EM 9023 • April 2011

Best Management Practices for Maintaining Soil Productivity in the Douglas-fir Region

Edited by Sam D. Angima and Thomas A. Terry

Introduction

Best management practices (BMPs) can be defined as effective and practical site-specific methods or techniques generally recommended for maintaining soil productivity and achieving related forestland stewardship objectives. Soils are a fundamental component of forestry production systems because they provide water storage, aeration, nutrients, plant anchorage, and suitable environments for soil organisms. Forestland owners can evaluate treatment options and use decision-support tools to select the BMPs that best fit their conditions and management objectives. These decisions require a basic understanding of soil science principles, soil morphology, landform origin, soil classification, nutrient cycling, and assessment methods used to help identify risks (hazards and likely consequences) associated with soil disturbance and potential soil productivity losses.

Objectives of this publication

The chapters in this publication are based on presentations and discussions from a workshop on BMPs for maintaining soil productivity in the Douglas-fir region. The workshop was held Sept. 22, 2009, in Shelton, Wash., and was sponsored by the Northwest Forest Soils Council and Western Forestry and Conservation Association.

This publication presents key concepts that form the basis for developing and selecting site-specific BMPs for maintaining soil productivity. The topics covered include soil characteristics that affect forest productivity, soil stewardship, soil survey, risks and prescription options, mass wasting, nutrient deficiencies, and ways of using field evaluations (risk assessment) to identify red flags before beginning field operations. Landowners, forest managers, and others who prescribe and implement forest management activities that could affect soil productivity should be well informed and experienced on these topics. They must be able to interpret the landscape and prescribe BMPs on the basis of management

CONTENTS

Chapter 1
Understanding and Managing Risk..........3
Richard E. Miller and Thomas A. Terry

Chapter 2
Soil Characteristics That Affect Productivity and Influence Best Management Practices................................5
Darlene Zabowski and Sam D. Angima

Chapter 3
Soil Survey Information for Forestland Managers/Management of Soil Erosion 10
Steve Campbell

Chapter 4
Managing Mass-Wasting Risk When Conducting Forest Practices 12
Jeffrey D. Grizzel

Chapter 5
Managing Soil Disturbance 18
Ronald L. Heninger, William Scott, Alex Dobkowski, and Thomas A. Terry

Chapter 6
Maintaining Adequate Nutrient Supply—Principles, Decision-Support Tools, and Best Management Practices............ 33
Robert B. Harrison, Douglas A. Maguire, and Deborah Page-Dumroese

Oregon State University Extension Service

objectives and risk assessment (of hazards and consequences). The guiding principles described in this publication will help in this decision-making process.

Note: Because different disciplines require use of specific units of measure, this publication uses both metric and standard units. Please use the Plant Management Network online conversion tables for unit conversion: *http://www.plantmanagementnetwork.org/guidelines/convert/*.[1]

This publication will be revised periodically to keep the information current. The editors and authors welcome feedback on the topics and principles covered, particularly with respect to topics and concepts that need more clarification or depth of coverage and to concepts and principles that were particularly helpful. Please visit the following website to offer your feedback: *http://extension.oregonstate.edu/people/employeeSearch/formMail_1.php?E_No=791&path=detail&E_FName=Sam&E_LName=Angima*.

[1] When using this website, click on the specific unit of measure you are interested in (e.g., yield and rate) to move to the next page that has the appropriate conversions.

Key references and other resources

Heilman, P.E., H.W. Anderson, and D.M. Baumgartner. 1979. *Forest Soils of the Douglas-fir Region*. MISC0246. Pullman, WA: Washington State University Extension.

Perry, D.A., R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, and R.F. Powers (eds.). 1989. *Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems*. Portland, OR: Timber Press.

Chapter 1
Understanding and Managing Risk

Richard E. Miller and Thomas A. Terry

Guiding concepts

Many factors influence forest productivity, so it is important that forest managers and those prescribing and implementing forest practices have a good understanding of the geology, soils, climate, vegetation, and stand conditions of areas that they manage before developing management plans. Forest managers should learn to recognize and manage risk. The U.S. Environmental Protection Agency (EPA) considers risk to be the chance of harmful effects to human health or ecological systems. A concern in forestlands is the risk of management practices causing a decline in forest productivity or some other detrimental outcome.

Risk has two components: (1) potential hazard and (2) subsequent consequences (table 1.1). A hazard is a given set of actions (stressors) and conditions (e.g., treatment intensity and site factors) that could impact the site. A stressor is any physical, chemical, or biological entity that can induce an adverse response to specific natural resources or entire ecosystems, including plants and animals, as well as to the environment in which they interact (refer to the U.S. EPA reference listed at the end of this chapter). Consequences relate to whether outcomes resulting from the action (stressor) have the potential to be positive, negative, or inconsequential for a given factor or value of interest (e.g., site productivity, tree growth, wildfire potential, or water quality).

A potential site stressor (e.g., road building or tree harvesting) may pose low or high hazard potential depending on slope, terrain, and equipment used (table 1.2).

The objective is to manage risk (hazards + consequences) at a low-to-moderate level, or to the level of risk you are willing to accept. If the desired activity (stressor) and conditions are likely to elevate risk to the moderate-to-high category, consider using mitigation efforts to reduce the anticipated hazard or consequences to acceptable levels.

Table 1.1. Potential hazards + consequences = risk

Hazard	Consequences	
(Stressor, intensity, site conditions)	Low	High
	Potential risk	
Low	Low	Moderate
High	Moderate	High

Best management practices (BMPs) should be designed to manage the anticipated risk from a proposed activity at a specific site. BMP prescriptions should be site specific (considering site conditions and potential hazards and consequences), be cost effective, have a low probability of causing a decrease in soil productive capacity or other detrimental impacts, and have a high likelihood of meeting specified management objectives.

Usually, multiple factors and risks must be considered when designing BMPs for a given site. Risks can vary depending on the issues of concern (table 1.3). This example shows the risks that could result from utilization intensity of harvested material on a low-productivity site where soil nutrients are limited. Markets and product price affect the intensity of harvest utilization, but soil productivity, fire risk, and visual impacts should also be considered. In many situations, trade-offs have to be made depending on which factor (e.g., risks associated with fire damage or reductions in soil productivity) is more important for different portions of the tract; then BMPs are modified accordingly. For example, if soil organic matter is in relatively low supply and you want to

Table 1.2. Example of stressor factors and potential hazards and consequences in a forestry management system

	Risk =			
	Potential hazard		+	Consequences
Stressor	**Low**	**High**		
Road building				
Slope	Gentle	Steep		Erosion
Terrain	Stable	Unstable		Mass wasting, sediment
Soil drainage	Well-drained	Poorly drained		Cost, maintenance
Harvesting				
Equipment	Helicopter	Rubber-tired skidders		Soil compaction
Utilization	Bole-only	Total biomass		Nutrient removal

Table 1.3. Example of multiple risks and trade-off considerations on a highly nutrient-deficient site where the consequence of removing high levels of biomass has the potential to negatively impact soil quality while reducing wildfire potential

Stressor	Factor of concern	
(Utilization level)	**Soil quality**	**Fire**
	Potential risk	
Bole only	Low	High
Whole tree	Moderate	Moderate
All biomass	High	Low

minimize the potential for nutrient and water supply limitations over the long term (potential negative consequence), you may want to compromise by increasing biomass utilization levels near homes and roads to reduce fire risk and decreasing utilization (level or intensity) across the remaining tract to maintain soil productivity.

In summary, we suggest five important steps to manage risk:

1. Assess potential hazards and consequences.
2. Consider trade-offs among multiple risks.
3. Mitigate where appropriate to avoid or reduce unacceptable risk.
4. Balance potential risks and costs of mitigation (e.g., why use a helicopter to log gentle slopes with well-drained soils?).
5. Design and implement site-specific BMPs.

Subsequent chapters in this publication describe many site-based risk factors common to the Douglas-fir region and offer suggestions for developing site-specific BMPs to maintain and enhance soil productivity, avoid mass wasting, and minimize erosion and sedimentation. Remember to review applicable state forest practice regulations when developing BMPs to make sure that proposed practices meet these requirements as well.

Key references and other resources

United States Environmental Protection Agency. Basic Information About Risk Assessment. *http://epa.gov/riskassessment/basicinformation.htm#risk*.

Washington State Department of Natural Resources. 2009. *Forest Practices Illustrated: A Simplified Guide to Forest Practices Rules in Washington State*. Olympia, WA: Washington State Department of Natural Resources, Forest Practices Division. *http://www.dnr.wa.gov/BusinessPermits/Topics/ForestPracticesRules/Pages/fp_fpi.aspx*.

Chapter 2
Soil Characteristics That Affect Productivity and Influence Best Management Practices

Darlene Zabowski and Sam D. Angima

Soil profile and master horizons

Douglas-fir forests occupy a wide range of soils. Having a conceptual understanding of how soils are formed and positioned on the landscape and how soil characteristics affect forest productivity will help forest managers maintain healthy, productive forests. If you dig a pit in any forest soil, you will see different layers in the profile. These layers are called master horizons. These horizons are distinguished by differences in composition and color as well as soil structure and texture. In a typical forest soil, you are likely to see some or all of master horizons O, A, E, B, C, and rock (figure 2.1).

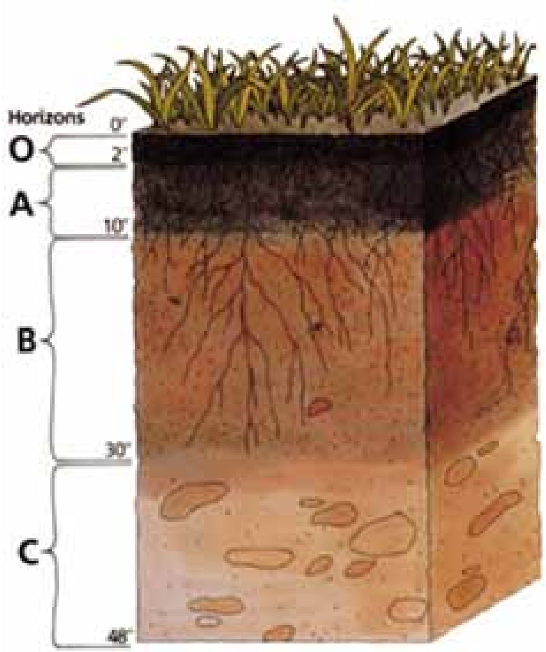


Figure 2.1. Soil profile diagram showing master horizons.

Image courtesy of USDA-NRCS.

Description of master horizons

The following descriptions can help you identify which master horizons your soil may have:

- **O Horizon**: organic horizon or forest floor; composed mostly of leaves, needles, and other organic matter; usually above mineral horizons
- **A Horizon**: a surface mineral horizon; mixture of organic matter and mineral material; usually darker in color than horizons below because of higher organic matter content
- **E Horizon**: can be a surface mineral horizon directly beneath an O or A horizon; light in color (usually off-white or gray); common in undisturbed forest soils and develops this color after loss of clay, iron, aluminum, or organic matter
- **B Horizon**: mineral horizon with
  - an increase in clay, iron, aluminum, and organic matter that has been deposited from the E horizon above; or
  - substantial alteration of the original parent material that eliminated original rock structure and formed clays or oxides with a resultant change in color and structure; or
  - both of these characteristics
- **C Horizon**: mineral horizon little altered from its parent material and lacking properties of an A, E, or B horizon
- **Rock**: parent rock relatively unchanged or with some signs of weathering

If you have used a soil survey map, you might have noticed some small letters that accompany the master horizons, such as O*i*, O*e*, or O*a*. These letters are called subordinate horizon designations and are used to indicate some specific distinctive properties of a master horizon that help you identify and understand why one soil might be different from another soil on your property. For example,

- *i* stands for organic matter that is slightly decomposed but still recognizable in its original form (e.g., needle fragments),
- *e* stands for organic matter that is intermediate in decomposition, and
- *a* stands for organic matter that is highly decomposed and not recognizable.

Basic soil physical properties

Understanding the following physical properties of a soil will help you interpret what you see in the field.

Color

Horizon color offers clues about the nutritional status, type of horizon, and processes occurring in that horizon. You will find three basic colors in horizons:

- Organic matter—usually black or brown
- Free iron oxides—usually reddish (in well-drained soils), yellowish brown or orange (in less drained or oxidized soil), or gray to bluish gray (in poorly drained soils)
- Uncoated mineral grains—usually gray but may be any color depending on the minerals present

Soil color can also be described using color charts and noted by horizon on soil profile descriptions. For example, the 10YR4/3 soil color can be interpreted as follows:

- Hue (10YR) is the dominant primary color (yellow-red).
- Value (4) describes the lightness or darkness (0 = black and 10 = white).
- Chroma (3) describes the intensity and brightness of the colors.

Texture

Soil texture describes the proportion of various mineral-size particles in the soil that are less than 2 mm in diameter:

- Sand particles are smaller than 2 mm but larger than 0.05 mm in diameter.
- Silt particles are smaller than 0.05 mm but larger than 0.002 mm in diameter.
- Clay particles are smaller than 0.002 mm in diameter.

After the particle size distribution is determined with tests in a soil lab, texture is determined according to the percentages of sand, silt, and clay by using the soil textural triangle (figure 2.2) or the two-axis Canadian soil texture triangle (figure 2.3). This method yields common terms such as clay loam, sandy loam, and silty clay loam. The textural class of a soil directly affects water-holding capacity, water movement, aeration or porosity, bonding of soil particles into stable aggregates, soil microorganisms, root growth, and soil temperature dynamics.

Stones, cobbles, and gravel are larger than 2 mm in diameter, and their presence is used to modify a soil texture (e.g., a gravelly sandy loam). These coarse materials can affect soil trafficability, water-storage capacity, and forest productivity. For example, if you have more than 80% stone in your soil, the volume of fine soil is greatly reduced; this, in turn, greatly limits forest productivity.

The USDA Natural Resources Conservation Service provides a useful field guide for determining soil texture on this website: *http://soils.usda.gov/education/resources/lessons/texture/*.

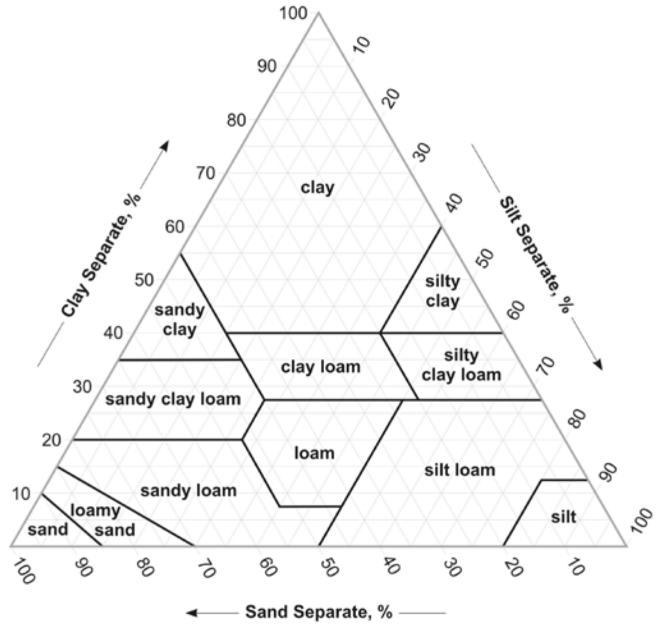


Figure 2.2. Soil textural triangle used for determining soil texture.

Image courtesy of USDA-NRCS.

