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keeping your forest soils healthy and productive

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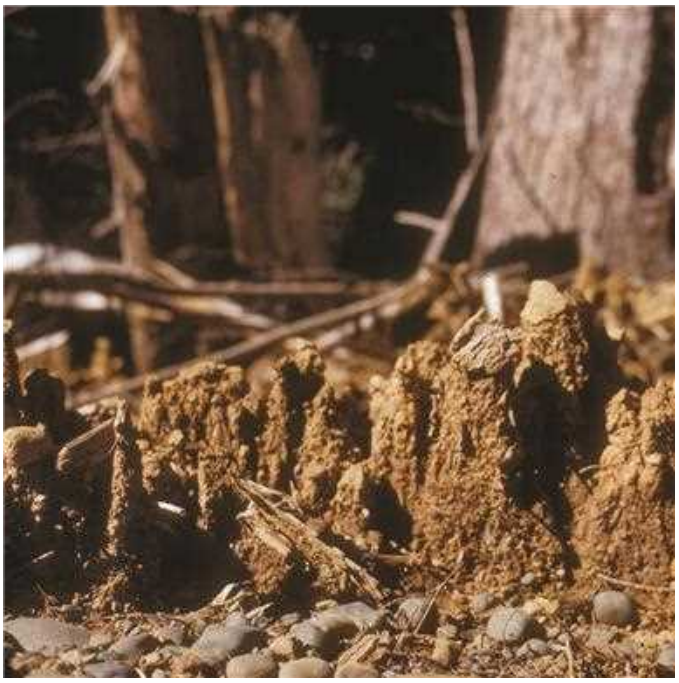

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Keeping Your Forest Soils Healthy and Productive

Authors: Ole T. Helgerson and Richard E. Miller

Why forest soils are important to you

Soils are an integral structural part of your woodland and the larger forest ecosystem. Important forest soil functions include:

- Providing water, nutrients, and physical support for the growth of trees and other forest plants
- Allowing an exchange of carbon dioxide, oxygen, and other gasses that affect root growth and soil organisms
- Providing a substrate for organisms linked with vital ecosystem processes
- Harboring root diseases and other pests
- Affecting water quantity and quality

Thus, how you protect and manage forest soils affects your forest's short- and long-term productivity and the water quality of adjoining streams and lakes, including their suitability for fish habitat and other uses.

This publication will provide you with:

- An understanding of soil characteristics important to woodland management
- Management practices for maintaining and enhancing soil quality
- A guide for obtaining soil-specific information from USDA soil surveys
- A list of useful references
- A glossary of forest soil terminology

Forest soil development and components

Washington has many different forest soils that result from various combinations of five soil-forming factors. Despite the large number of soil types in this state, the same soil management principles generally apply to all soils. The following discussion of the five soil-forming factors (Fig. 1) provides a useful foundation for understanding forest soils—their characteristics, functions, and management.

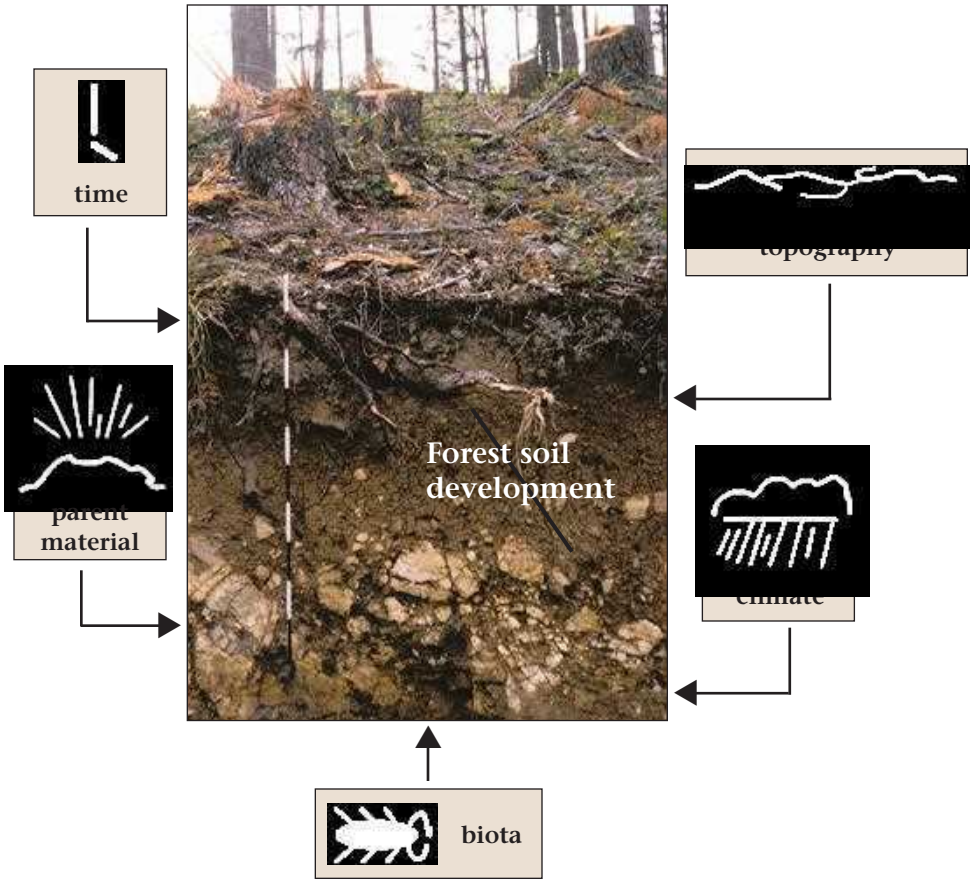

Figure 1. **Washington's climatic, geologic, and related biotic differences create a wide range of soil types when combined with time.**

Images courtesy of Dr. Richard Miller, USDA Forest Service, retired

PARENT MATERIALS

Parent materials are the substrate on which other soil-forming factors act. Most Washington forests grow on mineral soils derived from rock, also called mineral soils. Parent materials vary across Washington's physiographic and geologic provinces (Fig. 2), and strongly influence soil characteristics. For example, forest soils derived from volcanic rocks in the southern Washington Cascades, or from uplifted marine sediments in the Coast Ranges, are generally fertile, but vary in depth, rock content, and water-holding capacity. Glacial deposits are common parent materials in the Puget Trough and Olympic Peninsula. Associated soils vary greatly in productivity because these deposits range from coarse gravels and sands to compacted tills containing much clay and silt. Granite-derived soils, which are found mostly in the North Cascades and Okanogan Highlands, have both poor fertility and

water-holding capacity, and erode readily on steep slopes. These geologically complex areas offer diverse mixes of parent materials.

Many East-side (i.e., that part of Washington east of the Cascade Range Crest) soils originally derived from native rocks are overlain by or mixed with volcanic ash, coarse pumice, or windblown, silty deposits called loess. Throughout Washington, volcanic eruptions, floods, and landslides bury and relocate existing soils and rocks, reassembling parent materials for new soils. These natural events can be small and localized, involve entire mountainsides, or as with volcanic ash fall, cover hundreds of miles.

Figure 2. Broad-scale differences in the geology, climate, and vegetation of Washington's physiographic and geologic provinces yield distinct soil types.

Adapted from Franklin and Dyrness, 1973

Soil parent materials in your locale are described in your county's soil survey report, local Natural Resources Conservation Service (NRCS) office, or NRCS Web site (http://soils.usda.gov/survey/online_surveys/washington/index.html).

TIME Physical and chemical weathering and biological processes gradually change parent materials into recognizable layers or horizons of different color, texture, and structure (Fig. 3). These processes also release nutrients from organic matter and soil minerals. Most released nutrients are captured by vegetation and later recycled in organic residue.

CLIMATE Horizon development starts when newly exposed parent materials are exposed to weathering. Some forest soils, such as those found in the blast zone of Mt. St. Helens or on recently exposed glacial till, are extremely young with little or no horizon development. Soils that are thousands or even millions of years old can have strongly developed horizons. Soils generally become more productive as they develop structure and accumulate organic matter and related nutrients. However, extremely old soils in high-rainfall areas can be leached of many of their mineral nutrients.

Climate affects soil development mostly through precipitation and temperature. Soils develop faster in the warmer, wetter climates found on the west side of the Cascade Range compared to colder or drier climates such as higher elevation or East-side sites. Climate also helps determine vegetation and soil biota, which affect soil development.

TOPOGRAPHY Topography influences soil formation largely through its relationship with climate and the effects of gravity combined with slope. Precipitation,

cloudiness, and temperature change with elevation and distance from the ocean, while solar radiation inputs change with slope, aspect, and cloud cover. These topographic-climate interactions affect rates of soil development through soil movement on steeper slopes, plants, and soil organisms. The net result is that soils tend to be thicker and more productive on north-facing slopes (because more vegetation is present) and near the base of a slope (because of gravity-caused soil and water movement), but thinner and rockier on south-facing slopes and near ridge-tops. Soils in depressions or near the bottom of slopes may be wet enough to become hydric, which means they are "sufficiently wet in the upper part to develop anaerobic conditions during the growing season" (NRCS, 2007). Such soils can require special management, especially during timber harvest. Contact your local NRCS or Washington Department of Natural Resources (DNR) office if you think your woodland has hydric soils.

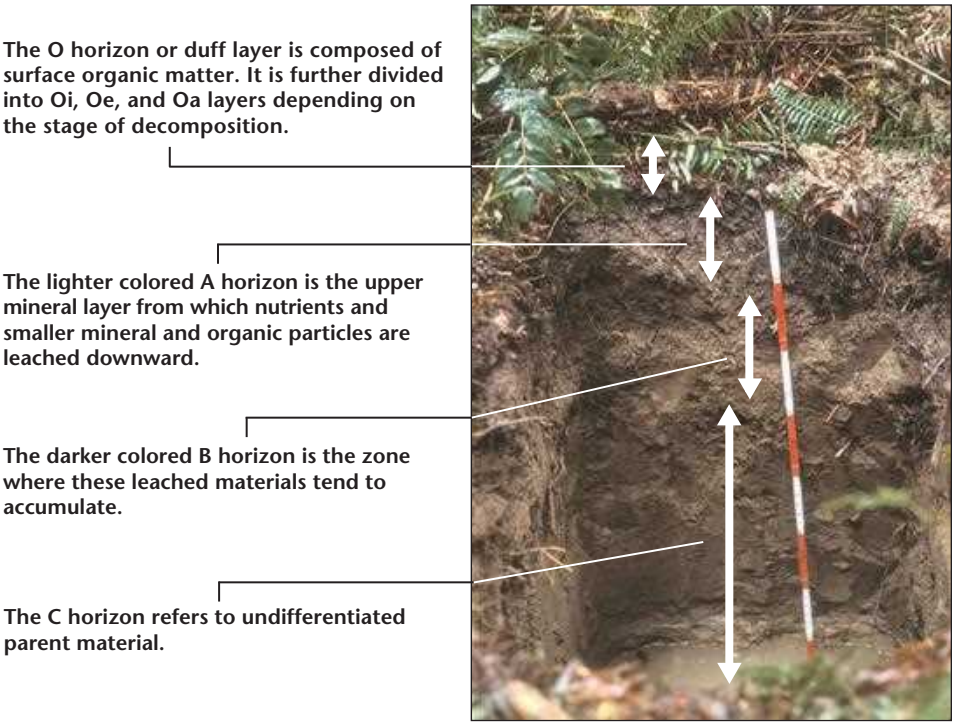

Figure 3. **A simplified forest soil profile illustrating soil horizons. Horizon development is a useful indicator of soil type. The O, A, and B horizons hold most of a soil's nutrient capital and biologic activity.**

Image courtesy of Dr. Richard Miller, USDA Forest Service, retired

BIOTA

Soil biota consist of a complex food web of plants, vertebrates, invertebrates, and microbes interacting among themselves and with mineral and organic soil components (Fig. 4; Table 1). Although much remains to be discovered about soil biota, they are known to be essential to forest productivity by:

- Absorbing, transforming, retaining, and releasing mineral nutrients from organic matter and mineral soil
- Adding nitrogen (N) through biological N-fixation
- Building soil structure, which increases aeration, water absorption, and water-holding capacity
- Enhancing water and nutrient uptake by trees and other vegetation

