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Biotic and Abiotic Processes in Eastside Ecosystems:

The Effects of Management on Soil Properties, Processes, and Productivity

Alan E. Harvey, J. Michael Geist, Gerald I. McDonald, Martin F. Jurgensen, Patrick H. Cochran, Darlene Zabowski, and Robert T. Meurisse

AUTHORS

Alan E. Harvey is the supervisory plant pathologist and project leader of the Root Diseases and Soil Microbiology Project at the Intermountain Research Station, U.S. Department of Agriculture, Forest Service, Moscow, Idaho. J. Michael Geist is the supervisory research soil scientist; Pacific Northwest Research Station, U.S. Department of Agriculture. Forest Service, Forestry and Range Science Laboratory, La Grande, Oregon. Gerald I. McDonald is the principal plant pathologist of the Root Diseases and Soil Microbiology Project, Intermountain Research Station, U.S. Department of Agriculture, Forest Service, Moscow, Idaho. Martin F. Jurgensen is a professor of forest soils at Michigan Technological University in Houghton, Michigan. Patrick H. Cochran is a research soil scientist, Pacific Northwest Research Station, U.S. Department of Agriculture, Forest Service, Forest and Range Experiment Station, Bend, Oregon. Darlene Zabowski was a research soil scientist, Pacific Northwest Research Station, U.S. Department of Agriculture, Forest Service. Forestry Sciences Laboratory, Wenatchee, Washington and is now an assistant professor, Department of Forestry at the University of Washington. Seattle, Washington. Robert T. Meurisse is a regional soil scientist. Pacific Northwest Region, U.S. Department of Agriculture, Forest Service, Portland, Oregon.

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ABSTRACT

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Productivity of forest and range land soils is based on a combination of diverse physical, chemical and biological properties. In ecosystems characteristic of eastside regions of Oregon and Washington, the productive zone is usually in the upper 1 or 2 m. Not only are the biological processes that drive both soil productivity and root development concentrated in limited organic horizons, but also they have evolved historically in a natural system that includes mostly modest surface disturbance. Typical disturbances include erosional, seismic, or tip-over events, and modest surface heating by periodic wildfire. This combination of properties and processes produces soils with an extremely wide range of productivity potential, but productivity can be highly sensitive to disturbances from heavy machinery or fire, when fuel accumulations are well beyond historical norms. Limited moisture-holding capacity and nitrogen storage often impose a need for carefully balancing developing vegetation with available soil resources.

Keywords: Soil management strategy, soil productivity, soil sustainability, soil damage, soil moisture, soil microbiology, soil-disease interaction, soil-climate interaction, soil wood, coarse woody debris, organic matter, water storage and use, nutrient cycling, nitrogen fixation, ectomycorrhizal activity, carbon cycling, harvest effects, fire effects, fertilizer effects, forest health, physical properties, chemical properties.

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INTRODUCTION

Inland, the Pacific Northwest has a diverse geologic history, varying microclimates within diverse macroclimates, and a record of extensive natural and human-caused disturbances. The resulting soils and their associated vegetation are on landscapes that are spatially complex, and differ in appearance, function, and response to management actions. Depending on their suite of properties, soils range from very sensitive to relatively tolerant of disturbance. Thus, management prescriptions must be site specific.

Soils develop over extended periods (decades to centuries), depending on the characteristics of landform and ecosystem. Because physical site disturbances are rare, eastside soils are the result of the chemical and physical properties of parent materials, such as erosional and glacial deposits, gradually decomposing bedrock, overlaying deposits of volcanic ash and pumice, and windblown soil from adjacent regions (loess). Chemical weathering of rock requires many centuries. The principal volcanic ash and pumice deposit on eastside soils dates from the eruption of Mount Manama, about 6600 years ago. Loess deposition has been cumulative and required many thousands of years. However, the surface 30 cm (perhaps most important from the standpoint of either short or long-term productivity) are strongly affected by accumulating deposits of organic materials input by vegetation, mostly over time spans from a few decades to several hundred years (Harvey and others 1987).

Eastside soils are typified by specific forest floor horizons, consisting, at the surface, of a modest amount of litter (usually 3-5 cm) underlain by humus (sometimes less than one cm thick); then a mineral horizon enriched by organic matter from overlying materials (about 5-40 cm) and, finally, a mineral base that may or may not contain organic material, ash, or loess deposits that improve general fertility and water storage capacity. Interspersed within this mix are deposits of old decayed wood (150-550 years old) that can be deep (5-20 cm) and located throughout the shallow soil profile. About 5 to 10 percent or more of the top 30 cm of these soils can consist of woody materials (Harvey and others 1987; Meurisse and others 1991; Page-Dumroese and others 1991, 1993).

Soil fertility, of course, is critical to productivity. Eastside ecosystems are climatically limited (low water input during the growing season), and soils are mostly young with highly variable fertility. Water and nutrients tend to accumulate and cycle in surface layers, primarily organics, volcanics, and loess, when present. Most critical processes are at soil depths ranging from 5 to 40 or more cm. Concentration of these processes near the soil surface makes them potentially sensitive to disruption and highly variable from site to site (Jurgensen and others 1990).

Some eastside forest sites were beneath ice caps only 10,000 years ago. Existing vegetation systems often have developed only recently and are largely typical of a changing postglacial climate. Where ash, loess, or other fire deposits are present, however, water and nutrient storage can lead to vegetation types typical of a moister climate, and substantial buffering of climate or site perturbations is likely. Where such soil deposits do not exist or are limited, soil productive capacities may be tightly linked to organic horizons and little buffering is possible.

Root morphology and the ability of terrestrial vegetation (especially trees) to “mine” variable soils is not well understood. For eastside ecosystems, feeder root production seems concentrated within the most fertile shallow soil horizons; this concentration contributes substantially to the deposition and cycling of nutrients and carbon in those horizons (Keyes and Grier 1981; Vogt and others 1987). Whether tree root systems are adapting to deep sources of water, nutrients, or both, is unknown. Large root-to-top ratios are typical of trees growing in dry and/or infertile environments (Vogt and others 1987), so energy requirements for exploiting resources in short supply are higher than where resources are abundant. How much can trees adapt to changing environments across time and space? Information on above/below-ground interactions of trees and stands across environmental and temporal gradients will eventually be required to fully understand and interpret soil/vegetation interactions that govern site productivity processes and their responses to change.

Eastside ecosystems are highly valuable in their ability to balance long-term soil and rooting processes with aboveground productivity. Consequently, wide variations in site productivity, tree mortality, vegetation response to soil disturbance, and soil stability are characteristic. Based on combinations of site, soil, vegetation, and management history, however, these responses should be predictable. The following information provides both scientific tools and perspectives for making such predictions.

THE PHYSICAL AND CHEMICAL NATURE OF EASTSIDE SOILS

Soil Origin

East of the Cascades Range, volcanic ash and pumice depositions are a major influence on many soils and associated vegetation. The most encompassing deposition occurred about 6600 years ago from the eruption of Mount Mazama, which produced Crater Lake, in Oregon. That eruption blanketed areas of eastern Oregon and Washington and beyond. An earlier eruption of lesser influence came from Glacier Peak in the northern Washington Cascades Range about 12,000 years ago (Fryxell 1965). The eruption of Mount St. Helens, including the 1980 eruption, have had comparatively little effect on forests east of the Cascades Range.

Estimated minimum fallout areas for Mount Mazama was 900,000 km^2 and for Glacier Peak, 260,000 km^2. The less expansive Glacier Peak deposition spread east-southeast in a fairly narrow belt from the source; the Mount Mazama fallout was broadly north and east, with some southerly coverage. In both eruptions, the deposition of thick, coarse pumice now found near the volcanoes rapidly thins and becomes increasingly fine with greater distance from the source. The Mazama ash is most evident (Fryxell 1965) and deposits up to 1 m thick are common as far away as northeastern Oregon and northeastern Washington. The original deposition has been altered at many locations by wind and water erosion. Also, road building, livestock grazing, logging, and other human activities have had some local effects on deposits.

Vegetation and Associated Soil Properties

Conditions created by changes in climate and volcanic ash deposition have affected the abundance, growth, and kinds of plants and thereby altered the distribution patterns of vegetation on landscapes. For example, grassland, juniper (*Juniperus occidentalis* Hook.), and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) were much more widely distributed than the more productive mixed conifer and spruce-fir types in the warmer, drier period before ash-fall, according to pollen counts from local bogs (Mehringer 1985). Ash deposited on grasslands eroded away, but much of the ash deposited on forested sites remained and resulted in soils with high water-holding capacities. These ash soils and the colder, wetter climate of today support large acreages of mixed conifer and spruce-fir forests.

Four major forest types represent 93 percent of the forested landscapes and occupy about 21.4 million acres east of the Cascades in Oregon and Washington (Reid 1947). These types are ponderosa pine, mixed conifer, lodgepole pine (*P. contorta* Dougl. ex Loud.), and spruce fir. The mixed conifer type consists of various mixtures of interior Douglas-fir (*Pseudotsuga menziesii* var *glauca* (Beissn; Franco), white fir (*Abies concolor* (Gord. & Glend.) Lindl.) or grand fir (*A. grandis* (Dougl. ex D. Don) Lindl.), western white pine (*Pinus monticola* Dougl. ex D. Don), western larch (*Larix occidentalis* Nutt.), and western redcedar (*Thuja plicata* Dorm ex D. Don). In the southern Oregon Cascades, the spruce fir type consists primarily of Shasta red fir (*A. magnifica* Murr. var, *shastensis* Lemm.) and certain associated species, but elsewhere the type consists of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*A. lasiocarpa* (Hook.) Nutt.).

Forest Types and Associated Soil Properties

Soil moisture and soil temperature regimes are paramount variables affecting the distribution, species nix, and productivity of inland Northwest forests. Four different soil moisture regimes combine with three different soil temperature regimes (table 1) to broadly influence the kind and character of forest vegetation including forest types (table 2). Descriptions of these forest types, which follows, further indicate the differing character of eastside forests and associated soils.

Ponderosa pine type-Ponderosa pine forests occupy the warmest, driest forested sites of the inland Northwest. Available soil moisture is closely related to pine distribution and productivity. In the central Oregon pumice plateau, however, frost pockets limit distribution, and ponderosa pine is often replaced by lodgepole pine (Cochran 1973, 1975). Sugar pine (*Pines lambertiana* Dougl.) commonly occurs on volcanic cones and buttes. Mean annual precipitation ranges from 41 to 89 cm; precipitation generally falls during autumn and winter when evapotranspiration is low. Mean annual temperatures range from 7 to 18°C. The soils are usually dry at depths of 10 to 61 cm for 60 or more consecutive days during summer and autumn (Daubenmire and Daubenmire 1968, Donaldson and DeFrancesco 1982, Hall 1973).

Table 1 - Soil moisture and temperature[1] regimes in western-montane forests

Soil moisture regimes		Soil temperature regimes	
Name	**Description**	**Name**	**Description**
Semi-arid (aridic)	Soil moisture control section is dry more than half the time that the soil temperature is above 41° F. Never moist for 90 consecutive days where soil temperature is above 47° F.	**Cool (mesic)**	The mean annual soil temperature is 8 C (47° F) or higher, but lower than 15° C (59° F). The difference between mean summer and winter temperature is more than 5° C (9° F).
Moderately dry (xeric)	The soil moisture control section is dry for 45 days or more consecutive days within the 4 months after the summer solstice. Typified in Mediterranean climates where winters are moist and cool and summers are warm and dry.	**Moderately cold (frigid)**	The mean annual soil temperature is lower than 8° C (47° F) and the mean winter and summer soil temperture is more than 5° C (9° F).
Moist (ustic)	Soil moisture control section is dry for 90 or more cumulative days but is moist in some part for more than 180 cumulative days. Soil moisture is limited, but available when conditions are suited for plant growth.	**Cold (cryic)**	Soils have a mean annual temperature higher than 0° C (32° F) but lower than 8° C (47° F) with an 0 horizon.
Moderately wet to wet (udic)	Soil moisture control section is not dry far as long as 90 days (cumulative) and not dry for as long as 45 consecutive days in the 4 months after the summer solstice. Stored soil moisture plus rainfall > ET amount.		

[1] Measured at 50-cm depth

Table 2-Moisture and temperature regimes of eastern Oregon and Washington and their associated major forest types

Semi-arid to moderately dry, cool to cold	Ponderosa pine
Moderately dry to moderately wet, moderately cold to cold	Ponderosa pine (interior Douglas-fir, larch), mixed conifer (grand or white fir)
Moist to moderately wet, cool to cold	Mixed conifer (western white pine-western redcedar), lodgepole pine, spruce-fir

Ponderosa pine forests generally grow on three broad but distinct groups of soils (Dyrness and Youngberg 1966). In Oregon, probably the most prominent and contiguous of these soils are those from air-laid pumice and ash. These cinder- and pumice-soils often overlie older, loamy soils buried at depths of about 30 to more than 150 cm. These soils are coarse, but store relatively high amounts of readily available soil moisture (Carlson 1979, Dyrness and Youngberg 1966, Larsen 1976). Soil organic matter is concentrated within 15 to 25 cm of the surface and declines rapidly with depth. Although these soils are relatively resilient, assurance of site productivity potential requires that the nutrient regime be maintained by conserving organic matter and minimizing soil displacement.

The second most prominent group of ponderosa pine soils are those that are moderately deep and dark colored, fine, and fine-loamy; these soils are derived from basalts, andesites, and clayey sediments. When wet these soils are easily puddled and compacted, but when dry they have relatively high strength. On slopes greater than 30 percent, surface erosion is especially significant when vegetation is removed (Carlson 1974, Paulson 1977, Wenzel 1979).

The least prominent group of ponderosa pine soils are those that are coarse, loamy, and shallow to deep; these soils are derived from rhyolite, andesite, granitics, glacial till, and outwash. They usually have low organic matter content and low plant-available, water-holding capacity (less than 8 to 10 cm). For this group, soil displacement and erosion represent potential hazards to long-term productivity, particularly on slopes greater than 30 percent, and organic matter, surface soil nutrients, and moisture conservation are critical for maintaining long-term productivity of ponderosa pine (Harvey and others 1989b, Powers and others 1989).

Mixed conifer type-Mixed conifer forests occupy a wide range of soil conditions. At the lowest elevations, soils are relatively warm and dry; at the highest elevations, they are cold and wet. Species composition is diverse. Species composition and stand productivity are governed by available soil moisture, nutrient supply, and temperature (Daubenmire and Daubenmire 1968, Hall 1973).

The dominant feature of the interior mixed-conifer sites is the presence of various amounts of surface-deposited pumice and volcanic ash. Deposition thickness ranges from about 15 to more than 76 cm. This layer is generally underlain by older, buried soils of various origins with textures from sandy foams to clays. Some buried soils contain gravel and stone. Total soil depth ranges from about 0.3 to more than 1.5 m (Donaldson and DeFrancesco 1982).

Temperature is a major factor affecting productivity and species composition in this forest type, and two distinct temperature-related soil groups can be described. The larger and more productive-the frigid regime-has mean annual soil temperatures of about 6 to 8 °C and mean summer soil temperatures of 16 to 17 °C.

Elevation ranges from 600 to 1672 m. Mean annual precipitation ranges from 46 to 127 cm. For most sites the soils are dry at depths of 20 to 61 cm for 60 consecutive days or more. A few localized areas are dry for less than 45 consecutive days and usually have western redcedar/clintonia or western hemlock/clintonia plant associations. The range of vegetation-from low to high elevations, as well as from dry to wet soil conditions-is Douglas-fir, western larch, lodgepole pine, grand fir, white fir, western white pine, western redcedar, and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Climax species are: Douglas-fir on the driest sites; grand fir and white fir on moister sites; and western redcedar on the wettest sites. This soil temperature group supports the most productive forests within the ecosystem. Productivity for this frigid regime soil commonly ranges from 5.9 to 8.0 $m^3ha^{-1}yr^{-1}$ (Donaldson and DeFrancesco 1982, Hall 1973, Johnson and Simon 1987, Volland 1985). Root disease problems are particularly common in these types (McDonald and others 1987).

The other major temperature-related soil group--the cryic regime--has mean annual soil temperatures of about 3 to 7 °C and mean summer soil temperatures of less than 16 °C. Elevation ranges from 1064 to 1800 m. Mean annual precipitation ranges from 51 to 127 cm. Although some of the soils are dry for 45 to 60 consecutive days during the summer, many localized areas are dry for less than 45 days. Predominantly, vegetation includes: white fir, grand fir, Douglas-fir, lodgepole pine, Engelmann spruce, and subalpine fir. Western redcedar, western hemlock, western larch, and western white pine are minor components. Site productivity potentials generally range from 3.5 to 5.9 $m^3ha^{-1}yr^{-1}$, except on the driest, coldest sites, where they can be less (Donaldson and DeFrancesco 1982, Hall 1973, Johnson and Simon 1987, Volland 1985). Root diseases are also common in these forests (McDonald and others 1987).

Because so many of the soils in the mixed conifer forests are derived from or are strongly influenced by volcanic ash, they generally have relatively high water-holding capacities. Plant-available water capacities of 25 to 30 cm are common. Natural soil bulk densities average about 0.6 g/cm^3 but can vary, depending on location and management effects. These low densities provide for rapid infiltration, high water-storage capacity, and good aeration (Donaldson and DeFrancesco 1982, Volland 1985). Maintaining long-term productivity requires protection from excessive compaction and displacement of the surface soil (ash and organic matter components). These frigid and cryic soil regimes are among the most fertile of the inland Pacific Northwest forests, but to maintain productivity levels, management of nutrient reserves and organic matter is critical (Geist and Strickler 1978, Harvey and others 1987, Sachs and Sollins 1986).

Lodgepole pine type-Lodgepole pine forests of the inland Pacific Northwest usually occupy relatively moist, cool to cold sites where mean annual precipitation ranges from 50 to 127 cm and mean annual air temperature from 4 to 16 °C. Mean summer soil temperatures range from 7 to 16 °C. Lodgepole pine forests in much of Oregon and Washington grow predominantly on soils derived from silt loam volcanic ash and loamy sands from pumice and ash (medial and cindery Typic Vitrandepts and Cryandepts). In the pumice plateau of central Oregon, these forests are usually in nearly flat basins that may have water tables at depths of 30 cm or more. These soils generally have high amounts of readily available water storage, low bulk densities, and moderate to low fertility. Most nutrients are concentrated within 15 cm of the surface (Cochran 1971, 1985; Geist and Strickler 1978; Youngberg and Dyrness 1959).

Spruce-fir type-Most of the eastside spruce-fir forests are similar to Rocky Mountain subalpine fir-Engelmann spruce forests, but are not as widespread. This type occurs in the coolest and wettest forested zones. Mean annual soil temperatures are about 3 to 7 °C. These forests are mostly at elevations from 1612 to 2260 m and are often in frost pockets and other habitats, such as glaciated valley bottoms characterized by cold air accumulation. Common soil parent materials are ash plus colluvium, however, ash plus alluvium and basalt materials also occur. Soils are more acid than in the lower forested zones, with pH values typically 4.5 to 4.9. Well-developed but relatively thin organic layers occur. Major tree species in this type are subalpine fir, Engelmann spruce, and lodgepole pine. For this forest type, some locations may also include Douglas-fir, grand fir, western larch, and western white pine (Franklin and Dyrness 1988, Johnson and Simon 1987).

Along the east slopes of the southern Oregon Cascades, about 43° north latitude, the complement to the spruce fir type is the Shasta red fir zone. Common associates are white fir, western white pine, lodgepole pine, and mountain hemlock (*T. mertensiana* (Bong.) Carr.). In specialized habitats, Douglas-fir, ponderosa pine, incense cedar (*Libocedrus decurrens* Torr.), Engelinann spruce, Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) and subalpine fir may also be present. Without disturbance, these soils usually have well-developed organic layers (Franklin and Dyrness 1988). Usually coarse and stony, these soils are developing in glacial outwash and volcanic ash mixtures. Usually, fertility is relatively low.