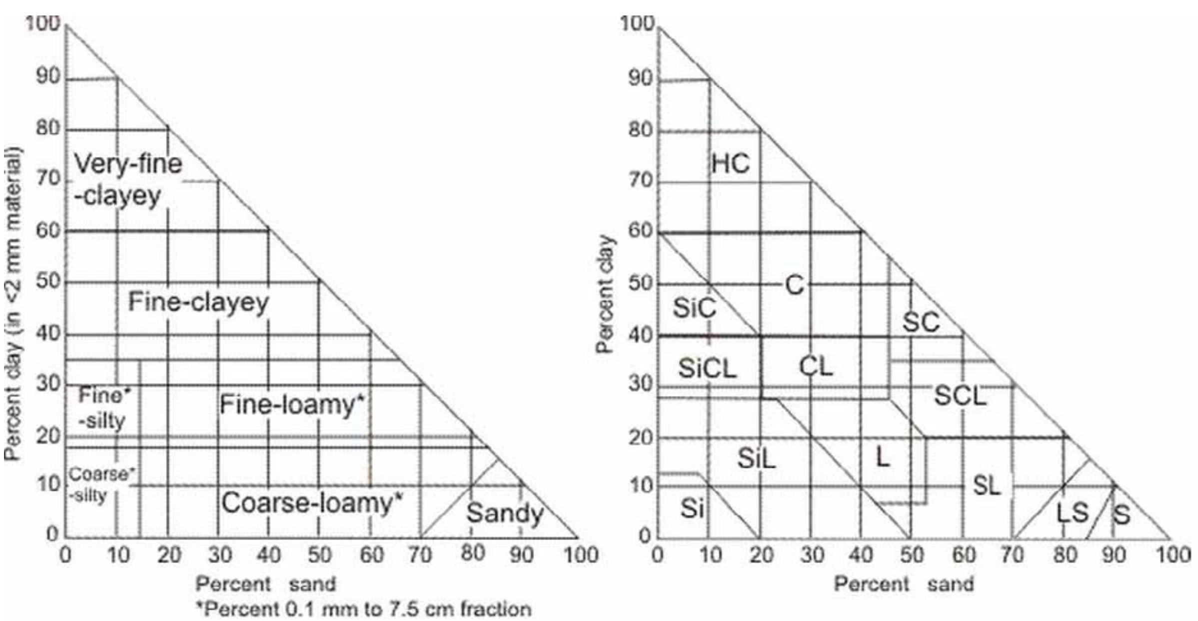
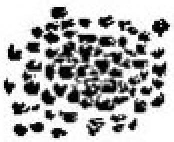


Figure 2.3. Canadian soil texture triangle that uses only two axes to determine soil texture from percentages of sand and clay. Abbreviations for the texture classes: HC, heavy clay; C, clay; SiC, silty clay; SiCL, silty clay loam; CL, clay loam; SC, sandy clay; SiL, silt loam; L, loam; SCL, sandy clay loam; SL, sandy loam; Si, silt; LS, loamy sand; S, sand.

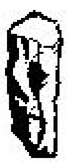
Reproduced by permission from Figure 41 in *The Canadian System of Soil Classification*, 3rd ed., 1998.



Granular. Roughly spherical, like grape nuts. Usually 1–10 mm in diamteter. Most common in A horizons, where plant roots, microorganisms, and sticky products of organic matter decomposition bind soil grains into granular aggregates.

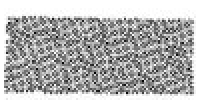
Platy. Flat peds that lie horizontally in the soil. Platy structure can be found in A, B, and C horizons. It commonly occurs in an A horizon as the result of compaction.

Blocky. Roughly cube shaped with more or less flat surfaces. If edges and corners remain sharp, we call it angular blocky. If they are rounded, we call it subangular blocky. Sizes commonly range from 5–50 mm across. Blocky structures are typical of B horizons, especially those with a high clay content. They form by repeated expansion and contraction of clay minerals.

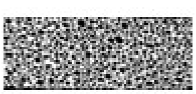


Prismatic. Larger, vertically elongated blocks, often with five sides. Sizes are commonly 10–100 mm across. Prismatic structures commonly occur in fragipans.

Columnar. The units are similar to prisms and are bounded by flat or slightly rounded vertical faces. The tops of columns, in contrast to those of prisms, are very distinct and normally rounded.



Massive. Compact, coherent soil not separated into peds of any kind. Massive structures in clayey soils usually have very small pores, slow permeability, and poor aeration.



Single grain. In some very sandy soils, every grain acts independently, and there is no binding agent to hold the grains together into peds. Permeability is rapid, but fertility and water holding capacity are low.

Figure 2.4. Types of soil structures.

Images and descriptions courtesy of USDA-NRCS.

Structure

Soil structure is the arrangement of soil particles into clumps or aggregates. The degree of aggregation varies in different soils and ranges from single grained (each particle acts independently) to massive (particles are completely stuck together; figure 2.4). Soil strength, root penetration, soil air and water movement, and ease of erosion are significantly dependent on soil structure.

Though soil texture is not easily changed in any given soil, soil structure is especially vulnerable to management activities. For example, a granular structure can quickly change to a platy structure if equipment compacts moist or wet soil. Such changes can increase soil strength (restricting root elongation), reduce large or macropore space (lessening aeration), and restrict water infiltration (increasing water runoff potential).

Bulk density and porosity

If you took a cup of undisturbed soil (void of rocks), weighed it (oven-dry weight) to get its mass, and then divided this mass by the volume of the cup, you would get its bulk density in units of g/cm^3. The higher the bulk density, the more compacted (massive) the soil. Texture, organic matter content, and amount of volcanic material can affect soil bulk density. Soils high in organic matter or volcanic ash content can have relatively low bulk densities. Typically, a good range for bulk density is 0.75 to 1.0 g/cm^3 for surface soils in high-productivity sites. At a soil bulk density of 1.6 g/cm^3, root penetration is seriously impeded. If you suspect you have compacted soils, it would be wise to check the soil's bulk density.

Porosity refers to the void space occupied by air and water in soils. Porosity is important for gas exchange and drainage of water. Larger macropores (diameter larger than about 0.05 mm) are particularly important for adequate oxygen supply to plant roots, diffusion of carbon dioxide produced by respiring organisms and plant roots, and water infiltration and drainage.

Water-holding capacity

Water is a very important soil component that is required for plant growth and adequate nutrient supply. Small pores (micropores) in the soil are responsible for capillary action that draws water from wet areas to dry areas in the soil. These small pores are more prevalent in clayey soils than sandy soils; therefore, these two types of soils have different water-retention capabilities (clayey soils will have a greater water-holding capacity than sandy soils).

Soil water-holding capacity is important in the Pacific Northwest, where a relatively low percentage of the annual rainfall occurs during the growing season. This limitation is particularly important for young trees during summer months as their roots are not fully developed and may not be deep enough to obtain the water necessary for growth. Soil depth is an important factor in tree growth. In general, deeper soil means better potential for tree growth because the volume of soil that can be occupied by plant roots has a direct effect on soil water supply and the capability of that soil to supply nutrients for plant growth. Soil water content also affects soil strength. With the exception of sandy soils, dry soils usually have higher soil strength than moist soils. Impedance of root growth is greatest in high-strength soils with poor soil structure.

Temperature

Dry soils warm faster than wet soils, especially in the spring. This is because the heat capacity and ability to conduct heat is higher for water than soil solids. In physics terms, a higher moisture content in surface soil reduces the increase in temperature per absorption of a unit quantity of heat and increases the soil's thermal conductivity and downward conduction of heat rather than its retention in the surface zone (Hillel 1998).

Douglas-fir root growth is temperature sensitive. Minimal root growth occurs at temperatures of 5°C to 10°C (41°F to 50°F), and maximum root growth occurs at about 20°C (68°F). Water uptake by Douglas-fir roots ceases at about 5°C (41°F). Soil temperature also affects microorganism activities and, therefore, the speed of nutrient and organic matter cycling. Organic matter cycling generally increases with increasing soil temperature as long as moisture is available.

Certain forest management practices can affect soil temperature. Reducing stand density and crown cover during thinning or final harvest will increase soil temperature during the growing season, as will removal of harvest residuals (slash) and surface organic matter. Weeds shade the soil from sunlight, so weed control may hasten soil warming.

Key references and other resources

Brady, N.C., and R.R. Weil. 2008. *The Nature and Properties of Soils*, 14th ed. Upper Saddle River, NJ: Prentice Hall.

Helgerson, O.T., and R.E. Miller. 2008. *Keeping Your Forest Soils Healthy and Productive*. EB2019. Pullman, WA: Washington State University Extension. *http://cru.cahe.wsu.edu/CEPublications/eb2019/eb2019.pdf*.

Hillel, D. 1998. Soil temperature and heat flow. p. 309–334 in *Environmental Soil Physics*. San Diego, CA: Academic Press.

Lopushinsky, W., and T.A. Max. 1990. Effect of soil temperature on root and shoot growth and on budburst timing in conifer seedling transplants. *New Forests* 4:107–124.

Soil Science Society of America. Glossary of Soil Science Terms. *https://www.soils.org/publications/soils-glossary/*.

Warren, J.M., F.C. Meinzer, J.R. Brooks, and J.C. Domec. 2005. Vertical stratification of soil water storage and release dynamics in Pacific Northwest coniferous forests. *Agricultural and Forest Meteorology* 130(1–2):39–58. doi:10.1016/j.agrformet.2005.01.004.

Chapter 3
Soil Survey Information for Forestland Managers/Management of Soil Erosion

Steve Campbell

Sources of soil survey information

Soil mapping is the systematic examination, description, and classification of soils in a given area. This information is compiled into soil surveys. Normally, soil observations are made at selected areas representing landform, slope, and other environmental conditions such as vegetation. You can get soil survey information from four sources.

1. Hard-copy soil survey reports with soil maps and compact discs

Hard-copy soil survey reports are available for most soil survey areas from USDA Natural Resources Conservation Service state soil scientists. Because of updating, data in these reports may not be the current official soil survey data.

2. Electronic files of soil survey reports and maps from the Web

Electronic soil survey reports are available at *http://soils.usda.gov/survey/printed_surveys/*. These are just like the hard copies but in electronic form. The listed dates indicate when each report was published.

3. Web Soil Survey

Web Soil Survey information is available at *http://websoilsurvey.nrcs.usda.gov/*. This is the most current soil survey data available online. You can customize these maps and reports using soil data that pertains to your properties and particular needs. A general step-by-step procedure on how to use the Web Soil Survey is available at *ftp://ftp-fc.sc.egov.usda.gov/MI/technical/soils/WSS_brochure.pdf*, and for forestry use at *http://extension.oregonstate.edu/lincoln/sites/default/files/documents/Websoilsurvey-forestry.pdf*.

4. Soil Data Mart

The Soil Data Mart website is available at *http://soildatamart.nrcs.usda.gov/*. It allows downloading of spatial and tabular soil survey data and generates reports of soil properties and interpretations.

All online versions of soil surveys have systematic "help" procedures to help you obtain the information you need.

Soil survey data helps you make informed forest management decisions about everything from property purchases to site-specific actions such as road building, harvesting, site preparation, planting, vegetation control, and thinning. For example, knowing soil physical properties—such as texture, rock fragment content, available water capacity, drainage class, depth to bedrock or other root-restricting layers, and erodibility—can help you determine road placement, harvest areas, harvest systems, what species to plant, and what areas might be prone to windthrow. Forest productivity information—such as site index and growth rate—can help you decide the intensity of management for each soil and landform condition and identify areas that are best managed at a low level of intensity or left undisturbed. And you can use soil properties to interpret ratings for forest management practices and risks associated with a certain type of soil.

The following list provides examples of soil interpretive ratings for various forest management activities:

- Construction limitations for haul roads/log landings
- Hand planting suitability
- Harvest equipment operability
- Log landing suitability

- Mechanical planting suitability
- Mechanical site preparation (deep)
- Mechanical site preparation (surface)
- Potential erosion hazard (off-road/off-trail)
- Potential erosion hazard (road/trail)
- Potential fire damage hazard
- Potential seedling mortality
- Road suitability (natural surface)
- Soil rutting hazard

Management of soil erosion

Soil properties that affect erosion hazard

Following are examples of soil properties that affect erosion:

- **Soil texture** is the proportion of sand, silt, and clay. The soil survey can show which areas on your property are sandy or clayey and the topography and slope associated with each of these soil types, allowing you to identify management units that are most hazardous for erosion.
- **Soil structure** is the aggregation of soil particles into structural units. Usually, granular structures allow for ease of water movement, whereas blocky and platy structures impede water movement and accelerate erosion.
- **Organic matter** binds soil particles together, reducing the erosion hazard. The higher the organic matter content, the lower the erosion hazard.
- **Permeability** is the rate at which water moves through the soil profile. The faster the permeability, the less the erosion hazard.
- **Steeper and longer slopes** present a greater erosion hazard.

Practices to reduce erosion on forestlands

From the Web Soil Survey, you can identify which areas are high and low erosion hazards and what mitigation measures may be needed to prevent soil erosion. Several practices can be used for erosion control, either individually or in combination depending on soils, slope, rainfall, organic matter content, and stage of forest growth. The most common practices include (1) maintaining road culverts and ditches and using water bars or rolling dips; (2) leaving slash and surface duff on site to reduce soil exposure, which is consistent with fire management and reforestation objectives designed to protect the soil surface from rainfall impact and runoff and minimize soil compaction and displacement during harvesting; (3) tilling soils to improve water infiltration on skid trails and landings; and (4) seeding noninvasive grasses on exposed soils in critical areas.

Key references and other resources

Garland, J. 2000. *Designing Woodland Roads*. EC 1137. Corvallis, OR: Oregon State University Extension Service. *http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/20520/ec1137.pdf*.

Garland, J., and D.J. Jackson. 2002. *Planning Woodland Roads*. EC 1118. Corvallis, OR: Oregon State University Extension Service. *http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/18889/ec1118.pdf*.

Helgerson, O.T., and R.E. Miller. 2008. *Keeping Your Forest Soils Healthy and Productive*. EB2019. Pullman, WA: Washington State University Extension. *http://cru.cahe.wsu.edu/CEPublications/eb2019/eb2019.pdf*.

Washington State Department of Natural Resources. 2009. *Forest Practices Illustrated: A Simplified Guide to Forest Practices Rules in Washington State*. Olympia, WA: Washington State Department of Natural Resources, Forest Practices Division. *http://www.dnr.wa.gov/BusinessPermits/Topics/ForestPracticesRules/Pages/fp_fpi.aspx*.

Chapter 4
Managing Mass-Wasting Risk When Conducting Forest Practices

Jeffrey D. Grizzel

Mass wasting defined

Mass wasting, sometimes called mass movement, landsliding, or mass erosion, is defined as the downslope movement of soil, regolith, and rock under the force of gravity. When the driving forces acting on a slope exceed the resisting (or stabilizing) forces, mass wasting or slope movement occur.

Types of mass wasting

There are four general types of mass wasting: creep (figure 4.1), slump-earthflow (figure 4.2*A*), deep bedrock failure (figure 4.3*A*), and debris avalanche/debris flow (figures 4.4*A* and 4.5*A*). One or more of these mass-wasting processes are present in nearly every forested landscape in the Pacific Northwest. The frequency and relative importance of each type vary widely from site to site and are dependent on a wide range of factors including climate, topography, vegetation, geology, hydrology, and land use.

Creep is the slow, progressive deformation of the soil profile over time. Creep rates are generally less than a few millimeters per year, and creep occurs to varying degrees on almost every slope. Typically, creep rates are fastest at the soil surface and decrease with depth. Frost heave, thermal contraction and expansion of the soil profile, and alternating wet/dry cycles are important factors affecting the rate of creep. Because this form of mass wasting occurs so slowly, it cannot be detected with the naked eye. In the forest, creep often appears in the form of disfigured or distorted trees and cracks in the soil (figure 4.1). Trees that exhibit signs of creep are often said to be "J-shaped" or have "pistol butts." Accelerated rates of creep may indicate the slope is predisposed to other forms of mass wasting such as slump-earthflow movement (figure 4.2*A* and *B*).

Figure 4.1. Evidence of creep in the form of tree bole sweep.

Photo by Venice Goetz, Washington State Department of Natural Resources, reproduced by permission.