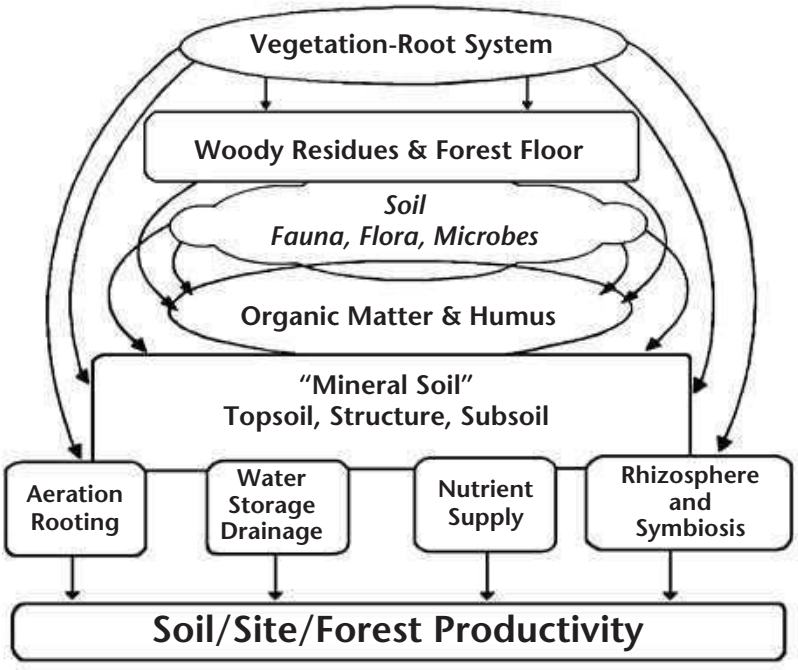

Figure 4. **Forest soil productivity depends on interactions among many components to create conditions for tree, mushroom, and other forest product growth. Management practices that adversely affect any one of these key components may reduce overall productivity.**

Adapted from Powers et al., 2000

Table 1. **Some organisms found on and in forest soils have significant impacts on forest health.**

Soil Organism	Function or Effects
Plants	
• Trees, shrubs, and forbs	Key sources of photosynthesis that provide food (energy), structure, and biochemicals for nearly all other soil organisms; organic matter provides habitat and benefits soil properties
Mammals	
• Domestic and wild grazing animals	Generate manure that speeds nutrient cycling; excessive grazing can compact soils and reduce organic matter inputs and soil aeration
• Mountain beaver and pocket gophers	Food for predators; potentially serious reforestation pests
• Flying squirrels	Eat mycorrhizal truffles and spread spores; food for predators
• Humans	Variously decrease, maintain, or enhance forest productivity
Insects	
• Shredders (termites, millipedes, sowbugs, wood borers, carpenter ants, pen-knife turtle mites)	Provide initial breakdown of plant tissue, including wood
• Fungivores (turtle mites, springtails)	Eat fungal mycelia; release nutrients near roots
• Predators (predacious mites, ants)	Recycle nutrients from other insects; help decompose wood
Worms, nematodes, and molluscs	Intermediate decomposition and nutrient cycling
Fungi	
• Mycorrhizae	Essential for most trees and many other plants
• Decomposers	Initial nutrient cycling and decomposition of wood into humus (e.g., brown cubical rot); create wildlife habitat
• Pathogens	Important as yield-reducing root diseases; decompose wood into humus; accelerate forest succession from blowdown; provide wildlife habitat
• Edible mushroom species	Support human economies
Microbes	
• Protozoa	Graze on rhizosphere bacteria; release nutrients
• N-fixers	Add between 1 and 150 lb of N per acre (1–170 kg/ha) per year
• Nitrifying bacteria	Convert ammoniacal N (NH_3) from proteins to highly plant-available nitrate (NO_3)
• De-nitrifying bacteria	Remove oxygen from nitrate, releasing N to the atmosphere
• Element transformers	Transform chemical states of sulfur (S), iron (Fe), and manganese (Mn)

A single square meter of forest soil may support 250,000 arthropods ranging in size from the microscopic mite to the highly visible, orange-striped, shiny, black millipede (Fig. 5). Millipedes eat between one-third to one-half of the deciduous and conifer foliage that falls to the forest floor. Their fecal pellets provide food for smaller arthropods and microbes. A single gram of soil may hold numerous kilometers of mycorrhizal hyphae and tens to hundreds of millions of bacteria representing more than 10,000 species. As much as 50 percent of a tree's photosynthesis may be used to support its fine roots and the fungi and bacteria in the surrounding 2–3-mm-thick rhizosphere.

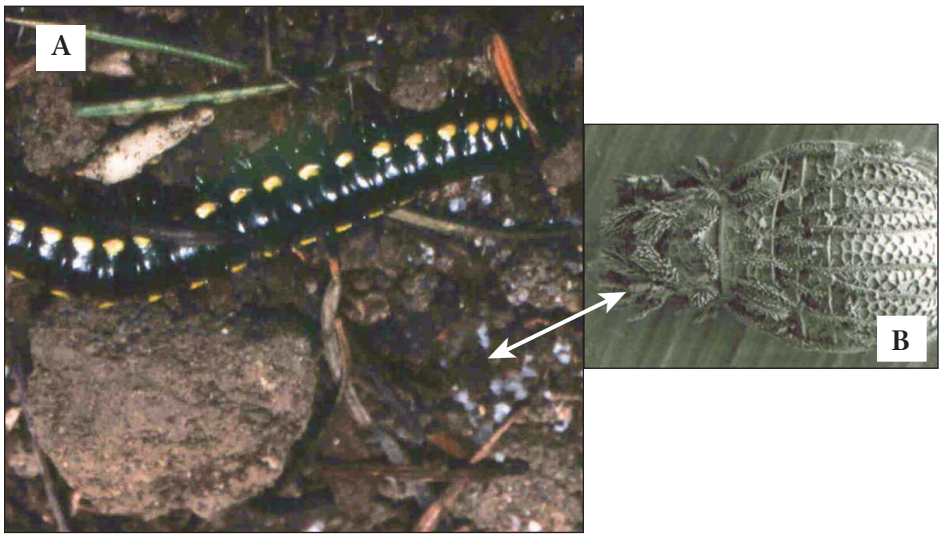

Figure 5. **Forest soil biota include an extraordinary array of arthropods, such as this millipede (A) and microscopic turtle mite (B), that are essential for decomposing organic matter and recycling nutrients.**

Images courtesy of Dr. Andy Moldenke, Oregon State University

Whereas soil-forming factors are largely outside human control, forest practices can greatly affect soil biota. Unfortunately, many of the consequences of these practices on soil biota are as yet unknown. Maintaining adequate levels of organic matter and minimizing soil compaction appear to generally benefit all soil biota. Research provides further useful insights about the management of three important soil biota types: mycorrhizal fungi, N-fixers, and pests.

Mycorrhizal fungi and their management

Many species of mycorrhizal fungi symbiotically colonize Pacific Northwest tree and shrub roots, most commonly as ectomycorrhizae living on the outside of stubby rootlets (Fig. 6), but also as endomycorrhizae within roots. Mycorrhizae are especially important because many tree and shrub species do not grow well, if at all, without them. For the host plant, mycorrhizal benefits include greatly magnified water and nutrient uptake, enhanced nutrient cycling, disease protection, soil development, and interconnected plant root systems by thread-like mycorrhizal hyphae. This latter function may help reduce competition among plants of

different species. Above-ground fruiting bodies of mycorrhizal fungi also provide high-value chanterelle and matsutake (pine) mushrooms, while underground fruiting bodies provide truffles. Flying squirrels eat truffles, spreading truffle spores, and in turn provide food for predators such as the northern spotted owl.

Although mycorrhizal fungi populations change as forests develop, forest practices can also alter their numbers. Timber harvest, site preparation, and fire can shift mycorrhizal fungi populations and in extreme situations reduce mycorrhizal benefits and seedling growth. To sustain mycorrhizal fungi:

- Avoid or greatly restrict soil compaction.
- Obtain prompt reforestation after timber harvest.
- Leave cull logs and patches of undisturbed duff.
- Retain scattered standing conifers as well as hardwoods and shrubs that co-host conifer mycorrhizae.

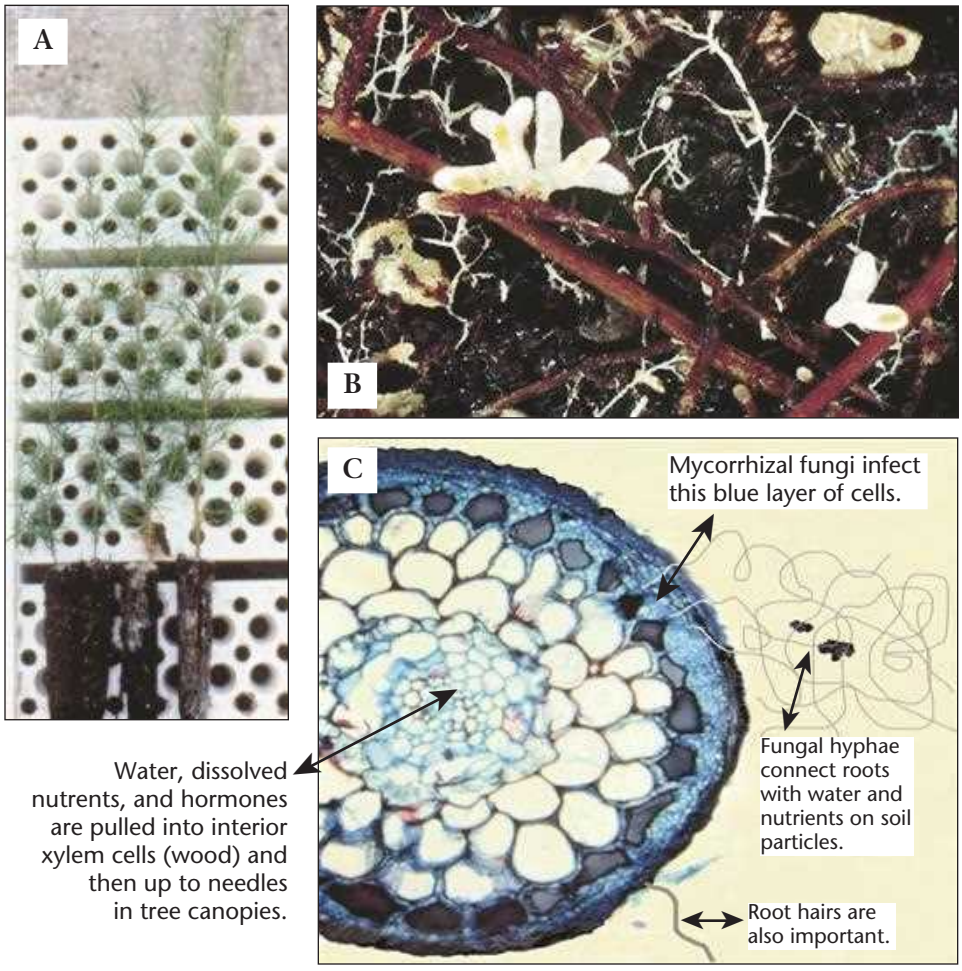

Figure 6. White mycorrhizal hyphae can form a mycelial mat on Douglas-fir seedlings (A), while ectomycorrhizal root tips will grow on lodgepole pine (B). This ectomycorrhizal root cross section illustrates how mycorrhizae aid water and nutrient uptake (C).

Image A courtesy of Dr. Michael Castellano, USDA Forest Service; Image B courtesy of Dr. James Trappe, USDA Forest Service, retired; and Image C courtesy of Dr. Randy Molina, USDA Forest Service

The benefits of treating seedlings with cultured mycorrhizal inoculum are not clearly defined. The current thinking is that mycorrhizae species infecting nursery seedlings and those found at planting sites are sufficient for most reforestation, but seedlings planted in highly disturbed soils, especially granitic soils or pastures being converted to forest, may benefit from supplemental mycorrhizal inoculation, either from commercial inoculum or soil obtained from a nearby healthy forest stand.

For additional information on mycorrhizal fungi pertaining to Pacific Northwest forests, see http://www.fs.fed.us/pnw/mycology/index.html. Perry (1994) also provides a good description of mycorrhizae in forest soils.

N-fixers and their management

Three groups of soil microbes fix atmospheric N into a usable form: free-living soil microbes, microbes in the rhizosphere surrounding roots, and symbiotic microbes that fix N within root nodules on plants such as red alder, *Ceanothus* species (Fig. 7), and legumes. Some atmospheric N is also fixed above ground by lichens on tree branches. Annual rates of N-fixation are about 1 lb/acre for free-living microbes, 2–3 lb/acre for rhizosphere microbes, and up to 150 lb/acre or even more for red alder. Symbiotic N-fixation rates are greatest when growth of the host plant is rapid, and thus supportive of these organisms. Fixation rates are slower on productive sites already rich in N. Conversely, rates can be high on infertile sites such as glacial outwash.