Soil Properties

Soils act as heat sinks and sources and serve as the repository of mineral nutrients and water. Soils also provide an anchoring medium for the roots of higher plants, and house a complex, dynamic microbial population. This microbial population decomposes organic material deposited on and within the soil profile and drives the nutrient cycling processes within the ecosystems.

Chemical soil properties-Soil organic matter content is one of the most important attributes of any soil and enhances both chemical and physical properties. Organic matter contains most of the nitrogen (N), phosphorus (P), and sulfur (S) that will become available to higher plants, and these nutrients are commonly deficient. Soil organic matter is usually concentrated near the soil surface. Percentages decline rapidly with soil depth, as shown by examples of representative soils from broad vegetation groups and parent material sources (tables 3 and 4). Concentrations of nutrient bases-extractable potassium (K), calcium (Ca), and magnesium (Mg)-in soils also differ when grouped according to combinations of parent rock and associated forest types. In northeastern Oregon, the concentrations of bases are notably higher under ponderosa pine, which is strongly associated with basalt and andesite parent rock. Soils of volcanic ash origin are commonly lower in base concentrations, regardless of associated forest type (table 4). Concentrations often increase at lower depths in the soil as clay content increases (Geist and Strickler 1978). Soils of the central Oregon pumice plateau that support ponderosa and lodgepole pines are even lower in extractable bases than the ash soils of northeastern Oregon, apparently because of less weathering in the pumice (Geist and Cochran 1991, Youngberg and Dyrness 1964). Because chemical properties are highly variable in the inland Pacific Northwest, site specific conditions must be assessed in making management decisions.

Table 3-Mineral soil organic carbon in representative soils of eastern Washington and Oregon

Moisture-temperature Regime	Forest types	A Horizon		Total Solum or 90 cm depth
		(Organic carbon)	(% of total)	mg
Moderately dry-Moderately cold (Xeric-Frigid)	Ponderosa pine	30	41	74
	Grand fir-Douglas-fir	9	10	94
Moderately dry- cold (Xeric-Cryic)	Ponderosa pine	20-22	55-64	37-38
Moderately wet Moderately cold (Udic-Frigid)	Grand fir-Engelmann spruce	20	38	53
Moderately wet- cold Andisols (Udic-Cryic)	Engelmann spruce- subalpine fir	44	34	128

Table 4-Total nitrogen (N) available phosphorus (P), and extractable cations at 4 different depths for some northeastern Oregon soils in the spruce-fir, mixed conifer, ponderosa pine, and lodgepole pine types

	Spruce fir			Mixed conifer		
Soil depth	**N**	**Available P**	**Extractable cations**	**N**	**Available P**	**Extractable cations**
cm	%	PPM	meq/100g	%	PPM	meq/100g
0-15	0.22	45	4.4	0.1	63	11.2
15-30	0.16	21	3.0	0.06	36	9.3
30-60	0.09	17	2.7	0.04	22	11.2
60-90	0.06	26	8.8	0.03	12	14.8
	Ponderosa pine			**Lodgepole pine**		
0-15	0.11	44	14.8	0.09	51	6.0
15-30	0.07	31	14.2	0.05	31	6.2
30-60	0.04	24	16.7	0.03	17	9.5
60-90	0.03	17	24.3	0.03	12	15.4

Physical soil properties-Bulk density (dry weight per unit volume), porosity, pore-size distribution, texture, hydrologic conductivity, soil depth, and rock content are all related to water-holding capacity and availability to plants. When combined with site attributes like elevation, slope, and aspect, these properties greatly influence the amount and kind of vegetation on a landscape, particularly in regions with very low summer precipitation like the Pacific Northwest. Soils forming in ash and pumice have very high porosities and high water-storage capacities (table 5). Soils of basalt origin contrast markedly with soil of ash origin (table 6). The water retention difference between 0.1 and 15.0 bars of water stress is used to approximate plant-available water capacity.

A physical-chemical binding between organic matter and mineral soil particles also contributes to the development of soil structural characteristics. Increased organic matter results in greater macropore space and pore continuity within the soil. These factors contribute markedly to the ability of soil to store water and the rate of water movement into and through the soil. High water intake reduces vulnerability to overland erosion by water. Organic matter interaction with soil particles also increases the ability of soil to store water for plant growth.

Soils with internal layers of unweathered pumice have high porosities and store large amounts of water. The pumice particles are bridged, however, greatly reducing the degree of root proliferation. Consequently, much of the water stored in such layers is not reachable for plant growth (Cochran 1971).

The most water-limited landscapes of the eastside are those supporting grasslands, shrubland, and juniper woodland. Where the large array of interacting factors affecting water availability result in more favorable conditions, stress-tolerant ponderosa pine is found. As water availability improves, the mixed conifer type occurs first, then the lodgepole pine type, and finally, the spruce-fir type.

Primarily because of their high porosity, soils dominated by pumice and ash have low thermal conductivities, low heat capacities by volume, low thermal diffusivities, and low thermal contact coefficients. These thermal properties-when combined with the usually dry air mass, frequency of clear skies, and the high elevations in eastern Washington and Oregon-result in a high frequency of radiation frosts during the growing season, particularly in flats and depressions. Radiation frost is an important factor governing the distribution pat-

Table 5-Generalized comparisons of physical properties for surface layers of ash-, pumice-, and basalt-derived soils, 0 to 30-cm depth (adapted from Geist and Strickler 1978, Meurisse and others 1991, Youngberg and Dyrness 1964).

Property	Ash, eastern Oregon	Pumice, central Oregon	Basalt, eastern Oregon	Ash, eastern Washington	Sandstone, eastern Washington
Bulk density mg/m^3	0.7	0.6	0.9	0.6	1.6
Porosity, % by volume	73	77	65	77	40
Clay, % by weight	10	8	20	3	10
Coarse fragments, % by Volume	4	25	30	0	0
Available water, % by Volume	30	30	13	26	14

tern of lodgepole pine and ponderosa pine on the pumice-mantled topography of central Oregon. These soils are also particularly susceptible to frost heaving, which can either kill plant seedlings or retard their growth and lengthen the time necessary for reestablishment of vegetation after disturbances (Cochran 1973, 1975). Physical soil properties, like chemical soil properties, are highly variable and require consideration of site specific conditions.

Soil surface erosion-Because the soils of the inland Pacific Northwest are, in themselves, variable and are on variable landscapes, their potential for surface erosion is also highly variable. As a general rule, however, the high infiltration rates in most soils of this region usually mean that erosion hazard is relatively low on slopes of less than 30 percent. On steeper slopes, surface erosion hazard can increase measurably if the soils are barren. Also, even on gentle slopes, when water is concentrated from roads or ditches, the soils from ash and pumice are subject to gullying because of their low density and cohesion.

Soil ravel and mass wasting-Soils on the east slope of the Cascades, especially in central Washington, are subject to mass wasting, which includes slump-earth flow and debris torrent failures. Slump earth-flow failures are mostly in the fine-textured soils, and debris torrent failures occur in weakly cohesive ash, pumice, and other materials that often overlie compacted tills (Helvey and others 1985). Dry ravel can be significant

Table 6-Soil water held between 0.1 and 1 bars (low soil-water stress), and 1 to 15 bars (medium to high water stress) in 2 example parent materials

	Soil Depth cm	Low 0.1 to 1 bars	Medium 1 - 15 bars
		Percentage of soil water by volume	
Ash	0-15	26.1	4.4
	15-30	26.9	4.9
	30-60	24.7	5.7
	60-90	11.8	6.2
Basalt	0-15	11.7	5.1
	15-30	11.2	5.2
	30-60	9.9	5.0

on slopes greater than 40 percent in pumiceous, cindery, and ashy soils (Helvey and others 1985). These conditions are confined to specific areas in the central Oregon Plateau and eastern portions of the central Washington Cascades. Where these conditions occur, even minimal disturbances can lead to regeneration difficulties.

THE STATUS OF ORGANIC MATTER IN EASTSIDE SOILS

Soil organic matter is an important factor for the continued productivity of eastern Oregon and Washington forests. It has an integral and sometimes critical role in soil water availability, nutrient cycling, seedling establishment, growth, and erosion control. Additions, alterations, and reductions of this organic resource have a great influence on both biotic and abiotic properties of any given site (Harvey and others 1987). Soil organic matter has a variety of physical and chemical characteristics that greatly affect soil physical and biological properties, plant nutrition, and the spread of insects and diseases (Larsen and others 1980).

In unmanaged forests of this region, organic matter decomposition is frequently slow, leading to surface organic matter accumulations. Such accumulated litter and woody residues represent potential fuel for wildfire, an important force in the development of all inland Pacific Northwest forests (Habeck and Mutch 1973). If fuel accumulation is excessive, the resulting fire may be extremely hot and soil organic matter losses large. Many forests in eastern Oregon and Washington have high fuel loadings because of extensive overcrowding, stand stagnation, and tree mortality from insect and disease attack. The danger of catastrophic wildfire is increasing on these sites. If ground fuels are reduced by a combination of forest management activities, the potential for severe fire damage is lowered. These same management activities, however, can also have negative effects on soil organic contents. The interactive roles of wildfire, forest management practices, and organic matter decay are critical for forest productivity in this region (Harvey and others 1979).

Nature and Distribution of Soil Organic Matter

The type and distribution of soil organic matter in eastside forests varies widely and depends on stand age stand location, tree species, and fire history. Old-growth stands (150 to 250 years old) are useful references for the extent of organic matter accumulation in natural, unmanaged forests. They represent a long-term interaction between forest, climate, and soil processes and are indicative of a balance between site productivity and stability. As such, old-growth stands provide a model with which to estimate the effect of management activities on soil organic content and site productivity. The majority of soil organic matter in these old-growth forests is found in surface organic layers (forest floor and soil wood) and woody residue (table 7). Each of these soil organic components has a unique chemical and physical character based on the type of organic materials present and the nature of underlying mineral soil. Consequently, each organic material supports specific microbial populations and contributes to rooting activities that affect tree growth.

Woody residue can be any size, but material larger than 7.5 cm in diameter can become a long-term component of the soil ecosystem. Wood less than 7.5 cm in diameter usually decays rapidly and is converted to soil humus or consumed by fire (Edmonds 1991, Reinhardt and others 1991). Often, organic matter content in large woody residue may equal or surpass that of other soil components (table 7). Generally, the amount of woody litter in undisturbed stands increases as site moisture conditions improve and as fire hazard decreases.

Woody residue decay is primarily a function of invertebrate activity, the colonization of wood by white-rot and brown-rot fungi, and the microclimate of the soil surface (Edmonds 1991, Harmon and others 1986). Because most woody residues in eastside forests are from conifers, brown-rot fungi largely control the decay patterns. Initial sapwood decay is usually of the white-rot type, which eventually shifts to brown-rot. Heartwood is generally decayed by brown-rot fungi. Brown-rot fungi thrive under the following conditions: high temperatures, low moisture, acid pH, and increased wood lignin content (Larsen and others 1980).

Table 7-Soil organic content in old-growth forests of the northern Rocky Mountains

Site	Yield capability	Woody residue	Forest floor	Soil wood	Mineral soil[2]	Total	Proportion in mineral soil
	$m^3ha^{-1}ya^{-1}$	.... Mg ha [1]					%
Cedar/hemlock (Montana)	7.7	83	50	51	145	329	44
Subalpine fir (Montana)	7.7	146	36	36	153	371	41
Cedar/hemlock (Idaho)	9.5	154	23	48	201	426	47
Douglas-fir (Montana)	4.9	45	26	37	133	241	55

[1] From Jurgensen and others 1990
[2] Sampled to a depth of 30 cm. These values do not include root weights.

"Soil wood" is the term used to describe conditions where woody residues become incorporated into the forest floor. Soil wood is often covered by litter and not noticed as a soil component. For the inland Pacific Northwest, soil wood can comprise more than 15 percent of the organic matter in the uppermost 30 cm of soil (table 7). Soil wood amounts generally increase as stand productivity increases. On highly productive sites, soil wood can equal or surpass other kinds of organic matter in the forest floor. Virtually all soil wood is of brown-rot origin, and usually comes from large residues with appreciable amounts of heartwood. Pine species and Douglas-fir are particularly good sources for soil wood, which can remain in the soil for hundreds of years (Harvey and others 1981, McFee and Stone 1966).

The forest floor is a combination of three recognizable layers: the litter layer (O_i), consisting of freshly fallen, needles, twigs, and other debris that have undergone only slight decomposition; the fermentation or duff layer (O_e), plant materials undergoing active decomposition but still identifiable; and the humus layer (O_a), unrecognizable, dark brown or black, amorphous organic material that has undergone extensive decomposition. Both the duff and humus layers are usually permeated with fungal mycelia and root mats. The extent of forest floor development is a function of litter inputs and decomposition rates, fine root turnover, previous stand management, and fire history (Edmonds 1991).

Surface mineral horizons in eastside forests also contain significant amounts of organic matter, especially if the soil has a significant volcanic ash content (table 3). The surface 30 cm of mineral soil is the zone of greatest importance, since root numbers (and presumably root activity) decrease rapidly below this depth (Kimmins and Hawkes 1978, Strong and LaRoi 1985). The surface 5 to 10 cm of mineral soil is a transition zone below the humus layer, which has high organic matter content (table 3) and root numbers. Deeper mineral soil has a lower organic and nutrient content and lower available water-holding capacity (tables 4 and 6).

Total soil organic content generally reflects site productivity, being highest in moist cedar/hemlock or white fir stands and lowest on dry ponderosa pine sites (table 7). High-elevation subalpine fir stands are an exception because low temperature limits both organic-matter decomposition and tree growth. Organic matter in the forest floor, soil wood, and surface mineral horizons usually make up less than 15 percent (by volume) of the top 30 cm of soil (Harvey and others 1976b). Normally, however, this 15 percent has the highest concentrations of nutrients (especially N), has a substantial canon exchange capacity, and supports most of the N-fixing and ectomycorrhizal activities. This uppermost 15 percent is also the part of the soil most likely to be disrupted or destroyed by forest management activities (Page-Dumroese and others 1991). Deeper soil horizons, however, can be important to tree growth, especially on dry, sandy soils, and can be subjected to compaction by heavy equipment (Cochran 1985, van Rees and Comerford 1986).

The Effects of Forest Management Operations

Nearly all forest management operations can alter the cycling of aboveground organic materials and their subsequent incorporation into the soil. In the past, timber removal was not considered detrimental to site productivity because of long stand-rotation ages and the large amounts of organic matter usually left after harvest. Recent trends towards increased woody residue removal and intensive site preparation, however, have raised concerns about how such management affects soil processes and site productivity (Harvey and others 1976a, McColl and Powers 1984). Most of these concerns have focused on possible soil nutrient losses, or changes in nutrient availability (Smith 1985, White and Harvey 1979). The contribution of organic matter to soil nutrient cycling is a major concern; however, the loss of organic matter may additionally affect such soil characteristics as water-holding capacity, aeration, drainage, and cation exchange, and may greatly affect long-term productivity.

Clearcut harvesting, which is used in this region to manage for early successional species such as Douglas-fir, causes greater losses of soil organic matter than other harvesting systems. Historically, clearcutting operations have included forest floor removal (exposing mineral soil); the control of competing grasses, shrubs, and trees; followed by prescribed burning or scarification (Graham and others 1989a). Clearcutting operations remove much of the woody residue and surface soil organic matter present on a site, though amounts vary according to the intensity of the treatment and the distribution of organic matter in the soil (table 8). Soils containing higher proportions of organic matter in woody residue on the forest floor are more affected by these operations than soils containing higher portions of surface mineral layers.

Table 8-Surface organic contents after clearcutting and site preparation

	Residue treatment[2]			
Soil component	**None**	**Prescribed burned**	**Intensive removal**	**Uncut**
Cedar/hemlock (Idaho)	Mg[3]	Mg	Mg	Mg
Wood residue	146.0	57.9	10.6	154.3
Forest floor	16.7	5.5	13.3	23.2
Soil wood	50.9	22.4	51.6	47.9
Total	213.6	85.8	75.5	225.4
Subalpine fir (Montana) Wood residue	--	55.2	43.7	145.7
Forest floor	--	30.2	35.8	36.0
Soil wood	--	37.6	43.2	35.9
Total	--	123.0	122.7	217.6

[1] From Jurgensen and others 1992.

[2] Site was clearcut to a 12.7-cm-diameter top. Residue treatments: none, residue left; prescribed burned, broadcast burned in the fall; intensive removal, residue removed by blading with a crawler tractor.

[3] Dry mass ha^{-1} of organic material on top of mineral soil.

Losses of organic matter from forest floor and mineral soil after timber harvesting are generally a result of increased organic matter decomposition by soil microorganisms (Hendrickson and others 1982). High soil moisture, temperature, and alkalinity after harvesting-especially if fire is used for slash disposal (table 9)-increase microbial activity (Hungerford 1980, Jurgensen and others 1981). Mixing of the forest floor into the mineral soil during harvest and site preparation also increases rates of organic matter decomposition and the release rate of nutrients (Salonius 1983). This mixing effect is more pronounced when site preparation follows logging (Graham and others 1989a). Many of the practices that caused deleterious effects have been dramatically changed in recent years, however (Meurisse 1988).

Site preparation is often critical to attaining satisfactory stocking of seedlings in eastside forests. Site preparation in this region is primarily by burning or mechanical means, such as soil scarification or scalping (Gutzwiler 1976). Mechanical equipment, such as dozers and grapple pilers, can remove most woody residue or displace the forest floor and surface mineral soil over large areas. Such extensive machine piling, windrowing, or soil scarification significantly affect subsequent seedling establishment and growth (Graham and others 1989b, Minore and Weatherly 1988). Prescribed burning can also be used effectively to reduce fuel loadings and prepare the soil for planting, but care is needed to ensure that such operations do not remove too much organic matter and adversely affect site productivity.

Table 9-Soil moisture and temperature on a cedar-hemlock site in northern Idaho after clearcutting and site preparation treatments [1]

Soil component	Residue treatment [2]							
	None		Prescribed burned		Intensive removal		Uncut	
	H20 %	Temp deg C	H20 %	Temp deg C	H20 %	Temp deg C	H20 %	Temp deg C
Forest floor	88	15.4	43	14.3	104	15.3	90	11.7
Soil wood	158	13.4	122	12.8	206	12.4	232	11.4
Mineral soil [3]	47	12.0	38 1	11.5	61	10.7	41	10.5

[11 From Jurgensen and others, 1992.

[2] Site was clearcut to a 12.7-cm-diameter top. Residue treatments: none, residue left; prescribed burned, broadcast burned in the fall; intensive removal, residue removed by blading with a crawler tractor.

[3] Mineral soil to a depth of 30 cm.

When regeneration is established from seed, removing large amounts of soil organic matter by various site preparation techniques to expose mineral soil is sometimes desirable (Shearer and Stickney 1991). Normally, however, such extensive soil disturbance is not required if the site is planted with nursery stock. Site preparation methods used before planting seedlings would be less intensive than those used for seedbed preparation, and would have less effect on soil organic content (Harvey and others 1987). How much postharvest organic matter to leave will be influenced by whether the stand is to be established by planting or by relying on natural regeneration. When using natural regeneration, however, managers must always be aware of the risk that extensive seedbed preparation may have on soil organic matter reserves, which are needed for subsequent stand growth and development.

Loss of organic horizons during harvesting and site preparation may seriously reduce site productivity, stability, and regeneration potential. Studies worldwide have shown that high rates of organic matter removal from forest sites are linked to substantial long-term growth reductions of various conifer species (Bollard and Will 1981, Farrell and others 1986, Smith 1985, Weber and others 1985). Substantial losses in productivity have been reported in the northern Rocky Mountains as a result of forest-floor or surface soil displacement and soil compaction, 15 to 25 years after clearcutting (Bosworth and Studer 1991, Clayton and others 1987). Consequently, postharvest treatments should be planned to limit damage to fragile organic horizons-especially for the high-stress, diseased stands common in many areas of eastern Oregon and Washington. Often these stands have heavy fuel loadings that warrant intensive site treatments and forest floor removal to achieve adequate regeneration. Even on these sites, however, productivity will be maintained or improved by conserving as much organic matter as possible.