Slumps and earthflows are in a class of mass wasting known as deep-seated landslides. The plane along which these landslides travel is typically more than 10 feet (3 m) below the ground surface and can sometimes be more than 100 feet (30.5 m) deep. Like creep, slump-earthflow movement is typically slow (on the order of millimeters to a centimeter per year), but on rare occasions, these landslides can fail catastrophically and move rapidly—as much as a few meters per second. Slumps commonly exhibit rotational movement along an arc-like failure plane. As a result, they often consist of a series of intact, down-dropped blocks, and the surrounding ground has a "benchy" appearance (figure 4.2*A* and *B*). As the slump blocks move progressively farther downslope, they break apart to form an earthflow. While slump terrain is often benchy, earthflow terrain is often highly irregular and hummocky. In addition to benchy and hummocky ground, other indicators of slump-earthflow terrain include small, midslope ponds or wetlands, vertical scarps, ground cracks, exposed soils, and tipped or downed trees. Slumps and earthflows can be relatively small (<1 acre [0.4 ha]), or they can encompass hundreds or even thousands of acres. Because these types of landslides often move very slowly, slump-earthflow terrain can be covered with mature forests. These types of landslides often form where structurally weak materials overlie stronger, more erosion-resistant rocks or sediments.

Like slumps and earthflows, deep bedrock failures are also classified as deep-seated landslides. The plane along which this type of landslide travels is often tens, and sometimes hundreds, of feet below the ground surface (figure 4.3*A* and *B*). As the name implies, this type of landslide involves large amounts of rock and commonly occurs along zones of weakness within the underlying bedrock. Deep bedrock failures can move very rapidly (meters per second) and can encompass large areas (hundreds or even thousands of acres).

Debris avalanches and debris flows are shallow landslides in which the failure plane is within about 10 feet (3 m) of the ground surface. Typically, these types of landslides involve mostly soil and colluvium;[1] rock comprises a relatively small fraction of the total landslide mass. Debris avalanches and debris flows move rapidly (as much as several meters per second) and typically begin in steep, convergent terrain. Debris avalanches begin on hillslopes and have

[1] Unconsolidated, unsorted earth material deposited on sideslopes and/or at the base of slopes by mass movement (e.g., direct gravitational action) and by local, unconcentrated runoff.

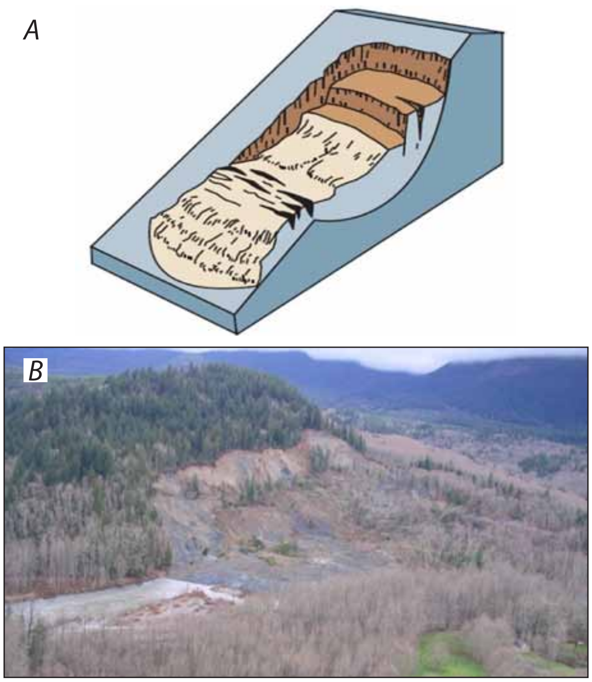


Figure 4.2. ***A*****, diagram of a slump-earthflow landslide;** ***B*****, slump-earthflow along the North Fork Stillaguamish River in Snohomish County, Wash.**

Illustration courtesy of U.S. Geological Survey. Photo by author Jeffrey D. Grizzel.

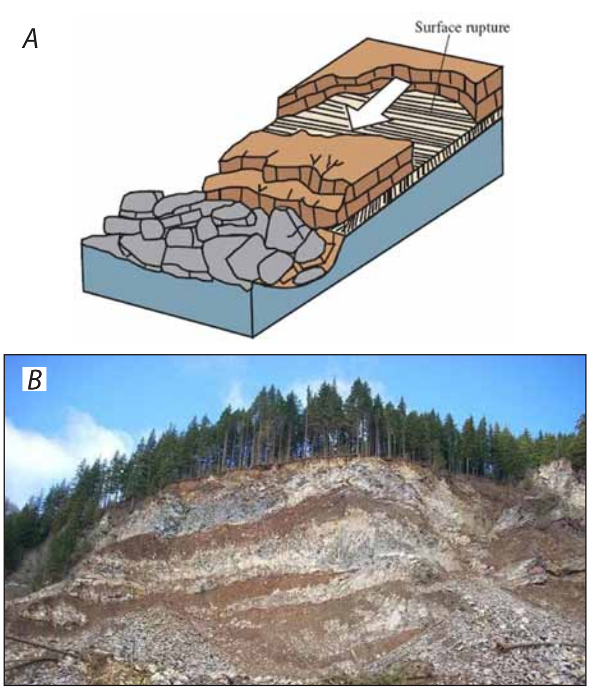


Figure 4.3. ***A*****, diagram of a deep bedrock failure;** ***B*****, deep bedrock failure near the Columbia River Gorge in Washington.**

Illustration courtesy of U.S. Geological Survey. Photo by Don Nelsen, reproduced by permission.

relatively low water content (figure 4.4*A* and *B*). In contrast, debris flows occur in steep-gradient stream channels, have high water content, and are very mobile (figure 4.5*A* and *B*). As a result, debris flows (sometimes called debris "torrents" or debris "floods") can travel long distances (often several kilometers) from the point of initiation. Debris avalanches can transform into debris flows if the landslide mass enters a steep-gradient stream channel and becomes fluid-like.

Factors affecting landslide initiation

Mass wasting is a natural process, but land use practices such as forestry can increase the frequency and magnitude of this form of erosion. In natural or unmanaged settings, the following factors influence mass-wasting processes:

- **Hydrology**: High-intensity rain or rain-on-snow storm events west of the Cascades and high-intensity summer thunderstorms east of the Cascades often initiate shallow landslides. Annual and seasonal variations in precipitation can influence creep rates and the movement of deep-seated landslides.
- **Vegetation**: Forest canopies intercept and retain rain and snow, reducing soil moisture inputs. Forest canopies allow intercepted rain and snow to be evapo-rated back into the atmosphere, and trees withdraw or transpire water from the soil profile as part of their normal growth processes. Tree roots reinforce the soil profile, increasing its structural strength.
- **Geology**: Parent materials affect the particle size distribution and mineralogy of overlying materials, weathering patterns, and resulting material strengths. Bedrock structure and associated jointing and fracturing influence faulting patterns.

A

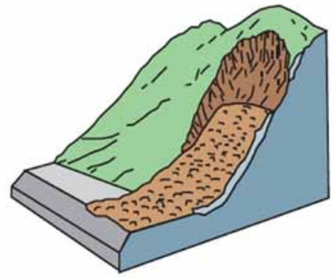


Figure 4.4. ***A*, diagram of a debris avalanche; *B*, debris avalanche in southwest Washington.**

Illustration courtesy of U.S. Geological Survey. Photo by Dean Adams, Washington State Department of Natural Resources, reproduced by permission.

A

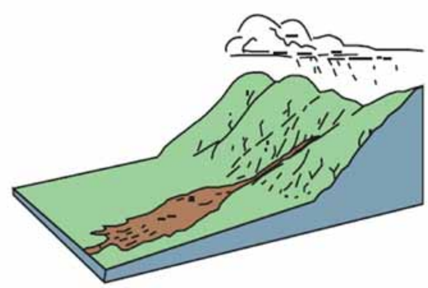


Figure 4.5. ***A*, diagram of a debris flow; *B*, multiple debris flows in southwest Washington.**

Illustration courtesy of U.S. Geological Survey. Photo by Dave Norman, Washington State Department of Natural Resources, Division of Geology and Earth Resources, reproduced by permission.

In managed settings, the following forestry-related factors can increase the potential for certain forms of mass wasting:

- **Hydrology**: Road construction and maintenance practices can alter natural hydrologic flowpaths.
- **Vegetation**: Loss of vegetation results in reductions in canopy interception, evapotranspiration, and rooting strength.
- **Geology**: Road cutslopes and fillslopes are often steeper than the natural slope angle, standard cut-and-fill construction techniques redistribute the slope-mass balance, and fill materials may not be adequately compacted.

Risk analysis

To effectively mitigate the effects of forest practices on mass-wasting potential, you must first analyze the risks present. Risk is a function of the mass-wasting hazard (the likelihood that mass wasting will occur) and the resulting consequences or degree of adverse impact (figure 4.6). Mass-wasting risk is low when there is a low likelihood of mass wasting and the degree of adverse impact is negligible. Mass-wasting risk is very high when there is a high likelihood of mass wasting and the degree of adverse impact is severe.

Analyzing mass-wasting (landslide) risk involves three steps that should be conducted in advance of initiating any forest practices activities on your site.

Step 1. Review available data and information to establish a preliminary hazard and consequence rating.

In this step, you review aerial photos, topographic maps, geologic maps, soil maps, landslide and hazard-zone mapping, pertinent published reports, and GIS-based digital elevation models. LiDAR-based (Light Detection and Ranging) digital elevation models for parts of western Washington can be obtained through the Puget Sound LiDAR Consortium: *http://pugetsoundlidar.ess.washington.edu/*. The objective is to use this data and information to identify and map (1) portions of your site with a moderate to very high landslide potential and (2) downslope or downstream resources that could be impacted by a landslide originating from your site.

Step 2. Validate the preliminary hazard and consequence ratings by conducting a field review of your site.

Do the site conditions reflect your preliminary hazard and consequence ratings? If not, where do adjustments need to be made? Are all downslope and downstream resources that could be impacted by a landslide accounted for? If not, supplement your original mapping.

Step 3. Assign a final mass-wasting risk rating for the site.

If the risk is something other than "low," you should consider developing and implementing mitigation measures to reduce the potential for the proposed forest practices to trigger mass wasting.

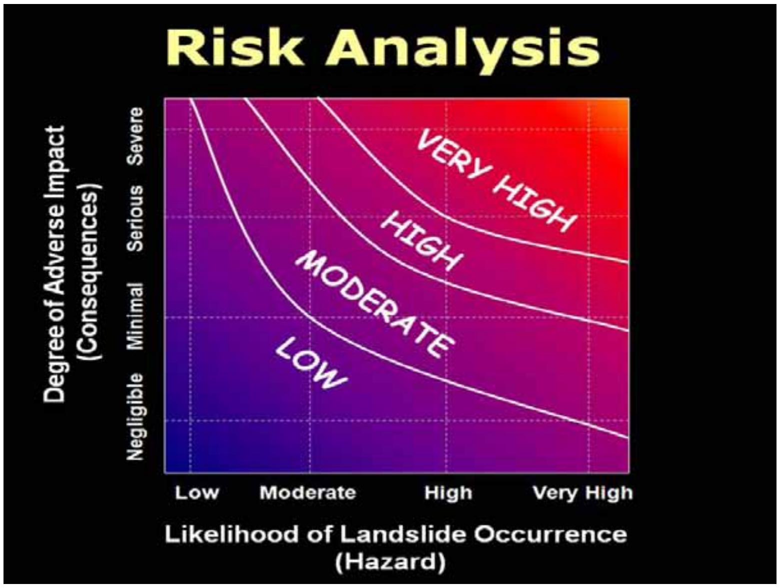


Figure 4.6. Conceptual model of landslide risk expressed as a function of landslide hazard and consequences.

Graph by author Jeffrey D. Grizzel.

Figure 4.7. Avoiding operations in areas with high mass-wasting potential is the lowest-risk mitigation option and often results in a complex mosaic of buffers and harvested areas.

Photo by David Parks, Washington State Department of Natural Resources, reproduced by permission.

Figure 4.8. Yarding corridors often provide an effective alternative to road construction across unstable terrain.

Photo by author Jeffrey D. Grizzel.

Mitigation requirements/options

A wide range of mitigation measures can be implemented to reduce the potential for forest practices to trigger mass wasting. Some of these measures are mandatory (required by law) in some states. These measures vary in complexity and cost, and each approach should be tailored to the site or situation. Note that both Oregon and Washington State Forest Practices Rules may require that more complex measures be developed by a licensed engineering geologist.

The lowest-risk mitigation option is to avoid operations on areas with a high likelihood of mass wasting. This option, commonly known as avoidance, excludes landslide-prone terrain from harvest areas and often results in a complex mosaic of buffers and harvest units (figure 4.7). Since high-hazard sites are avoided, the potential for harvesting or road construction activities to trigger mass wasting is relatively low.

In areas prone to shallow landslides, thinning may be a reasonable alternative to clearcutting since it conserves rooting strength. Thinning also mitigates some of the hydrologic effects that may contribute to slope movement (e.g., reductions in interception and evapotranspiration). During thinning operations, take care to avoid scarring or damaging residual trees. The creation of narrow yarding corridors through unstable slope buffers often avoids otherwise necessary road construction (figure 4.8). You should locate the corridors in areas free of signs of instability to minimize the number and width of corridors as well as scarring and damage to trees along the corridor margins.

Full-bench road construction ensures excavated materials (e.g., soil and rock) are not placed along the outer edge of the road where they could become saturated and trigger a landslide (figure 4.9). When constructing roads in steep or unstable terrain, always deposit excavated soil and rock in a stable location away from the outer edge of the road. Take care to ensure that road cutslopes are stable and do not pose a rockfall hazard to those traveling in the area.

Where road construction across steep-gradient streams is proposed, use of durable, angular rock as fill material helps prevent road failure if the culvert should become plugged (figure 4.10). The angular nature of the rock ensures the individual pieces interlock, forming a structurally sound crossing. If possible, the road grade atop the culvert should be dipped to prevent the stream from being diverted in the event the culvert inlet becomes obstructed.

Key references and other resources

Burns, S.F., T.M. Harden, and C.J. Andrew. 2007. *Homeowner's Guide to Landslides: Recognition, Prevention, Control, and Mitigation*. Portland, OR: Portland State University. *http://www.oregongeology.org/sub/Landslide/homeowners-landslide-guide.pdf*.

From the Oregon Department of Geology and Mineral Industries:

- Debris Flow Advisories and Warnings. *http://www.oregon.gov/DOGAMI/Landslide/debrisflow1.shtml*.
- GIS overview map of potential rapidly moving landslide hazards in western Oregon. *http://www.oregongeology.org/sub/publications/IMS/ims-022/ims-022.htm*.
- Landslide Hazards in Oregon. *http://www.oregongeology.org/sub/publications/landslide-factsheet.pdf*.
- Statewide Landslide Information Database for Oregon (SLIDO). *http://www.oregongeology.org/sub/slido/index.htm*.

Sidle, R.C., A.J. Pearce, and C.L. O'Loughlin. 1985. *Hillslope Stability and Land Use*. Water Resources Monograph no. 11. Washington, D.C.: American Geophysical Union.

Swanson, F.J., L.E. Benda, S.H. Duncan, G.E. Grant, W.F. Megahan, L.M. Reid, and R.R. Ziemer. 1987. Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. p. 9–38 in *Streamside Management: Forestry and Fisheries Interactions*, E.O. Salo and T.W. Cundy (eds.). Contribution no. 57. Seattle, WA: Institute of Forest Resources, University of Washington.

Washington Forest Practices Board. 2004. *Section 16 – Guidelines for Evaluating Potentially Unstable Slopes and Landforms*. Olympia, WA: Washington State Department of Natural Resources, Forest Practices Division.

Figure 4.9. Full-bench construction ensures that no unstable fill material is placed along the outside edge of the road and that hill-slopes below the road remain at their natural angle of repose.

Photo by author Jeffrey D. Grizzel.

Figure 4.10. Dipped rock fills result in stable road prisms at stream crossings. Note the large-arch culvert, heavy-rock armoring, and minimal fill over the culvert.