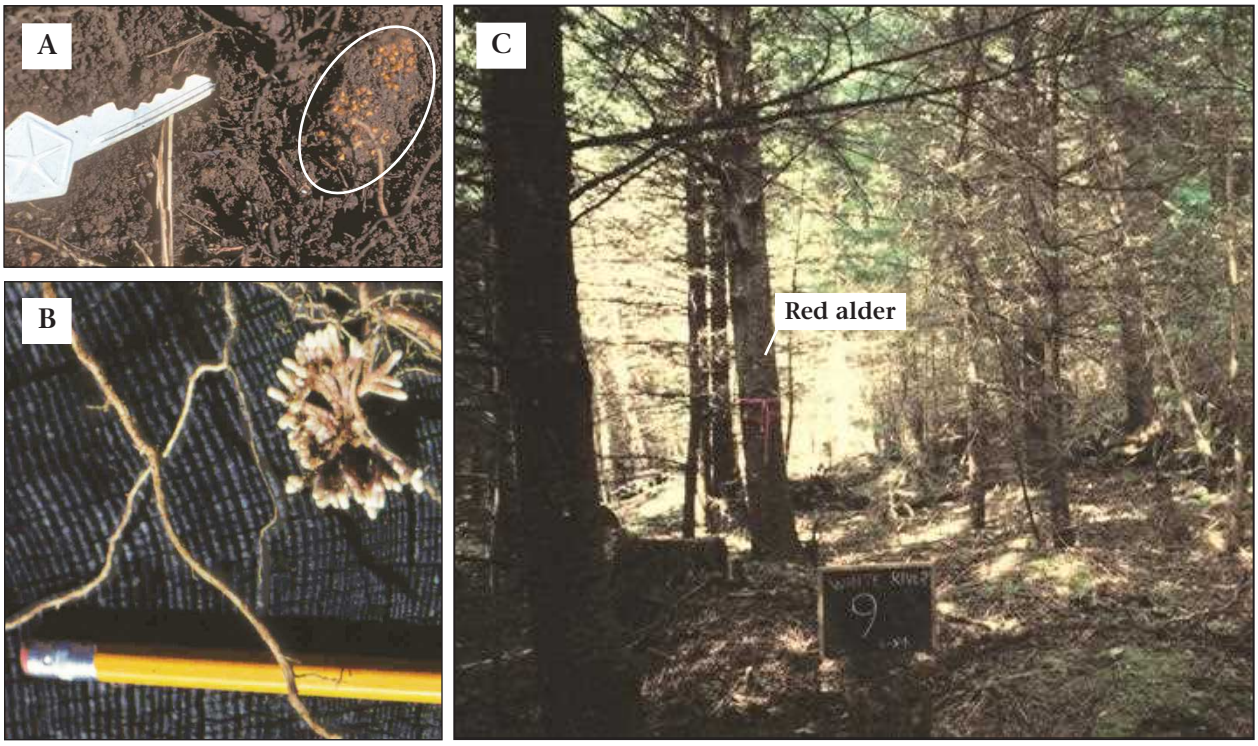

Figure 7. **N-fixing root nodules on red alder *(Alnus rubra)* are common to West-side forests (A), while slickleaf Ceanothus *(Ceanothus velutinus)* are common to many East-side forests (B). In return for photosynthate from the host plant, the microbes in the nodules convert nearly inert atmospheric N_2 into a form plants and animals can use. On suitable sites, red alder will improve the growth of Douglas-fir, as seen in this 20-year-old mixed species stand (C).**

Images courtesy of Dr. Richard Miller, USDA Forest Service, retired

Symbiotic N-fixing host plants can increase growth of adjoining conifers. However, there is a tradeoff in mixed-species stands because the amount of N fixed is proportional to the number and vigor of the N-fixers. For example, more and more vigorous N-fixing alder mean fewer surviving coniferous crop trees. If uncontrolled, N-fixers such as scotch broom (also a persistent noxious weed), red alder, and *Ceanothus* species can suppress or even eliminate conifers. Individual conifers that survive may be exceptionally large, but too few in number to improve conifer yields per acre.

Using N-fixers to increase productivity is most feasible on N-deficient but otherwise productive sites. To keep the number and size of N-fixers at levels that do not suppress the desired number of conifer crop trees, cut or use herbicides. An alternative solution is to use less competitive N-fixers such as clover or introduce N-fixing plants after crop trees are established and when surplus growing space is available, such as after pre-commercial or commercial thinning.

The benefits of red alder on an N-poor site were documented in southwest Washington (Miller and Murray, 1978). There, at a stand age of 30 years, Douglas-fir growing with red alder averaged more than two-fold the stem volume than trees in the adjoining pure Douglas-fir stand. Growth benefits extended about 50 feet beyond the mixed-species stand. Spacing red alder trees at 30-foot intervals (about 50 trees per acre) within N-deficient Douglas-fir stands is suggested to provide a reasonable balance between N-fixation by red alder and loss of growing space for Douglas-fir.

On droughtier East-side sites, shrubby N-fixing *Ceanothus* species can quickly occupy sites after timber harvest or site preparation and kill or suppress conifer seedlings. Research clearly suggests that controlling grass and shrubs in such environments in the first few years after planting greatly increases seedling survival and growth. Compared to West-side forests, research is less clear as to whether long-term conifer growth can be increased by associated N-fixers on the East side, on which sites it is feasible, or how many N-fixers are needed.

Soil pests and their management

Some soil biota create extensive management problems. Soil pathogens include common root diseases such as laminated root rot (*Phellinus weirii;* Fig. 8), *Annosus* root rot, and *Armillaria*. Root diseases can be reduced during harvest, site preparation (postharvest treatments used to enhance reforestation), and reforestation. Methods include tip-over felling (pushing trees over to expose the larger roots), removing stumps, treating stumps in thinned units with registered borax products, and planting resistant tree species (Hanley and Edmonds, 1999). However, stump removal may not expose all diseased roots to drying and can compact clayey soils.

Additional information on insects and diseases affecting Pacific Northwest forests can be found at http://www.fs.fed.us/r6/nr/fid/wid.shtml.

Mammal pests include mountain beaver (*Aplodontia rufa*) and pocket gophers (*Thomomys* sp.), which can destroy young conifers unless intensive control measures are taken to secure successful reforestation. These pests are most effectively controlled during site preparation and planting by trapping or baiting in accordance with federal and state regulations.

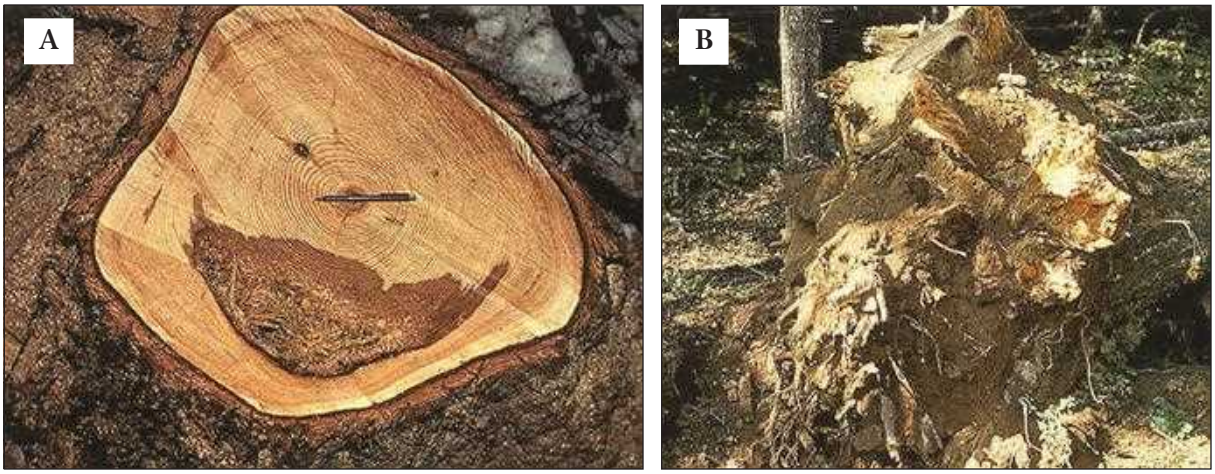

Figure 8. **Laminated root rot inhibits growth in Douglas-fir and grand fir, as indicated by crescent-shaped stump decay (A), a windthrown tree (B), and de-laminating roots (C). Other symptoms include poor crown growth and excessive production of small cones.**

Images courtesy of USDA Forest Service

Soil physical attributes

Key physical attributes of forest soils affecting management practices are organic matter, texture, structure, and bulk density. Understanding these attributes is important for appraising the risk of compaction and erosion during timber harvest and site preparation as well as hastening recovery of damaged soils toward more productive conditions.

ORGANIC MATTER

Organic matter is supplied to the soil from above- and below-ground sources. Above-ground organic matter originates mostly from plants, with some from animals. Forest litter, including slash after logging, ranges greatly in amount, size, nutrient content, and stage of decomposition (Fig. 9). Historically, moist forests on the Olympic Peninsula contained at least 100 tons per acre of above-ground organic matter compared with about one-fourth or less of those amounts on droughtier East-side sites (see the section on "Fire and forest soils," page 20). Plants also provide organic matter directly within soil from root exudates and the yearly death of fine roots.

Decomposition rates are based on the size and nutrient content of organic matter, which range from coarse woody debris (CWD) consisting of snags, large logs, and branches down to 3 inches (75 mm) in diameter; forest floor litter or duff (smaller branches, needles, and leaves); and microscopic bits of humus. Foliage tends to decompose most quickly because of its small size and high nutrient content. Wood decomposes more slowly than foliage because of its lower mineral content, with larger-sized pieces decomposing the slowest. Logs can provide a long-term source of plant nutrients because of their considerable volume.

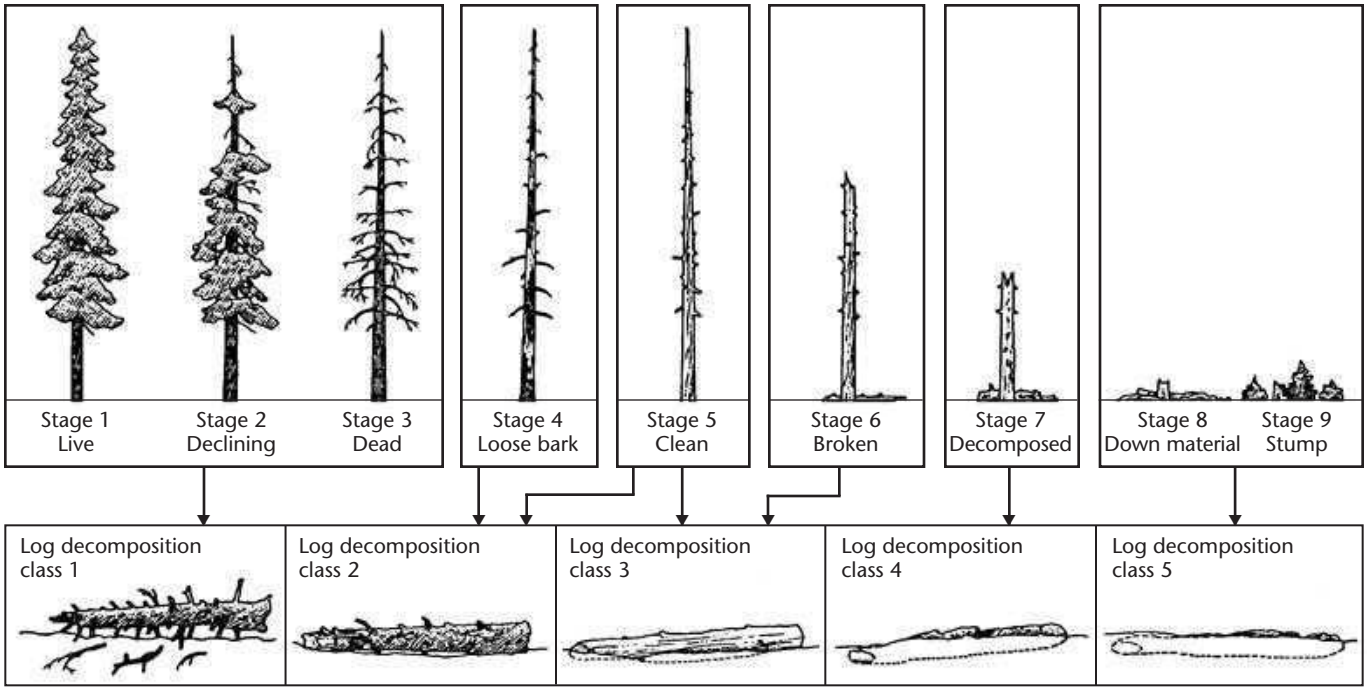

Figure 9. **Snags (standing dead trees) in various decay classes (stages of decomposition) are important to soil productivity and wildlife. Lines connecting snags with logs denote possible log decomposition classes that a snag could fall into. Decomposition rates vary by size and species.** ***Adapted from Pederson, 1995***

Atop the mineral soil, duff is known as the O horizon (Fig. 3), which is subdivided into the Oi layer (easily recognizable undecomposed litter), the Oe layer (somewhat recognizable partially decomposed debris), and the Oa layer (unrecognizable bits of organic matter or humus).

Humus is organic matter nearing its end stage of decomposition after being processed by various soil biota. Sizes range from visible to microscopic specks. Humus has a high proportion of compounds such as lignins that resist digestion by soil flora and fauna, and is important in retaining nutrients and building soil structure.