After harvesting timber on these sites, a large amount of woody residue is added to the soil surface. How much should be left to become part of the soil organic supply will depend on stand species composition, amount of decay and defect, rates of wood utilization, and whether any site preparation is used (Harmon and others 1986, Harvey and others 1989a). Often, however, woody residues after harvesting and site preparation are less than what was present before harvest (table 8). During harvest, large decayed logs, which are very important to soil nutrient and microbiological processes, are often destroyed or fragmented (Jurgensen and others 1992).

In general, more woody residue can remain on cooler, wetter habitat types (subalpine fir and Engelmann spruce) than on the warmer, drier ones (Douglas-fir and ponderosa pine). A minimum value of 22 to 36 metric tons ha^{-1} of residual woody material has been recommended to maintain long-term site productivity on such moist sites (Harvey and others 1987). Leaving more wood could benefit many sites, but might create a significant fire risk. After considering fire hazard and various other site preparation objectives, Reinhardt and others (1991) established a fairly wide range of allowable woody residue loadings (22-125 metric tons ha^{-1}) for mixed conifer forests in the northern Rocky Mountains. But for drier sites in this region, this recommendation is likely high. Site-specific woody residue guidelines are needed for the generally dry, high stress forests in eastern Oregon and Washington.

Perspectives for Eastside Ecosystems

Soil organic matter is an important factor in the continued productivity of eastern Oregon and Washington forests. Compared to soil conditions in preharvest old-growth stands, timber harvesting and extensive site preparation displaces or destroys surface soil organic matter over large areas. Such organic matter losses have important implications for soil chemical, biological, and physical properties, especially on infertile sites that are prone to drought. Severe wildfires would have similar consequences. Removing large woody debris, which is the source of soil wood, may also have considerable consequences for long-term site productivity.

Maintaining adequate amounts of organic matter on many forest sites in eastern Oregon and Washington may increase the risk of wildfire and favor the activity of certain root-rotting fungi. Careful prescribed burns or mechanical site preparation, however, can be practiced on most sites with relatively little effect on soil organic content. On the very dry sites in this region, with their historically low soil organic and N content and high fire potential, this situation will be the most difficult to resolve.

THE MICROBIOLOGY OF EASTSIDE SOILS

The Soil as a Biological Entity

Traditionally, some have viewed soil as inert and inanimate, and soil properties have often been perceived as distinctive but relatively unchanging-except for plant nutrients-and based on mineral constituents. The organic horizons have, until recently, been largely ignored. Soil microbes have also been ignored, except for a few high-profile organisms (such as soil-borne pathogens and mycorrhizal fungi). Predictions by forest growth models have keyed almost exclusively on vegetation, gross land form, and site characteristics-the aboveground characteristics of the last rotation were assumed to be the best indicator for predicting growth, ignoring soil and related soil-borne processes. If soil potential was reduced, the assumption was that fertilizing could offset any damage. This approach has fostered a significantly overoptimistic view of the health and productivity potential for second generation forests (Gast and others 1991, Powers 1991).

Contemporary studies indicate that soil quite literally resembles a complex living entity, living and breathing through a complex mix of interacting organisms-from viruses and bacteria, fungi, nematodes, and arthropods to groundhogs and badgers. In concert, these organisms are responsible for developing the most critical properties that underlie basic soil fertility, health, and productivity (Amaranthus and others 1989, Harvey and others 1987, Jurgensen and others 1990, Molina and Amaranthus 1991, Perry and others 1987). Biologically driven properties resulting from such complex interactions require time lines from a few to several hundreds of years to develop, and no quick fixes are available if extensive damages occur (Harvey and others 1987).

Microbial Ecology

The variety of organisms residing in forest soils are extensive; all contribute to soil development and function, some in very critical ways (Amaranthus and others 1989). Although this section concentrates on the microbes (primarily bacteria and fungi), we recognized that several orders of insects, earthworms, and burrowing mammals make significant and sometimes critical contributions to organic matter decomposition, soil mixing, and microbe propagule movement within many forest soils (Molina and Amaranthus 1991, Wilson 1987).

The numbers and biomass of microbes in forest soil can be staggering; for example 10 to 100 million bacteria and actinomycetes, 1000 to 100,000 fungal propagules, and several kilometers of hyphae (fungal strands) can be present in a single gram of soil (Bollen 1974). The biomass related to such numbers is also staggering. Old-growth Douglas-fir forests of the Pacific Northwest can contain 4200 kg/ha dry weight of fungal hyphae and 5400 kg/ha of ectomycorrhizal root tips alone (Fogel and others 1973). Bacterial biomass could equal or exceed fungal biomass, and the total biomass of an inland cedar/hemlock forest should be very nearly comparable to a coastal Douglas-fir forest. Thus, microbial biomass in eastside forests could easily reach 10,000 kg/ha and are a force to consider in management methods.

Input to soil structure-The role of microbes in producing structure in non-agricultural soils is often overlooked. The development of soil and the stability of its structure is a direct result of the input of complex carbon compounds to the soil. Much of this carbon input and the conversion processes are mediated or facilitated by microbes (Amaranthus and others 1989, Perry and others 1987). Structure greatly affects the pore distribution in the soil, especially the large pores that permit the storage of water and rapid movement of air on which plant roots are highly dependent. Thus, maintaining structure is critical to soil productivity and sustainability, and because the processes are dynamic, they require a constant high rate of carbon input, conversion, and loss.

Aboveground and belowground processes are tightly interconnected. Photosynthetic plants fix carbon and transport it to the roots and soil via leaf litter; soil microbes then reprocess, convert, and store the carbon. Soil carbon is ultimately released back to the atmosphere by microbial (and other small animal) respiration. Thus, aboveground and belowground productivity are directly connected, not only via direct transport of carbon to roots, but also through the production of organic litter. Microbial decomposers convert plant litter into soil components through the activities of several groups of organisms directly associated with plant root systems. By way of the interconnected microbial community, native plants modify the soils in which they grow. Up to 80 percent of a stand's annual carbohydrate production may be invested in supporting the mycorrhizal feeder-root system (Fogel and others 1973). At least 15 percent of annual energy production is directed to mycorrhizae. This high rate of energy distribution indicates how critical belowground microbial processes are to aboveground growth potential (Read 1991).

Rhizosphere-Perhaps the most interesting and dynamic microenvironment in forest soil is the rhizosphere-the region within 2 mm of any root surface. The root surface is termed the rhizoplane. Both the rhizoplane and the rhizosphere tend to have more available high-energy substances-sugars, starches, gels, amino- and organic-acids, for example-than soil away from roots. High-energy substances are derived both from the sloughing of cellular materials (root caps, surface cells) and from the leakage of materials directly through root cell walls (Molina and Amaranthus 1991). The rhizosphere of young roots tends to have the highest concentration of leakage products. Generally, rhizosphere substance concentrations vary with the age, season, health, and species of plant.

Microbial communities inside the rhizosphere are quite different from those outside. Outside, the soil organisms can generally derive energy from the breakdown of complex organic molecules contained in a wide variety of organic debris, including wood (Edmonds 1991, Fogel and others 1973). Organic debris is an important source of energy for free-living, N-fixing microbes in all inland Western forest soils (table 10).

Table 10-Contribution of surface organic materials to nonsymbiotic nitrogen fixation in three old-growth forests of the inland Northwest (Jurgensen and others 1991)

Soil component	Subalpine fir (Montana)		Cedar-hemlock (Montana)		Cedar-hemlock (Montana)	
	Mg [1]	%N fix [2]	Mg	%N fix	Mg	%N fix
Woody residue	145.7	35	83.2	27	154.3	49
Forest floor	36.0	22	49.7	23	23.2	3
Soil wood	35.9	17	50.5	11	47.9	7
Mineral soil	--	26	--	39	--	41

[1] Dry weight (metric tonnes/ha) of organic material on top of mineral soil.

[2] Percentage of total nitrogen-fixation.

Rhizosphere organisms contribute a wide variety of products to the soil environment (Molina and Amaranthus 1991). Many simply metabolize root exudates into complex organics, adding them to the soil mixture. Others, however, contribute directly to the plant by releasing otherwise unavailable nutrients from the soil (Chanway and Holl 1991), providing direct pipelines from soil to root cells (such as with mycorrhizal fungi) and directly competing with root pathogens for a variety of nutrients (Molina and Amaranthus 1991, Ferry and others 1987). Also, the rhizosphere is home to a wide variety of root-damaging organisms, such as low-grade pathogens, feeder-root diseases, and root-rotting organisms. Infection of the root by mycorrhizal fungi often provides resistance to low-grade and feeder-root pathogens (Marx 1972, Zak 1964). The rhizosphere is another important microenvironment for nonsymbiotic N-fixing microbes that again can be important to soil N enrichment in Western forest soils (Dawson 1983, Li and Hung 1987, Rambelli 1973).

Compared to other soil environments, the rhizosphere region is an extremely competitive, energy rich environment. Without the appropriate vegetation, the contributions of this important microenvironment to forest soil development are lost.

The effects of symbionts on soils-Important microbes affected by the rhizosphere environment are various symbionts. The most important symbionts are: ectomycorrhizal fungi that infect tree roots to form functional “short roots,” and a small group of bacteria and actinomycetes that infect plant roots to form N-fixing structures (“nodules”) on legumes and other N-fixing plants. Both provide N directly to the host; both directly affect the rhizosphere environment and the supporting plant; and both parasitize the plant, taking energy but supplying nutrients in return (Amaranthus and others 1989, Jurgensen and others 1990, Molina and Amaranthus 1991, Ferry and others 1987).

The presence of N-fixing nodules provides host plants direct access to atmospheric N, making them far less dependent on soil N supplies. Mycorrhizal roots are distinctive, complex structures on tree and other forest plant roots in which a similar trade occurs. The invading fungi take energy from the plant, and, in return, greatly extend the root system access to soil nutrients by supplying nutrient release and transport mechanisms through the hyphal/rhizomorph (fungal root) networks in soil. As reported earlier, several kilometers of fungal hyphae have been recorded in a single gram of soil. This hyphal network also creates its own functional rhizosphere, termed the mycorrhizosphere (Rambelli 1973). Interconnections between fungal individuals within hyphal and rhizomorph networks are common (Ferry and others 1989).

Plant to plant connections via mycorrhizae make possible an interconnected network among individuals and within complex stands (between overstory and understory, for example) (Ferry and others 1989, Read and others 1985). Root grafting in eastside ecosystems is largely limited to within an individual tree, occasionally between individuals of the same species, but only very rarely between species. But within species, mycorrhizal networks are potentially limited only by the host range (number of species of hosts that the fungus can infect). Some fungi have very wide host ranges; thus, a stand can be extensively interconnected-aboveground to belowground, belowground between roots, between individuals (of the same or different species), or between groups of individuals-and even between one generation and the next (ferry and others 1989). So, in addition to nutrient movement in the soil via micro or macro pores, cracks, root channels, and so on, living conduits within and among higher plants and fungi provide a network for extensive exchange of nutrients and metabolites. This system is best developed in eastside forests within surface soil horizons that contain organic matter (table 11).

Table 11-Cumulative depth (centimeters of organic soil strata) and distribution of active ectomycorrhizal short roots in organic and mineral strata within and between sites (Harvey and others 1986)

	Cumulative depth/core of organic horizons	Total ectomycorrhizal short root-tips in Organic horizons (all)	Total ectomycorrhizal short root-tips in Mineral horizons (all)
	cm	.... percent	....
Old growth			
Western hemlock, Montana	3.8	[1] 89 a	11 b
Subalpine fir, Montana	3.5	93 a	7 b
Western hemlock, Idaho	2.5	89 a	11 b
Douglas fir, Montana	2.3	76 a	24 a
Western white pine, Idaho	2.0	93 a	7 b
Ponderosa pine, Washington	1.7	16 a	84 b
Grand fir, Idaho	1.5	70 a	30 a
Subalpine fir, Wyoming	.7	71 a	29 a
Second-growth (Montana)			
Pole sized lodgepole	1.9	82 a	11 a
Pole sized mixed conifer	1.8	89 a	11 a
12-year-old western larch	1.5	31 a	69 b
Pole sized Douglas-fir	1.2	66 a	34 a
Pole sized ponderosa pine	.6	86 a	14 a
12-year-old lodgepole pine	.5	76 a	24 a

[1] Differing letters indicate significant differences ($p = 0.05$) within site, based on two-sided t-test of numbers of short-root tips in combined strata

Can individuals (or groups) parasitize one another, that is to say, move nutrients or photosynthate around within a stand to balance temporary shortfalls? Such movement has yet to be widely demonstrated, except in simple microcosms (Read and others 1985), but it seems likely, particularly on highly variable sites that include harsh or infertile environments (ferry and others 1989). Positive responses of trees, to both the presence of ectomycorrhizae and to associated N-fixing plants, are demonstrable and common (Harvey and others 1991, Jurgensen and others 1990). A wide variety of external climatic and soil variables may condition this response, but maximum plant dependency on microbial symbionts seems most likely on inherently harsh or damaged sites (Boucher and others 1982, Harvey and others 1991, Perry and others 1989).

Nutrient channeling and cycling-The above descriptions of microbial structures and processes suggest that they are likely to provide highly critical conduits for the input and movement of materials within soil and between the soil and the plant. Nitrogen and carbon have been mentioned and are probably the most important. Although the movement and cycling of many others are mediated by microbes, sulfur, phosphorus, and iron compounds are important examples (Amaranthus and others 1989, Molina and Amaranthus 1991).

The relation between forest soil microbes and N is striking. Virtually all N in eastside forest ecosystems is biologically fixed by microbes (Boring and others 1988). Only a small amount of N comes into eastside forests directly from the atmosphere as precipitation or dust (probably less than 2 kg/ha per yr), except downwind from major pollution sources. Next to temperature and moisture, availability of N is probably the most limiting factor in forest productivity (Boring and others 1988, Jurgensen and others 1990). Most forests, particularly in the inland West, are likely to be limited at some time during their development by supplies of plant-available N (Miller and others 1992). Thus, to manage forest growth, we must manage the microbes that add most of the N and that make N available for subsequent plant uptake.

Symbiotic N fixation is the most efficient process by which forest sites acquire N from the atmosphere; however, the process depends on development and vigor of appropriate hosts. Generally, hosts are best suited to this function and most vigorous (with attendant high fixation capacity) during the early stages of forest development. For old-growth or heavily shaded conditions, hosts are much reduced in numbers and vigor (Borman and Gordon 1989). Unfortunately, relatively few hosts are present at any stage, and their ability to support fixation depends on high plant vigor (Jurgensen and others 1990). Release of N from these host plants can be slow. If internal demand for N is high until it dies and decomposes, the plant may release very little N, except as falling leaves and fine root turnover. The harshest, most infertile sites have the greatest need for added N, but the most efficient N fixation depends on limited hosts growing under good conditions that are not often available. So, because some eastside forest sites are relatively harsh, they are unlikely to meet long-term N requirements from this source.

The other principal source of soil N is nonsymbiotic fixation by free-living microbes that depend on the breakdown of soil organic materials for the energy to fix N (jurgensen and Davey 1970). Nitrogen input potential from this source is much lower than from symbiotic fixation (table 12). The fixation process is energy intensive, but energy available from the breakdown of soil organic matter, or leaked from other organisms, is much lower than that supplied to symbiotic N-fixers by host plants. In addition, nonsymbiotic N-fixers are not efficient in breaking down complex soil organic matter directly; they depend on their ability to scavenge energy-containing materials released as byproducts of activities from other organisms, primarily decomposers. Thus, energy availability for this process is limited and depends on other groups of organisms. Substantial N fixation often occurs in rhizosphere and mycorrhizosphere environments, however, because of the availability of high-energy leakage products there (Dawson 1983, Li and Hung 1987). Despite the generally low rates of N input from nonsymbiotic N fixation, this source of N is usually constant and N is rapidly released because of the short life span of the microbes; this source is sustained throughout the life of a forest stand and increases with organic matter accumulations characteristic of dense or old-growth forests (Jurgensen and others 1990). Both amounts of organic matter and rates of N fixation are important; either can be critical in eastside forests.

Decomposition and pathogenesis-A major characteristic of western forests is the tendency to accumulate fixed carbon (Olsen 1963). Ecologically speaking, the photosynthetic process is less limited in this environment than microbial respiration-the process that drives decomposition. Resulting excess carbon (accumulated fuel) and frequent lightning can combine to aid the recycling process through wildfire, an essential decomposition force in these ecosystems (Habeck and Mutch 1973, Olsen 1981). In the absence of fire, plant nutrients would eventually be locked away in accumulating debris, turnover would be slow, and ecosystem development would be severely impaired. Thus, biological decomposition and fire support the nutrient turnover required for vegetation to develop over long periods of time, especially in relatively harsh, infertile environments. Even subtle differences in temperature, moisture, or both can change this balance and the resulting fire regime (Harvey and others 1979, Olsen 1981). Fire cycles can vary widely between climatic regions, but, in the absence of human intervention, a relatively stable balance between fire and microbial decomposers is normal within a climatic region.

Table 12-Nonsymbiotic nitrogen fixation in forests of the Western United States

Forest type	Location	N fixation (kg N/ha/yr)	Reference
Douglas-fir			
Old growth	Oregon	1.0	Sollins and others 1987
	Oregon	1.4	Silvester and others 1982
	Montana	0.8	Jurgensen and others 1991
various ages	Montana	0-1.0	Jurgensen and others 1987
23-yr-old	Oregon	0.4-1.1	Heath and others 1988
Subalpine fir			
Old growth	Montana	0.7	Larson and others 1978
Various ages	Montana	0-1.7	Jurgensen and others 1987
	Montana	1.5	Jurgensen and others 1991
Cedar-hemlock			
Old growth	Idaho	2.9	Jurgensen and others 1991
	Montana	0.8	Jurgensen and others 1991
various ages	Idaho	0 - 4.3	Jurgensen and others 1987
	Montana	0 - 1.8	Jurgensen and others 1987
Mixed conifer			
Various ages	Idaho	< 0.1 - 4.8	Harvey and others 1989
120-yr-old	British Columbia	0.3	Cushon and Feller 1989
Lodgepole pine			
80-yr-old	Wyoming	< 0.2	Fahey and others 1985
Aspen - mature	Utah	0.6	Skujins and others 1987

Insects and diseases are part of a balanced ecosystem that includes fire, biological decomposition processes, and the development of vegetative communities that thrive in the temporally and spatially variable, resource-limited eastside environment (Harvey and others 1992). Although usually viewed as pests at the tree and stand scale, insects and disease organisms perform useful functions on a broader scale. The role of native soil pathogens will be highlighted in this discussion. Root disease fungi, for example, can infect both individuals and localized groups of individuals (stands). Fungi can be devastating at these scales. Annual losses from individual tree mortality can be 2 to 3 percent, and productivity losses to 30 percent are common in inland Western forests (Byler 1984, Filip and Goheen 1984). We have seen stands where productivity has essentially ceased because of root disease fungi.

Most insects and diseases, including root-rot organisms, tend to select stressed hosts (Waring 1987). Stress-selection can provide increased "recycling" of individuals or groups of host plants that are not well suited to their current environment. For example, if geographically and climatically diverse systems are often visited by fire, some vegetation becomes stressed by the attendant rapid changes. Removal of stressed vegetation facilitates rapid replacement; and many "pests," including root-rots, facilitate early and rapid decomposition and recycling of nutrients from such potentially maladapted hosts (Harvey and others 1992).