Photo by Rick Roames, Washington State Department of Natural Resources, reproduced by permission.

Chapter 5
Managing Soil Disturbance

Ronald L. Heninger, William Scott, Alex Dobkowski, and Thomas A. Terry

Guiding principles and decision-support tools

Logging practices such as whole-tree harvest, processing at roadsides, and felling and yarding with ground-based equipment may require special attention to meet soil stewardship objectives. These practices may lead to soil disturbance, compaction and puddling, displacement, and at times, soil removal. Soil disturbances can be detrimental, inconsequential, or beneficial for tree growth depending on the conditions (e.g., pore space distribution, organic matter content, soil texture, and climate) and the severity of disturbance.

Field observations and research findings have shown that when losses in forest productivity have occurred, there has generally been topsoil loss (figure 5.1), strong compaction and puddling (figure 5.2), reduced aeration (figure 5.3), or combinations of these factors.

Soil compaction per se may or may not be detrimental depending on soil type, degree of severity, and rainfall/climate. In some cases, compaction can positively affect early seedling growth because of improved soil moisture-holding capacity (e.g., in low-bulk-density soils [Andic or volcanic soil properties] [Ares et al. 2005] and coarse-textured soils). Shrubs competing with trees also can be damaged in traffic routes, thereby reducing competition and positively influence tree growth. Soil compaction is most apt to be detrimental on fine-textured soils or soil layers (e.g., subsoil compacted layers) with low organic matter content and when soils are wet or at their plastic limit (the water content at which soils start exhibiting plastic behavior). Soil disturbance that reduces macropore space and disrupts pore-space continuity can restrict water flow and create saturated soils. Many tree species are negatively impacted when roots are in an anaerobic environment (saturated soils) for extended periods.

Figure 5.1. Slash piles with topsoil removal at a landing.

Photo by author Thomas A. Terry.

Figure 5.2. Seedlings took about 1 year longer to reach 1.3 m in height on compacted and puddled skid trails on high-clay-content soils with significant summer moisture deficit in Springfield, Ore. (Heninger et al. 2002).

Photo by author Ronald Heninger, reproduced by permission of Weyerhaeuser Company.

Figure 5.3. Saturated soils where soil macroporosity has been reduced and infiltration or drainage impeded.

Photo by author William Scott, reproduced by permission of Weyerhaeuser Company.

Decision-support tools helpful for soil management related to the operation of ground-based equipment include an up-to-date soil survey, soil disturbance classification systems, and soil operability ratings.

Up-to-date soil survey[1]

Surveys of the forest soil resource are useful for understanding expected or likely interactions between forest practices and soils, and for extending knowledge gained from research. Soil surveys from the USDA Natural Resources Conservation Service (USDA-NRCS) are a useful source of available soil information (see Chapter 3). Soil surveys are essential for rating soils by their potential risk for detrimental disturbance during ground-based harvesting and site preparation. Because significant portions of forestlands are mapped as complexes (areas of two or more soils so intricately mixed or so small in size that they cannot be shown separately on the soil map), harvest/site preparation units may require preparation of local maps (using professional help) to identify soils of various risk ratings.

Soil disturbance classification system

Soil disturbance classification systems are useful tools for describing different types of soil disturbance that could occur during ground-based equipment operations. Figure 5.4 shows a soil disturbance classification developed and used by Weyerhaeuser Company (Scott 2007). This classification system describes a continuum of increasing levels of soil disturbance caused by machinery traffic: undisturbed condition (Class 0), topsoil compaction (Class 1), topsoil churned with forest floor and puddling (high plasticity and low permeability) with subsoil being compacted (Class 2), topsoil partly

[1] Can be integrated with GIS.

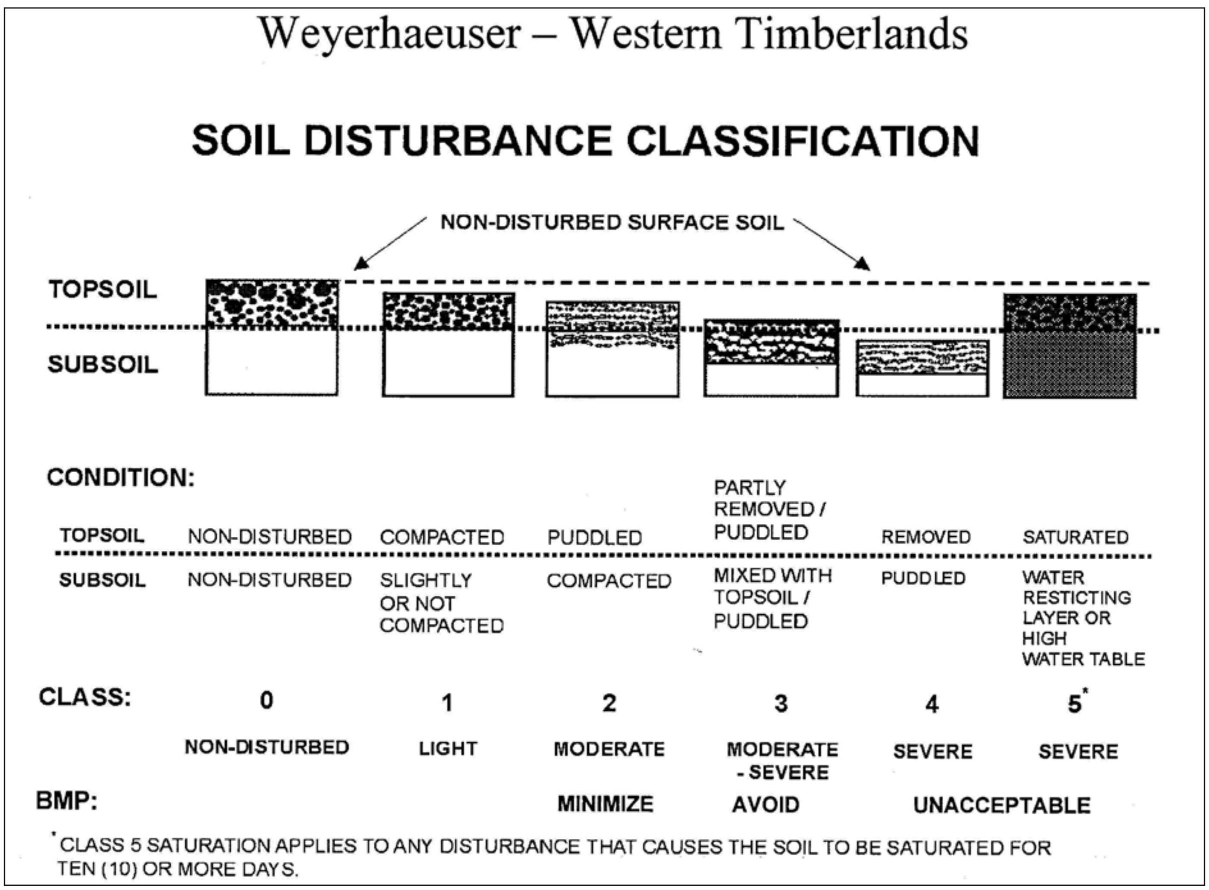


Figure 5.4. Soil disturbance classification and best management practices prescription by Weyerhaeuser Company (Scott 2007).

Graph by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Co.

Figure 5.5. Soil disturbance Class 1.

Photo by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

Figure 5.6. Soil disturbance Class 2.

Photo by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

removed and mixed with subsoil (Class 3), and topsoil being displaced and subsoil puddled (Class 4). When disturbed, soils that are poorly drained or have a high water table can disrupt internal drainage and cause soils to become saturated (Class 5)—this can occur with any of the soil disturbance classes. Best management practices (BMPs) are designed to minimize Class 2 and avoid Class 3, 4, and 5 disturbances. Class 1 soil disturbance generally is considered a negligible risk for causing detrimental soil disturbance, and it represents the target BMP condition where ground-based equipment traffic occurs.

Soil disturbance Class 1. As machinery travels across the ground, topsoil is compacted, but there is no churning or puddling. Compaction reduces the flow of water and air through the topsoil. Macropores and channels (e.g., old roots, animal burrows, and worm holes) are reduced, and their continuity is disrupted. The fine roots are largely undisturbed and in place. The subsoil may or may not be affected depending on the depth of topsoil (figure 5.5). This level of light compaction would generally have a negligible detrimental impact on seedling growth and can have early positive impacts on soils with low bulk density or coarse texture.

Soil disturbance Class 2. Continued use of the skid trail by machinery results in increased and deeper compaction and mixing or churning of the forest floor with the soil surface. The forest floor and some light slash are stirred into the soil. The machine tracks or tires stir, puddle, and severely alter the structure of the topsoil. Macropore space and large channels are compressed and reduced and become discontinuous. Depth of churning and debris mixing is confined to the surface topsoil. The subsoil can be compacted depending on the depth of topsoil but is not churned (figure 5.6). This type of disturbance may or may not be detrimental. Soils with high clay content and low organic matter and those that experience summer drought are most likely to restrict seedling growth until the roots grow out of the compacted zone.

Soil disturbance Class 3. As traffic continues, some of the topsoil is removed (displaced in side berms), and the rest is mixed or churned with the subsoil. The subsoil is compacted to a greater depth. Forest floor and slash are often mixed into the soil. Macropore space is severely reduced to the depth of churning and puddling (figure 5.7). This type of disturbance should be avoided as much as possible.

Soil disturbance Class 4. As traffic continues, the topsoil is completely removed (displaced in side berms or bladed away) or completely mixed with the subsoil. Subsoil is compacted or puddled. Organic debris is often incorporated into the soil. Excessive blading, heavy traffic, dragging logs, and turning machines are common causes (figure 5.8). Avoid removing topsoil as it is generally porous and higher in organic and nutrient content than subsoil. Trees planted where topsoil has been removed will generally have reduced growth potential.

Soil disturbance Class 5. Any disturbance that disrupts internal water movement and forces water to the surface or causes the soil to be saturated with free water on the surface or in the rooting depth for longer than 10 days, particularly in the winter dormant period, is disturbance Class 5 (figure 5.9). When disturbed, soils that are poorly drained or have a high water table can become saturated. Ten days is sufficient time to cause seedling mortality of Douglas-fir and western hemlock when the rooting zone soil is saturated. Soil disturbances ranging from Class 1 to 4 can often cause saturated soil conditions on

- toe-slope positions or concave areas that often accumulate excess water from surrounding areas;
- soils with clay-textured subsoils—commonly known as an argillic B horizon—that drain slowly, have massive structure, or both; and
- coarse-textured soil with “cemented” subsoils, which are mostly formed by glaciers in very few places.

Figure 5.7. Soil disturbance Class 3.

Photo by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

Figure 5.8. Soil disturbance Class 4.

Photo by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

Figure 5.9. Soil disturbance Class 5.

Photo by author William Scott, reproduced by permission of Weyerhaeuser Company.

Soil operability ratings[2]

Soil operability ratings classify the susceptibility of individual soils to compaction and puddling on the basis of physical properties of the soil and how quickly the soil can be changed to a Class 3, 4, or 5 disturbance with likely negative consequences for tree growth.

The soil operability risk rating system provides a tool to help (1) assign appropriate harvest systems that fit physical soil characteristics or properties and (2) schedule harvest operations on higher-risk soils during more favorable times of the year when soils or conditions are drier. This rating system suggests the best time of the year for operating on a given soil with ground-based machines and is influenced by the following factors:

- **Topsoil depth**: Soil operability risk increases with decreasing topsoil depth. Shallow topsoils are more susceptible to losses in productivity than deeper topsoils.
  (Very deep topsoil = low risk; Shallow topsoil [≤10-inch depth] = very high risk)
- **Moisture and permeability**: Soil operability risk increases with increased soil moisture. Wetter soils are more easily puddled or compacted than drier soils.
  (Rapid permeability = low risk; Very slow permeability = very high risk, potential for saturation)
- **Texture and structure**: Soil operability risk decreases as soil texture gets coarser. Clayey soils are more susceptible to compaction and puddling than sandier soils. Soils that have an impermeable horizon and massive structure are subject to saturation with compaction.
  (Sandy texture = low risk; Clayey texture = high to very high risk; Cemented till or massive clay = very high risk, potential for saturation)
- **Depth to water table**: Soil operability risk increases as the depth to water table decreases. Shallow depth to water table is riskier than deeper depth to water table.
  (Deep depth to water table = low risk; Shallow depth to water table = very high risk, potential for saturation)

Operability rating is a relative scale with five classes (table 5.1).

These ratings can be used to develop a soil database spreadsheet based on USDA-NRCS model soil descriptions. For example, a soil database can be developed that assigns a soil operability risk rating to a soil on the basis of certain characteristics (table 5.2).

When applying model soil descriptions to operability ratings, remember that there is variation in soil characteristics. It is best to verify the conditions in the field and adjust the rating depending on those field conditions. Sometimes the ratings are adjusted to lower or higher ratings.

[2] Can be integrated with GIS.

Table 5.1. Example of soil operability risk ratings by Weyerhaeuser Company

	Soil operability risk rating				
Soil property	Low	Moderate	High	Very high	Potential for saturation
Topsoil depth	Very deep	Deep	Moderate	Shallow	Shallow
Infiltration and permeability	Rapid	Moderate	Slow	Very slow	Very slow
Texture/structure	Sandy/ single grained	Loamy	Clayey	Clayey	Clayey/massive
Depth to water table	Very deep	Deep	Moderate	Shallow	Very shallow

Table 5.2. Example of database spreadsheet showing key variables in determining risk ratings for soil series

Soil series	Topsoil depth (in.)	Topsoil texture[1]	Topsoil permeability[2]	Subsoil texture[1]	Subsoil permeability[2]	Water table depth (ft)	Risk rating
Bellpine	6	Si Cl Lo	M	Si Cl	S	6	Very high
Digger	11	V Gr Lo	R	V Gr Lo	R	6	Low
Hazelair	11	Si Cl Lo	M	Si Cl	M	1–2	Saturation
Kinney	14	Gr Lo	M	Cl Lo	M	6	Moderate
Blachly	25	Cl Lo	M	Si Cl	M	6	High

Source: USDA-NRCS model soil description for the specific county in which the soil is located.

Note: Key determining factors are in red.

[1] Texture abbreviations: Si Cl Lo, silty clay loam; V Gr Lo, very gravely loam; Gr Lo, gravely loam; Cl Lo, clay loam; Si Cl, silty clay.

[2] Permeability is the number of inches per hour that water moves downward through the saturated soil. R, rapid at 6.0 to 20 in./hour; M, moderate at 0.6 to 2.0 in./hour; S, slow at 0.06 to 0.2 in./hour.

Key points:

Bellpine: Shallow topsoil, heavy-textured topsoil and subsoil, and slow permeability in subsoil = very high risk (topsoil depth ≤10 inches).

Digger: Moderate topsoil depth and coarse-textured topsoil and subsoil with fast permeability = low risk.

Hazelair: Moderate topsoil depth and heavy-textured topsoil and subsoil with moderate permeability would be a high risk; but in this case, depth to water table is 1 to 2 feet, which = saturation risk.

Kinney: Moderate topsoil depth and coarse-textured topsoil with heavy-textured subsoil and moderate permeability = moderate risk.

Blachly: Deep topsoil overridden by clay loam topsoil and silty clay subsoil with moderate permeability = high risk.

Low-risk soil operability ratings. Low-risk soils are characterized as having deep topsoils, coarse texture, and rapid permeability (figure 5.10*A*, *B*, and *C*).

High-risk soil operability ratings. High-risk soils are characterized as having moderately deep topsoil, clayey texture, and slow permeability (figure 5.11*A*, *B*, and *C*).

Very-high-risk soil operability ratings. Very-high-risk soils are characterized as having shallow topsoil (≤10 inches), clayey texture, and very slow permeability (figure 5.12*A*, *B*, and *C*).

Saturation-risk soil operability ratings. Saturation-risk soils are generally poorly drained and have a high water table within 4 feet of the surface. Key indicators are water-loving plants such as ash, sedges, rushes, and skunk cabbage (figure 5.13*A*, *B*, and *C*).