Organic matter roles

Organic matter on and in the soil provides the following important functions:

- Food and habitat for creatures ranging from arthropods and microbes to birds and mammals
- Protection of underlying mineral soil from water erosion
- Retention and cycling of nutrients
- Improvement of soil structure
- Increased water-holding capacity
- Stabilization of soil on slopes

Organic matter management

Timber harvest and site preparation can affect both the amount and distribution of organic debris left on a site. Some practical questions are: how much and what sizes should be left to maintain productivity while allow-

ing access for reforestation and managing wildfire risk? Although definitive answers are not yet available, current research indicates that:

- CWD amounts differ by forest type: historically drier, more fire-prone East-side forests typically held less CWD than wetter, West-side sites.
- Organic matter is especially important for retaining water and nutrients in thin soils and those lacking clay or volcanic ash.
- A variety of CWD sizes and decomposition stages is desirable.
- Larger-sized CWD benefits particular wildlife species and serves as "ecologic legacies" for future forest stands.
- Forests managed for timber typically hold less dead wood than unmanaged forests.
- The amount of dead wood needed beyond the minimum required by forest practice regulations depends on the landowner's objectives.

Specific practices for managing CWD during timber harvest and site preparation include:

- Retaining cull logs and standing trees onsite as required by forest practice codes
- Minimizing duff disturbance and exposure of the mineral soil by designating skid trails or restricting the area to machine traffic
- Limbing trees before yarding, or returning branches removed at the landing to the harvested area
- Machine-piling slash to the minimum extent needed for planting access and fuels mitigation
- Leaving slash unburned or broadcast burning under moist or cool conditions

On one western Washington tree farm, previously unburned tractor-piled windrows created during brushfield rehabilitation were used as skid trails decades later during commercial thinning. The remaining mat of branches in the windrows helped protect the soil during harvest and yarding (O. Helgerson, personal observation).

SOIL TEXTURE

Soil texture refers to the proportions of three size classes of mineral particles (sand, silt, and clay) within a particular soil (Fig. 10). Soil texture is important because it strongly affects water- and nutrient-holding capacity, soil structure, and resistance to compaction (such as from heavy equipment used in logging, site preparation, and road construction). Most soils contain a mix of particle sizes, though sometimes one size dominates. To determine soil texture, feel the soil. Sand feels gritty and is visible as particles, silt feels silky (like flour), and clay feels sticky. The more clay a soil has, the more easily it can be squeezed into a ribbon or rolled into a thread when wet.

Sandy soils, because of their large pores, absorb and release water rapidly, are well aerated, and hold few nutrients. Sandy soils are often called light because they are easily worked. Silty soils hold and release water efficiently, offer good aeration, but can have weak nutrient-holding ability. Clay soils, with their very small pores, absorb water slowly and hold it tightly, and may become too poorly aerated for root growth. Clay particles, like similarly small humus particles, have large negatively-charged surfaces relative to their size that can hold positively-charged mineral nutrients such as calcium (Ca^{++}), magnesium (Mg^{++}), and potassium (K^{+}). Clay soils

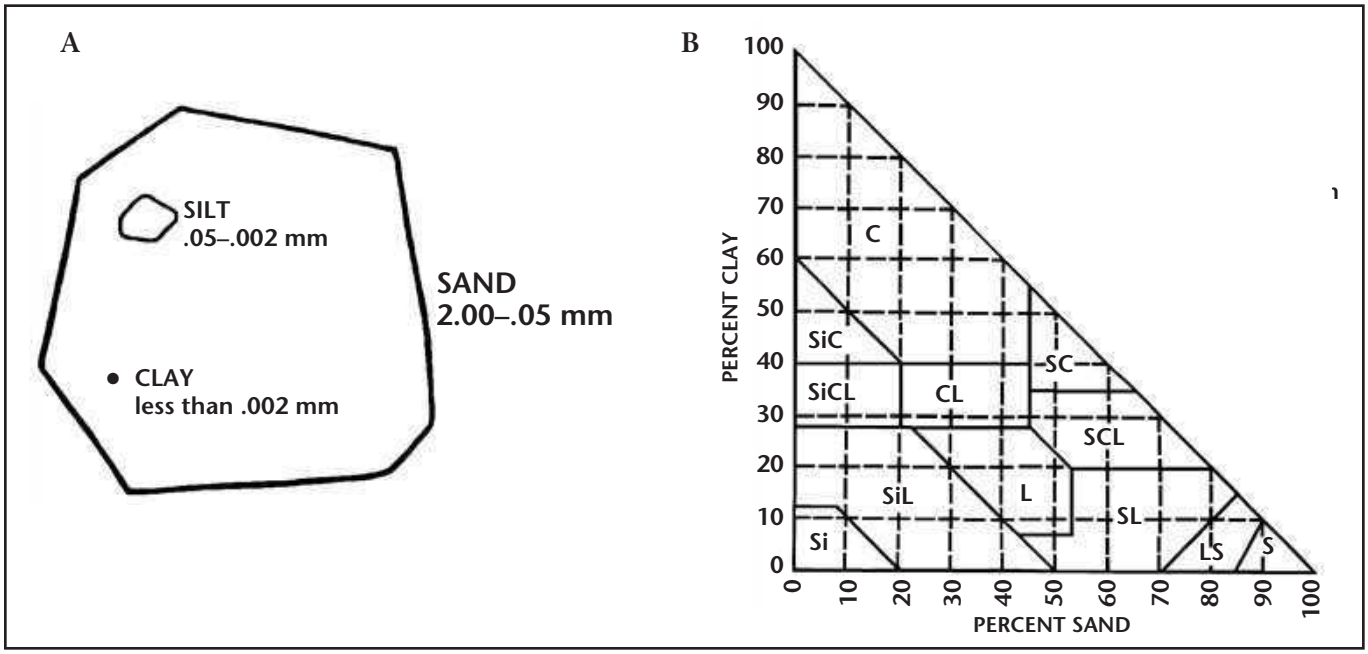

Figure 10. **Relative sizes of sand, silt, and clay particles (A) and percentages of clay and sand represent soil texture classes (B).**

Adapted from Johnson et al., 1990

are often called heavy because they are difficult to work. Loam-textured soils, which contain a mix of sand, silt, and clay, provide a range of pore sizes, and generally favor tree growth because they have an optimal combination of water availability (Fig. 11), aeration, and nutrient-holding ability. Conversely, large rock fragments (gravel, cobbles, stones, and boulders), which can occupy a significant volume within some forest soils (Fig. 12), reduce the amount of fine soil available for storing moisture and nutrients, and thus tend to reduce productive capacity.

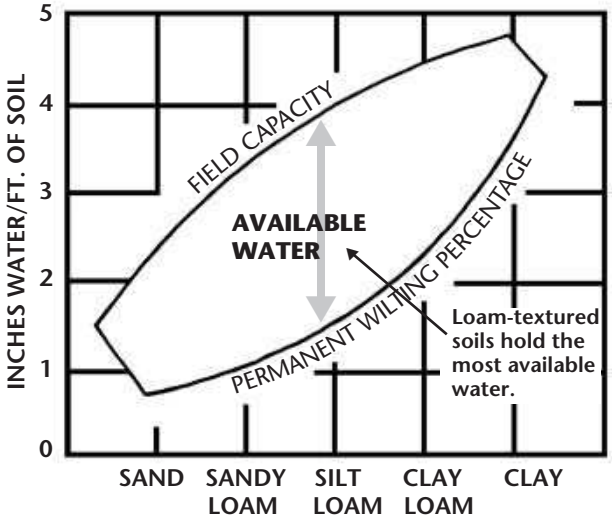

Figure 11. **The ability of a soil to hold water available to plants depends largely on soil texture. Field capacity represents water that soils retain temporarily against the pull of gravity, while the permanent wilting percentage represents a soil water content too low to keep most plants alive.**

Adapted from Johnson et al., 1990

Soil texture management

Forest management activities should be designed around soil texture. For example, clay soils typically are firmer than other soil textures when dry, but much more susceptible

to compaction, rutting, and puddling when moist or wet. Clayey soils thus create problems in forest road design. Retaining organic matter benefits forest productivity by increasing structure and aeration in clayey soils and water-holding capacity in sandy soils.

For a more in-depth discussion of soil texture and forest road design, see Kramer (2001).

Figure 12. **When large rock fragments occupy a large volume of soils, the amount of fine soil needed for plant growth is reduced.**

Image courtesy of Dr. Richard Miller, USDA Forest Service, retired

SOIL STRUCTURE AND BULK DENSITY

Soil structure refers to how a soil's sand, silt, clay, and humus particles assemble into larger particles termed aggregates or peds that are glued together by clay, root exudates, and humus. The peds create pore space essential for forest productivity. Productive forest soils have about 50–70 percent total pore space, which is composed of larger pores between peds and finer pores within peds. The large pores release water more quickly, promoting exchanges of oxygen, carbon dioxide, and other gasses, while the fine pores hold water more tightly for slower release during the growing season. In clayey soils, large pores enhance tree growth by providing aeration; in sandy soils, small pores increase water-holding capacity.

Bulk density is the oven-dry weight of soil occupying a given volume, including both particles and pore space. A large increase in soil bulk density caused by equipment traffic is a good indicator of reduced soil pore space and structure. Forest soil densities typically range from about 0.8 to 1.3 Mg/m^3 (megagrams per cubic meter). Productive forest soils typically have low bulk densities, often below 1.0 Mg/m^3 (about 62 pounds per cubic foot). Compared to total soil bulk density, the density of solid mineral sand, silt, or clay particles (individually, without pore space) is about 2.65 Mg/m^3 or 164 pounds per cubic foot.

***A note on conversion factors*: Soil scientists use metric nomenclature. A megagram equals 1,000 kilograms or about 2,200 pounds. A cubic meter is equivalent to 35.4 cubic feet or 1.31 cubic yards.**

Soil structure management

Soil structure develops slowly, but quickly changes after compaction and puddling (complete loss of structure) from the weight, traction slippage, and vibration of equipment traffic. As large pores are smashed into smaller

and discontinuous pores, bulk density and soil strength increase. Compacted (platy) soils are mechanically stronger and therefore better able to bear loads from logging equipment, but generally lose productivity (Fig. 13) because:

- Root growth is constrained by the mechanical resistance of stronger soil and reduced volume of readily available soil.
- Less water is available from decreased infiltration capacity (ability of precipitation to enter the soil), decreased porosity (ability to store water), and decreased percolation (ability of water to move through soil).
- Gas exchange is reduced, adversely affecting roots and soil biota.
- Soil biota are crushed.
- Soil erosion increases, especially on steep slopes.

Figure 13. **Platy structure in a silt loam soil indicates soil compaction. This was caused by repeated equipment traffic during timber harvest eight years earlier under wet conditions. Such soils have lost nearly all structure and productivity.**

Image courtesy of Dr. Richard Miller, USDA Forest Service, retired

The effects of soil compaction on productivity vary with soil texture. In coarse sandy soils with abundant large pores, some conversion to smaller pores can benefit plant growth because passage of water through the soil is delayed, increasing the amount of water available for plant uptake. In finer-textured soils, however, the consequences of compaction to plant roots and growth are usually negative, especially in clay where most large pores are between soil aggregates. Compaction smashes these aggregates, often resulting in soil layered in small plates, a visually apparent platy structure lacking large pores (Fig. 13). Compacted clayey soils can become so water-logged and oxygen-deficient that plant roots die.

Once soils are compacted, natural recovery of their structure is very slow, and tilling to reduce compaction is expensive. Thus, it seems prudent to minimize soil compaction. However, the amount of soil disturbance (compaction, rutting, and/or displacement) that is detrimental to productivity is difficult to define. One recommendation is to limit compacted and deeply rutted areas to less than 10 percent of the harvested area. Compaction and other soil disturbance are most likely during ground-based timber harvest and site preparation when soils are moist or wet. Techniques that can minimize soil disturbance include:

- Confining equipment to pre-designated skid trails (especially important for high ground-pressure haulers such as horses and rubber-tired skidders)
- Utilizing pre-existing skid trails or old windrows

- Limiting machine activity between skid trails to a single pass when harvesting or piling slash
- Operating when soils are dry (and strong), especially on clay-textured soils
- Operating when soils are frozen or covered with deep snow
- Using low ground-pressure machinery
- Using cut-to-length harvesters that lay a mat of branches ahead of the vehicle's tracks (Fig. 14)
- Piling the minimum amount of slash necessary to achieve fire management and reforestation goals
- Using shovels (hydraulic excavators) instead of tractors for piling slash
- Choosing long-tined brush rakes when using tractors for slash-piling
- Loosening highly compacted skid roads and landings with excavators or winged rippers (Andrus and Froehlich, 1983)

Figure 14. **Cut-to-length harvesters can place a mat of branches ahead of the machine to protect forest soil.** *Image courtesy of Dr. Richard Miller, USDA Forest Service, retired*

Logging systems vary in their effects on soil (Fig. 15). High ground-pressure horse logging is relatively benign because of the narrow skid trails and small areas compacted. Similarly, rubber-tired skidders can be less disruptive if restricted to designated skid trails or dry soils. When possible, low ground-pressure crawler tractors, excavators (shovels), and cut-to-length harvesters should also be restricted to designated trails.

