses of Jeffrey pine on a surface mine site to fertilizer and lime. Restoration Ecology 10(2):204-212.

Walker RF. 2005. Growth and nutrition of Jeffrey pine seedlings on a Sierra Nevada surface mine in response to fertilization three years after planting. Western Journal of Applied Forestry 20(1):28-35.Ward K, Cariveau D, May E, Roswell M, Vaughan M, Williams N, Winfree R, Isaacs R, Gill K. 2014. Streamlined bee monitoring protocol for assessing pollinator habitat. 16 pp. The Xerces Society for Invertebrate Conservation.

Ward K, Cariveau D, May E, Roswell M, Vaughan M, Williams N, Winfree R, Isaacs R, and Gill K. 2014. Streamlined Bee Monitoring Protocol for Assessing Pollinator Habitat. Portland, OR: The Xerces Society for Invertebrate Conservation. 16 pp.

Waring RH, Schlesinger WH. 1985. Forest ecosystems: concepts and management. Orlando (FL): Academic Press. 340 p.

Warren MS. 1993. A review of butterfly conservation in central southern Britain: II. Site management and habitat selection of key species. Biological Conservation 64(1):37–49.

Wearstler Jr K. 2004. Considerations for collecting and vegetatively propagating poplar woody plant materials. In: Riley LE, Dumroese RK, Landis TD, technical coordinators. National proceedings: forest and conservation nursery associations–2003. Fort Collins (CO): USDA Forest Service, Rocky Mountain Research Station. Proceedings RMRS-P-33. p. 55-56.

Wedin DA, Tilman D. 1996. Influence of nitrogen loading and species composition on the carbon balance of grasslands. Science 274:1720-1723.

Welker JM, Gordon DR, Rice KJ. 1991. Capture and allocation of nitrogen by *Quercus douglasii* seedlings in competition with annual and perennial grasses. Oecologia 87:459-466.

Wert S, Thoms BR. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Science Society of America Journal 45(3):629-632.

Western Federal Lands Highway Division [WFLHD]. 2005. Project development process flow chart. Vancouver (WA): US Department of Transportation, Western Federal Lands Highway Division. 206 p.

White AB, Fant JB, Kramer AT. In Prep. Developing genetically appropriate seed mixes of vulnerable plant species for restoration. A component of AB White's thesis for a Master of Science in Plant Biology and Conservation, anticipated from Northwestern University and Chicago Botanic Garden 2016.

Whiting D, Card A, Wilson C. 2007. Estimating soil texture: sandy, loamy or clayey. Fort Collins (CO): Colorado State University Extension, Colorado Master Gardener.

Wilde SA, Corey RB, Iyer JG, Voigt GK. 1979. Soil and plant analysis for tree culture. 5th revised edition. New Dehli (India): Oxford & IBH Publishing Co. 224 p.

Williams DW, Jackson LL, Smith DD. 2007. Effects of frequent mowing on survival and persistence of forbs seeded into a species-poor grassland. Restoration Ecology 15:24–33.

Williams NM, Cariveau D, Winfree R, Kremen C. 2011. Bees in disturbed habitats use, but do not prefer, alien plants. Basic and Applied Ecology 12(4):332–341.

Williams NM, Crone EE, T'ai HR, Minckley RL, Packer L, Potts SG. 2010. Ecological and life-history traits predict bee species responses to environmental disturbances. Biological Conservation, 143: 2280-2291.

Wilson GWT, Hetrick BAD, Schwab AP. 1991. Reclamation effects on mycorrhizae and productive capacity of flue-gas desulfurization sludge. Journal of Environmental Quality 20(4):777-783.

Winfree R. 2010. The conservation and restoration of wild bees. Annals of the New York Academy of Sciences, 1195: 69-197.

Winfree R, Aguilar R, Vázquez DP, LeBuhn G, Aizen MA. 2009. A meta-analysis of bees' responses to anthropogenic disturbance. Ecology 90:2068–2076.

Withrow-Robinson B, Johnson R. 2006. Selecting native plant materials for restoration projects: insuring local adaptation and maintaining genetic diversity. Corvallis (OR): Oregon State University Extension Service.

Wolf DD, Blaser RE, Morse RD, Neal JL. 1984. Hydro-application of seed and wood-fiber slurries to bind straw mulch. Reclamation and Revegetation Research 3(2):101-107.

Woodmansee RG, Reeder JD, Berg WA. 1978. Nitrogen in drastically disturbed lands. In: Youngerg CT, editor. Forest and soil land use. Fort Collins (CO): Colorado State University, Department of Forest and Wood Sciences. p. 376-392.

Wu Y-T, Wang C-H, Zhang X-D, Zhao B, Jiang L-F, Chen J-K, Li B. 2009. Effects of saltmarsh invasion by Spartina alterniflora. Biological Invasions 11:635–649.

Yetka LA, Galatowitsch SM. 1999. Factors affecting revegetation of *Carex lacustris* and *Carex stricta* from rhizomes. Restoration Ecology 7:162-171.

Youngberg CT. 1981. Organic matter of forest soils. In: Heilman PE, Anderson HW, Baumgartner DM, editors. Forest soils of the Douglas-fir region. Pullman (WA): Washington State University Cooperative Extension Service. p. 137-144.

Zoldoske DF. 1998. Selecting a drip irrigation system for vineyards. Fresno (CA): Center for Irrigation Technology.

Zuefle ME, Brown WP, Tallamy DW. 2008. Effects of non-native plants on native insect community of Delaware. Biological Invasions 10:1159–1169.

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