The major limiting factors for each soil operability risk rating are as follows:

- **Low risk**: short-term rainfall event restrictions (hours)
- **Moderate risk**: intermediate-term rainfall event restrictions (days)
- **High risk**: moderate-to-slow internal movement of water and air; longer-term rainfall event restrictions (seasonal)
- **Very high risk (very susceptible)**: shallow topsoil, clay subsoil, and slow infiltration; longer-term, seasonal rainfall event restrictions
- **Saturation risk (extremely susceptible)**: shallow topsoil or depth of rooting zone due to heavy clay texture or impervious layer within 24 inches of surface, or massive structure and high water table

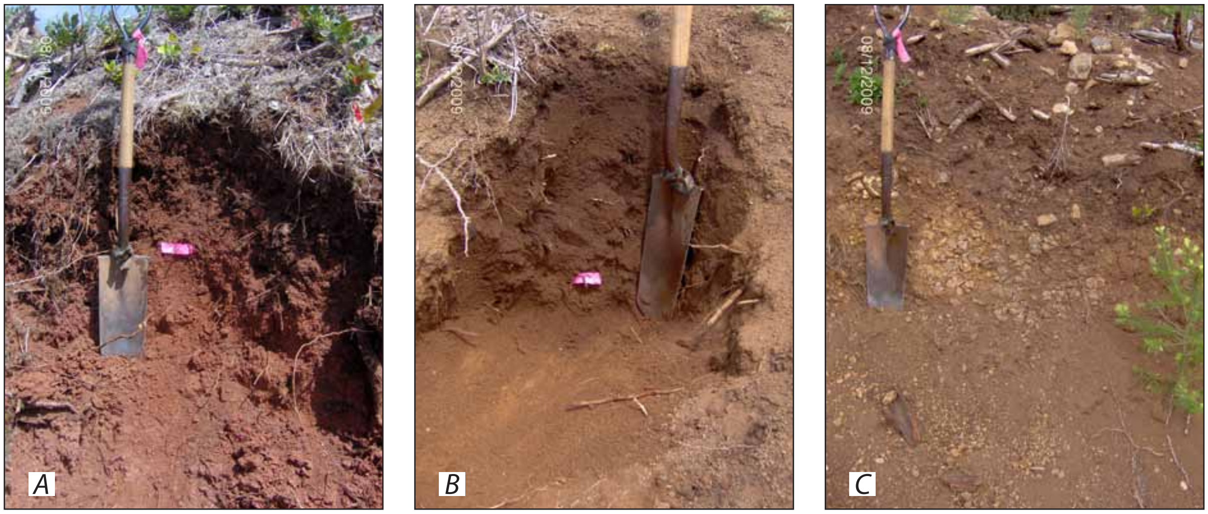


Figure 5.10. *A*, **low-risk deep topsoil, LO – Mulkey;** *B*, **low-risk deep topsoil CL LO over SI LO – Blachly;** *C*, **low-risk deep phase, CO LO – Kinney.**

Photos by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

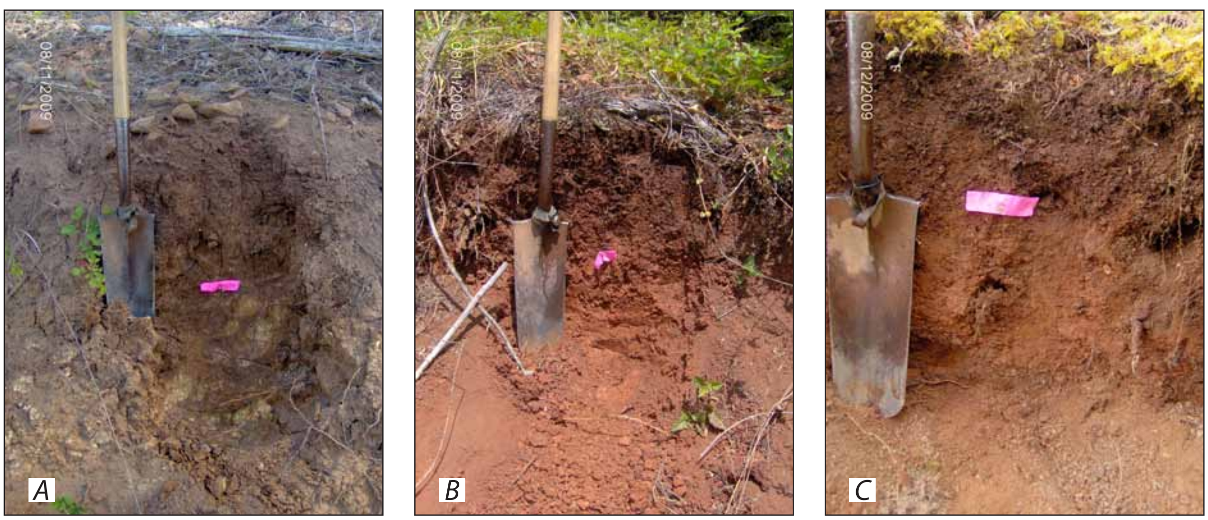


Figure 5.11. *A*, **high-risk clay loam – Willakenzie;** *B*, **high-risk deep topsoil, SI CL LO – deep variation of Peavine;** *C*, **high-risk topsoil SI CL LO – Bellpine.**

Photos by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

Figure 5.12. ***A*, very-high-risk shallow topsoil – Nekia; *B*, very-high-risk shallow topsoil – Holderman; *C*, very-high-risk shallow topsoil SI CL LO – normal Peavine.**

Photos by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

Figure 5.13. ***A*, ash species saturation risk; *B*, sedges saturation risk, poorly drained – Fluvents; *C*, skunk cabbage saturation risk, poorly drained, high water table.**

Photos by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

By following operator BMPs, you can conduct ground-harvest operations somewhat outside of the recommended window with limited soil disturbance. However, there is a greater risk of unacceptable soil disturbance. Therefore, avoid situations in which the risk is high because of site conditions and time of year. Schedule higher-risk soils during the driest time of the year. Take extra precautions when operating during higher-risk conditions. For example, place slash on designated skid trails, avoid trafficking in wet areas, use equipment that lifts rather than skids logs, use low-ground-pressure equipment, or avoid ground-based operations and cable yard.

Maps can be developed for each tree farm property indicating assigned soil operability risk ratings. The maps (figure 5.14) are useful tools for planning site preparation and ground-based harvesting activities that depend on soil properties and prevailing conditions for the season. Equipment operators, harvest managers, and audit personnel can also use the maps as a self-monitoring tool to access and track whether BMPs were followed and if they were effective.

Soil disturbance rehabilitation—conditions warranting treatment and BMPs

Although it is best to avoid disturbance levels that are likely to require rehabilitation, sometimes this is unavoidable. When thinning, it is prudent to avoid Class 3–5 disturbances because trying to rehabilitate such disturbance adjacent to standing trees could cause excessive root damage.

The following types of soil disturbance conditions should be considered for rehabilitation:

- Temporary roads and landings (figure 5.15)
- Large, contiguous Class 2–4 disturbance areas (figure 5.16)
- Deeply rutted areas that have a high potential to erode and move sediments into streams (figure 5.17)
- Areas that are aesthetically displeasing and in public view

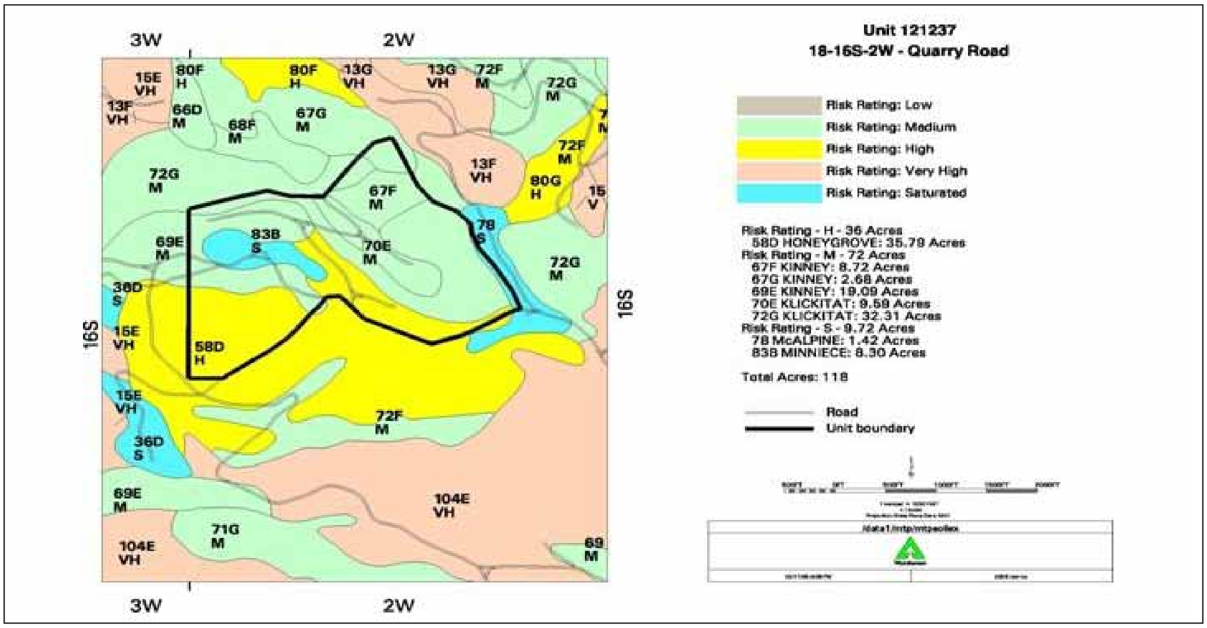


Figure 5.14. Example of a GIS map with designated soil operability risk ratings (based on USDA-NRCS soil mapping and key properties of soils and site; Table 5.2).

Graph by Carol Berry-Ross, reproduced by permission of Weyerhaeuser Company.

Figure 5.15. Temporary logging road (Class 4 soil disturbance).

Photo by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Company.

Figure 5.16. Large area of contiguous disturbance (log landing) with topsoil removal and compaction (Class 3–4 soil disturbance).

Photo by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Company.

Figure 5.17. Deeply rutted Class 3 soil disturbance with the potential for erosion and movement of sediments into streams.

Photo by author William Scott, reproduced by permission of Weyerhaeuser Company.

Research results have shown that impacts of soil disturbance on site productivity and the need for soil rehabilitation can vary by soil type and climate zone (Heninger et al. 2002). Seedling growth is generally reduced more by Class 2 and 3 soil disturbances on soils with low organic matter, high clay content, and frequent summer droughts than on soils with high organic matter, low clay content, and infrequent summer droughts (Heninger et al. 2002), so the need for rehabilitation should be evaluated accordingly. Research studies have demonstrated that tillage of disturbance Class 2 and 3 skid trails on soils with low organic matter, high clay content, and summer drought periods can restore the growth potential to that of undisturbed soil (Heninger et al. 2002). Rehabilitation was not needed for the same level of disturbance on soils with high organic matter, low clay content, and infrequent summer droughts where Douglas-fir seedling growth was not negatively impacted (Miller et al. 1996).

To restore Class 4 soil disturbance areas in temporary logging roads and landings, till the area to the depth of compaction when soils are friable (not too wet or too dry and easy to till), and then replace the topsoil that was removed. If disturbance Class 3 and 4 ruts are deep, pull back topsoil from adjacent side casts or berms into ruts prior to tillage. An excavator with tillage tines on the excavator bucket is effective and preferred for tillage because it can replace displaced topsoil and organic matter as well as till the soil to the desired depth. Cat tractors with rock-ripping tines or a winged subsoiler will also work but may be more costly (Andrus and Froehlich 1983). Schedule tillage operations for periods when the soil is friable.

On disturbance Class 5 areas, open blocked drainage ways first, and then determine if soils

Figure 5.18. Tillage of a temporary road by using an excavator.

Photo by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Company.

Figure 5.19. Replacement of (*A*) topsoil and (*B*) organic matter (logging slash) during rehabilitation of a temporary logging access road.

Photos by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Company.

become friable enough for further rehabilitation. Disturbance Class 5 usually cannot be restored by tillage alone.

Seedlings should be planted on the berms adjacent to Class 2–3 skid trails or traffic lanes rather than in the compacted traffic lane. This provides seedlings with immediate access to nondisturbed soil, and planting is usually easier.

Key principles related to soil disturbance rehabilitation mitigations

- Effectively till to the depth of compaction when soils are friable. Tillage can be accomplished with subsoilers or modified excavator buckets with tillage tines (figure 5.18).
- After tillage, replace displaced topsoil and organic matter (figure 5.19*A* and *B*). Failing to complete this step may result in tree growth loss and an increased risk of erosion.
- Where surface runoff and erosion could occur, install water bars as needed.

Monitoring

Ideally, harvesting equipment operators and contractors should be trained to recognize detrimental soil disturbance and limit its occurrence. In addition, landowners should periodically conduct quality-control monitoring to ensure standards are being met.

Monitoring should include identifying areas needing mitigation prior to closing the harvest contract and before site preparation begins. A visual determination of the extent of soil disturbance should be done first followed, if needed, by a statistically designed audit method (Page-Dumroese 2009a, 2009b) to identify settings that are clearly within or outside of the predetermined guidelines set by the landowner and where mitigation is required.

Harvesting-related BMPs

In general, BMPs are defined as practices (usually a combination of practices) that have been determined (on the basis of current knowledge, including technological, economic, and institutional considerations) to be the most effective and practicable means of achieving production and environmental quality goals (Dobkowski and Heninger 2002). BMPs provide a cost-effective means of achieving soil management strategies and standards; they are a prudent approach to resource management based on state-of-the-art knowledge. BMPs evolve as more scientific and operational knowledge is gained. In forestland management, there are BMPs for all phases of harvesting—planning, engineering and setting layout, yarding-equipment recommendations, felling and cutting operations, and soil auditing.

Good communication between the landowner, harvest manager, and equipment operators is essential for implementing ground-based harvesting BMPs:

- Hold a preharvest meeting with the crew for each setting to develop a strategy to manage the amount of soil disturbance.
- Identify potential variation in soil conditions within the setting.
- Identify draws, seeps, slopes, and other areas that may need special attention.
- Train operators to distinguish topsoil from subsoil. Use a road cut bank or dig a small soil pit to visually examine these soil layers (horizons) and their color.
- Decide on a wet-weather contingency plan and the severity and levels of soil disturbance that are not to be exceeded.

Suggested BMPs for consideration during the harvest-planning phase:

- Soils can be classified into a soil operability risk rating that shows increasing vulnerability to traffic-related disturbance that may later cause erosion and sedimentation concerns as well as seedling growth reductions. The types of equipment to use and the timing of ground-based harvesting operations depend on the soil operability risk rating.
- Plan to log the most sensitive soils during the driest time of year using the most appropriate harvesting equipment. Avoid sensitive areas as much as possible.

Suggested BMPs for felling and cutting:

- Coordinate falling and bucking to facilitate shovel yarding.
- Use directional falling methods that fall trees into the unit and away from riparian buffers and sensitive areas (wet or shallow soils, steep draws, etc.).
- Leave tree-length logs to allow equipment to operate without being too close to riparian buffers or sensitive areas.

Suggested BMPs for yarding:

- Use shovel yarding when the majority of the setting is less than 25% slope.
- Limit long-distance yarding using tracked and rubber-tired skidders except where it is not feasible to build a road (rubber-tired skidders generally cause more disturbance than shovel yarders).
- Adhere to the following guidelines when using skidders:
  - Use only on deep soils during the driest part of the year (topsoil depth >15 inches) unless soil disturbance is limited to predominantly Class 1 (after Scott 2007) or soils have coarse texture or significant rock content with good drainage.
  - Operate on ground with slopes less than 15%.
  - Use engineered skid trails with directional falling to the trails.
  - Prebunch logs.
  - Do not displace or remove topsoil from the skid trails with a push blade.