On steep sites, properly designed skyline cable systems cause very little soil disturbance, especially compared to older style high-lead logging. Skylines typically hold the leading ends of logs above the ground until reaching the landing, whereas high-lead systems drag entire logs across the soil surface for much of the distance. Successful skyline operations entail knowledge and experience in selecting, rigging, and operating the appropriate cable system, and using intermediate supports when necessary. See Adams (1998) for further information on preventing forest soil compaction during timber harvest.

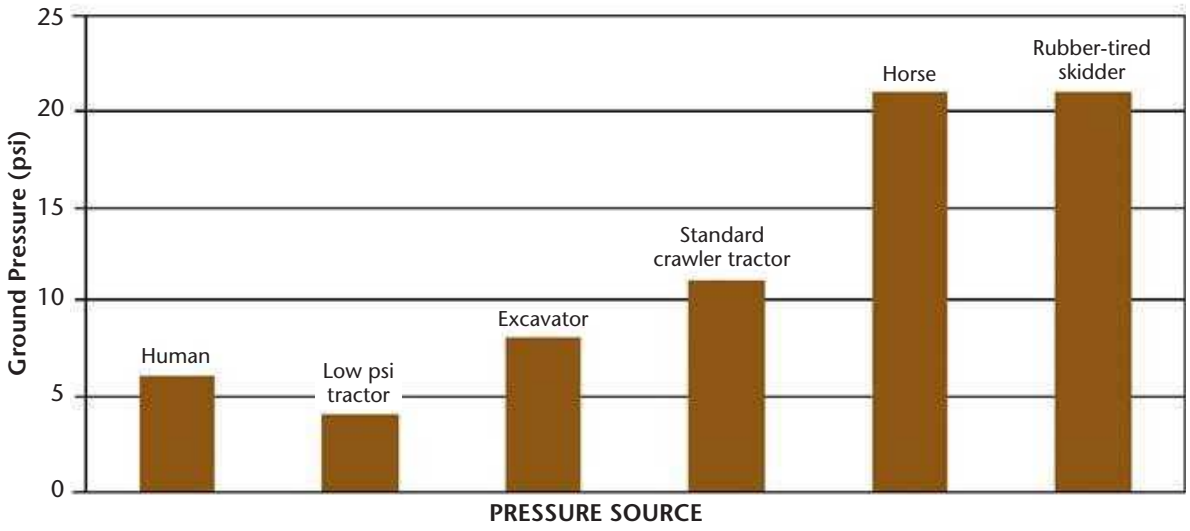

Figure 15. **Approximate standing or (static) ground pressures of a human, horse, and various types of forestry machinery indicate relative potential impacts to soil. Actual ground pressures also depend on load weight and slope gradient.**

The forest management system you select for your woodland can also affect the soil's productive capacity and subsequent tree growth. The potential for soil damage appears to be less for even-aged management systems because of the relatively few equipment entries during the life of a stand compared to uneven-aged systems that involve repeated harvest entries. For more information on management systems and timber harvest options, see Harvey et al. (1994) and Barg and Hanley (2001).

Soil nutrients

Although wood is largely carbon, hydrogen, and oxygen, plant growth still requires more than a dozen nutrients from the soil (Fig. 16). Most mineral nutrients are initially released from parent material by chemical weathering and bacterial-mycorrhizal action. For East-side forest soils, the relatively young loess or ash mantles can be an important nutrient source. Two nutrients, N and sulfur (S), are acquired from the atmosphere. Most N comes from biological N-fixation, while small amounts of N and S are gathered from natural and industrial processes via precipitation.

Nutrients are either retained and recycled within the soil or captured by plants and then recycled into the soil by the many types of soil-related organisms previously described (see Table 1). The net effect is that soil organic matter and soil microbes act together as a sponge to hold and slowly release most nutrients within forest ecosystems.

Trees can mediate nutrient availability. Red alder adds N and can increase phosphorus (P) availability, but tends to acidify soils. Western red cedar and big-leaf maple tend to provide Ca-rich litter, which can improve soil structure. A range of organic matter sizes helps provide a continuous release of nutrients over time. Leaves, needles, fine roots, and twigs decompose and release nutrients most rapidly because of their small size and nutrient concentrations. CWD decomposes more slowly, providing a longer-term nutrient source and habitat for soil organisms.

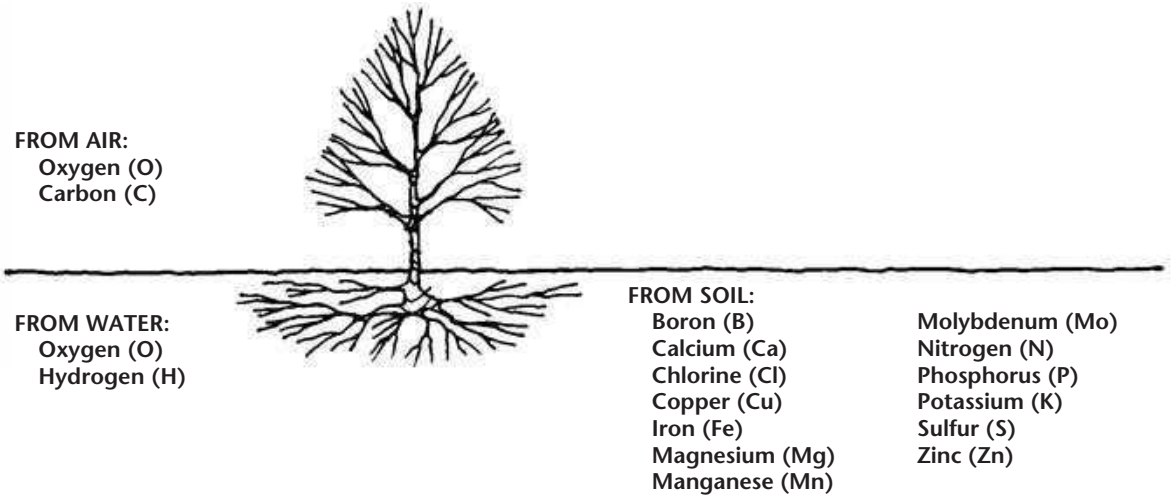

Figure 16. **The nutrients listed here are essential for tree growth. Growth is curtailed when one or more nutrients decline in supply below their optimum availability level. Conversely, plant growth can be increased by supplying one or more deficient nutrients.**

Adapted from Johnson et al., 1990

SOIL NUTRIENT MANAGEMENT

Because forest ecosystems inevitably lose nutrients, either naturally or from harvesting timber, there is much interest in nutrient management for maintaining long-term forest productivity. Research indicates ways that woodland management affects nutrient loss, but is less specific as to where, when, or how much nutrient loss decreases productivity. Removing tree trunks may have little effect on site productivity, but "cleaning up" branches and foliage (i.e., slash) appears to have greater potential for nutrient removal than leaving them onsite. Increased decomposition after timber harvest frees mineral nutrients from organic matter, which increases mineral nutrient leaching until the site is revegetated. Fire volatilizes nutrients into the atmosphere, which can also increase leaching and erosion, with highly variable effects (see the section on "Fire and forest soils," page 20).

Over the long term, the best way to ensure adequate amounts of nutrients on your woodland site is to hold sizes and amounts of organic matter that are compatible with fire risk and reforestation. Using N-fixing plants as previously described and applying fertilizer can also increase productivity. For East-side soils with a loess or ash mantle, minimizing surface soil disturbance is important in maintaining productivity.

Application of commercial fertilizers can increase tree growth where the nutrients erase growth-limiting shortages in the native soil. However, recommended fertilization practices differ between western and eastern Washington (Moore et al., 1988; Hanley et al., 2006). Contact a WSU Extension or Washington DNR forester before fertilizing to assist you in developing a plan consistent with your forest and management goals.

On the West side, increases in total volume growth tend to be greatest in stands with a below-average site index, and least on highly productive sites. Financial returns, however, are usually best from forests of

mid-quality. Applying about 440 lb per acre of urea prills (approximately 200 lb N per acre) 10 years before final harvest is advisable for several reasons:

- The growth effect lasts about 10 years.
- Increased growth goes onto trees most likely to be marketed.
- Investment costs are recovered sooner than if fertilizer were applied earlier.

Urea is a waxy, water-soluble, organic compound containing 46 percent N. Its high N content and ease of handling facilitate application. Prills are solidified droplets of molten urea that are available in a range of sizes. Urea is usually applied from a centrifugal spreader, either from the ground for smaller areas or by helicopter for larger projects (Fig. 17). Large prills are typically used in aerial applications. Applying urea during cool, wet weather minimizes volatilization.

Figure 17. **Helicopters are the usual means for spreading fertilizer in Northwest forests. For smaller projects, tractor-mounted or even human-carried centrifugal spreaders work well.** *Image courtesy of Dr. Richard Miller, USDA Forest Service, retired*

Douglas-fir and western hemlock typically respond well to N fertilizer in the Cascade Range and Puget Trough, but negligibly in coastal forests. On a poor-quality site, thinned 15–20-year-old western red cedar responded to both dicalcium phosphate and N (Harrington and Wierman, 1985). Application of bio-solids from sewage treatment facilities has also increased the growth of recently planted and older Douglas-fir stands (Harrison et al., 2002; Fig. 18).

For East-side forests, fertilizer prescriptions are more complex than on the West-side. Responses vary depending on soil parent material and habitat series (Moore et al., 1988).

Figure 18. **Commercial application of treated municipal sewage is an alternative to commercial fertilizers at Pack Forest near Eatonville immediately after clearcut harvest (A) and in a pole-sized stand of Douglas-fir (B).**

Images courtesy of Dr. Richard Miller, USDA Forest Service, retired

Fire and forest soils

Fire is a natural part of Northwest forest ecosystems that can significantly affect forest soils. Before European settlement, fires in dry East-side forests tended to be frequent (occurring on the order of decades), low-intensity (having relatively little heat output), and consumed mostly understory fuels and vegetation. Fires in wetter West-side forests tended to be infrequent (occurring on the order of centuries), high intensity, catastrophic, and stand-replacing. Fires of varying intensity tended to occur on terrain between these climatic regimes. Because of increased accumulations of fuels from past fire suppression, East-side forests now experience more frequent catastrophic fires.

Fire affects soil nutrient loss, erosion, and biota depending on its intensity and duration. Burning immediately releases N, P, and S to the atmosphere. Mineral nutrients leached from ash and bared mineral soil easily erode from the direct impact of rain and creation of a hydrophobic (water-repelling) layer below the soil surface, which reduces the soil's infiltration capacity for water.

An intense fire coupled with high-intensity rain can severely reduce soil productivity. In contrast, low-intensity fires, created by burning under cool and wet conditions or small fuel loads, retain more duff and organic matter, cause less damage to surface roots and soil biota, expose less mineral soil, and lose fewer nutrients (Harvey et al., 1994).

FUELS, FIRE, AND SOIL MANAGEMENT

Minimizing soil damage from fire is a prudent goal. However, on drier sites, prescribed fire can be a useful site preparation tool when relying on a mineral soil seedbed for natural regeneration or facilitating tree planting by removing slash. Prescribed fire must always be designed and conducted carefully to prevent damage to soil, residual trees, and surrounding property. Techniques that protect soils include mechanically reducing fuel loads and burning when weather and fuel conditions favor incomplete combustion of duff.

Amounts of CWD that balance wildfire risk with soil productivity, protection, and wildlife needs were researched in fire-prone northern Rocky Mountain forest types. Those results provide a guide for similar interior Washington forests. Estimated suitable CWD ranges (regarded as similar to the upper amount of pre-settlement fuel loads) are:

- 5–10 tons per acre for warm, dry ponderosa pine and Douglas-fir sites
- 10–20 tons per acre for cool Douglas-fir sites
- 8–24 tons per acre for cool lodgepole pine and low subalpine fir types

In that study, an 18-inch dbh (diameter at breast height, 4.5 feet above the ground) tree contributed about 1 ton of CWD (Brown et al., 2003).

Burning slash piles or conducting prescribed burns requires a permit from the Washington Department of Natural Resources. Contact your local forest practices forester for planning and permitting assistance before conducting prescribed burns.

Soil erosion and nutrient loss are greatest immediately after wildfire, especially on steep slopes. Erosion can be reduced by felling trees on contours, grass seeding, and mulching. Your local NRCS office can provide additional ideas and details on implementation.

Soils, sediment, and water quality

Healthy forest soils act like a giant sponge, absorbing precipitation, holding water against the force of gravity, and then slowly releasing it. In actively managed (working) forests, road construction, soil compaction, and organic matter removal from harvesting and site preparation can change the amount and timing of water flows and cause excessive soil erosion with the consequence of degrading water quality and fish habitat. Roads, particularly those built to older design standards or that are not maintained, are regarded as causing most of the soil erosion and stream sedimentation coming from managed Pacific Northwest forests (Fig. 19). Dry ravel (the gradual downslope movement of surface soil) from steep cutbanks can also fill ditches and end up in streams.