Decomposers and pathogens can play various, interactive roles. Time, space, and ecosystem change are important variables in these roles. What may be devastating to individual trees or stands at a given moment may provide long-term ecosystem benefits (Harvey and others. 1992). Fundamental potential (climate, soil) of forest sites should first be matched to appropriate vegetation and stand characteristics at each stage of development, fully considering the historical norms under which the vegetation developed. Then, forest management through manipulating pest damages has a much greater chance of success.

Pests are a part of even the healthiest eastside ecosystems. Pest roles-such as the removal of poorly adapted individuals, accelerated decomposition, and reduced stand density-may be critical to rapid ecosystem adjustment. But these roles need not be fulfilled at maximum rates over extensive areas at any one time; when they are, the cause is more fundamental than simply pest activities out of control (Harvey and others 1992). In some areas of the eastside and Blue Mountain forests, at least, the ecosystem has been altered, setting the stage for high pest activity (Gast and others 1991). This increased activity does not mean that the ecosystem is broken or dying; rather, it is demonstrating functionality, as programmed during its developmental (evolutionary) history.

Soil Microbes as Ecosystem Drivers

To reemphasize, photosynthetic plants produce basic foodstuffs that build plant bodies. These bodies provide energy sources for microbes. Microbes, in turn, drive many of the most critical ecosystem processes that create the total environment in which plants grow, especially the soil environment (Harvey and others 1987, Jurgensen and others 1990). Microbes are responsible for the input of N; those that attack living plants (inclusive of insects) directly regulate the genetic nature of plant populations, both individually and collectively, and also regulate population dynamics (Burdon 1990, Linhart 1991). Microbes are also the primary intermediaries for required communications between plant to soil, soil to plant, and plant to soil to plant, as well as movement of material within the soil (Amaranthus and others 1989, Perry and others 1989).

Soil Microbes and Microbial Processes as Indicators of Health and Productivity

From an ecosystem perspective, the mere presence of pests may not indicate long-term forest health problems. Such damage, however, may sometimes be a useful indicator depending on our understanding of other ecological questions.

Because they are critical for ecosystem development and function, microbes will, no doubt, eventually be used to measure transfer rates between roots and soil of critical nutrients and metabolites. Acid rain and pollution-caused reductions of ectomycorrhizal fungi are well documented in parts of Europe (Arnolds 1991, Cherfas 1991, Rühling and Soderström 1990). Similarly, microbes are highly sensitive to the presence of a variety of toxic materials (Fritze 1992). Population changes for specific organisms should be good indicators of the presence of toxins in the system. Examples are the effect of heavy metal pollutants and organic toxins on both fleshy fungi and leaf-inhabiting fungi (Hawksworth 1990, Nordgren and others 1985). In addition, fungi, like some higher plants, can accumulate heavy metals (Rizzo and others 1992) and might serve as a sink for damaging pollutants, even at extremely low concentrations.

Fungi should be particularly useful as forest health indicators because they form visible fruiting bodies (such as mushrooms). Unfortunately, timing and density of fruiting is highly responsive to weather, and thus, may not be easy, particularly because our knowledge of fungal community dynamics in forested ecosystems remains limited. Observations in Europe, however, suggest that dramatic reductions in the diversity and population density of forest floor fungi may be a direct result of extensive pollution (Cherfas 1991). Forest managers should remain alert to changes in potentially polluted areas. Lichens are also useful indicators of air pollutants, probably because of the importance of the fungal component in their combined fungal and algal structures and their near total dependence on aerosol nutrients (Eversman 1985).

Plants without chlorophyll are common in inland Pacific Northwest forest ecosystems. At least one group of these plants depends on interconnections with chlorophyllous hosts through mycorrhizae. These are relatively small but easily seen herbaceous plants, such as Indian-pipe (*Monotropa uniflora* L.) and pinedrop (*Pterospora andromedea* Nutt.). They use common infection by the mycorrhizal fungus as an indirect means of parasitizing an energy-producing host. Thus, their presence, population size, and behavior may provide valuable clues as to the health and diversity of the mycorrhizal community and its respective hosts. Much research remains to be done on these plants.

Eastside Perspectives

Microbial processes are fueled primarily by plant debris that is concentrated in and most characteristic of organic horizons. These horizons are shallow, subject to site disturbance (tables 8 and 11), and thus easily changed or destroyed. These ecosystems have evolved to accommodate natural disturbances, primarily by wildfire and climate, as well as a wide range of pest activities; however, these ecosystems have not developed under circumstances that exclude fire, or that include soil compaction or extensive physical dislocation of soil horizons. Any of these factors can pose short-term risks. Fire especially, when it occurs after excessive fuel buildup, may be severe and highly damaging to soil systems. Also, compacted soil layers will eventually return to original conditions only after long periods of time. Ecosystem damage from these factors is likely to be detrimental to the full range of microbe functions.

FIRE AND EASTSIDE SOILS

General Effects of Fire on Forest Soils

Several reviews of fire effects on soil are available in the literature (Harvey and others 1989a, Hungerford and others 1991, Viro 1974, Wells and others 1979), and only a brief summation of these general effects will be given here. Fire has been an important factor in the development of forest ecosystems and soils in eastern Washington and Oregon. The role of fire changed with the arrival of Europeans, but its effects continued to be important to soils and ecosystems in this area, both by its exclusion and its use. Some ecosystems depend on fire for establishment; others depend on fire to develop certain successional paths (Weaver 1974). In addition to the direct effects of fire on soil, changes in ecosystem type or path can also indirectly change soil properties and processes.

The effects of fire on soils are numerous and highly variable, depending on the type and intensity of the fire and the amount of surface fuels consumed. Fire can affect soils physically, chemically, and biologically; it can alter nutrient cycles, soil development, and site productivity. If litter or the critical organic (O) horizons are not entirely destroyed by fire, then fire effects on soil are usually minimal.

Fires generally have little effect on soil physical properties, but high intensity fires can make clay soils coarser and more erodible (Chandler and others 1983) or affect soil porosity and structure (Dyrness and Youngberg 1957). If fire removes all of the litter layer, raindrop impact can alter the structure of the soil at the surface, decrease porosity, and increase bulk density; these changes will also reduce water infiltration and increase surface runoff and soil erosion (McNabb and Swanson 1990). Fire can also cause water-repellent layers to form in soils, and decrease water movement down the soil profile (DeBano and others 1976). Microclimatic effects of fire depend on whether the understory or both the understory and overstory are consumed. Removal of understory vegetation can increase solar radiation to the soil surface and increase air and soil temperatures, but it may have little effect if the overstory is undisturbed. Soil moisture-can be increased or decreased by fire, depending on whether soil infiltration is reduced (decrease in soil water) or vegetation is removed (reduces interception and transpiration and increases soil water).

Changes in soil chemical properties or soil processes largely result from the loss of protective woody debris and O-horizon material. Carbon is volatilized from organic matter and litter above 200°C and N above 300°C. Consequently, N can be lost from soils with fires of moderate intensity (Hungerford and others 1991).

Phosphorus and (S) can be volatilized at temperatures of 750 to 800°C and are not normally lost except by very high-intensity fires (Hungerford and others 1991). Major cation nutrients contained in organic matter, such as Ca, Mg, and K, are not normally lost through volatilization, but deposited in ash as oxide and carbonate salts, with trace amounts of phosphates. These salts are highly soluble, particularly those of K, and can be leached from the soil with high rainfall (Viro 1974). Ammonification and nitrification are enhanced immediately after fire, but ammonium and nitrate usually return to pre-burn concentrations within a few years after fire (Jurgensen and others 1981).

Normally, these nutrients are readily available for plant uptake after fire, and create short-term increases in soil fertility that can last several years. If the organic matter of the mineral soil is reduced (as happens with a high-intensity, long-duration fire), however, the cation exchange capacity of the soil is also reduced and the ability of the soil to retain nutrients leached from ash decreases. The increase in cations other than hydrogen or aluminum and the loss of organic acids from decomposition also increases soil pH, a change that can be beneficial to many plants and organisms. A decrease in organic acids and an increase in pH can reduce podzolization (a soil-forming process creating an acidic, highly leached soil). Hall (1980) has suggested that repeated fires could alter the rate of podzolization in forest soils.

Fire effects on soil flora and fauna vary widely with fire severity, soil type, and individual organisms. Bacteria are killed at temperatures of 110 to 210°C (wet and dry soil, respectively), and fungi are killed at 60 to 120°C (Wells and others 1979). Severe fires sometimes sterilize soil, but low-intensity fires may cause only short-term effects on soil flora. Death of soil organisms can disrupt ecosystem functions because flora and fauna that decompose organic matter, mycorrhizae, N-fixers, and other organisms are essential to element cycling. Bissett and Parkinson (1980) found that fire changed the relative prominence of different soil organisms, and believed that the successional path of the soil flora in O horizons had been altered by fire. The effects of fire on mycorrhizae vary, but severe fires can suppress mycorrhizae in the top 10 cm of soil (Wright and Heinselman 1973) or decrease mycorrhizae by consuming soil organic substrates (Harvey and others 1976b). Fire sometimes also controls root diseases (Ahlgren 1974), but increases infection in other cases by creating infection courts in damaged roots (Littke and Gara 1986). The effects of fire on soil fauna are less well known, but are believed to decrease populations, although effects may be less and of shorter duration (Ahlgren 1974).

Many of the effects of fire on soils and vegetation alter the nutrient cycle of the burned ecosystem. Woody debris, the O horizon, and understory and overstory organic matter are either partially or totally consumed. Water inputs (precipitation can be altered by the amount of condensation on foliage) and outputs (leaching) can be affected by fire, as well as by processes within the soil ecosystem. The movement of nutrients through plant and soil organisms is an essential part of the nutrient cycle, and the elimination of vegetation or soil flora and fauna will drastically alter the ecosystem cycling rates in the short term. The rates of transfers and transformations of elements within the ecosystem can be changed by the loss of organisms responsible for decomposition and nutrient immobilization, reduced plant uptake and litter-fall, differences in soil water movement (changes in transpiration and evaporation), and other effects. Nutrient cycling will eventually adjust to changes caused by even severe fires, but excess available nutrients can be lost from the site until cycling rates increase.

In the late 1800s, the pattern of fire in the inland Pacific Northwest changed with the coming of Europeans. With this change, forest and range soils and ecosystems were shifted to a different successional direction. In a geologic sense, this change in soil processes has been brief and is reversible. In human timeframes the effects appear long-lasting. Pre-1900 fire conditions and soil properties and processes will be considered briefly here; then, an examination will be made of how this shift in fire pattern has altered current soil properties and processes.

Pre-1900 Fire Conditions and Eastside Soils

Before the late 1800s, burning of forests and ranges by Native Americans was common and frequent (Arno 1985). Because of the high frequency and resulting low fuel build-up, most of these burns were probably not high-intensity fires, and did not have long-lasting effects on soil. The practice may have loosened nutrient cycles by rapidly changing litter to available nutrients, but, depending on the fire frequency, this change may have had little effect on site productivity. Most wildfires of this time were probably of similar intensity and effect. The ecosystem type and location of a burn is most important in determining how much a fire affected soil, largely because fire frequency was correlated with the ecosystem type and elevation (Agee 1993 (table 2)).

Pre-1900 fires were frequent in low-elevation ponderosa pine and Douglas-fir forests and in range lands throughout the inland Pacific Northwest. How many of the fires were caused by Native Americans is not known, but comparisons of fire frequency between habited and uninhabited areas suggest that native burning was a primary factor in the short fire frequencies in many areas (Gruell 1985). Most Native American fires were in low-elevation areas, but they undoubtedly spread to high-elevation forests at times; most high-elevation fires are believed to have been caused by lightning (Arno 1985). Little information is available on pre-human fire conditions of eastside forests.

Knowledge of the general effects of fire on soils can be used to estimate the effects of fire on physical, chemical, biological, and nutrient cycling of both high- and low-elevation forest soils. Frequent underburning of low-elevation ponderosa pine and Douglas-fir probably had little effect on soil properties because most of these fires were probably of low intensity, but would have affected some aspects of nutrient cycling. Fire would accelerate litter decomposition and provide a periodic flush of available nutrients. The periodic reduction of understory vegetation would release captured nutrients and reduce atmospheric N fixation, if N-fixing plants were prominent on the site. The effects of fire on high-elevation true fir and lodgepole pine forests are probably similar to the effects of fire today, that is, highly variable. In areas of low fire frequency and high fuel buildup, fires may consume large amounts of woody debris and the O horizon. This consumption could subject shallow soils to a serious loss of productivity by reducing the organic matter that is essential for maintaining soil structure, water retention, organism population structure, cation exchange sites, and erosion prevention (Harvey and others 1989a).

Post-1900 Fire Conditions and Eastside Soils

Studies comparing pre-1900 forest and range ecosystems of the inland Pacific Northwest with post-1900 conditions generally indicate a buildup of fuels and biomass in forests since 1900 (Gruell 1983, van Wagtendonk 1985), largely a result of fire suppression in the region, which has changed soil processes and the response of soils to fire. In general, when wildfires occur now in the inland Pacific Northwest, they are of much greater intensity because of high fuel loading (van Wagtendonk 1985). Two common results of the high fuel loading are loss of all forest floor material and combustion of much large woody debris, and heating of the mineral soil, causing a loss of soil organic matter, organisms, structure, and cation exchange capacity.

Because of fuel buildup, wildfire effects on inland Pacific Northwest forests can be much greater than wildfire effects before 1900 (Brown 1983). Normally, three factors determine the extent of wildfire effects on site productivity: ecosystem type, fire intensity, and frequency of fire (Klock and Grier 1979). Fire sometimes acts as a means of releasing nutrients stored in organic matter that, because of moisture or temperature limitations, normally decomposes extremely slowly.

Grier (1975) examined the effects of a high-intensity fire on a mixed conifer forest on eastern slopes of the Cascade Range in Washington. Wildfire resulted in a loss of 96 percent of the forest floor biomass and 97 percent of the forest floor N. Grier estimated that 39 percent of the ecosystem N was lost. Volatilization and ash convection also resulted in losses of 35 percent of the K, 11 percent of the Ca, and 15 percent of the Mg. Throughout much of the burn area, the entire forest floor was consumed. The thick ash layer over the mineral soil contained high accumulations of nutrients, however, and these nutrients were not lost by leaching below the rooting zone during the first year after the wildfire. Helvey (1980), examining the effects of the same fire for seven years, found runoff and stream sediment in the second and subsequent years was double that before the burn, probably resulting in accelerated nutrient loss into the stream system.

Post-1900 Prescribed Burning and Eastside Soils

Prescribed fires are usually intended to reduce slash loading after timber harvesting, to facilitate planting or regeneration, and reduce fire hazard. Prescribed underburning to reduce surface fuels and understory vegetation can also reduce fire hazard. As with natural fires, the effects of prescribed fires on forest soils are highly variable.

The most common use of prescribed fire is to reduce slash, either by broadcast burning or piling slash and burning (Graham and others 1989a). Usually confined to small areas, piling and burning slash usually results in consumption of all organic matter underneath the pile and extensive soil heating. The effects of broadcast burning depend on the severity of the fire; severity is controlled by moisture conditions at the time of fire, management of the fire, slope, and the type of area burned. Sites with fire regimes adapted to frequent fire are less likely to be negatively affected by prescribed burning than are sites where fire is rare (McNabb and Cromack 1990).

Most well-implemented broadcast burns result in limited loss of organic matter and exposure of mineral soil which minimize soil effects. McNabb and Swanson (1990) state that because fire severity is usually limited, mineral soil loss after prescribed fire is usually minor. Highly erodible soils, or steep slopes can combine with high-intensity rainfall to cause erosion if too much mineral soil is exposed. Jurgensen and others (1981) found that no long-term depletion of soil N resulted from prescribed broadcast burning of slash on a subalpine fir site, and that regeneration benefited through increased soil N availability.

Prescribed burning usually causes only short-term reductions in populations of fungi and soil invertebrates and can increase bacteria (Borchers and Perry 1990), but these effects vary depending on the site and fire severity. Harvey and others (1980a, b) found that broadcast burning in partial cuts either reduced or rapidly eliminated mycorrhizae in clearcuts of Douglas-fir/larch forests in western Montana. At a high-elevation forest in eastern Washington, Lopushinsky and others (1992) found that broadcast burning resulted in the best seedling performance in the first two years after planting, and that even piling and burning slash positively affected seedling growth. Harvey and others (1989a) recommend limiting the use of site preparation methods that disturb shallow soils because of possible root damage and loss of organic matter. They recommend broadcast burning at low to moderate intensity.

Studies of underburning in inland Pacific Northwest forests to reduce fire hazard and to develop open stands are not as common as those of slash disposal. Landsberg (1992) found decreased ponderosa pine growth in central Oregon with prescribed underburning and greater losses of soil nutrients at sites with low fertility. Nissley and others (1980) found that losses of N and S with prescribed underburning was correlated to fuel consumption. They measured N losses of 38 percent and S losses of 43 percent from the forest floor. Further examinations of prescribed underburning may be necessary to determine the relative costs and benefits of this procedure, but, in general, well managed prescribed fires do not appear to damage most forest sites.

Applying Fire in Eastside Forest Management

Fire has been both used and excluded from forests of the eastside in recent times. Fire as a tool has potential both to damage and enhance ecosystems and productivity. Where prescribed burns are used properly, their benefits (for example, reduced fire hazard, obtaining natural regeneration, better planting spots allowing more careful planting) should outweigh the drawbacks. Martin (1981) suggests several techniques for using prescribed burning to maintain or improve soil productivity. Prescribed fires should be implemented on soil types where effects will be minimal (such as Mollisols, and many well-developed Andisols and Inceptisols) and where benefits are most likely. In the future, restrictions on the use of prescribed burning because of air pollution controls may limit the use of fire, unless wildfire hazard reductions and forest health management can justify its continued use.

FERTILIZER APPLICATION AND EASTSIDE SOILS

The Site Factor

Application of fertilizers to complex ecosystems in highly diverse environments, typical of eastside forests, poses interesting challenges (Miller and others 1992), particularly for forests that are stress- and mortality-prone, and where ecosystems and soils may be sensitive to the effects of disturbances. A primary problem is the extreme variation in physical and soil environments across short distances with a superimposed, highly variable climate and complex vegetation structures-that is, with four to ten conifer species occupying many forested sites.

The Vegetation Factor

In general, inland Pacific Northwestern trees have adapted to their environment either by maintaining high genetic plasticity-that is, being broadly adapted to a range of environments, as are, for example, western white pine, western larch and, to a lesser extent, ponderosa pine (Minore 1979; Rehfeldt 1982, 1986; Rehfeldt and others 1981), or by being very closely adapted to specific environments, as are Douglas-fir, the white firs, and lodgepole pine (Hamrick 1976; Minore 1979; Rehfeldt 1979, 1983). Environmental or genetic "generalists" operating well within their environmental range will be the most predictable targets for fertilization in highly variable, frequently disturbed environments. Conversely, closely site-adapted species, such as genetic or environmental "specialists," will be the most difficult targets for fertilization.

Nutrients like N are likely to have significant effects on the phenology of eastside species, and, therefore, their effects may be even more unpredictable than with other nutrients. Applications of N to many tree species are likely to induce major changes in the distribution of C between tops and roots, generally favoring the production of tops at the expense of roots (Alexander and Fairley 1983, Brix 1983). Generating forest stands with high ratios of tops to roots in ecosystems with periodic drought and soils of limited moisture and nutrient storage capacity could be risky.

Managing stress in treated stands could be the determining factor governing the net benefits of applying fertilizers. The resulting stress ecology cannot be analyzed without examining the interactions of stress, pests, and selected microbial activities that are important to eastside forests.

The Pest Factor

High stress predisposes forests to pest attacks (Horn 1985, Karban and others 1988). Also, increasingly specific evidence indicates that several important native root pathogens normally resident in the most productive eastside ecosystems may be highly attuned to host stress (Entry and others 1991, Matson and blaring 1984, McDonald and others 1987). Native pests, especially root diseases, may perform critical functions in ecosystems. Perhaps most important of the native, soil-borne diseases are *Armillaria* and *Phellinus* root rots. Fertilizer applications may result in delayed stress reactions and increased damage caused by various pests, particularly root diseases. For several fertilizer plots throughout northern Idaho, this indeed may be true (Moore and others 1993).