Prepare dirt spurs (temporary access roads) prior to logging and use them under the following conditions:

- Yarding distances are greater than 500 feet (150 m).
- There is a need to get the operation off of the main logging road system.
- Use of a planned dirt spur will lessen the number of logging trails or allow sensitive areas to be harvested with minimal disturbance.

If dirt spurs are used:

- First log out the spur.
- Make the spur as narrow as possible.
- Limit the amount of topsoil removal when removing stumps.
- Windrow topsoil along the edge of the spur so that it can be used when the road is rehabilitated.
- Do not operate on dirt spurs during wet weather.
- Rehabilitate all dirt spurs (via cultivation, topsoil replacement, or woody debris replacement); water-bar the spur if water runoff and erosion are potential issues.

The greatest level of soil disturbance from shovel yarding is likely to occur along roadsides (figure 5.20). Roadside soil disturbance is very visual and often gives the impression that the level of soil disturbance is widespread throughout the unit (public perception). Use extreme care when entering and exiting the setting with equipment to avoid detrimental soil disturbance.

Suggested BMPs for entering the unit with harvesting equipment:

- Use natural breaks in the topography to enter a setting (avoid wet areas and culvert basins).
- If using shovel logging, use the shovel's boom to assist turning on the road to enter a setting.
- Use the machinery arm to lift up the front of the machine, walk into the unit, and avoid turning track on cut bank (figure 5.21).
- "Quarter the shovel" off the road into the setting (figure 5.22).
- Use brush and low-grade logs to bridge ditches. After use, remove this material.
- Minimize the number of entries and exits (e.g., fuel equipment before daily entries into cutblock).

Figure 5.20. Example of soil disturbance caused by shovel-yarder traffic at the roadside.

Photo by author Ronald L. Heninger, reproduced by permission of Weyerhaeuser Company.

Figure 5.21. Use the shovel's boom to assist turning on the road to enter a setting and to lift up the front of the machine.

Photo by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Company.

It is very important to maintain a systematic logging pattern to minimize the number of trails. Take note of the following:

- Keep logging trails as straight as possible.
- Minimize the area disturbed by yarding.
- Plan shovel trails to parallel but not cross suspected shallow subsurface water flow.
- Place tops and limbs on traffic lanes and walk on harvest residuals *before* significant soil disturbance occurs, particularly on more sensitive soils (figure 5.23).
- If equipment causes soil and mud to ooze up through the slash while trafficking, it may cause a problem for site preparation and plantation establishment, so monitor this carefully. Buried slash can impede planting, and the puddled soil and slash may impede drainage, causing saturated conditions.

Use logging debris when crossing a draw or wet area, but make sure you are in regulatory compliance. Be certain to remove the debris after crossing to reopen drainage, and check for other applicable requirements.

Summary

Soil disturbance can be managed to acceptable levels to avoid erosion and ensure that soil productive capacity is maintained through successive crop cycles by using soil management decision-support tools, including a soil disturbance classification and risk rating system, along with crew training and implementation of appropriate BMPs, including soil disturbance monitoring. In certain cases, soil rehabilitation (replacement of topsoil, tillage, and replacement of organic matter and woody debris) may be necessary to restore disturbed areas back to their full productivity potential (e.g., on temporary logging roads and Class 3 and 4 soil disturbances).

Key references and other resources

Adams, P. 1998. *Soil Compaction on Woodland Properties*. EC 1109. Corvallis, OR: Oregon State University Extension Service. http://hdl.handle.net/1957/13878.

Adams, W.P. 2005. Research and policies to address concerns about soil compaction from ground-based timber harvest in the Pacific Northwest: Evolving knowledge and needed refinements. Paper presented at the Council on Forest Engineering Conference on Soil, Water, and Timber Management: Forest Engineering Solutions in Response to Forest Regulation, July 11–14, 2005, Fortuna, CA.

Andrus, C.W., and H.A. Froehlich. 1983. *An Evaluation of Four Implements Used to Till Compacted Forest Soils in the Pacific Northwest*. Research Bulletin 45. Corvallis, OR: Oregon State University Forest Research Laboratory.

Figure 5.22. "Quarter the shovel" off the road, and walk into the setting.

Photo by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Company.

Figure 5.23. Place tops and limbs on the traffic lane and walk on harvest residues *before* significant soil disturbance occurs, particularly on more sensitive soils.

Photo by author Alex Dobkowski, reproduced by permission of Weyerhaeuser Company.

Ares, A., T.A. Terry, R.E. Miller, H.W. Anderson, and B.L. Flaming. 2005. Forest harvesting effects on soil physical properties and Douglas-fir growth on a Coastal Washington Site. *Soil Science Society of America Journal* 69:1822–1832.

Curran, M.P., R.L. Heninger, D.G. Maynard, and R.F. Powers. 2005. Harvesting effects on soils, tree growth and long-term productivity. p. 3–17 in *Productivity of Western Forests – A Forest Products Focus*, C.A. Harrington and S.H. Schoenholtz (eds.). General Technical Report PNW-GTR-642. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

Curran, M.P., D.G. Maynard, R.L. Heninger, T. Terry, S. Howes, D. Stone, T. Niemann, and R.E. Miller 2007. Elements and rational for a common approach to assess and report soil disturbance. *Forestry Chronicle* 83:852–866.

Curran, M.P., D.G. Maynard, R.L. Heninger, T.A. Terry, S.W. Howes, D.M. Stone, T. Niemann, R.E. Miller, and R.F. Powers. 2005. An adaptive management process for forest soil conservation. *Forestry Chronicle* 81(5):717–722.

Curran, M.P., R.E. Miller, S.W. Howes, D.G. Maynard, T.A. Terry, R.L. Heninger, T. Hiemann, K. van Rees, R.F. Powers, and S.H. Schoenholtz. 2005. Progress towards more uniform assessment and reporting of soil disturbance for operations, research, and sustainability protocols. *Forest Ecology and Management* 220:17–30.

Dobkowski, A., and R. L. Heninger. 2002. *Forest Soil Management Training Manual and Best Management Practices for Ground-Based Harvest Equipment*. Forest Research Technical Note. Federal Way, WA: Weyerhaeuser Company.

Helgerson, O.T., and R.E. Miller. 2008. *Keeping Your Forest Soils Healthy and Productive*. EB2019. Pullman, WA: Washington State University Extension. *http://cru.cahe.wsu.edu/CEPublications/eb2019/eb2019.pdf*.

Heninger, R., W. Scott, A. Dobkowski, R. Miller, H. Anderson, and S. Duke. 2002. Soil disturbance and 10-year growth response of coast Douglas-fir on non-tilled and tilled skid trails in the Oregon Cascades. *Canadian Journal of Forest Research* 32:233–246.

Garland, J.J. 1997. *Designated Skid Trails Minimize Soil Compaction*. EC 1110. Corvallis, OR: Oregon State University Extension Service. *http://hdl.handle.net/1957/13887*.

Miller, R.E., J. Smith, P. Adams, and H. Anderson 2007. *Growth of Douglas-fir Near Equipment Trails Used for Commercial Thinning in the Oregon Coast Range*. Research Paper PNW-RP-574. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

Miller, R.E., W. Scott, and J.W. Hazard. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. *Canadian Journal of Forest Research* 26:225–236.

Napper, C., S. Howes, and D. Page-Dumroese. 2009. *Soil-Disturbance Field Guide*. Publication 0819 1815-SDTDC. USDA Forest Service, National Technology and Development Program.

Oregon Department of Forestry. Forest Roads Manual. *http://www.oregon.gov/ODF/STATE_FORESTS/roadsmanual.shtml*.

Page-Dumroese, D., A.M. Abbott, and T.M. Rice. 2009a. *Forest Soil Disturbance Monitoring Protocol, Volume 1 – Rapid Assessment*. General Technical Report GTR-WO-82a. Washington, D.C.: USDA Forest Service.

Page-Dumroese, D., A.M. Abbott, and T.M. Rice. 2009b. *Forest Soil Disturbance Monitoring Protocol, Volume 2 – Supplementary Methods, Statistics, and Data Collection*. General Technical Report GTR-WO-82b. Washington, D.C.: USDA Forest Service.

Page-Dumroese, D., M. Jurgensen, W. Elliot, T. Rice, J. Nesser, T. Collins, and R. Meurisse. 2000. Soil quality standards and guidelines for forest sustainability in northwestern North America. *Forest Ecology and Management* 138:445–462.

Page-Dumroese, D., M. Jurgensen, A. Tiarks, F. Sanchez, R. Fleming, M. Kranabetter, R. Powers, F. Ponder Jr., D. Stone, J. Elioff, and A. Scott. 2006. Soil physical property changes on the North American Long-Term Soil Productivity (LTSP) study sites: 1 and 5 years after treatment. *Canadian Journal of Forest Research* 36:551–564.

Powers, R.F., D.A. Scott, F.G. Sanchez, R.A. Voldseth, D.S. Page-Dumroese, J.D. Elioff, and D.M. Stone. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. *Forest Ecology and Management* 220:31–50.

Scott, W. 2007. *A Soil Disturbance Classification System*. Long-Term Site Productivity Paper no. 07-3. Federal Way, WA: Weyerhaeuser Company, Western Timberlands R&D. *http://extension.oregonstate.edu/lincoln/sites/default/files/documents/soil_disturbance_classification_system.pdf*.

Chapter 6 Maintaining Adequate Nutrient Supply— Principles, Decision-Support Tools, and Best Management Practices

Robert B. Harrison, Douglas A. Maguire, and Deborah Page-Dumroese

Background

Maintaining adequate nutrient supply to maintain or enhance tree vigor and forest growth requires conservation of topsoil and soil organic matter. Sometimes nutrient amendments are also required to supplement inherent nutrient-pool limitations or replenish nutrients removed in harvested material. The goal is to maintain the productive potential of the soil and, when economically feasible and environmentally acceptable, enhance productivity where nutrient supply significantly limits growth. Nitrogen (N) is most frequently the limiting nutrient in Pacific Northwest forests, particularly on soils with low N pools (Gessel and Walker 1956; Heilman 1971; Turner et al. 1988, Chappell et al. 1991).

General principles of nutrient management

Soil N nutrient pools vary across the landscape (figure 6.1), and even across relatively short distances within a stand. Soil N is highly correlated with soil carbon/organic matter (figure 6.2). Nitrogen enters most forest ecosystems by fixation of atmospheric N and subsequent incorporation into organic matter. This organic matter eventually dies, decomposes, and releases mineralized N that becomes available for plant uptake. Nitrogen is maintained in the ecosystem by cycling living plants to soil organic matter and then to mineralized nutrients and then back to living plants, but large amounts of N are often held in dead organic matter and remain unavailable until further decomposition and mineralization.

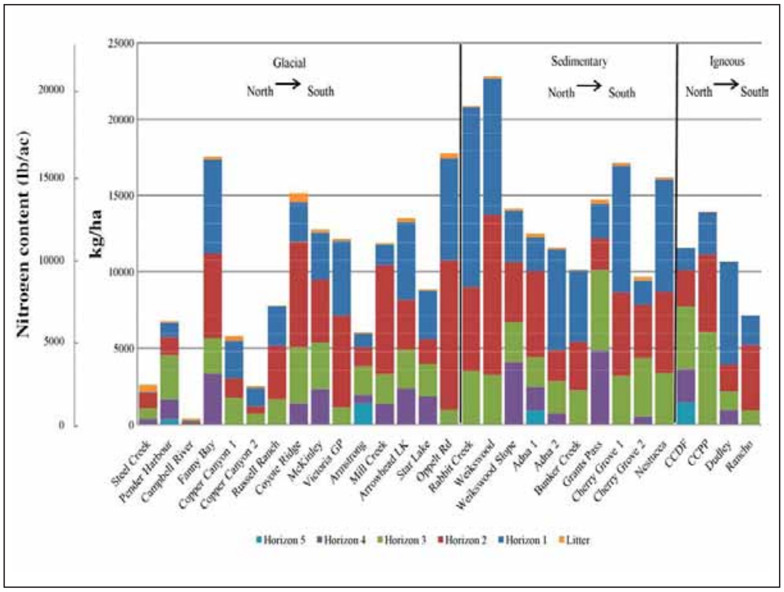


Figure 6.1. Soil nitrogen at selected locations west of the Cascades from Vancouver Island, British Columbia, to southern Oregon with glacial, sedimentary, and igneous parent material.

Graph by author Robert B. Harrison, unpublished data.

Factors affecting levels and retention of soil nutrient pools

Plant nutrients are supplied to the soil from a number of different sources:

- Mineral weathering
- Atmospheric fixation (carbon by photosynthetic tissues, N by N-fixing microorganisms)
- Atmospheric dry and wet deposition
- Organic matter mineralization
- Soil amendments (e.g., fertilizers and biosolids)

Forests growing on soils with large N pools generally have higher productivity than those on soils with small N pools, particularly when soil aeration and temperature are not limiting to decomposition and mineralization. Organic matter and topsoil conservation is critical for nutrient-pool conservation because the forest floor and topsoil horizons are generally higher in organic matter content than subsoil horizons, and the organic matter in surface horizons generally provides a greater proportion of available N than the more decay-resistant organic material in deeper soil horizons.

Soil nutrient pools should be maintained or enhanced rather than depleted (nutrient removals should not exceed inputs over the long term). Nitrogen and other nutrient concentrations vary by tree component. For example, the concentration of N in foliage is greater than that in branches or bole wood (table 6.1). Therefore, the level of nutrient removal is not exactly proportional to the mass of harvested material; rather, it depends on utilization intensity and the type of material removed.

Management of nutrition in perennial forest crops such as Douglas-fir has several advantages over managing fertility for annual agricultural crops. In coastal Douglas-fir, nutrient uptake can occur year-round when temperature and moisture conditions permit. Multiple cohorts, or age classes, of needles allow internal translocation of nutrients from older needles before they are shed, facilitating internal conservation of nutrients. Tree growth also builds on a perennial structure accumulated from previous years' nutrient uptake and growth. Finally, the primary tree component removed for commercial use is the stem or bole, which has a relatively low concentration of nutrients compared with tree foliage and fine branches. Of course, this is not the case in whole-tree harvesting, in which limbs and tops may be deposited at the roadside or removed during a biomass harvest. In many agricultural crops, the nutrient-rich foliage or fruiting structures comprise the bulk of the harvest.

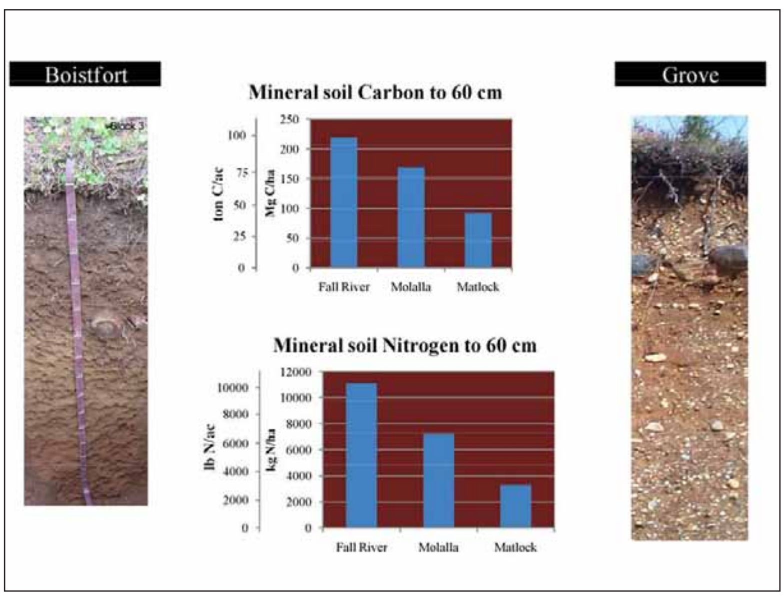


Figure 6.2. Mineral soil carbon and nitrogen to a 0.6-m depth at three regional soil productivity studies (after Ares et al. 2007 and Slesak, Schoenholtz, and Harrington, unpublished data). The Boistfort soil (residual soil derived from basalt) is located at the Fall River, Wash., site; the Kinney soil formed from basic agglomerate residuum (photo not shown) is at the Molalla, Ore., site; and the Grove soil (glacial outwash) is at the Matlock, Wash., site.