Landslides are another source of sediment in water. Landslides are usually shallow (less than 5 feet deep), fast-moving flows of soil and debris associated with saturated soils. Although they occur in undisturbed areas, under some conditions landslides are associated with timber harvest and road building (Fig. 20). Most landslides are small, but even so can plug ditches; large slides may dam rivers or destroy structures and human lives.

Landslide prediction is imprecise. Risk factors to watch for include high rainfall, slopes that are steep or have small ponds or depressions, pistol-butted (trunks curved into hillsides) or tilted trees, cracks in the soil, groundwater seepage, and topography showing hummocks or evidence of either old or recent landslides. The Washington DNR can assist in assessing risk if landslide indicators are present and developing suitable management practices.

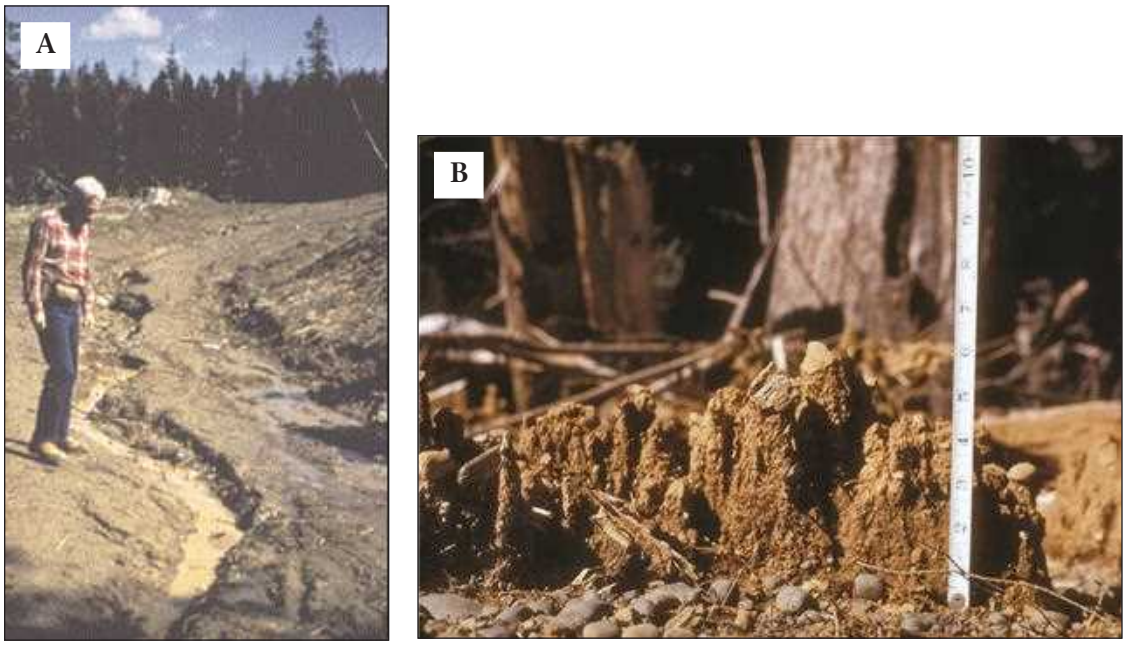

Figure 19. **Unless guided into the forest to be filtered, erosion from forest roads can degrade adjoining stream water quality (A) and create small castle-like columns under gravel and rock. A 6-inch erosion depth suggests that as much as 50 cubic feet of soil could have been lost from a 100-square-foot area (B).**

Image A courtesy of Washington Department of Natural Resources; image B courtesy of Dr. Richard Miller, USDA Forest Service, retired

Figure 20. **Landslides can vary in size from this small event to entire mountainsides. Although small, the soil movement shown here is enough to plug culverts and ditches, as demonstrated in the enlargement on the right.**

Images courtesy of Dr. Ole Helgerson, Washington State University

SOIL AND WATER QUALITY MANAGEMENT

Sound overall goals for soil and water quality management are to 1) keep as much soil as possible onsite and out of water bodies and 2) direct water and suspended sediment from road surfaces and ditches into an adjoining forest for filtration and slowed release into streams (Fig. 21). Techniques that can be used to maintain or repair the hydrologic function of your forest include good road design, construction, and maintenance. Rolling dips, water bars, culverts and other drainage diversion structures vary according to the type of road use and installation and maintenance costs. To assess which is best for a particular application, see Washington DNR (2006). Inspecting and cleaning ditches and culverts to prevent blowouts should be done annually.

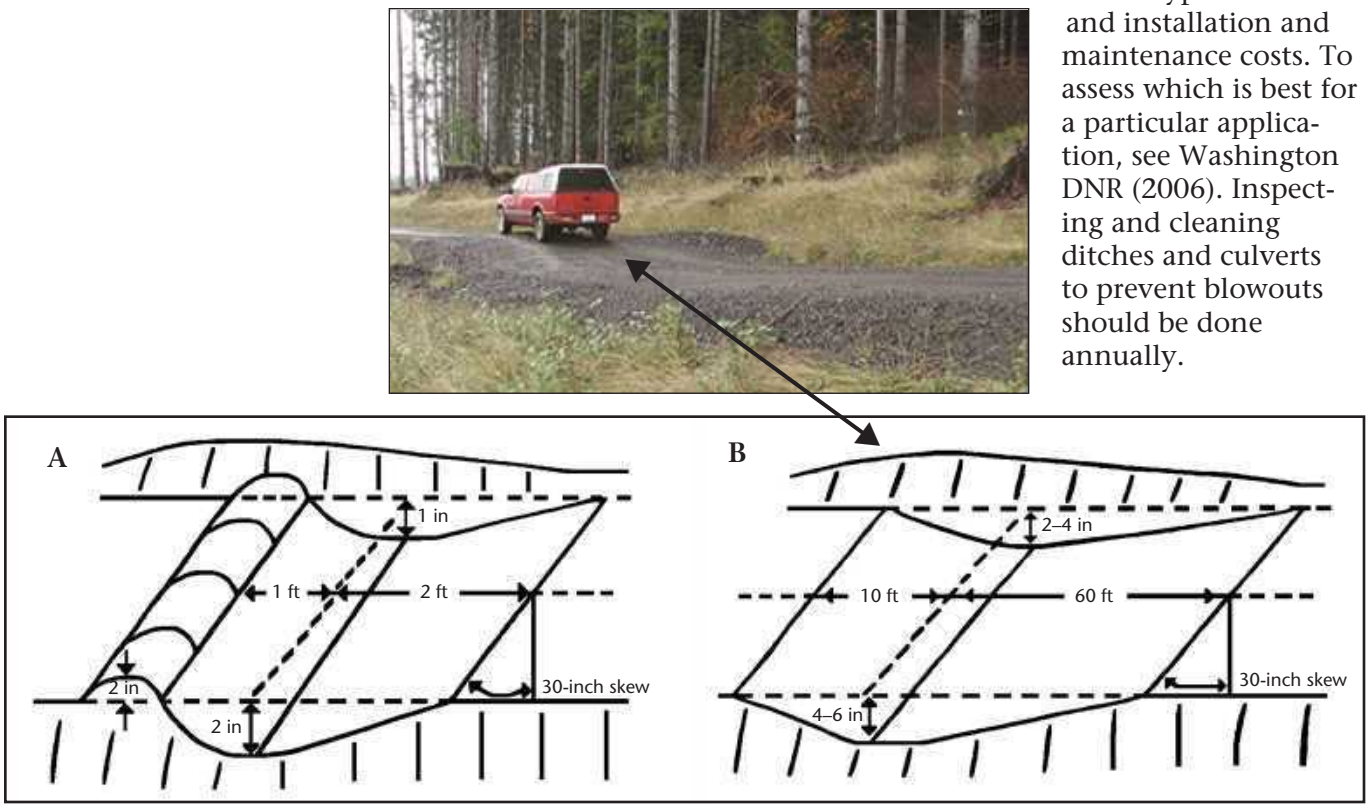

Figure 21. **Water bars (A) and gentler rolling dips (B) shunt water from road surfaces to the adjoining forest, reducing maintenance costs and protecting water quality.** *Images courtesy of Washington Department of Natural Resources*

Practices previously described for minimizing soil compaction and displacement during harvesting and site preparation, such as using low ground-pressure machinery, designated skid trails, and leaving as much slash onsite as is consistent with fire management and reforestation, also help minimize erosion (Fig. 22). Tilling soils to facilitate water infiltration can be useful on strongly compacted soils such as skid trails or landings, but otherwise should be avoided. Grass seeding and other erosion controls may be needed after excessively hot or extensive fire.

Several Extension and other publications provide specific practical advice on reducing sediment from forest roads (Adams, 1997, 1998; Brannon et al., 2001; Garland, 1993, 1997, 2000; Garland and Jackson, 2002; Kramer, 2001) and guidelines for road construction and drainage (Washington DNR, 2006, 2007).

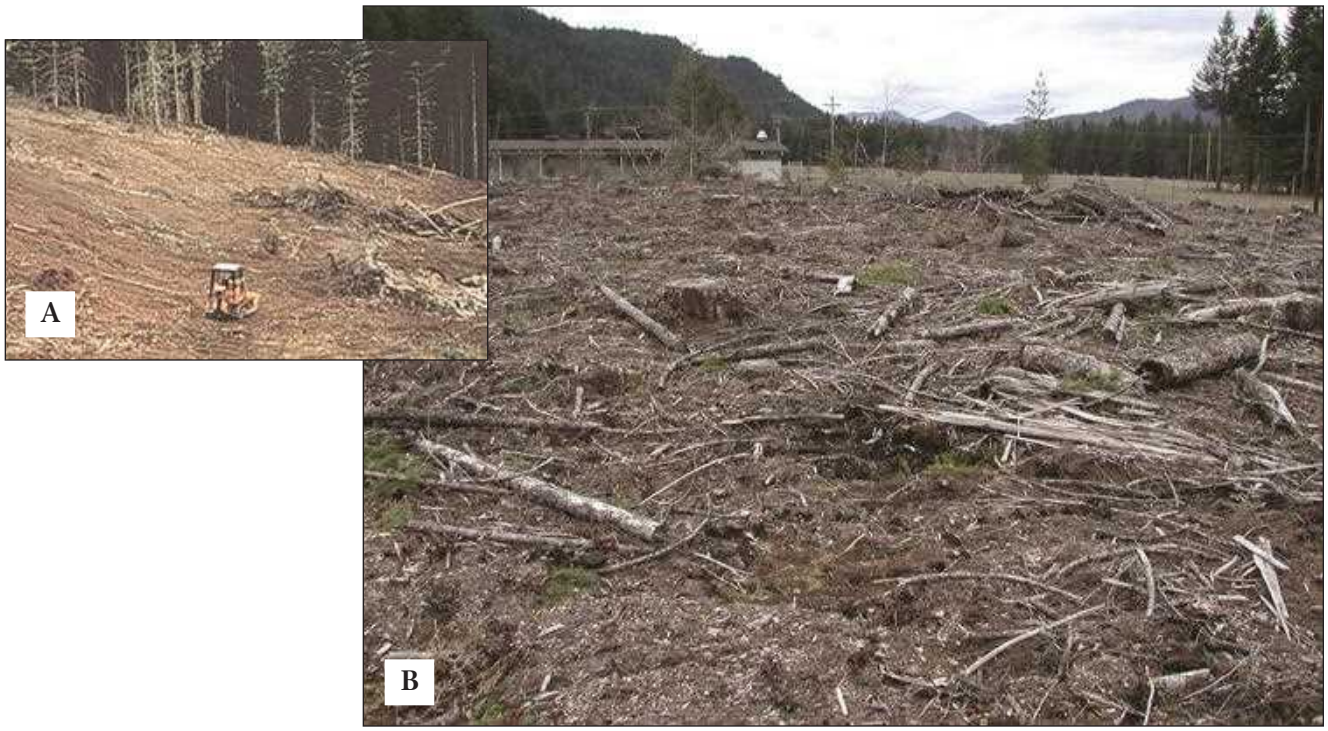

Figure 22. **This excessive mechanical site preparation compacts soil, increases its erosion potential, removes organic matter needed for long-term productivity, and costs money for equipment time (A). Good site preparation retains well-distributed slash at amounts compatible with reducing fire risk, controlling competing vegetation, and increasing planting access (B).**

Image A courtesy of Oregon State University, image B courtesy of Dr. Ole Helgerson, Washington State University

Soil surveys as guides for identifying and managing your woodlands

Soil surveys are county-wide compilations of useful soils information (Fig. 23) available for most Washington counties from WSU Extension, local conservation districts, NRCS offices, and http://soils.usda.gov/survey/printed_surveys/state.asp?state=Washington&abbr=WA. Soil surveys identify and map soil series or complexes of series. An individual soil series has distinctive soil characteristics and is often named after a local feature, such as Everett very gravelly sandy loam. Soil surveys contain two sections useful to woodland owners: 1) photomaps on which you

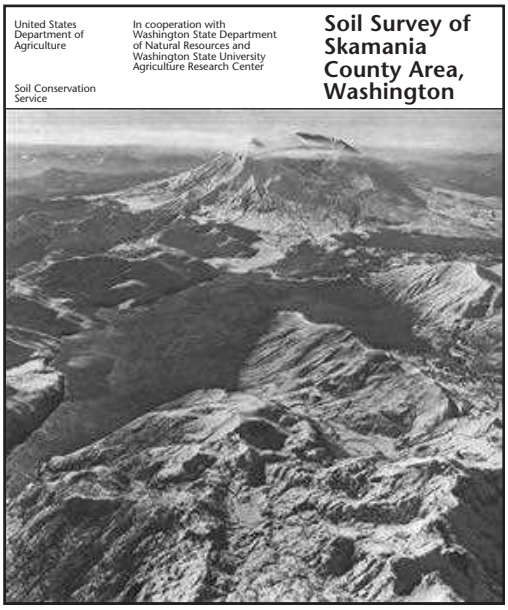

Figure 23. **Organized by county, soil surveys provide useful information on forest and wildlife management, agriculture, and construction.**

can locate your property and identify its soil series, and 2) tables describing the characteristics and suitability of each soil series for forestry, agriculture, and construction.