Native, soil-borne diseases like *Armillaria* and *Phellinus* are also sensitive to soil physical and chemical characteristics (Blenis and others 1989, Entry and others 1991, Horn 1985, Matson and Waring 1984, Rykowski 1981, Swift 1968) and to nutrient balance or metabolic byproducts in host trees (Entry and others 1991, Moore and others 1993). Thus, direct addition of nutrients may influence root diseases with or without alteration of stand stress (Rykowski 1981, Swift 1968).

The Soil Biological Factor

Beneficial microbial activities may also play an important role in the regulation of fertilizer effects. Direct effects of fertilizer on the structure of the soil microbial community have also been reported (Arnebrandt and others 1990, Laiho and others 1987). A general reduction in microfungal activities could disturb the competitive balance between organism types or between products resulting from the activity-for example, the balance of saprophytes to pathogens or N conversion and fixation products. The specific reduction of mycorrhizal activities in stands after fertilization (Alexander and Fairley 1983, Laiho and others 1987) raises the possibility of significantly reduced ability to acquire nutrients, particularly if large root-to-shoot ratios and intense mycorrhizal inputs are required on low productivity or harsh sites (Keyes and Grier 1981). Mycorrhizal activities lead directly to increased resistance of trees to root diseases of many types (Cervinkova 1990, Marx 1972, Zak 1964), thus, any reduction of mycorrhizal activities after fertilization raises the possibility of increased feeder-root disease problems.

Opportunities

Although applying fertilizers to the sensitive and complex ecosystems characteristic of eastside ecosystems appears somewhat risky, it does offer some opportunities. Applying N at 225 to 560 kg/ha has increased growth of eastside type forests (Shafii and Moore 1989). Many sites are likely to respond to N because it and moisture are normally the limiting factors for growth of inland forests (Jurgensen and others 1979, Shafii and Moore 1989). Thus, using N fertilizer offers an excellent opportunity to enhance growth in stands specifically managed for maximum growth, especially with widely adapted species on relatively good sites. Rust-resistant white pines growing on good pine sites, especially those with high soil-moisture storage capacities, represent the best possible opportunity for maximum response with minimum risk. Young stands with high proportions of white pines, western larch, and ponderosa pine may also benefit, especially if sites are within the high productivity end of their geographic range on good soils. Sites with very low N-for example, those heavily disturbed by site preparation or wildfire, and with indigenous vegetation acclimated to higher N concentrations than on the disturbed site-might also be highly responsive to fertilizer (Harvey and others 1989a). This treatment could offer useful site amelioration; the added N should help alleviate stress and might solve pest problems rather than make them worse. Although accelerating growth with N additions appears attractive, care must be exercised not to bring about shortages of other nutrients. Reduced K and K-mediated metabolites in tissues of N-fertilized stands may be a contributing factor to increased susceptibility of N-treated trees to root diseases and other pests (Moore and others 1993).

INFLUENCE OF WEATHER AND STAND ON SOIL WATER USE IN PONDEROSA PINE

A modeling exercise that evaluated moisture input to eastside forest soils during a 95-year period and the rates of use of that moisture by forest stands of various types was based on plot data from both above and below the ground. This exercise allowed evaluation of the potential for forest stands to generate more biomass than available moisture input and storage could support. Under such conditions, stand stress is increased and the potential for health problems is very high. Implications for forest health management are covered in the summary and conclusion.

Do current forest problems result from changes in climate, management-related changes in vegetation, or a combination of causes? Insofar as stands located near Bend, Oregon, are representative, these questions can be analyzed with the following ecosystem process models.

Demonstration Stands

Long-term weather records were examined from stations throughout the inland Pacific Northwest for evidence of differences in crop-year maximum and minimum average temperatures and total precipitation. Long-term crop-year total precipitation, average maximum, and average minimum temperatures for Spokane and Vancouver, WA, and for Moscow, ID, from NCDC (National Climatic Data Center) weather station data supplied on CD-ROM (Earth Info, Boulder, CO) provided basic climatic data. The Wickiup Dam record, the local station, covered the period from 1943 to 1990. This record was extended back to 1895 by linear regression of the climate records from Wickiup Dam and from the three long-term stations, 1943 through 1989.

On the basis of low r^2 values for temperatures and high values for precipitation (table 13), specific years were selected to stand in for the early record at Wickiup Dam on the basis of precipitation. The Vancouver record showed good agreement with Wickiup Dam (table 13), but this record covered the period from 1900 to 1989. To extend back to 1895, the record from Moscow was used because of a better r^2 (table 13). Years were selected from Wickiup Dam to simulate its early record by sorting Vancouver and Moscow data and then selecting the closest year to the target year. We concluded that weather in the vicinity of Wickiup Dam is probably little or no different today than 90 years ago (tables 14 and 15).

Table 13-Regression coefficients for three Pacific Northwest stations and the Wickiup Dam record for the years 1943 through 1989

Independent station	Dependent station	Maximum temperature	Minimum temperature	Precipitation
Moscow, Idaho	Wickiup Dam	.23	.00004	.26
Spokane, Washington	Wickiup Dam	.1	.12	.18
Vancouver, Washington	Wickiup Dam	.14	.006	.58

Table 14-Reconstructed from crop year (August 1 to July 31) weather record for Wickiup Dam showing target year precipitation from section station actual year precipitation from section station and actual record year temperatures (degrees F) and precipitation (inches) at Wickiup Dam

Moscow records				**Wickiup Dam record**		
YEAR	**PPT**	**YEAR**	**PPT**	**MAXT**	**MINT**	**PPT**
1895	(17.31)	1945	(17.78)	57.10	26.40	13.58
1896	(17.79)	1945	(17.78)	57.10	26.40	13.58
1897	(23.04)	1943	(22.99)	58.90	25.40	29.95
1898	(21.77)	1949	(21.29)	59.50	25.20	14.54
1899	(23.43)	1959	(24.62)	59.70	33.10	14.85
5-year average				58.50	27.30	17.30
Vancouver Records						
1900	(47.30)	1951	(47.11)	55.40	26.90	24.81
1901	(43.29)	1963	(43.30)	58.40	30.70	24.24
1902	(40.64)	1975	(40.60)	57.10	29.10	19.34
1903	(42.84)	1963	(43.30)	58.40	30.70	24.24
1904	(42.32)	1965	(42.27)	58.80	29.70	20.33
1905	(34.62)	1966	(34.48)	57.00	28.50	19.24
1906	(35.95)	1957	(36.01)	57.70	30.60	22.67
1907	(42.78)	1971	(42.59)	55.40	28.20	24.99
1908	(37.27)	1953	(37.24)	56.60	28.50	22.67
1909	(36.67)	1967	(36.32)	58.20	30.50	18.08
1910	(42.34)	1965	(42.27)	58.80	29.70	20.33
1911	(35.46)	1960	(35.05)	58.30	30.40	18.49
1912	(33.12)	1973	(32.88)	56.50	29.30	13.99
1913	(36.96)	1964	(37.10)	57.60	30.40	16.69
1914	(38.79)	1952	(39.09)	56.20	28.80	17.42
20-year average				57.64	28.93	19.70

Table 15-Actual summary records for Wickiup Dam 1970-89 for crop year August 1 to July 31 in degrees F and inches

Actual year	Fill-in year	MAXT	MINT	PPT
1970	1980	58.20	31.30	20.06
1971	1971	55.40	28.20	24.99
1972	1972	57.00	30.00	22.57
1973	1973	56.50	29.30	13.99
1974	1974	56.20	29.60	29.48
1975	1975	57.10	29.10	19.34
1976	1976	56.50	29.10	16.86
1977	1977	58.70	29.70	10.64
1978	1978	57.70	31.80	24.45
1979	1979	57.00	29.50	16.05
1980	1980	58.20	31.30	20.06
1981	1981	58.70	31.00	21.57
1982	1843	58.90	25.40	29.95
1983	1983	54.80	31.20	31.53
1984	1984	56.50	30.70	25.84
1985	1985	56.30	28.70	19.35
1986	1986	56.30	29.30	27.18
1987	1987	58.80	31.60	19.97
1988	1988	80.20	29.90	19.12
1989	1989	58.40	30.10	23.25
Last 5-yr average		58.00	29.90	21.77
20-yr average		57.37	29.84	21.81

Old-Growth and Regeneration on the Same Plot

To compare conditions before and after forest management began, we needed stand information. Stand data were collected in 1988 to compare stand structures before and after management (Cochran and Hopkins 1991). These authors measured second-growth diameter on nineteen 0.4-acre plots at each of three areas near Wickiup Dam. The first area, Sugar Cast, is 18 miles northeast of the dam on a flat site about 12 m higher than the 1310 m elevation of the dam. Its long-term average rainfall was estimated to be 53.3 cm (Larsen 1976). Fort Rock, the second area, is on a flat site at 1554-m elevation about 8 miles east of Sugar Cast. Long-term rainfall here was 45.7 cm (Larsen 1976). Both belong to the ponderosa pine climax series of plant communities (Volland 1976); plot records showed no white fir. The third area, Bend Ranger District, is 10 miles northwest of Sugar Cast, 8 miles west of Bend along the Century Loop Road. Elevation of this site is 1615 m and long-term rainfall was judged at 88.9 cm (Cochran, personal communication). The two plots selected here supported more than 5 percent area covered by white fir, which places them in the mixed-conifer climax series (Volland 1976).

Diameters of heartwood and sapwood of stumps and snags left after a 1920 logging operation were measured. Stumps were destructively sampled to develop regressions for estimating diameters at breast height and total height of trees represented by the stumps. (See appendix B for the equations used.) See Cochran and Hopkins (1991) for computational details for the regeneration. All the stump data on 0.4-acre plots and the first 30 trees of the second-growth stands were used with these regressions and other equations (see appendix B) to estimate volumes, basal area, trees per hectare, average diameter, stem carbon, leaf carbon, respiration surface, and all-sided leaf area index. Percentage of basal area in sapwood was estimated for each old-growth stand directly from the stump measurements. A published regression was used to estimate the sapwood area of both the stumps and second-growth (Hunt and other 1991). The compiled plot specific data are listed in table 16.

Table 16-Individual plot of parameters for old-growth and regeneration on 6 plots in the Deschutes National Forest in central Oregon.

Plot	Stand	Trees/ha	BA m2/ha	Ave DBH cm	Avg HT m	Ave SW%	STEM C kg/ha	RESP V m3/ha	LAI [1] m2/m2	COVER %
FR 10	old-growth	119	18.7	43.2	21.0	35	36939	11.6	4.3	25
	regen	459	21.8	23.8	13.0	86	9519	11.3	12.3	37
	regen	459	21.8	23.8	13.0	37	9519	9.2	5.2	37
FR16	old-growth	56	10.1	45.7	21.4	79	20,831	10.5	5.3	14
	regen	489	26.9	26.0	13.8	86	11,869	13.8	15.2	35
	regen	489	26.9	26.0	13.8	37	11,869	11.2	6.5	35
SC1	old-growth	81	18:0	47.2	23.7	79	46,231	24.0	10.5	22
	regen	729	33.9	22.9	17.8	76	14,988	21.1	17.1	44
	regen	729	33.9	22.9	17.8	37	14,988	18.4	8.2	44
SC2	old-growth	44	17.4	68.3	28.9	94	46,905	24.2	10.6	20
	regen	585	34.9	26.8	17.0	77	15,633	19.6	17.6	39
	regen	585	34.9	26.8	17.0	37	15,633	16.7	8.4	39
BRDI	old-growth	113	30.2	53.8	24.6	69	80,024	36.2	14.9	36
	regen	729	35.2	23.1	13.3	59	12,708	16.0	13.4	51
	regen	729	35.2	23.1	13.3	37	12,708	14.8	8.5	51
BRDQ	old-growth	113	49.1	70.3	29.2	82	142,000	65.4	26.5	56
	regen	1389	31.7	15.3	9.7	66	10,378	15.5	14.3	47
	regen	1389	31.7	15.3	9.7	37	10,378	14.0	7.6	47

[1] All-sided leaf area index.

Accuracy of the sapwood basal area regression to predict old-growth percentages of sapwood (%SW) was tested by plotting residuals of measured %SW on predicted %SW (figs. 1, 2, and 3). On the white fir plots (Bend), the regression overestimated %SW (fig. 1). The regression yielded a constant 86 percent but plot I averaged 69 percent, with a range from 0.35 to 0.94; and plot Q averaged 82 percent with a range of 0.68 to 0.94. On the high-quality ponderosa pine climax plots (Sugar Cast 1 and 2, fig. 2), plot 1 averaged 85 percent (± 0.61 to 0.98) and plot 2 averaged 94 percent (± 0.90 to 0.95). The regression would provide about the same stand value of leaf area index as the actual measurements (fig. 2). Plots 10 and 16 in the Fort Rock area (fig. 3) were quite different. Plot 16 was like Bend plot I. It averaged 79 percent (± 0.56 to 0.91). Plot 10 was unlike any other (large negative deviations in fig. 3). It averaged 37 percent sapwood and ranged from 21 to 44 percent. These values were much like small diameter trees found on other plots. A %SW of less than 50 was used to signify oppressed individuals or dominants growing on a moisture-limited site. The significance of this plasticity will be evident later.

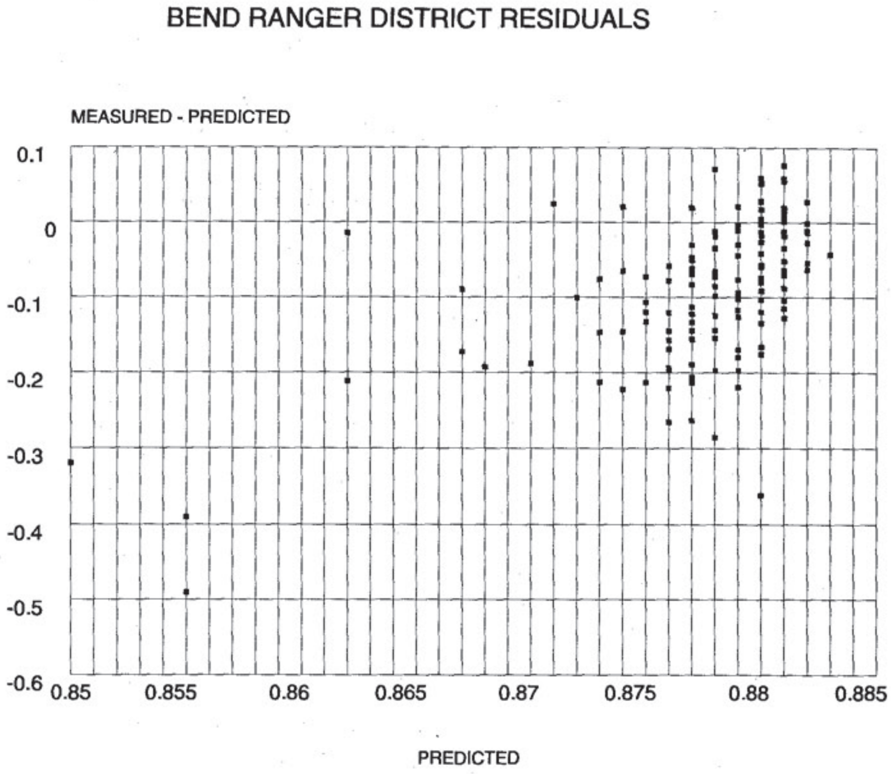

Figure 1. Residuals of percentage sapwood measured and predicted from regression. Sapwood and heart-wood diameters measured on old-growth ponderosa pine stumps located on Bend Ranger District plots I and Q of the Deschutes National Forest and belonging to a mixed-conifer plant association.

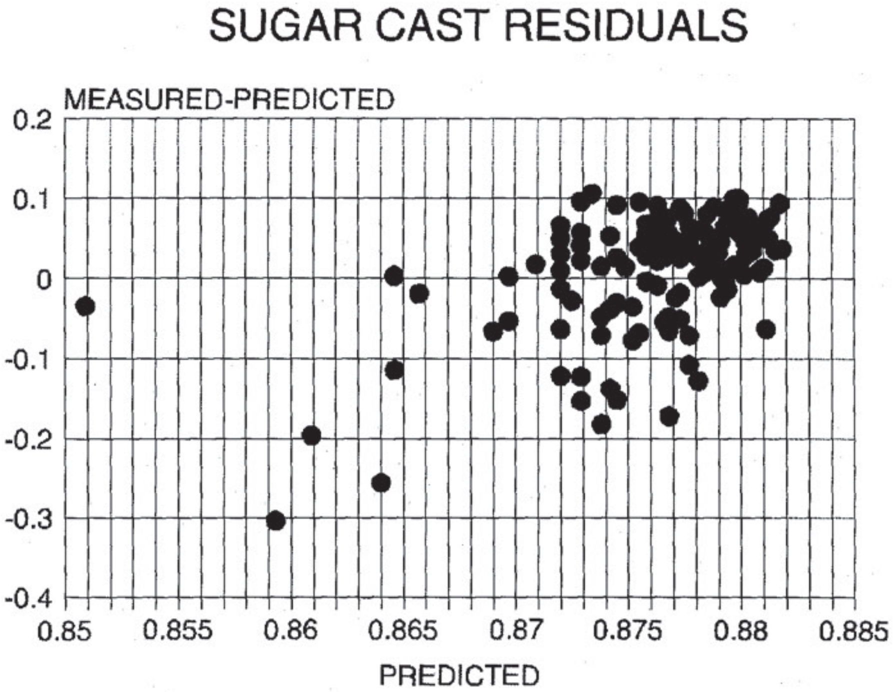

Figure 2. Residuals of percentage sapwood measured and predicted from regression. Sapwood and heart-wood diameters measured on old-growth ponderosa pine stumps located on sugar cast plots 1 and 2 of the Deschutes National Forest and belonging to a ponderosa pine plant association.

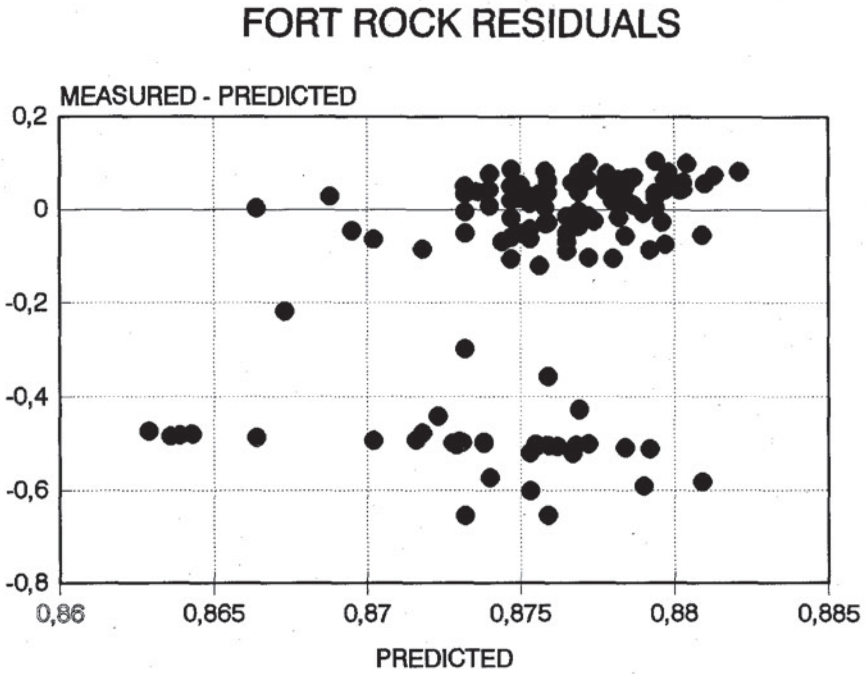

Figure 3. Residuals of percentage sapwood measured and predicted from regression. Sapwood and heart-wood diameters measured on old-growth ponderosa pine stumps located on Fort Rock plots 10 and 16 of the Deschutes National Forest and belonging to a ponderosa pine plant association.