Photos by authors Darlene Zabowski (*left*) and Robert B. Harrison (*right*).

Table 6.1. Examples of Douglas-fir tree component nitrogen (N) concentrations for a 47-year-old fertilized stand and a 5-year-old stand on the same site (Fall River Long-Term Soil Productivity Study, a highly productive site in western Washington)

	N concentration (%, dry-mass basis)	
Tree component	Age 47 years[1]	Age 5 years[2]
Foliage	2.02 (0.07)	1.55 (0.4)
Bark	0.40 (0.05)	…
Live branches	0.26 (0.04)	…
Live branches + bark	…	0.89 (0.3)
Bole wood	0.08 (0.01)	
Bole wood + bark	…	0.42 (0.2)
n (number of samples)	14	12

Note: Values are mean ± one standard error. Standard errors are shown in parentheses.

[1] *Source*: Ares et al. (2007).

[2] *Source*: Peterson et al. (2008).

However, despite the low concentrations of N in wood, the large mass of bole wood/ha relative to foliage and live limbs in whole-tree harvested stands can result in N removals in bole wood exceeding removals in foliage and branches. For example, a 47-year-old stand of Douglas-fir and western hemlock at Fall River, Wash., had 39 Mg/ha (17 tons/acre) of foliage plus live limbs and 341 Mg/ha (152 tons/acre) of bole wood plus bark. The corresponding amount of N in these components was 225 kg/ha (200 lb/acre) in foliage and live branches and 359 kg/ha (320 lb/acre) in bole wood and bark (Ares et al. 2007).

The annual N demand of a typical Douglas-fir stand is approximately 45 kg/ha/year (40 lb/acre/year) from age 25 to 50 years (Cole 1986; figure 6.3). Internal recycling of nutrients is a significant source of N for meeting these annual requirements. On average, roughly 20% of annual uptake is retained and accumulated in tree biomass; the rest is shed as fine roots die and senesced foliage and branches fall to the forest floor. This fine root, branch, and foliage material decomposes, and the resulting mineralized N and other nutrients become available again for uptake by trees and other forest vegetation. Soil N supply generally is adequate for seedling growth after regeneration harvesting but can become limiting on N-deficient sites, particularly in the presence of intensely competing vegetation and as nutrient demand increases with accelerating growth and crown expansion (figures 6.3 and 6.4).

The amount of N removed during harvest depends on the yarding procedure and utilization intensity. In whole-tree yarding, all aboveground tree components are yarded to the landing regardless of utilization intensity. However, during this operation, a considerable amount of branches and needles can remain on site as these components are broken off during transport. In contrast, only logs are yarded when the trees are limbed and bucked where they fall (bole-only yarding). Utilization intensity is determined by the proportional amounts of logs and chipped or bundled biomass (e.g., foliage, branches, tops, and cull logs) that are removed from the site for subsequent use. Utilization intensity is also determined by the minimum diameter and length of logs demanded by the market and opportunities for using biomass held in residual bole-wood, branches, and foliage. Bole-only yarding removes about 5% of the total site N pool (the amount of N existing on the site including above- and belowground biomass and mineral soil components). In contrast, whole-tree yarding removes about 10% of the total N pool (Edmonds et al. 1989).

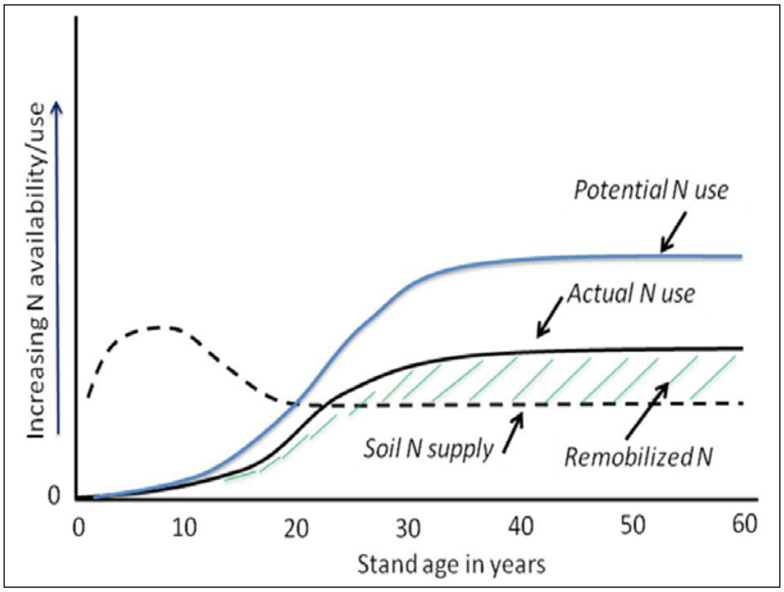


Figure 6.3. Conceptual diagram of soil nitrogen (N) nutrient supply and uptake of a Douglas-fir stand showing the importance of recycling (remobilized N) within the tree. Nutrient availability from the soil is highest when tree demand for nutrients is lowest. The potential N-use curve compared with the actual N-use curve reflects the deficit not available to trees on N-deficient sites during the maximum growth and nutrient uptake period. The difference between potential and actual N use will depend on the degree of N limitation on the site and other factors that may be limiting growth potential.

Graph by author Robert B. Harrison, adapted from the southern pine diagram of Fox et al. (2007).

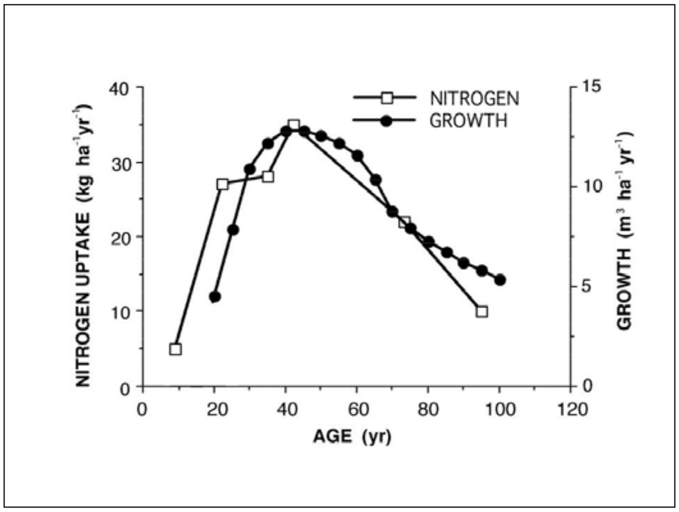


Figure 6.4. Example of nitrogen uptake of a Douglas-fir stand with age compared with the volume growth (tree boles) of the stand.

Graph from Turner (1975).

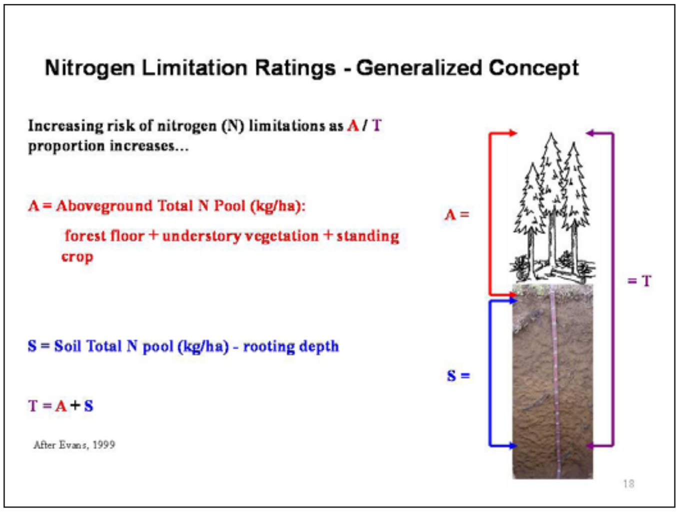


Figure 6.5. The likelihood of having a nutrient supply limitation due to biomass removal increases as the A/T proportion increases (i.e., when a high percentage of the site's nutrient pool is in the standing crop and forest floor) because the aboveground biomass can be removed during harvest and the forest floor can be removed or displaced during site preparation.

Illustration by author Thomas A. Terry, reproduced by permission of Weyerhaeuser Company.
Photo by author Darlene Zabowski.

Removing an increasing proportion of the nutrient pool increases the risk of causing a negative impact on nutrient supply and tree growth. Evans (1999) concluded from a review of the literature that the risk of declining tree productivity was low for 10% removal of an essential nutrient and serious for 30% removal and that imminent decline was likely if nutrient-pool removals approached 50% or greater. One method for assessing the potential impacts of organic matter removal is to estimate the ratio of the aboveground N pool to the total above- and belowground N pool. For example, if the aboveground pool (pool A in figure 6.5) was removed from the Boistfort soil, it would deplete 9% of the N pool, whereas removing this pool on a Grove soil would deplete 16% of the N pool (figure 6.5). The risk of detrimental impacts from whole-tree yarding on the N pool is greater on the Grove soil because it has a relatively small total N pool, and a relatively high proportion of it resides in the aboveground biomass.

Best management practices (BMPs) implemented for biomass retention and removal during harvest and site preparation depend on trade-offs among several risk factors, including potential adverse effects of wildfire, erosion, and invasive weeds, and the implications for planting quality. Nutrient limitations or shifts in nutrient availability that may affect long-term productivity should also be considered. Key BMPs include the following:

- **Take extra precaution during harvest activities in or around ecologically sensitive areas, riparian zones, and areas characterized by organic or shallow soils with low nutrient pools.** Intensive biomass harvesting should not be conducted in these areas.
- **Conservation of large woody debris (figure 6.6) is important from a wildlife and biotic diversity perspective and also must be considered when retention guidelines are specified during harvest (Bull 2002).** Retain all large legacy wood that exists on the forest floor and large standing snags where it is safe to do so. Wildlife reserve trees or green recruitment trees should also be identified and left in areas where they will not become a safety hazard. These trees will produce large woody debris with time. Large woody debris (>7 inches [18 cm] in diameter) functions as habitat for a variety of organisms (e.g., fungi, mosses, insects, and amphibians). Retention of both large and fine woody debris can protect a site from erosion, soil compaction and rutting, and surface runoff. Forest practice regulations in some states (e.g., Washington and Oregon) have specific requirements for large woody debris and recruitment tree retention.
- **Removing only logs (bole-only harvest) presents a relatively low risk of loss in productivity, whereas whole-tree yarding may create a greater risk depending on how much of the nutrient pool is removed relative to the total pool before harvest.** Fox (2000) emphasized that productivity losses caused by nutrient losses in harvested material are likely to be highly dependent on specific site characteristics, particularly available nutrients. Evans (1999) concluded from a review of the available literature that removing less

Figure 6.6. Conserve a range of woody debris sizes to meet wildlife, soil biology, and biodiversity objectives.

Photo by author Thomas A. Terry, reproduced by permission of Weyerhaeuser Company.

than 10% of the nutrient pool presented a low risk of productivity losses on many soils.

- **Retain at least 30% of the fine woody debris on slopes conducive to ground-based harvesting and 50% or more on steeper slopes.**
- **When removing logging residuals for biomass harvest or fuel reduction, or when piling slash to create planting spaces, it is best to wait until the residuals dry so that needles and fine branches can fall off and remain distributed as uniformly as possible across the site.** Slash piles created for site preparation should be small and located such that the site can be planted in a manner that maintains the desired spatial distribution of planted trees.
- **Some displacement of the forest floor to create planting spots can improve planting quality and subsequent root growth (increased soil temperatures in the spring), but too much mineral soil exposure (displacement) can reduce water available to seedlings as a result of increased weed competition and increased evaporation from the surface soil.** Logging slash removal or slash piling that exposes mineral soil can significantly increase invasive weeds such as Scotch broom (Harrington and Schoenholtz 2010). High levels of competing vegetation can reduce planted seedling survival and early growth.

Nutrient deficiencies—diagnosis and correction

On the majority of sites in the Pacific Northwest, N is most frequently the limiting nutrient to Douglas-fir growth. In general, response to N fertilization tends to be greatest in stands with a below-average site index and least on highly productive sites. Our ability to predict the degree to which a specific site will respond to N fertilization, however, is still weak.

Use of foliar diagnosis for identifying deficient stands is problematic because foliage is difficult to sample in older stands, nutrient concentration can vary from year to year depending on weather conditions (e.g., amount and timing of rainfall and many other factors), and nutrients from older needles can be recycled to younger tissue. In addition, the limited evidence to date suggests that the total amount of N and other nutrients in the forest canopy (determined largely by total foliage mass) is more important than the concentration of nutrients in the foliage.

Nitrogen-deficient foliage tends to be yellowish green, and leader growth on branch terminals and lateral branches tends to be less vigorous than that on trees with adequate concentrations of N (figure 6.7). Needle size and needle density per unit length of shoot also decline under N-deficient conditions.

Swiss needle cast (SNC), a foliar disease caused by a fungus that grows within intercellular spaces of needles, causes yellowing and premature loss of foliage in Douglas-fir (Hansen et al. 2000). Foliage is retained on the most severely impacted trees for only 1 year or less (figure 6.8). Although SNC symptoms can appear similar to those of N deficiency, foliar N concentrations are actually highest in trees with the lowest foliage retention. It is still unclear whether relatively high N concentrations cause the disease by providing a N-rich feeding substrate or represent an effect associated with translocation of foliar N to surviving foliage. The key distinguishing characteristics of SNC include progressive yellowing and browning of infected foliage through winter and spring; sparse crowns caused by premature foliage loss, particularly in the spring just prior to bud break; and tiny black fruiting bodies (pseudothecia) that plug stomatal openings on the underside of needles and inhibit photosynthesis (Scharpf 1993 ; Filip et al. 2000).

Walker and Gessel (1990) developed nutrient deficiency levels for seedlings by using the solution culture method (table 6.2). These values should be used with caution when examining foliage from older stands. Ballard and Carter (1985) identified three N-deficiency levels in Douglas-fir on the basis of foliar N concentration (%, dry-mass basis):

1. Very severe: <1.05%
2. Severe: >1.05 to 1.3%
3. Slight-moderate: >1.3 to 1.45%

When implementing foliage sampling in established stands, collect foliage from the upper third of crowns on dominant and codominant trees. Foliage sampling should be limited to the dormant season, preferably between October and February, to avoid seasonal changes. Always collect needles that were formed in the most recently completed growing season.

Figure 6.9 shows a generalized relationship between nutrient concentration and tree growth that illustrates the range from deficiency to luxury consumption to toxicity. The goal of any nutrient amendment is to reduce deficiency levels and improve growth rates while achieving an acceptable rate of return on the investment.

Figure 6.7. Douglas-fir branches to the right of the black line show typical symptoms of nitrogen deficiency; the branch on the left shows no nitrogen-deficiency symptoms.

Photo by author Thomas A. Terry, reproduced by permission of Weyerhaeuser Company.

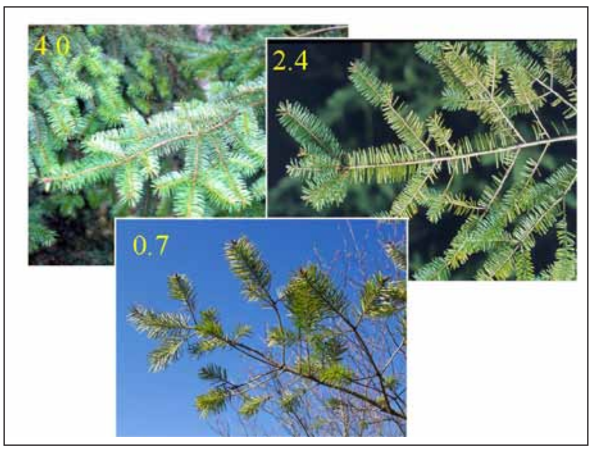


Figure 6.8. Douglas-fir branches with various levels of foliage loss and yellowing due to Swiss needle cast, a foliar disease caused by the fungus *Phaeocryptopus gaeumannii*. The number in upper left corner of each photo indicates foliage retention in years.