Using a soil survey is relatively easy. Starting with your property's legal description (township, range, and section), locate your property on the photomaps. The mapping unit symbols for the various soil series are defined in the "Guide to Mapping Units" located ahead of the photomaps. After identifying your soil series, access forestry and other information from tables about productivity (site index; Fig. 24), suitable species for reforestation, and specific management limitations for equipment use, road building, and erosion hazards. The appropriate tables can be scanned or photocopied and added as appendices in your forest stewardship or road management plans.

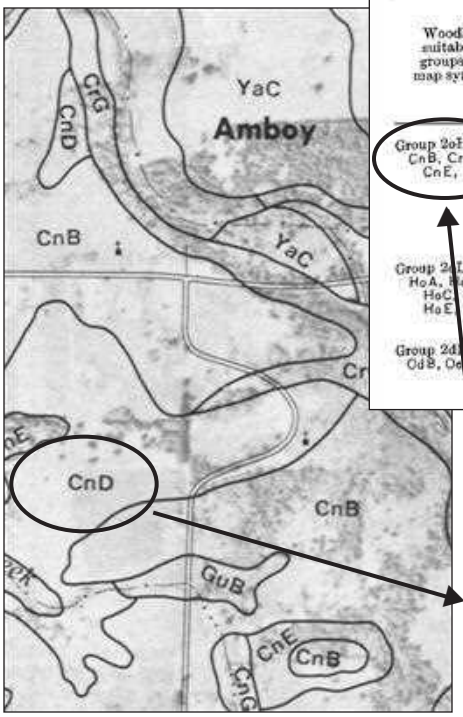

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TABLE 3.—*Woodland suitability groups of soils and interpretations*

Woodland suitability groups and map symbols	Potential productivity: Principal species	Potential productivity: Average site index for Douglas-fir	Management hazards or limitations: Seedling mortality	Management hazards or limitations: Plant competition	Management hazards or limitations: Equipment limitation	Management hazards or limitations: Erosion hazard	Management hazards or limitations: Windthrow hazard	Common understory plants
Group 2oH3: CnB, CnD, CnE, CrE.	Douglas-fir, western hemlock, grand fir, western redcedar, red alder. Noble fir is suited at higher elevations.	170	Moderate..	Moderate..	Slight.....	Slight to severe.	Slight.....	Swordfern, salal.
Group 2oL3: HoA, HoB, HoC, HoD, HoE	Douglas-fir, grand fir, Oregon white oak.	158	Slight.....	Moderate..	Slight to moderate.	None to severe.	Moderate..	Salal, Oregon-grape, vine maple, swordfern.
Group 2oL3: OdB, OdD, OsE..	Douglas-fir, western redcedar, grand fir, red alder.	161	Slight.....	Moderate to severe.	Slight.....	Slight to severe.	Slight.....	Oregon-grape, swordfern, salal.

Map symbol	Mapping unit	Described on page	Capability unit: Symbol	Capability unit: Page	Woodland suitability group: Symbol
BpB	Bear Prairie silt loam, 0 to 8 percent slopes--	7	IIIe-2	50	3oM3
BpC	Bear Prairie silt loam, 8 to 15 percent slopes----------	8	IIIe-2	50	3oM3
CnB	Cinebar silt loam, 3 to 8 percent slopes-------	8	IIe-3	49	2oH3
CnD	Cinebar silt loam, 8 to 20 percent slopes------	8	IIIe-2	50	2oH3
CnE	Cinebar silt loam, 20 to 30 percent slopes-----	8	IVe-4	52	2oH3
CnG	Cinebar silt loam, 30 to 70 percent slopes-----	8	VIe-3	53	2rH5
CrE	Cinebar stony silt loam, 3 to 30 percent slopes----------	9	VIe-1	55	2oH3
CrG	Cinebar stony silt loam, 30 to 70 percent slopes----------	9	VIe-4	53	2rH5

Figure 24. **To use a soil survey, first identify your soil mapping unit using photo maps at the back of the survey, then reference appropriate tables.**

Adapted from McGee, 1972

References and further resources

The following sources of information were used either directly (as cited within the text, in **bold form** below) or indirectly (as supplemental material) to prepare this publication. They are presented here under headings that correspond to subjects covered in this Bulletin for readers wanting additional detail on a particular topic.

FOREST SOIL DEVELOPMENT

Fisher, R.F. and D. Binkley. 2000. *Ecology and management of forest soils*. New York: Wiley. 350 pp.

Franklin, J.F. and C.T. Dyrness. 1973. *Natural vegetation of Oregon and Washington.* USDA Forest Service, Pacific Northwest Research Station, PNW-GTR-8. http://www.treesearch.fs.fed.us/pubs/26203. 427 pp. [1988 version available from Oregon State University Press, ISBN 0-87071-356-6. 464 pp.]

Goldin, A. 1992. *Soil survey of Snoqualmie Pass area, parts of King and Pierce Counties, Washington.* USDA Soil Conservation Service. ftp://ftp-fc.sc.egov.usda.gov/MO1/text_pdf/washington/wa634_text.pdf. 362 pp.

Heilman, P.E., H.W. Anderson, and D.M. Baumgartner. 1979. *Forest soils of the Douglas-fir region*. Washington State University Extension, MISC0246. 298 pp.

Johnson, C.W., F.A. Baker, and W.S. Johnson. 1990. *Urban and community forestry: A guide for the interior western United States.* Ogden, UT: USDA Forest Service, Intermountain Region. http://www.fs.fed.us/psw/programs/cufr/products/cufr_195_REF90_57.PDF. 377 pp.

McGee, D.A. 1972. Soil survey of Clark County, Washington. USDA Soil Conservation Service. http://www.or.nrcs.usda.gov/pnw_soil/wa_reports.html. 71 pp. + tables and maps.

SOIL ECOLOGY

Harvey, A.E., J.M. Geist, G.I. McDonald, M.F. Jurgensen, P.H. Cochran, D. Zabowski, and R.T. Meurisse. 1994. *Biotic and abiotic process in eastside ecosystems: The effects of management on soil properties, process and productivity.* Portland, OR: USDA Forest Service, Pacific Northwest Research Station, PNW-GTR-323. http://www.fs.fed.us/pnw/pubs/gtr323.pdf. 80 pp.

Meurisse, R.T., W.G. Ypsilantis, and C. Seybold, tech. eds. 1999. *Proceedings, Pacific Northwest forest and rangeland soil organism symposium.* March 17-19, 1998, Corvallis, OR. Portland, OR: USDA Forest Service, Pacific Northwest Research Station, PNW-GTR-461. http://www.fs.fed.us/pnw/pubs/pnw_gtr461.pdf. 227 pp.

Natural Resources Conservation Service (NRCS). 2004. *Soil biology and land management.* Soil Quality - Soil Biology Technical Note Number 4. http://www.nm.nrcs.usda.gov/technical/tech-notes/soils/soil3.pdf. 20 pp.

NRCS. 2007. Hydric soils: Overview. http://soils.usda.gov/use/hydric/overview.html.

Pederson, R.J. 1995. *Managing small woodlands for cavity nesting birds.* Washington State University Extension, MISC0160. 6 pp.

Perry, D.A. 1994. *Forest ecosystems.* Baltimore: Johns Hopkins University Press. 649 pp.

Powers, R.F., D.L. Hauxall, and G.M. Nakamura, tech. coordinators. 2000. *Proceedings of the California Soils Council conference on forest soils biology and forest management.* February 23-24, 1996, Sacramento, CA. Albany, CA: USDA Forest Service, Pacific Southwest Research Station, PSW-GTR-178. http://www.fs.fed.us/psw/publications/documents/psw_gtr178. 113 pp.

Soil Science Society of America. 2007. Glossary of soil science terms. https://www.soils.org/sssagloss/index.php.

SOIL PESTS

deCalesta, D.S., R.E. Duddles, and M.C. Bondi. 1993. *Controlling mountain beaver damage in forest plantations.* Oregon State University Extension Service, EC1144. http://extension.oregonstate.edu/catalog/pdf/ec/ec1144.pdf. 6 pp.

deCalesta, D.S., K. Asman, and N. Allen. 2003. *Controlling pocket gophers damage to conifer seedlings.* Oregon State University Extension Service, EC1125. http://extension.oregonstate.edu/catalog/pdf/ec/ec1255.pdf. 8 pp.

Hanley, D. and B. Edmonds. 2001. *The rotten truth: Control of common forest root rots of the Pacific Northwest.* Washington State University Department of Natural Resource Sciences, WSU Extension, and USDA, VT0094. http://cru84.cahe.wsu.edu/cgi-bin/pubs/VT0094.html. 36 minutes.

FERTILIZATION

Hanley, D.P., H.N. Chappell, and E.H. Nadelhoffer. 2006. Fertilizing coastal Douglas-fir forests. Washington State University Extension, EB1800. http://cru84.cahe.wsu.edu/cgi-bin/pubs/EB1800.html. 16 pp.

Harrington, C.A. and C.A. Wierman. 1985. *Response of a poor-site western redcedar stand to precommercial thinning and fertilization.* Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, PNW-RP-339. http://www.fs.fed.us/pnw/pubs/pnw_rp339.pdf. 18 pp.

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.

Miller, R.E. and R.D. Fight. 1979. *Fertilizing Douglas-fir forests.* USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, PNW-GTR-83. http://www.fs.fed.us/pnw/pubs/gtr83.pdf. 35 pp.

Miller, R.E. and M.D. Murray. 1978. The effects of red alder on growth of Douglas-fir. Pp. 283-306 in: Briggs, D.G., D.S. DeBell, and W.A. Atkinson, compilers. *Utilization and management of alder.* Proceedings of a symposium, April 25-27, 1977, Ocean Shores, WA. Portland, OR: USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, PNW-GTR-70. http://www.fs.fed.us/pnw/pubs/journals/pnw_1978_briggs001.pdf. 388 pp.

Miller, R.E., D.L. Reukema, and T.A. Max. 1993. Size of Douglas-fir trees in relation to distance from a mixed red alder—Douglas-fir stand. *Canadian Journal of Forest Research* 23: 2413-2418. http://www.fs.fed.us/pnw/pubs/journals/pnw_1993_miller002.pdf. 6 pp.

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.* Portland, OR: USDA Forest Service, Pacific Northwest Research Station, PNW-RP-513. http://www.fs.fed.us/pnw/pubs/rp_513.pdf. 32 pp.

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.* Washington State University Extension, EB1874. http://cru.cahe.wsu.edu/CEPublications/eb1874/eb1874.pdf. 20 pp.

SOIL COMPACTION

Adams, P.W. 1998. *Soil compaction on woodland properties.* Oregon State University Extension Service, EC1109. http://extension.oregonstate.edu/catalog/pdf/ec/ec1109.pdf. 8 pp.

Andrus, C.W. and H.A. Froehlich. 1983. *An evaluation of four implements used to till compacted forest soils in the Pacific Northwest.* Forest Research Laboratory. Oregon State University, Research Bulletin 45. 12 pp.

Garland, J.J. 1997. *Designated skid trails minimize soil compaction.* Oregon State University Extension Service, EC1110. http://extension.oregonstate.edu/catalog/pdf/ec/ec1110.pdf. 7 pp.

ROAD CONSTRUCTION AND MANAGEMENT

Adams, P.W. 1997. *Maintaining woodland roads.* Oregon State University Extension Service, EC1139. http://extension.oregonstate.edu/catalog/pdf/ec/ec1139.pdf. 8 pp.

Brannon, T.A., D.M. Baumgartner, and D.P. Hanley. 2001. *Roads on small acreage forests.* Washington State University Extension, EB1910. http://cru.cahe.wsu.edu/CEPublications/eb1910/eb1910.pdf. 16 pp.

Garland, J.J. 1993. *Road construction on woodland properties.* Oregon State University Extension Service, EC1135. 12 pp.