Plot specific data (table 16) were used to initialize the mountain climate simulator (MTCLIM, Hungerford and others 1989), the snow accumulation and melt model (SNOWMELT, Foltz 1987), and the individual tree-based forest ecosystem process model (TREEBGC, Korol 1993). A dry year (1945) and a wet year (1986) from the Wickiup record were run through MTCLIM to translate the record for the three plot areas. The MTCLIM parameter of most influence was elevation, because the plots were nearly flat (table 17). Accordingly, only two runs (wet and dry) were made for each. This set-up and data were used to analyze the effects of weather, site, stand age, soil organic matter, and amount of sapwood on both water use and biomass production (growth) of eastern Oregon ponderosa pine stands.

Table 17-Physiographic constants used to initialize the MTCLIM model for the Bend Ranger District Sugar Cast and Fort Rock plots

Plot	Elevation	PPT ISOHYET	Latitude	Slope	Aspect	East horizon	West horizon
FRIO	1554	45.7	43.7	1	102	1	1
FR16	1554	45.7	43.7	6	146	1	1
SC1	1341	53.3	43.7	10	6	1	1
SC2	1341	53.3	43.7	1	340	1	1
BRDI	1615	88.9	44.0	10	43	1	3
BRDQ	1615	88.9	44.0	10	76	1	12
WDDRY*	1310	17.3	43.5	0	0	1	1
WDWET**	1310	21.0	43.5	0	0	1	1

* Base station Wickiup Dam crop year August 1 1944, through July 31 1945, for SNOWMELT runs and January 1 through December 31 1945, for TREEBGC runs.

** Base station Wickiup Dam crop year August 1 1985, through July 31 1986, for SNOWMELT runs and January 1 through December 31 1986, for TREEBGC runs.

Analysis of Weather

To the extent that our reconstruction of the Wickiup record was accurate, annual precipitation during 1895 to 1899 (44 cm average annual) was slightly less than during 1985 to 1989 (44 cm average annual to 55.4 cm). For Spokane and Moscow, this comparison was 43.7 cm vs. 40 cm, and 52.6 cm vs. 59.7 cm, respectively. On a 5 year basis, the two periods were somewhat different. Over a longer term (20 years), the earliest period may have been slightly drier. The reconstructed Wickiup record (1895-1914) was 19.7 cm, vs. a 1970 to 1989 average of 21.8 cm. Comparable values for Moscow and Spokane were 22.3 cm vs. 26.5 cm and 16.6 cm vs. 16.4 cm.-a very small difference, if any, on a crop-year basis. Thus, if premanagement and postmanagement weather were different, it must be attributed to factors other than available water.

Output from the SNOWMELT model shows some good perspectives. For all plots, the largest difference between wet and dry years was precipitation as snowmelt and evaporation (table 18). Another important point, probably true for most of the forested ecosystems in eastern Oregon and Washington, is that snowmelt (even in dry years) exceeded the highest water-holding capacity of the driest site (Fort Rock 16 water-holding capacity = 1200 m^3/ha and dry year snowmelt = 1453 m^3/ha). Thus, water **storage** was more important than water **input**.

Table 18-Output in m3 of waterlha from the model SNOWMELT for the 6 area x years combinations on the Deschutes National Forest based on MTCLIM output from the Wickiup Dam base station and crop years August 1,1944-July 31,1945 (dry) and 1985-86 (wet)

Plot	Snowpack	Total PPT	Rain	Snowmelt	Evaporation
FRdry	1473	3607	1722	1453	432
FRwet	3718	6057	1648	2885	1524
SCdry	1915	4244	1872	1643	729
SCwet	4285	6721	1758	3586	1377
BDRdry	4384	7092	1953	3558	1481
BDRwet	7615	10696	2215	6091	2390

Analysis of Stocking

If the estimates of leaf area index obtained from old-growth reconstruction and the regenerated stands now occupying the 0.4-acre areas are correct, then our data cover the range of possibilities: from large increases in leaf area index with the regenerated stands to old-growth stands exhibiting the largest leaf area indices. Plots FR10, FR16, SC1, and SC2 all showed increases in leaf area index for regeneration, but BRD plot I remained virtually unchanged, and BRD plot Q regeneration produced about 0.5 of the leaf area index of the old-growth stand (table 16). Regeneration in the Fort Rock area increased leaf area index by a factor of three over replaced old growth (table 16). On the better quality Sugar Cast plots, the regeneration was carrying about 1.6 more leaf area index. Undisturbed regenerated stands should carry about 1.4 times their expected equilibria of leaf area indices at about 60 years of age (Long and Smith 1992). Accordingly, the Sugar Cast stands seem correct. The largest unknown is the role of fire in adjusting stocking and leaf area index. Also, the stands studied may have been thinned. In any event, these stands provided an excellent range of both stocking and leaf area indices for model runs.

The Question of Soil Water and Organic Matter

Water-holding capacity of the soil on the plots was estimated from soil maps (Larsen 1976) and land type classes by a soil scientist (D. Page-Dumroese, personal communication,). The Bend plots were estimated as land type 25 with a water-holding capacity of 6 to 10 percent and a depth of 1.25 m to yield 1524 m^3/ha. The Sugar Cast plots were estimated as land type 64 with a depth of 1 m and capable of holding 8 to 12 percent water for a capacity of 1200 m^3/ha. The Fort Rock plots were in the LX combination of land types 64 and 76. Plot 16 was assumed to be type 64 with the same capacity as Sugar Cast. Type 76 was assumed for plot 10, which has capacity of 4 to 8 percent and depth of 0.76 m to yield 610 m^3/ha waterholding capacity.

Recent evidence (Page-Dumroese and others, in preparation) shows that organic matter in the soil profile can increase water-holding capacity and that this effect is pronounced under old-growth canopies. Soils here were assumed to exhibit the following increases under premanagement canopies: Bend Ranger District plots I and Q increase 15 percent; Sugar Cast plot I increases 10 percent; Fort Rock plot 16 increases 8 percent; and Fort Rock plot 10 increases 6 percent. These increases were judged on the basis of soil depth and the potential of the site to produce organic matter (D. Page-Dumroese, personal communication). Potential to produce organic matter was keyed to leaf area index for premanagement stands (table 16).

The Question of Phenotypic Plasticity

The Fort Rock 10 combination of old-growth and regeneration was interesting. The average %SW determined for old-growth on this plot (37 percent) was so stable and far removed from the expected value of 86 percent that it forced consideration of phenotypic (physiologically based) adjustment. Appropriate values were computed for respiration volume, stem carbon, and leaf area index for the regeneration at %SW of 37 (table 16). Under this assumption, old-growth and its replacement stand supported nearly identical leaf area indices (table 16). Because %SW might be an important acclimating trait that affords opportunity to adjust water demand to specific conditions (both site and stand), simulation experiments were undertaken to determine TREEBGC on the regeneration stands by using the regression-determined values for %SW (wide sapwood) and a constant 37 percent (narrow sapwood). The assumed phenotypic adjustment of regeneration is illustrated for the water-holding capacity and stand characteristics of the soil at Fort Rock plot 16 (figs. 4 and 5). Daily maximum leaf water potential (parameter B(12) in. appendix A) was set at -2 mpa. When soil water reached about 10 to 15 percent of m^3/ha of water, it exceeded that value, which was interpreted as a signal that stomates close and all modeled physiological activities, except maintenance respiration, would cease. Output in the graphs and tables reflect this adjustment.

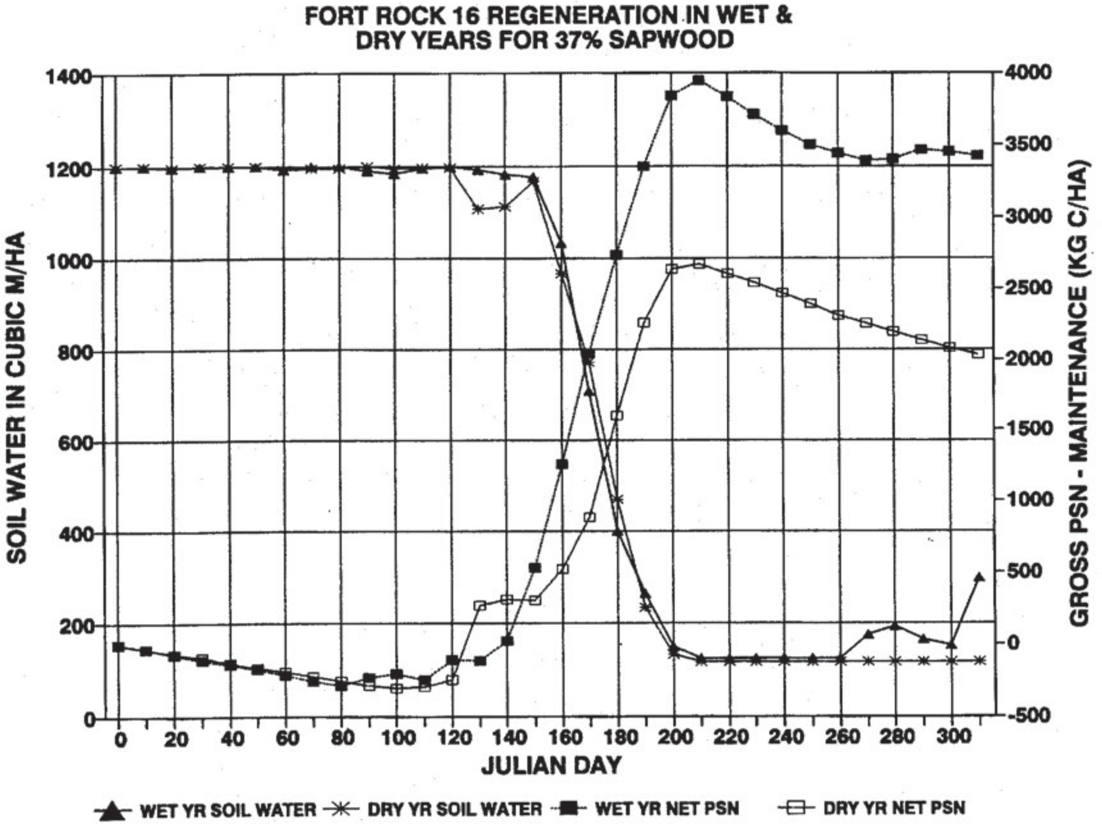

Figure 4. Net carbon and soil water output from TREEBGC initialized by Fort Rock plot 16 regeneration stand data for 37 percent sapwood run on Wickiup Dam weather records for dry and wet years translated by MTCLIM and SNOWMELT weather models.

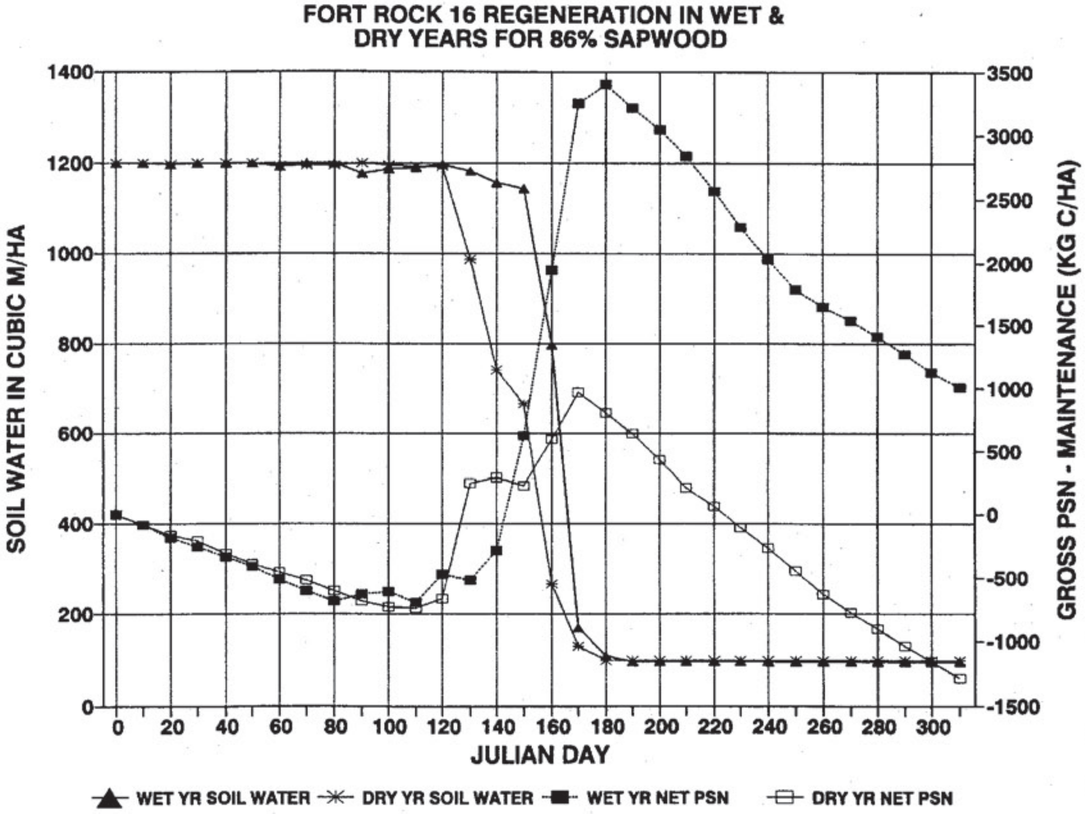

Figure 5. Net carbon and soil water output from TREEBGC initialized by Fort Rock plot 16 regeneration stand data for 86 percent sapwood run on Wickiup Dam weather records for dry and wet years translated by MTCLIM and SNOWMELT weather models.

As shown in both the water-use curves and net carbon gains or losses (growth respiration is not subtracted in the figures) (figs. 4 and 5), phenotypic adjustment could make the stand more competitive. A regenerated stand with 37 percent SW is expected to produce about 3500 kg of carbon/ha (includes growth respiration and maintenance respiration for days 310 to 365) by day 310 during the wet year and about 2000 kg (same inclusions for both figs. 4 and 5) for the dry year (fig. 4). On the other hand, larger maintenance respiration and water demand caused by a higher %SW cause the stand to perform less well (fig. 4). In the wet year, it produced about, 1000 kg of carbon; during the dry year, it went into carbon deficit at the rate of nearly 1500 kg of carbon/ha per yr.

A stand composed of trees supporting wide sapwood and functioning as depicted for the dry and wet years (fig. 5) would be expected to have a short life. Either the sapwood basal area regression is wrong or the water-holding capacity of the site was underestimated. This dichotomy brings up a major question about output from these models: Are the results realistic?

Initial Verification of Model Set-up

The physiological parameters used were obtained from an earlier version of TREEBGC known as FOREST-BGC, published by the original authors (Running and Coughlan 1988). TREEBGC contains new routines that allow specific parameterization for tree sizes and respiration volumes (Korol 1993). Constants were used that control water and light processing (Running and Coughlan 1988) for dry ponderosa pine sites in Montana (appendix A). One change from the recommended photosynthesis parameters was made. Inland populations of conifers have a photosynthetic physiology that loses most of its efficiency during winter dormancy (Jurik and others 1988, Koehn 1993, Koehn and McDonald 1991). Also, output from FOREST-BGC for Colorado forests shows a consistent over-estimation of net carbon production (Ryan and blaring 1992). Output from FOREST-BGC using constants, stand data, and weather from Montana, and adjustments made to account for winter dormancy, showed a 25 percent reduction compared to no winter dormancy constraints (McDonald 1991). Because time and data constraints prevented applying this method, winter dormant chlorophyll was emulated by preventing photosynthesis below 7.5° C (see parameter B(17), appendix A). Parameters for respiration were suggested by Korol (personal communication).

Water-use efficiency was calculated as net biomass (g/m^2)/water used (g/m^2) to compare model values with published values (Livingston and Black 1988). Their values ranged from 0.0009 to 0.0029 g/g H_2O. Our maximum value from the model was 0.0029 for the narrow sapwood regeneration on BRD plots I and Q for the wet year (tables 22 and 23). As a further test, production efficiency was calculated as net total biomass/projected leaf area index. Production efficiency is defined in terms of net aboveground biomass production (Waring 1983) divided by projected leaf area and includes wood increment + detritus (Gower and Grier 1989). Net carbon (gross carbon fixed - maintenance respiration - growth respiration) was used for the entire plant, and the litter-fall component was assumed to be offset by belowground processes. Biomass was assumed equal to a doubling of carbon production. Our values for production efficiency (figs. 6 through 10) agree well with published values (Grier and others 1992) for eastern Oregon ponderosa pine and values calculated from data presented for Douglas-fir growing in northern New Mexico (Gower and others 1992). We conclude that TREEBGC output, as parameterized for this analysis, was reasonable.

Carbon Production and Pest Susceptibility

An earlier study hinted at a relation between site quality and spruce budworm attack (Shepard 1959). Since then, many papers have forged a direct connection between carbon metabolism and insect and pathogen attack. Sharpe and Wu (1985) presented a model of bark beetle attack based on the interaction between water drawdown and carbon metabolism. Larsson and others (1983) established a stocking experiment in central Oregon ponderosa pine stands to experimentally control vigor: After 10 years, attack rates by mountain pine beetle varied by vigor. Dunn and Lorio (1992) conducted a girdling experiment in southern pines that showed reduced photosynthate supply can lead to increased attack by southern pine beetle and that more than simple carbohydrate concentrations are involved. Redfern (1978) demonstrated in a shade stress experiment that susceptibility of various conifer species to Armillaria can be differentially changed according to their shade tolerance. Many other studies have hinted at a link between vigor/stress and host/pest complexes. The following model runs will be interpreted on this basis.

Weather-Soil Interaction Analysis

Ordinating plots according to their water input and storage capacity provides a basis for comparing growth potential and susceptibility of the stand.

Low precipitation and low soil water-holding capacity-On the assumption that maintenance respiration has primary carbon allocation priority, wide-sapwood regeneration on Fort Rock plot 10 (fig. 6) is apparently stressed in both wet and dry years. Narrow-sapwood regeneration showed a slight carbon deficit in the dry year and almost normal growth in the wet year (fig. 6). Little growth or defense happens during the dry year and, depending on storage capacity and frequency of dry years, this stand tends toward a stressed condition.

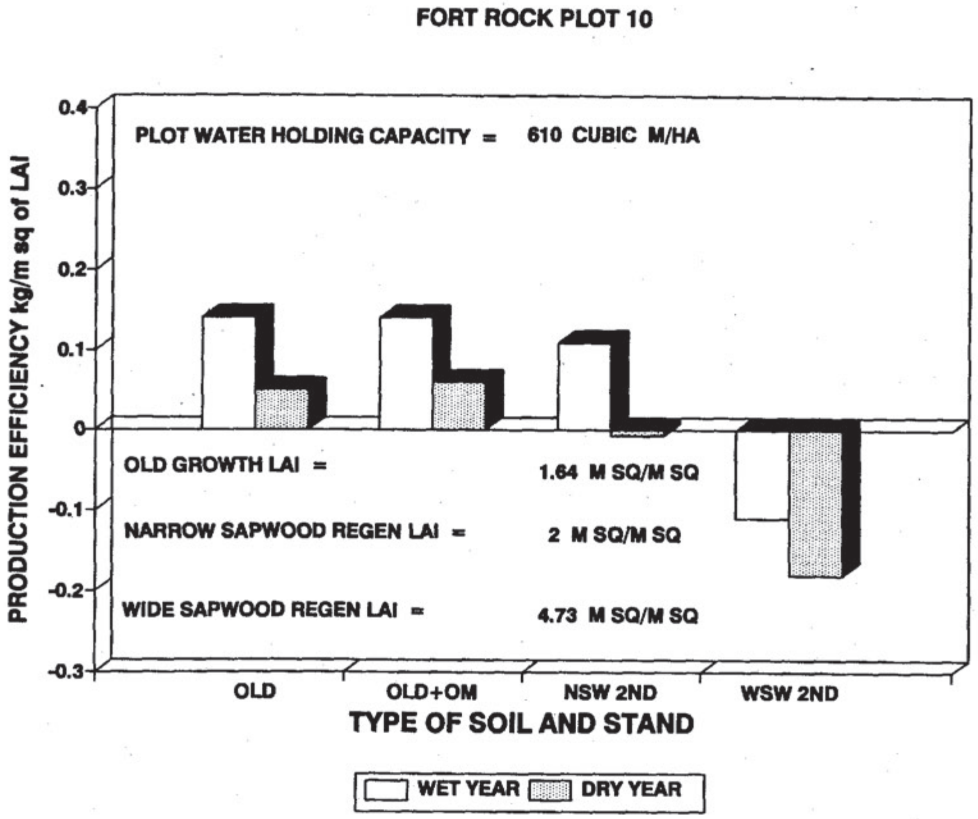

Figure 6. Production efficiency calculated from TREEBGC output after initialization by Fort Rock plot 10 old-growth and regeneration stand data and running on Wickiup Dam weather records for dry and wet years translated by MTCLIM and SNOWMELT weather models. Old + OM = old-growth stand data coupled with organic matter mediated increase in water holding capacity of 6 percent.