Photos by Alan Kanaskie, Oregon Department of Forestry, reproduced by permission.

Table 6.2. Seedling nutrient deficiency levels (foliar concentrations, %, dry-mass basis) developed using the solution culture method

Element	Douglas-fir	Hemlock	Western red cedar	Sitka spruce	True firs
Nitrogen	1.25	1.80	1.50	1.80	1.15
Phosphorus	0.16	0.25	0.13	0.09	0.15
Potassium	0.60	1.10	0.60	0.40	0.50
Calcium	0.25	0.18	0.20	0.06	0.12
Magnesium	0.17		0.12	0.06	0.07
Sulfur	0.35		0.4	0.15	

Source: Walker and Gessel (1990).

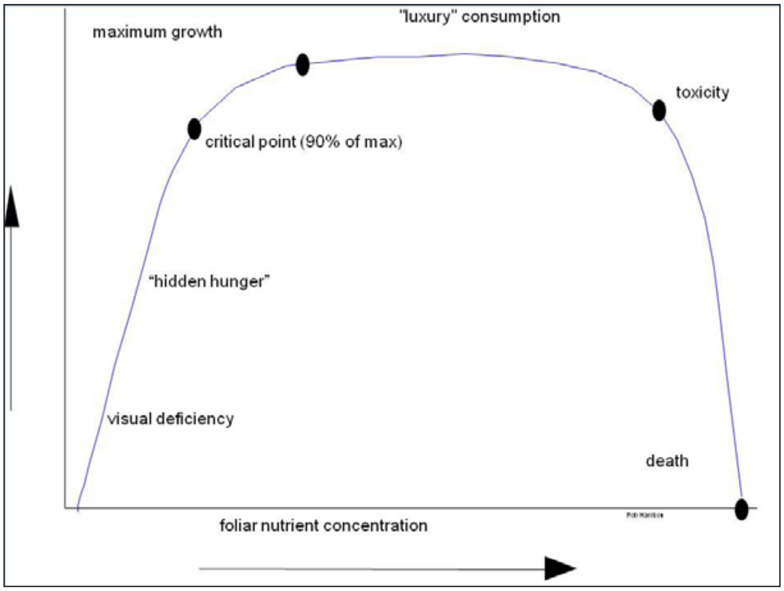


Figure 6.9. Generalized relationship between nutrient concentration (*x-axis*) and tree growth and vigor (*y-axis*).

Graph by author Robert B. Harrison.

Fertilization to maintain and enhance fertility and productivity

The Regional Forest Nutrition Research Project (now the Nutrition Project within the Stand Management Cooperative at the University of Washington) established several sets of regional fertilization trials in coastal Douglas-fir zones of Washington, Oregon, and British Columbia. In one large set of field trials, N was applied as urea at the rate of 224 kg/ha (200 lb/acre) of N in unthinned and thinned stands of Douglas-fir. Four-year N responses averaged 18% for unthinned stands and 29% for thinned stands (Peterson and Heath 1986; Opalach et al. 1987), but large differences in response were observed among stands. These early studies were designed to test the average response to N fertilization across the region rather than site-specific responses. The Stand Management Cooperative has installed a new set of replicated single-tree fertilization trials to develop better site-specific fertilization guidelines for Douglas-fir stands in the region.

On sites where Douglas-fir has responded to N fertilization with accelerated growth, it is unclear how long the added N is retained in the system, particularly with respect to its availability to the subsequent tree crop. Recent analysis of trees planted on old Regional Forest Nutrition Project research plots has demonstrated that growth is significantly greater on fertilized plots than on unfertilized plots (Footen et al. 2009). This carryover effect of N added 30 years before in the previous rotation suggests that this type of soil amendment may increase the labile pool of N available for growth of the succeeding stand. How long this effect lasts needs to be determined.

The timing of fertilization is largely an economic decision but also must be considered in the context of the long-term stand density regime (e.g., growth gains from fertilization in dense or unthinned stands can be lost to increased suppression mortality). Miller and Fight (1979) noted that applying 492 kg/ha (440 lb/acre) of urea prills (approximately 224 kg/ha [200 lb N/acre]) 10 years prior to harvest is an appealing strategy for addressing N deficiency in Douglas-fir stands because

- stand growth responses last about 10 years,
- increased growth goes into trees most likely to be marketed, and
- investment costs are recovered sooner than when fertilizer is applied earlier.

Application of treated biosolids is another option for increasing the N status of soils (Harrison et al. 2002).

With successive harvest of Douglas-fir crops from intensively managed forestlands in the Pacific Northwest, the appearance of other nutrient deficiencies becomes an increasing possibility (Walker and Gessel 1990). Three-year results from a recent set of trials suggest that Douglas-fir growth can show a significant response to applications of calcium and phosphorus (Mainwaring et al. in review). However, as was found in the case of N fertilization, significantly positive growth responses were limited to only a subset of the sites.

Alternative species for improving soil fertility levels

Red alder (*Alnus rubra*) is a N-fixing species that has often been suggested as a component of an alternating crop system (Douglas-fir/alder/Douglas-fir…) or of mixed alder/Douglas-fir plantations. Results from mixed-species trials suggest that red alder offsets Douglas-fir productivity by direct competition (Miller et al. 1999, 2005), and the differential growth rates of the two species require careful planning and management of stand density and spatial arrangement of the species mix. However, red alder should not be overlooked as a species with which to build soil N pools and/or produce a valuable crop on sites where Douglas-fir may not be suitable (e.g., laminated root-rot pockets).

Key references and other resources

Ares, A., T.A. Terry, K.B. Piatek, R.B. Harrison, R.E. Miller, B. Flaming, C. Licata, B. Strahm, C.A. Harrington, R. Meade, H.W. Anderson, L.C. Brodie, and J.M. Kraft. 2007. *The Fall River Long-Term Site Productivity Study in Coastal Washington: Site Characteristics, Experimental Design, and Biomass and Carbon and Nitrogen Stores Before and After Harvest*. General Technical Report PNW-GTR-691. Portland, OR: USDA Forest Service, Pacific Northwest Research Station. *http://www.treesearch.fs.fed.us/pubs/25956*.

Ballard, T.M., and R.E. Carter. 1986. *Evaluating Forest Stand Nutrient Status*. Land Management Report No. 20. Victoria, BC: British Columbia Ministry of Forests.

Bull, E.L. 2002. The value of coarse woody debris to vertebrates in the Pacific Northwest. p. 171–178 in *Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests*, W.F. Laudenslayer Jr., P.J. Shea, B.E. Valentine, C.P. Weatherspoon, and T.E. Lisle (eds.). General Technical Report PSW-GTR-181. Albany, CA: USDA Forest Service, Pacific Southwest Research Station.

Chappell, H.N., D.W. Cole, S.P. Gessel, and R.B. Walker. 1991. Forest fertilization research and practice in the Pacific Northwest. *Fertilizer Research* 27(1):129–140.

Cole, D.W. 1986. Nutrient cycling in world forests. p. 103–115 in *Forest Site and Productivity*, S.P. Gessel (ed.). Dordrecht, The Netherlands: Martinus Nijoff.

Edmonds, R.L., D. Binkley, M.C. Feller, P. Sollins, A. Abee, and D.D. Myrold. 1989. Nutrient cycling: Effects on productivity of northwest forest. p. 17–35 in *Maintaining the Long-Term Productivity of Pacific Northwest Forest Ecosystems*, D.A. Perry, R. Meurisse, B. Thomas, R. Miller, J. Boyle, J. Means, C.R. Perry, and R.F. Powers (eds.). Portland, OR: Timber Press.

Edmonds, R.L., and T. Hsiang. 1987. Forest floor and soil influence on response of Douglas-fir to urea. *Soil Science Society of America Journal* 51:1332–1337.

Evans, J. 1999. *Sustainability of Forest Plantations—The Evidence. A Review of Evidence Concerning the Narrow-Sense Sustainability of Planted Forests*. Report commissioned by the Department for International Development, London, UK. *http://www.riverpath.com/library/pdf/sustainability_of_plantation_forestry.pdf*.

Filip, G.M., A. Kanaskie, K. Kavanagh, G. Johnson, R. Johnson, and D. Maguire. 2000. *Silviculture and Swiss Needle Cast: Research and Recommendations*. Research Contribution no. 30. Corvallis, OR: Oregon State University Forest Research Laboratory.

Footen, P.W., R.B. Harrison, and B.D. Strahm. 2009. Long-term effects of nitrogen fertilization on the productivity of subsequent stands of Douglas-fir in the Pacific Northwest. *Forest Ecology and Management* 258:2194–2198.

Fox, T.R. 2000. Sustained productivity in intensively managed forest plantations. *Forest Ecology and Management* 138:187–202.

Fox, T.R., H.L. Allen, T.J. Albaugh, R. Rubilar, and C.A. Carlson. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. *Southern Journal of Applied Forestry* 31:5–11.

Gessel, S.P., and R.B. Walker. 1956. Height growth response of Douglas-fir to N fertilization. *Soil Science Society of America Proceedings* 20:97–100.

Hansen, E.M., J.K. Stone, B.R. Capitano, P. Rosso, W. Sutton, L. Winton, A. Kanaskie, and M.G. McWilliams. 2000. Incidence and impact of Swiss needle cast in forest plantations of Douglas-fir in coastal Oregon. *Plant Disease* 84:773–778.

Harrington, T.B., and S.H. Schoenholtz. 2010. Effects of logging debris treatments on five-year development of competing vegetation and planted Douglas-fir. *Canadian Journal of Forest Research* 40:500–510.

Harrison, R.B., E.C. Turnblom, C.L. Henry, P. Leonard, R. King, and R. Gonyea. 2002. Response of three young Douglas-fir plantations to forest fertilization with low rates of municipal biosolids. *Journal of Sustainable Forestry* 14:21–30.

Heilman, P.E. 1971. *Effects of Fertilization on Douglas-fir in Southwestern Washington*. Circular 535. Pullman, WA: Washington Agricultural Experiment Station.

Helgerson, O.T., and R.E. Miller. 2008. *Keeping Your Forest Soils Healthy and Productive*. EB2019. Pullman, WA: Washington State University Extension. *http://cru.cahe.wsu.edu/CEPublications/eb2019/eb2019.pdf*.

Mainwaring, D.B., D.A. Maguire, and S.S. Perakis. Three-year growth response of young Douglas-fir to nitrogen, calcium, phosphorus, and blended fertilization treatments in Oregon and Washington. *Canadian Journal of Forest Research*, in review.

Miller, R.E., H.W. Anderson, M. Murray, and R. Leon. 2005. *Comparative Effects of Urea Fertilizer and Red Alder in a Site III, Coast Douglas-fir Plantation in the Washington Cascade Range*. Research Paper PNW-RP-565. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

Miller, R.E., and R.D. Fight. 1979. *Fertilizing Douglas-fir Forests*. General Technical Report PNW-GTR-83. Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. *http://www.fs.fed.us/pnw/pubs/gtr83.pdf*.

Miller, R.E., E.L. Obermeyer, and H.W. Anderson. 1999. *Comparative Effects of Precommercial Thinning, Urea Fertilizer and Red Alder in a Site II, Coast Douglas-fir Plantation*. Research Paper PNW-RP-513. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

Moore, J.A., D.P. Hanley, H.N. Chappell, J. Shumway, S.B. Webster, and J.M. Mandzak. 1988. *Fertilizing Eastern Washington Coniferous Forests: A Guide for Nonindustrial Private Forest Landowners*. EB1874. Pullman, WA: Washington State University Extension. *http://soilslab.cfr.washington.edu/publications/SoilManagementWFCA2009/FertilizingWesternForests.pdf*.

Opalach, D., L.S. Heath, and H.N. Chappell. 1987. *Growth Response to Single and Multiple Nitrogen Fertilizer Applications in Thinned Douglas-fir Stands*. Regional Forest Nutrition Research Project Report no. 8. Seattle, WA: University of Washington College of Forest Resources.

Page-Dumroese, D. 2010. Is woody residue part of your plan for sustainable forestry? *Northwest Woodlands* Summer:20–22.

Peterson, C.E., and L.S. Heath. 1986. *Volume Growth and Volume Growth Response after Fertilization of Unthinned Douglas-fir Stands*. Regional Forest Nutrition Research Project Report no. 6. Seattle, WA: University of Washington College of Forest Resources.

Peterson, K.S., A. Ares, T.A. Terry, and R.B. Harrison. 2008. Vegetation competition effects on aboveground biomass and macronutrients, leaf area, and crown structure of five-year-old Douglas-fir. *New Forests* 35:299–311.

Scharpf, R.F. 1993. *Diseases of Pacific Coast Conifers*. Agricultural Handbook no. 521. Washington, D.C.: USDA Forest Service.

Turner, J. 1975. Nutrient cycling in a Douglas-fir ecosystem with respect to age and nutrient status. Ph.D. thesis, University of Washington, Seattle.

Turner, J., M.J. Lambert, and S.P. Gessel. 1988. Nitrogen requirements in young Douglas-fir of the Pacific Northwest. *Fertilizer Research* 15:173–179.

Walker, R.B., and S.P. Gessel. 1990. Technical note: Mineral deficiency symptoms of Pacific Northwest conifers. *Western Journal of Applied Forestry* 5(3):96-98.

Notes

Best Management Practices for Maintaining Soil Productivity in the Douglas-fir Region

Editors

Sam D. Angima, interim regional director, Oregon State University Extension; Extension staff chair and natural resource faculty, Lincoln County, Oregon State University, Newport, Oregon.

Thomas A. Terry, program manager, sustainable soil productivity, Weyerhaeuser Company (retired).

Authors

Alex Dobkowski, senior research forester, Weyerhaeuser Company, Centralia, Washington.

Steve Campbell, soil scientist, USDA Natural Resources Conservation Service, Portland, Oregon.

Jeffrey D. Grizzel, director of natural resources, Grant County Public Utility District, Ephrata, Washington.

Robert B. Harrison, professor of soil and environmental science, School of Forest Resources, University of Washington, Seattle, Washington.

Ronald L. Heninger, soil scientist, Weyerhaeuser Company (retired), Springfield, Oregon.

Douglas A. Maguire, professor of silviculture and biometrics, Hayes Professor of silviculture, and director of the Center for Intensive Planted-forest Silviculture, College of Forestry, Oregon State University, Corvallis, Oregon.

Richard E. Miller, soil scientist emeritus, USDA Forest Service, Pacific Northwest Research Station (retired), Olympia, Washington.

Deborah Page-Dumroese, research soil scientist, USDA Forest Service, Rocky Mountain Research Station, Moscow, Idaho.

William Scott, soil scientist, Weyerhaeuser Company (retired), Puyallup, Washington.

Darlene Zabowski, professor of forest soils/soil genesis and classification, School of Forestry Resources, University of Washington, Seattle, Washington.

Reviewers

The editors recognize the following reviewers for their input in enhancing the contents of this publication:

Jim Reeb, Ph.D., Extension forestry agent, Lincoln County, Oregon State University.

Paul Adams, Ph.D., Extension watershed management specialist, Department of Forest Engineering, Resources and Management, College of Forestry, Oregon State University.

Jim Boyle, Ph.D., professor emeritus, Department of Forest Resources, College of Forestry, Oregon State University (retired).

Scott Holub, Ph.D., Weyerhaeuser Company.

Shannon Berch, Ph.D., P.Ag., research scientist, British Columbia Ministry of Forests, Mines, and Lands.

Steve Cafferata, area forester, Weyerhaeuser Company (retired); family tree farm owner.

Background photo on first and last page by Tom Gentle, © Oregon State University.

Published April 2011.