Garland, J.J. and D.J. Jackson. 2002. *Planning woodland roads.* Oregon State University Extension Service, EC1118. http://extension.oregonstate.edu/catalog/pdf/ec/ec1118.pdf. 8 pp.

Garland, J. 2000. *Designing woodland roads.* Oregon State University Extension Service, EC1137. http://extension.oregonstate.edu/catalog/pdf/ec/ec1137.pdf (preview only). 28 pp.

Kramer, B.W. 2001. *Forest road contracting, construction and maintenance for small forest woodland owners.* Oregon State University College of Forestry, Research Contribution 35. http://fcg.cof.orst.edu/rc/RC35.pdf. 84 pp.

FIRE AND SOIL

Barkley, Y.C. 2006. *After the burn: Assessing and managing your forestland after a wildfire*. University of Idaho Extension, Idaho Forest, Wildlife and Range Experiment Station, Bulletin No. 76, Contribution No. 951. http://www.cnr.uidaho.edu/extforest/AftertheBurnFINAL.pdf. 80 pp.

Baumgartner, D.M., D.W. Breuer, B.A. Zamora, L.F. Neuenschwander, and R.H. Wakimoto, eds. 1999. *Prescribed fire in the intermountain region*. Washington State University Extension, MISC0231. 174 pp.

Brown, J.K., E.D. Reinhardt, and K.A. Kramer. 2003. *Coarse woody debris: managing benefits and fire hazard in the recovering forest.* Ogden, UT: USDA Forest Service, Rocky Mountain Research Station, RMRS-GTR-105. http://www.fs.fed.us/rm/pubs/rmrs_gtr105.pdf. 16 pp.

Moench, R. and J. Fusaro. 2002. Forestry: *Soil erosion control after wildfire*. Colorado State University Extension, No. 6.308. http://www.ext.colostate.edu/PUBS/NATRES/06308.html. 4 pp.

SOIL-RELATED SILVICULTURE AND HARVESTING OPTIONS

Barg, A.K and D.P. Hanley. 2001. *Silvicultural alternatives: Variable retention harvests in forest ecosystems of western Washington.* Washington State University Extension, EB1899. 20 pp.

Parker, R. and S. Bowers. 2006. *Timber harvesting options for woodland owners*. Oregon State University Extension, EC1582. http://extension.oregonstate.edu/catalog/pdf/ec/ec1582.pdf. 7 pp.

WASHINGTON FOREST PRACTICES

Washington Department of Natural Resources (DNR). 2006. *Forest practices board manual,* Section 3. http://www.dnr.wa.gov/forestpractices/board/manual. 31 pp.

Washington DNR. 2007. *Forest practices illustrated, a simplified guide to forest practice rules in Washington State.* http://www.dnr.wa.gov/forestpractices/illustrated. 152 pp.

Glossary[1]

A horizon. Topsoil, where seeds germinate and plant roots grow. It is made up of humus mixed with mineral particles.

aggregate. Many fine soil particles (sand, silt, clay) held in a single mass or cluster, usually by natural forces and substances derived from root exudates and microbial activity. Natural soil aggregates such as granules blocks or prisms are called peds. Clods are aggregates produced by tillage or logging.

B horizon. See subsoil.

biosolids. Treated sewage sludge that meets requirements for beneficial use.

bulk density. The mass of dry soil per unit bulk volume. The value is expressed as Mg per cubic meter, Mg m^{-3}.

C horizon. Soil layers, excluding bedrock, that are little affected by development processes and lack the properties associated with O, A, E, and B horizons.

capillary water. Water held as a film by surface tension around soil particles and in small capillary pores between particles. Surface tension is the adhesive force that holds capillary water in the soil.

coarse fragments. Mineral or rock particles larger than 2 mm in diameter.

cobble or cobblestone. A rounded or partly rounded fragment of rock 3–10 inches (75–250 mm) in diameter.

colluvium. Soil material, rock fragments, or both moved by creep, slide, or local wash and deposited at the base of steep slopes.

CWD or coarse woody debris. Snags, fallen logs, windblown trees, and branches larger than 3 inches in diameter on the soil surface. CWD is regarded as important in providing long-term ecologic legacies.

drainage class. The frequency and duration of saturation or partial saturation under conditions similar to those under which the soil developed. Seven drainage classes are recognized:

excessively drained: Water is removed from the soil very rapidly.

somewhat excessively drained: Water is removed from the soil rapidly.

well drained: Water is removed from the soil readily but not rapidly.

moderately well drained: Water is removed from the soil somewhat slowly during some periods.

somewhat poorly drained: Water is removed from the soil slowly so that the soil is wet at a shallow depth for significant periods during the growing season.

poorly drained: Water is removed from the soil so slowly that the soil is wet at shallow depths periodically during the growing season or remains wet for long periods.

[1]Adapted from Goldin (1992), Soil Science Society of America (2007), and the authors' experience

very poorly drained: Water is removed from the soil so slowly that free water remains at or very near the ground surface during much of the growing season.

dry ravel. The gradual downslope movement of surface soil.

duff. A generally firm organic layer on the surface of mineral soils that consists of fallen plant material in the process of decomposition. It includes everything from the litter on the surface to underlying pure humus.

ecologic legacies. Sufficiently large pieces of ecosystem structure such as standing trees, snags, and decomposing logs that can maintain associated biota into future ecosystems.

ectomycorrhizae. A mycorrhizal association in which the fungal mycelia extend inward, between root cortical cells, to form a network ("Hartig net") and outward into the surrounding soil. Usually the fungal hyphae also form a mantle on the surface of the roots.

endomycorrhizae. A mycorrhizal association with intracellular penetration of the host root cortical cells by the fungus as well as outward extension into the surrounding soil.

erosion. The wearing away of the land surface by geologic agents such as water, wind, and ice, or processes such as gravitational creep.

field moisture capacity. The moisture content of a soil, expressed as a percentage of the oven dry weight, after the gravitational, or free, water has drained away; the field moisture content two or three days after a soaking rain; also called normal field capacity, normal moisture capacity, or capillary capacity.

geomorphic surface. A mappable area of the earth's surface that has a common history; the area is of similar age and is formed by a set of processes during an episode of landscape evolution.

glacial drift. Pulverized and other rock material transported by glacial ice and then deposited. Also the sorted and unsorted material deposited by streams flowing from glaciers.

glaciolacustrine deposits. Material ranging from fine clay to sand derived from glaciers and deposited in glacial lakes mainly by glacial meltwater. Many deposits are interbedded or laminated.

gleyed soil. Soil that formed under poor drainage, resulting in the reduction of iron and other elements in the profile and in gray or blue colors or mottles (spots and streaks).

gravel. Rounded or angular fragments of rock up to 3 inches (2 mm–7.6 cm) in diameter. An individual piece is a pebble.

hardpan. A hardened or cemented soil horizon or layer with physical characteristics that limit root penetration and restrict water movement (see pan).

humus. The total organic compounds in soil exclusive of undecayed plant and animal tissues, their partially decomposed products, and soil biomass. The term is often used synonymously with "soil organic matter."

hydric soils. Soils that are wet long enough to periodically produce anaerobic conditions, thereby influencing the growth of plants.

hydrophobic soils. Soils that are water-repellent, often due to dense fungal mycelial mats or hydrophobic substances vaporized and reprecipitated during fire.

igneous rock. Rock formed by solidification from a molten or partially molten state. Major varieties include plutonic and volcanic rock. Examples are andesite, basalt, and granite.

infiltration. The downward entry of water into the immediate surface of soil or other material, as contrasted with percolation, which is movement of water through soil layers or material.

lacustrine deposit. Material deposited in lake water and exposed when the water level is lowered or the elevation of the land is raised.

lahar. Mudflow made up chiefly of volcaniclastic material on the flank of a volcano.

lignins. That portion of wood primarily composed of various phenolic structures that resist decomposition in soil

legacies. Portions of ecosystem structure (such as downed trees in various stages of decomposition, standing trees with cavities, or other habitat features) that maintain the viability of associated life form populations during changes in the surrounding ecosystem.

mineral soil. A soil consisting predominantly of and having its properties predominantly determined by mineral matter.

modal soil. A single profile description representing the most usual condition of each soil property of all soils in the class.

muck. Dark colored, finely dived, well decomposed organic soil material (see sapric soil).

mycorrihizae. Literally, "fungus root." The association, usually symbiotic, of specific fungi with the roots of higher plants. See also endomycorrhizae and ectomycorrhizae.

N-fixation. Conversion of molecular nitrogen (N_2) to ammonia and subsequently to organic nitrogen utilizable in biological processes.

O horizon. Soil layers dominated by organic material.

Oa layer: A layer occurring in humus consisting of well-decomposed organic matter of unrecognizable origin (sapric material).

Oe layer: A layer of partially decomposed litter with portions of plant structures still recognizable (hemic material). Occurs below the Oi layer on the forest floor in forest soils. It is the fermentation layer.

Oi layer: A layer of organic material having undergone little or no decomposition (fibric material). On the forest floor this layer consists of freshly fallen leaves, needles, twigs, stems, bark, and fruits. This layer may be very thin or absent during the growing season.

pan. A compact, dense layer in a soil that impedes water movement and root growth. For example, hardpan, fragipan, claypan, plowpan, and traffic pan.

ped. An individual, naturally formed soil aggregate such as a granule, prism, or block.

pedon. The smallest volume that can be called a soil. A pedon is three dimensional and large enough to permit study of all horizons.

percolation. The downward movement of water through soil.

permanent wilting percentage. The amount of water held by a soil (often expressed as a percent of dry weight), below which most plants will die.

permeability. The soil quality that enables water to move downward through the profile.

platy. Soil aggregates that are developed predominantly along horizontal axes; laminated; flaky.

pore space. The portion of soil bulk volume occupied by soil pores.

pyroclastic. The Greek word for fire-broken, referring to fragmented volcanic rock thrown out during an eruption.

rhizosphere. The zone of soil immediately adjacent to plant roots in which the kinds, numbers, or activities of microorganisms differ from that of the surrounding bulk soil.

root exudates. Low molecular weight metabolites that enter the soil from plant roots.

sandstone. Sedimentary rock containing dominantly sand-sized particles.

sapric soil. The most highly decomposed of all organic soil material. It has the least amount of plant fiber, highest bulk density, and lowest water content at saturation of all organic soil material (see muck).

saturated flow. The movement of water in soil that has pores filled to capacity with water.

sedimentary rock. Rock made up of particles typically deposited from suspension in water.

siltstone. Sedimentary rock made up of dominantly silt-sized particles.

site index. A designation of the quality of a forest site based on the height of the dominant stand at an arbitrarily chosen age. For example, if the average height attained by dominant and co-dominant trees in a fully stocked stand at the age of 50 years is 75 feet, the site index is 75 feet.

soil. A natural, three-dimensional body at the earth's surface. It is capable of supporting plants and has properties resulting from the integrated effect of climate and living matter acting on earthy parent materials, as conditioned by relief over periods of time.

soil biota. A term generally describing plants and animals living in the soil that can range in size from microbes to mammals

soil complex. A map unit of two or more kinds of soil or miscellaneous areas in such an intricate pattern or so small an area that it is not practical to display them separately at the selected scale of mapping. The pattern and proportion of the soils or miscellaneous areas are somewhat similar throughout the complex.

soil horizon. A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically-related layers in physical, chemical, and biological properties and/or characteristics such as color, structure, texture, consistency, kinds and number of organisms present, and degree of acidity or alkalinity.

soil mottling. Irregular spots of different colors that vary in number and size. Mottling generally indicates poor aeration and impeded drainage.

soil profile. A vertical section of soil extending through all its horizons and into parent materials or the C horizon.

soil separates. Mineral particles less than 2 mm in equivalent diameter and ranging between specified size limits. The names and sizes (in millimeters) of separates recognized in the United States are as follows:

very coarse sand:	1.0–2.0
coarse sand:	0.5–1.0
medium sand:	0.25–0.5
fine sand:	0.10–0.25
very fine sand:	0.05–0.10
silt:	0.002–0.05
clay:	< 0.002

soil series. A group of soils with profiles that are almost alike, except for textural differences in the surface layer or underlying material. All the soils of a series have horizons that are similar in composition, thickness, and arrangement.

soil structure. The combination or arrangement of primary soil particles into compound particles or aggregates.

soil texture. The relative proportions of sand, silt, and clay particles in a mass of soil.

subsoil. Technically, the B horizon; roughly, the part of the soil horizon below plow depth.

topsoil. The upper part of the soil, which is the most favorable material for plant growth. It is ordinarily rich in organic matter and used to top dress road banks, lawns, and land affected by mining.

tuff. A compacted deposit that is 50 percent or more volcanic ash and dust.

urea prills. Solidified drops of molten urea dripped through a screen from the top of a tower.

unsaturated flow. The movement of water in soil that does not fill pores to capacity with water.

xeric. A soil moisture regime common to Mediterranean climates that have moist, cool winters and warm, dry summers. A limited amount of moisture is evident but does not occur during optimal periods for plant growth. Irrigation or summer fallow is commonly necessary for crop production.

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