How would regeneration compare to the old-growth replaced? The old-growth, with a measured %SW of 37, fared equally well in normal and enhanced soil moisture conditions. Its production efficiency was near 0.14 kg/m^2. In the dry year, its production efficiency fell only 60 percent (fig. 6). It is not expected to make rapid growth, but would continue in a healthy state. The Fort Rock plot 10 model runs are summarized in table 19 to demonstrate dynamics of a limiting water resource. Two effects of reducing %SW are evident in the table. Respiration was nearly tripled to support the large amount of living tissue, and transpiration was increased, as was gross carbon fixation during the wet year. In the dry year, gross carbon fixation was reduced. Stomates were forced to close 40 days sooner with the high %SW in the wet year and 30 days sooner in the dry year. As expected (Long and Smith 1992), the regeneration stand showed an elevated leaf area index at age 56 but probably not the doubling shown for projected leaf area index under the wide sapwood scenario (table 19). Increased water-holding capacity resulted in only a small increase in production efficiency, from 0.136 to 0.141 and 0.048 to 0.060, respectively, for the wet and dry years. Both old-growth stands should remain healthy throughout either wet or dry years. The narrow sapwood regeneration would probably encounter increasing risk to bark beetles during dry years. This plot was too dry for *Armillaria* (McDonald 1991).

Table 19-Summary of TREEBGC runs over the Julian days of 1 through 365 of old-growth and replacement stands for Fort Rock plot 10 on the Deschutes National Forest for the dry year of 1945 and the wet year of 1986

Situation	Stomata closure	Soil water	Water use	Gross PSN	All RESPIR	Net biomass	WUE*
	Julian day	**m3/ha**	**kg/m2**	**kg C/ha**	**kg C/ha**	**kg/m2**	**g/g h20**
old wet o	210+	67	113	3413	2251	.232	.0021
old dry o	200	66	98.3	2135	1644	.098	.0010
old wet	210+	62	109.6	3327	2213	.223	.0020
old dry	200	60	95	2048	1654	.079	.0008
2nd wet37	210	55	116.7	3485	2436	.21	.0018
2nd dry37	190	62	102.3	2051	2108	-.012	-.0001
2nd wet85	170	52	170.8	3903	6512	-.522	-.0031
2nd dry85	160	68	127.1	1729	5920	-.838	-.0066

o = water holding capacity increased 6 percent as a result of increased organic matter in soil profile under old-growth and lacking under regeneration.

+ Physiological activity stopped at indicated Julian day but resumed later.

* Water use efficiency $\frac{\text{kg/biomass/m}^2}{\text{kg H}_2\text{0/m}^2}$

Low precipitation and moderate water-holding capacity-Fort Rock plot 16 was assumed to be similar to plot 10, except for doubled soil water-holding capacity. Old-growth %SW was slightly reduced from the expected value to 86 percent. Production efficiency for the old-growth, as well as the narrow sapwood regeneration, showed good balance between wet and dry years (fig. 7). Wide sapwood reproduction was supporting leaf area index three times larger than old-growth; its production efficiency was negative in both years (fig. 7). The old-growth, under both normal and elevated water capacity, showed high potential for added growth with only 8 percent increased water-holding capacity (fig. 7) Its production efficiency increased 1.25 times in the wet year, and 1.2 times in the dry year. Both old growth scenarios were balanced to their environment. Two pieces of information not available for improving this analysis were actual %SW (reproduction) and actual measurement of soil water-holding capacity from each plot. Both could be obtained for future analyses. Further dynamics of water use and assimilation can be seen in table 20.

All surviving Fort Rock plot 16 stand conditions are expected to remain healthy, this is in contrast to the neighboring plot 10. *Armillaria* root rot would not be expected on plot 16 because the site is too dry (McDonald 1991).

Table 20-Summary of TREEBGC runs over the Julian days of 1 through 365 of old-growth and replacement stands for Fort Rock plot 16 on the Deschutes National Forest for the dry year of 1945 and the wet year of 1986

Situation	Stomata closure	Soil water	Gross PSN	Water use	All RESPIR	Net biomass	WUE
	Julian day	m3/ha	kg/m2	kg C/ha	kg C/ha	kg C/ha	g/g h20
Old wet o	230+	356	5435	188.6	3101	.4668	.0025
Old dry o	230	135	3989	164.8	2483	.3012	.0018
Old wet	220+	338	4894	179.2	3028	.3732	.0021
Old dry	220	127	3679	155.6	2406	.2546	.0016
2nd wet85	180	109	5459	248	7258	-.3598	-.0015
2nd dry85	170	130	2511	188.3	6262	-.7502	-.0040
2nd wet37	210+	298	5322	188.1	3392	.3860	.0021
2nd dry37	210	116	3649	165.5	2635	.2028	.0012

o = water holding capacity increased 6% as result of increased organic matter in soil profile under old-growth and lacking under regeneration.

+ = Water-use efficiency. See footnote to table 19.

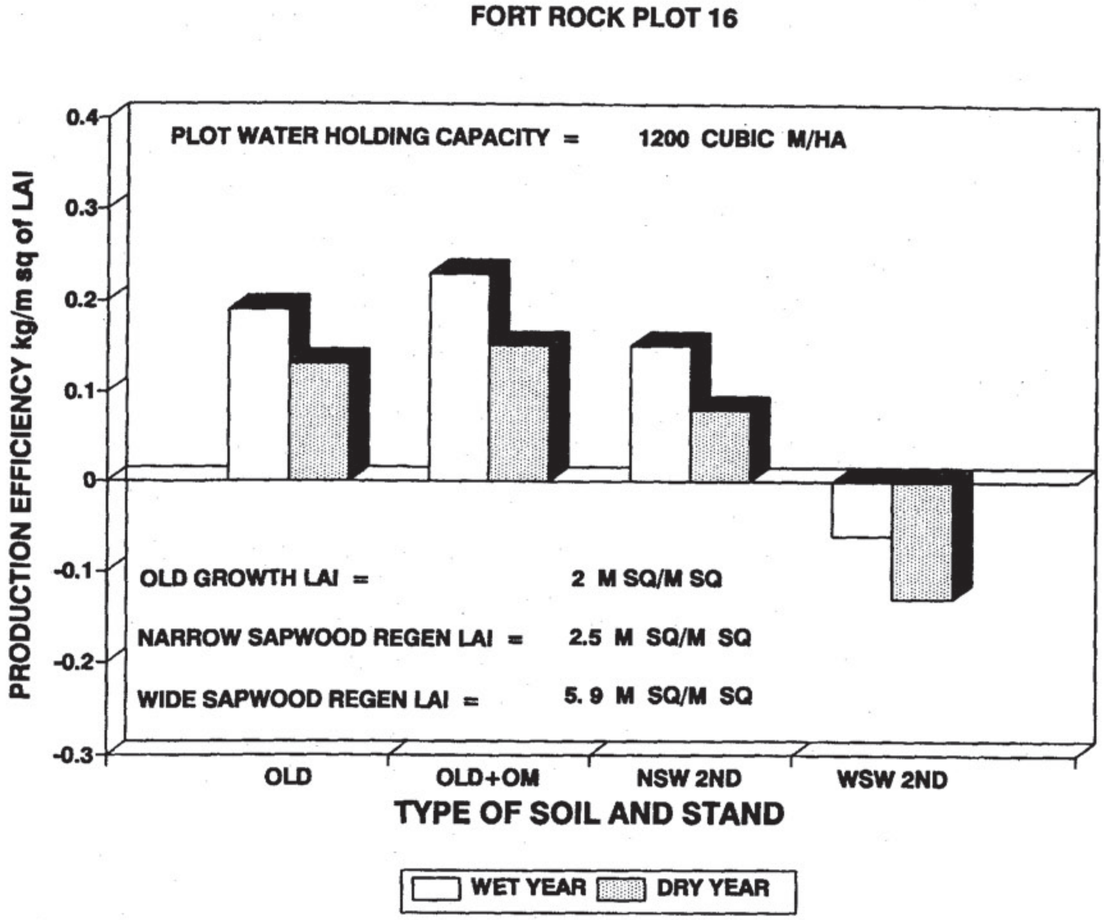

Figure 7. Production efficiency calculated from TREEBGC output after initialization by Fort Rock plot 16 old-growth and regeneration stand data and running on Wickiup Dam weather records for dry and wet years translated by MTCLIM and SNOWMELT weather models. Old + OM = old-growth stand data coupled with organic matter mediated increase in water holding capacity of 8 percent.

Moderate precipitation and moderate soil water-holding capacity-The two plots from Sugar Cast were similar (table 16). Both old-growth stands produced similar biomass. The reproduction stands were also alike but different from the old-growth (table 16). Thus, only plot 1 was analyzed. The old-growth seemed closer to using available water. An 8 percent increase in the water-holding capacity resulted in 1.5 times the production efficiency of the old-growth for the wet years and erased a carbon deficit for the dry year (fig. 8). Production efficiency of the narrow-sapwood reproduction stand was near normal in the wet year and well into the positive range for the dry year. The reduced projected leaf area index for the narrow-sapwood regeneration probably signifies a problem with the run. Possibly the regeneration was thinned or its actual %SW closer to 50.

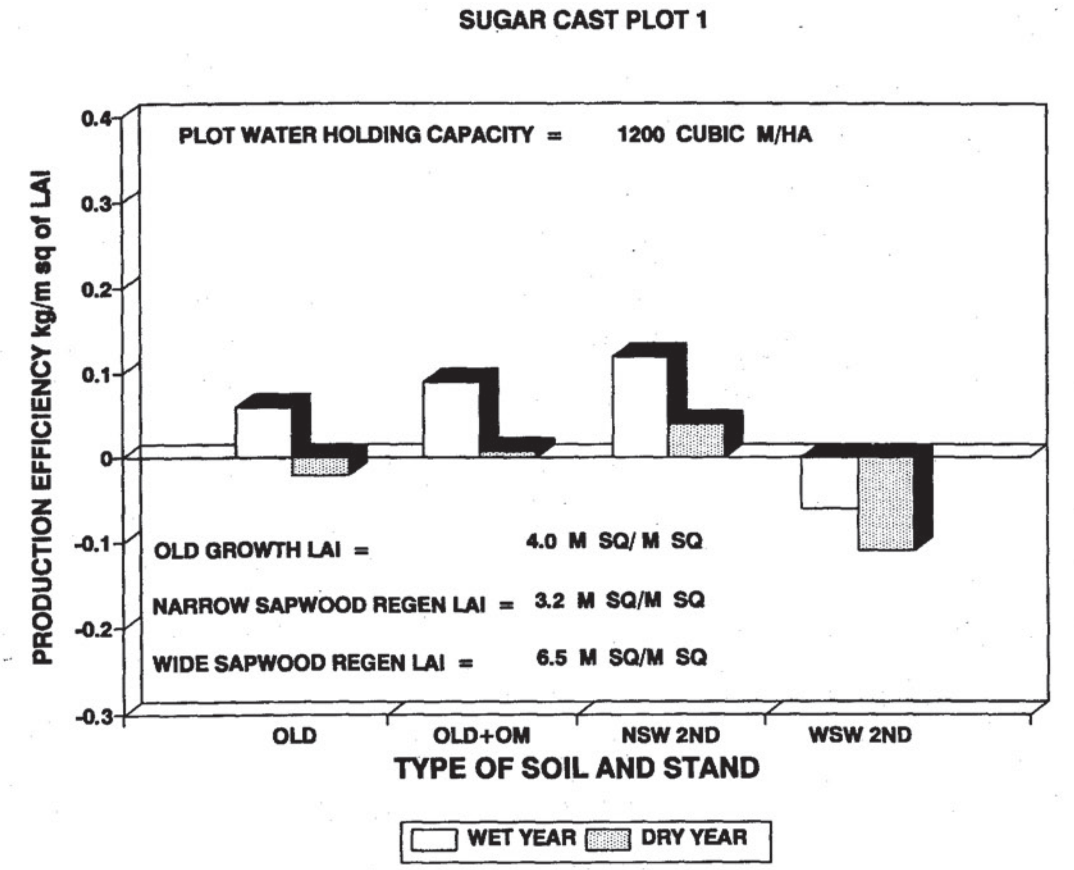

Figure 8. Production efficiency calculated from TREEBGC output after initialization by sugar cast plot 1 old-growth and regeneration stand data and running on Wickiup Dam weather records for dry and wet years translated by MTCLIM and SNOWMELT weather models. Old + OM = old-growth stand data coupled with organic matter mediated increase in water holding capacity of 10 percent.

Old-growth and reproduction close to carbon deficit show a problem with current use of TREEBGC. Measurements of such constants as B(11) through B(21) (appendix A) that deal with setting the physiology of water use, photosynthesis, and respiration (see table 21 for model output) are not available. Estimates for ponderosa pine growing in Montana were applied (Running and Coughlan 1988). To the extent these values apply, our results show the old-growth Sugar Cast stand was on a downward trend and reproduction at 49 years of age had not reached stability limits. The reproduction is expected to reach such a limit at about 1.5 to 2 times the equilibrium value for the leaf area index of 4.0. The wide-sapwood reproduction was already 1.6 times higher than that of old-growth (fig. 8), and the model indicates it is not suited for the site. This stand is water limited, as were both Fort Rock stands, and without additional water-holding capacity, other resources would not help. In a dry year, the snow melt was 1.4 times and rain was 1.6 times than the capacity of the soil to hold water (table 18). Enhancing water-holding capacity should be a principal management objective.

Even though this plot seems to have high production potential, during dry years the premanagement stand entered a period of risk for bark beetles. The model indicates that slightly increased water capacity would reduce this risk. This plot is also not subject to *Armillaria* attack because it is too dry (McDonald 1991).

Table 21-Summary of TREEBGC runs over the Julian days of 1 through 365 of old-growth and replacement stands for Sugar Cast plot 1 on the Deschutes National Forest for the dry year of 1945 and the wet year of 1986

Situation	Stomate closure	Soil water	Water use	Gross PSN	All RESPIR	Net biomass	WUE
	Julian day	m3/ha	kg/m2	kg C/ha	kg C/ha	kg C/ha	g/g h20
old wet o	210+	06	260.3	6710	4924	.3572	.0014
old dry o	200	122	210.2	4032	3872	.0320	.0002
old wet	200+	289	248	5947	4779	.2336	.0009
old dry	190	127	197.8	3597	3941	-.0688	-.0003
2nd wet85	180	113	302	5857	7972	-.4230	-.0014
2nd dry85	180	115	240.8	3292	6884	-.7184	-.0030
2nd wet37SW	210+	300	226.8	6057	4130	.3854	.0017
2nd dry37SW	200	118	179.8	3661	3063	.1196	.0007

o = water holding capacity increased 8% as result of increased organic matter in soil profile under old-growth and lacking under regeneration.

+ Physiological activity stopped at indicated Julian day but resumed later.

High precipitation and moderate soil water-holding capacity-The Bend Ranger District represents sites with high precipitation arid moderate soil water-holding capacity; BRD I and Q have different old-growth biomass measurements (table 16). The average age for all 19 plots was 40 years (Cochran and Hopkins 1991).

The TREEBGC runs indicated that the old-growth stand on plot I was in good balance with its environment (table 23 and fig. 10). Increasing water-holding capacity 15 percent, to simulate more organic matter only increased the production efficiency slightly for either wet or dry years, indicating the old-growth was well balanced. Also, production efficiency was near 0.1 even in the dry year. The stand was well buffered and, as shown by high soil water content remaining at Julian day 310 (table 22), was probably not water limited. This stand may be limited by some other resource, such as N. TREEBGC will be useful in the future for analysis of N relations.

Table 22-Summary of TREEBGC runs over the Julian days of 1 through 365 of old-growth and replacement stands for Bend Ranger District plot I on the Deschutes National Forest for the dry year of 1945 and the wet year of 1986

Situation	Stomata closure	Soil water	Water use	Gross PSN	All RESPIR	Net biomass	WUE
	Julian day	m3/ha	kg/m2	kg C/ha	kg C/ha	kg C/ha	g/g h20
old wet o	310	720	507.9	13144	7309	1.1670	.0023
old dry o	240	170	331.5	7848	5323	.5050	.0015
old wet	310	666	490.4	12719	5537	1.1074	.0023
old dry	230	151	310.5	7068	5166	.3804	.0012
2nd wet85	310	644	462.3	12186	6718	.9246	.0020
2nd dry85	230	151	293.8	7035	4815	.4440	.0015
2nd wet37	310	762	349.3	10046	5047	.9998	.0029
2nd dry37	310	470	241.3	6511	3596	.5830	.0024

o = water holding capacity increased 15% as result of increase organic matter in soil profile under old-growth and lacking under regeneration.

Both sapwood widths showed excellent performance on plot I, with narrow sapwood looking best (fig. 9). This stand might have been thinned. The premanagement ponderosa pine was and is doing as well as the postmanagement stand. Dry white fir climax sites have shown a significant tendency toward root rot in encroaching white fir and Douglas-fir in the northern Rocky Mountains (McDonald and others 1987). Perhaps TREEBGC parameterized for these species would show a tendency toward stress. All stand scenarios on plot I seem well protected from pest problems because of vigorous growth.

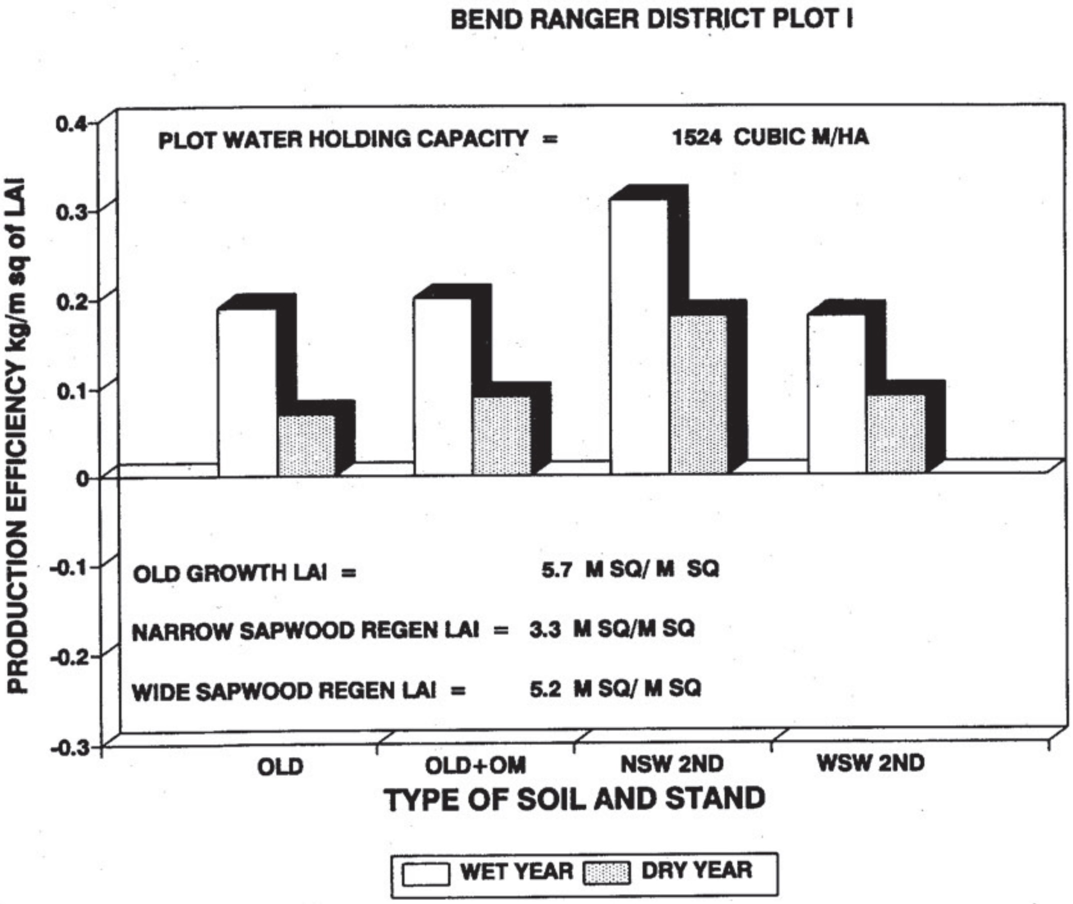

Figure 9. Production efficiency calculated from TREEBGC output after initialization by Bend Ranger District plot I old-growth and regeneration stand data and running on Wickiup Dam weather records for dry and wet years translated by MTCLIM and SNOWMELT weather models. Old + OM = old-growth stand data coupled with organic matter mediated increase in water holding capacity of 15 percent.

BRD-Q was an unusual plot because of the large calculated leaf area, 26.5 percent of its old-growth component. Theory indicates this value would be the expected equilibrium leaf area index. The regeneration stand should support leaf area indices of 40 to 50 LAI for 20 to 30 years, depending on current age. With a current cover of 47 percent, BRD-Q might achieve that goal; the old-growth stand was near the balance point. Under the assumption of 15 percent increased soil water capacity, the stand produced a net carbon gain, even during the dry year (table 23). For average water condition, BRD-Q was very close to balance and had only a slightly negative production efficiency for the dry year (fig. 10), indicating that plot Q had sufficient resources other than precipitation and that this stand would come under frequent stress if organic matter was depleted. This old-growth stand was probably N limited.

Table 23-Summary of TREEBGC runs over the Julian days of 1 through 365 of old-growth and replacement stands for Bend Ranger District plot Q on the Deschutes National Forest for the dry year of 1945 and the wet year of 1986

Situation	Stomate closure	Soil water	Water use	Gross PSN	All RESPIR	Net biomass	WUE
	Julian day	m3/ha	kg/m2	kg C/ha	kg C/ha	kg C/ha	g/g h20
old wet o	220+	660	737.5	13861	10417	.8368	.0011
old dry o	210	179	449	7915	7750	.0330	.0001
old wet	220+	611	719.6	13805	10191	.8222	.0011
old dry	210	142	429.8	7579	7808	-.0458	.0001
2nd wet85	310	621	479.4	12360	1501	1.0780	.0022
2nd dry85	230	141	303.9	7136	4976	.4320	.0014
2nd wet37	310	787	329.9	9469	4690	.9558	.0029
2nd dry37	300	175	230.5	6228 1	3362	.4610	.0020

o = water-holding capacity increased 15 percent as result of increased organic matter in soil profile under old-growth and lacking under regeneration.

+ Physiological activity stopped at indicated Julian day but resumed later.

The premanagement stand on this plot may include trees at elevated risk to bark beetles and *Armillaria*, although the regeneration appeared well protected by vigorous growth. Grand fir and Douglas-fir, however, would be at risk to root rot.

The regeneration stand for BRD-Q showed the most growth potential of any stand with either wide or narrow sapwood. Its narrow sapwood production efficiency was over 0.3 kg/m^2 (fig. 10), yet the modeled water-use efficiency was 0.0029 g biomass / g H_2O, a value measured for Douglas-fir seedlings (Livingston and Black 1988). None of the four BRD regeneration stands were stressed by limited water, even in the dry year. Their production efficiency for the dry year was almost equal to the next best plot (Fort Rock 16, old wet + organic matter, fig. 7) in a wet year. These stands were not limited by water when supporting ponderosa pine.

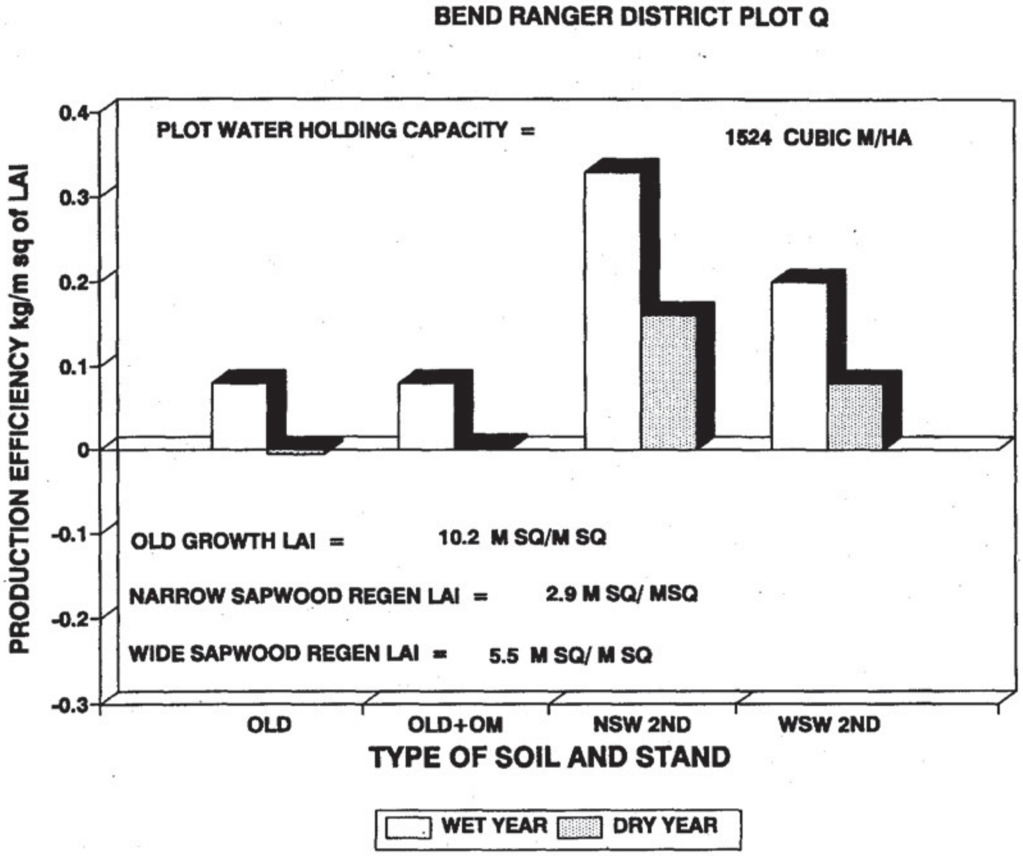

Figure 10. Production efficiency calculated from TREEBGC output after initialization by Bend Ranger District plot Q old-growth and regeneration stand data and running on Wickiup Dam weather records for dry and wet years translated by MTCLIM and SNOWMELT weather models. Old + OM = old-growth stand data coupled with organic matter mediated increase in water holding capacity of 15 percent.

Eastside Perspectives

Properly initialized and verified individual-tree process models, coupled with tested and calibrated climate models, could supply powerful analytical perspectives. This model exercise demonstrates that potential. “Potential” is emphasized because the suite of models used were not calibrated and verified for the Deschutes National Forest. MTCLIM and TREEBGC have been verified to provide reasonable results in Montana (Hunt and others 1991, McLeod and Running 1988, Nemani and Running 1989, Running and Nemani 1987). Snowmelt was verified on watersheds supporting ponderosa pine in the southwest (Foltz 1987). But to obtain the most information from these models more data are needed. Also needed are sapwood percentages, the age of all, trees, and local regressions of sapwood area to leaf area. These models also depend on accurately estimating maintenance respiration in various tissues, N concentration and good local determinations of specific leaf area. Other data needed include actual site soil water-holding capacity and N content. Even without all the best initialization parameters, application of these models produced very reasonable results and a rich set of analytical perspectives.

SUMMARY AND CONCLUSIONS

Soil structure, porosity, and nutrient capital are attributes of ecosystems least tolerant of actions during or after timber harvest. Harvest can initiate sudden shifts in forest ecosystem dynamics. Distribution of moisture and solar energy may change radically, altering soil and air temperatures and evapotranspiration rates at the soil surface and within the remaining canopy. Site degradation can be caused by excessive soil compaction, which is often coupled with the loss of surface soil containing a disproportionately high percentage of the soil organic matter, nutrient capital, and water-holding capacity. Silvicultural and harvest prescriptions should be specific to the capacities and sensitivities of the site, soil, and desired vegetation. Recovery times are too long and possible remedies too costly to justify management alternatives that permit significant soil degradation (Cochran and Brock 1985, Froehlich 1979, Froehlich and McNabb 1984, Froehlich and others 1985, Geist and others 1989, Graecen and Sands 1980, Harvey and others 1987, Jurgensen and others 1990, Sullivan 1988).

Managing eastside vegetation systems to balance them with soil and climatic characteristics requires considerable understanding of local- and ecosystem-scale characteristics. Generalized approaches will require site-specific modifications, and not all methodologies will be suitable for every site. Site-analysis methodologies to balance water and nutrient stores with vegetation-use rates will be important for maintaining long-term productivity and for regulating pest activities at both the stand and ecosystem scale. Fertilizer and other ameliorative or growth enhancing treatments will be required.

Fire Effects

Fire plays a natural and important role in balancing vegetation systems with site, soil and climate. This role includes recycling stored carbon and nutrients back to the soil, which, in turn, regulates moisture storage capacity. Management methods can meet these requirements, but prescribed fire and wildfire must be kept within historical norms, or within prescribed ameliorative treatments. Historical norms likely included some highly destructive events. Proper management can prevent such destruction by emphasizing fire control and fuel management on those sites most at risk. Until effective analytical procedures are in more general use, we recommend that fire intensities always be kept in the low to moderate range if possible; we fully recognize that intense wildfires cannot always be prevented and that they have occurred in the past. Most important, as with other forest disturbances and management actions, soil organic matter losses should be kept at a minimum. When prescribed burning is indicated, the forest floor should be moist. Proactive fuel management should be an integral part of all silvicultural operations.

Harvesting System Effects

Harvesting systems range from conventional hand-felling coupled with ground-based skidders (tracked or wheeled vehicles offering little or no log suspension), to high lead cable (one-end log suspension), loader line and carriage sets (full-log suspension or nearly so), to sky-line or balloon and helicopter (full-log suspension). The use of ground-based mechanical harvesters is increasing because of their speed of operation, maneuverability, and lower labor costs. These harvesters include feller-bunchers that travel to each tree (these cut and stack whole trees for ground skidders) and “cut-to-length” machines that operate on specified or chosen accessways. These last machines have an articulated arm with an end that can cut, delimb, section, and stack logs of prescribed length. Stacks are picked up and transported to landings by machines called forwarders. Both kinds of harvesters have been used in commercial thinning and final harvest operations in eastern Washington and Oregon.

Ground-based systems are more commonly used on slopes of 30 percent or less and often result in the highest vegetation and soil disturbance (mostly soil compaction and displacement). Disturbance grades downward from common ground-skidding to high lead, to skyline, and finally to balloon or helicopter removal systems (Dyrness 1965, Klock 1975). Removal costs generally rise in the same progression. Where units have reach-out arms, mechanical harvesters have been purported to cause less disturbance than conventional skidding because they stay on specified trails and travel on logging slash. In theory, this practice should significantly reduce the area and degree of compaction, displacement, and erosion, but the validity of such claims remains largely unsubstantiated. One problem in eastside forests may be that the amount of slash is too light to adequately cushion trails.

Even-Aged, Uneven-Aged, and No-Management Effects

Most public forestry agencies have shifted from even-aged to uneven-aged management, primarily because of the public perception that uneven-aged management is less damaging to the environment, better for wildlife, and will result in a more aesthetically pleasing landscape. Many forest structural attributes are retained with uneven-aged management, because fewer trees are cut at one time in a given area; silvicultural operations such as weeding and thinning, however, are necessary to allow reasonable growth rates for replacement trees.

With uneven-aged management, the potential for soil damage increases because, with fewer trees removed over larger areas, ground-based extraction to avoid excessive cost is mandatory. With this forest management approach the probability of excessive soil damage threatens long-term wood production. Short- and long-term growth reductions from traffic-induced soil compaction and soil displacement are expected, with poor inducements to remedy either. No “final removal” of the stand is made in uneven-aged management, and costs of remedying compaction are unlikely to be covered under the decreased return per unit area. Where dedicated access routes are used for harvest, growth loss needs to be evaluated for acceptability.

A “no management” approach is problematic and provides few options for either increased recreational use or managed production. Over time, no management is likely to result in increasingly unnatural pressures on the ecosystem without any means of relief and little opportunity would exist for mid-course corrections of potential ecosystem crises.

Productivity and Sustainability Under Management

Guidelines for the appropriate management of forest soils are not easily defined, because of the spatial complexity of soil and its variability both within and among sites. Management of soil resources can be characterized within a conservation strategy.

For the following definition, “productivity” is a baseline of acceptable biological growth measured under prescribed conditions and “sustainability” is the perpetuation of a desired ecosystem, including the functional soil processes that regulate the system. To maintain ecosystem productivity and sustainability, soil quality must be maintained. Targeted goals for soil maintenance may be defined in terms of several attributes (for example, organic matter, nutrients, water-holding capacity, bulk density), depending on knowledge about the particular ecosystem. A soil attribute might also be co-defined by parallel changes in one or more biological parameters, such as mycorrhizal activities or N-fixation rates. Conservation strategies can be expressed in rather simple terms, but real world applications are often complex. For example, sustaining vigorous vegetation growth requires manipulation as water and nutrient supplies change over time.

The Current Soil Management Strategy

In National Forests of the Pacific Northwest Region, the Forest Service has set soil conservation standards. These standards might be considered thresholds that affect productivity and sustainability. They stipulate that, for example, detrimental conditions shall not exceed 20 percent of an area, including allowance for roads. Because roads commonly are about 5 percent, this translates to about 15 percent for an actual treatment area (Meurisse 1988).

The Forest Service defines detrimental conditions as:

Compaction-an increase in bulk density of 15 percent or more over the normal background mineral soils, other than those derived from volcanic ash or pumice (in those soils, compaction is an increase in bulk density of 20 percent or more);

Puddling-depth of rutting in tracks is 6 inches or more; and

Displacement, removal, or both-the loss (mechanical or fire) of 50 percent or more of the topsoil or humus-enriched A1 and AC horizons, or both, from an area of 100 square feet or more, which is at least 5 feet wide (Meurisse 1988).

With these standards in mind, the authors would summarize their soil management concerns with the following warnings:

1. Keep the soil in place by minimizing or avoiding soil erosion and mechanical soil displacement, whether from natural or human-caused events.

2. Minimize influences that cause excessive areas and degrees of soil compaction.

3. Minimize loss of soil organic matter.

Soil and the Forest Health Issue

Insofar as soil bulk density, water, organic matter, and N storage regulate the amounts, types, and physiological condition of any vegetation that an ecosystems can support, they are pivotal to health problems. Other soil-related factors, such as selected nutrient or microbial characteristics may also be important to a lesser degree. Changes in stand densities and species distribution through fire exclusion, harvesting history, or both may restrict natural processes that balance aboveground vegetation with belowground resources. Without fire, the ecosystem must compensate by accelerating biological decomposition through recycling and mortality processes, including insect and disease activity-a process that assures that fire will eventually return to the system. Appropriate restoration of that balance, and prevention of soil degradation, will be prerequisite to returning forest health to premanagement levels.

Weather-Stand-Soil Interactions

The modeling exercise shows that evaluating relative risk requires something more than a casual analysis of site, soil, and vegetation. For some stand-soil-climate situations, adding or subtracting even small amounts of soil organic matter may greatly affect growth potential or pest risk. Yet, for other situations, even large increases in available water may have no effect. Retrospective climate evaluation with temperature and moisture measurements over a 95-year period showed that climatic factors are not likely to have been directly involved in recent forest health changes. Site modeling analysis of the type demonstrated should be highly useful in evaluating the likelihood of forest health problems.

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APPENDIX A

Physical constants used in MTCLIM and SNOWMELT models

Description	Model	Value
Site albedo	MTCLIM	0.15
Sea level atmospheric transmissivity	MTCLIM	0.65
Sea level atmospheric transmissivity	SNOWMELT	0.20
Temperature lapse rate	MTCLIM	6.4 (C/1000m)
Lapse rate for maximum temperature	MTCLIM	8.2 (C/1000m)
Lapse rate for minimum temperature	MTCLIM	6.0 (C/1000m)
Dew lapse rate	MTCLIM	2.7 (C/1000m)
Potential evapotranspiration	SNOWMELT	12 values[1]
Maximum cover density of snow shaded	SNOWMELT	% cover/plot
Fraction of snow actually shaded	SNOWMELT	% cover/plot
Threshold temperature for reflectivity	SNOWMELT	32°F
Initial calorie deficient of snowpack	SNOWMELT	-1 calorie
Caloric input or loss from pack/day	SNOWMELT	10 calories
Free water in snowpack	SNOWMELT	0
Snow on trees	SNOWMELT	0
Water equivalent in snowpack	SNOWMELT	0 inches
Recharge deficit for soil	SNOWMELT	0
Temperature at top of snowpack	SNOWMELT	32°F
Temperature at middle of snowpack	SNOWMELT	32°F
Temperature at bottom of snowpack	SNOWMELT	32°F
Base station temperature rain to snow	SNOWMELT	32°F

[1] Monthly potential ET January through December in inches/day 0.001, 0.001, 0.03, 0.16, 0.22, 0.32, 0.3, 0.38, 0.15, 0.1, 0.015, 0.001 determined as function of monthly radiation and air temperature (Campbell 1977).

APPENDIX A (continued)

Biological and physical constants used to initialize the individualized forest process model TREEBCG

Value	Description		
1	KSTART = START SIMULATION LOOP COUNTER		
366	STOP = STOP SIMULATION LOOP, DAY		
1	DAY OUTPUT CONTROL: 1 MEANS YES; 0 MEANS NO		
1	GRW OUTPUT CONTROL: 1 MEANS YES; 0 MEANS NO		
0	LNG OUTPUT CONTROL: 1 MEANS YES; 0 MEANS NO		
0	TREE OUTPUT CONTROL: 1 MEANS YES; 0 MEANS NO		
10	KPRINT = IF 10 THEN DAY OUTPUT ONCE EVERY 10 ITERATIONS		
1	YIELD TABLE = IF 1 THEN YIELD OUTPUT ONCE EACH YEAR		
0	KBEGIN = BEGIN PRINTING AFTER ITERATION > KBEGIN		
365	LOOP = LOOP TO THE CARBON/NIT SUBMODEL EVERY xx DAYS		
0	LIFE CYCLE REDEFINE B CONSTANTS WITH LOOP # (1=YES, 0=NO, *.LIF FILE)		
0	SEASONALLY REDEFINE B CONSTANTS WITH YEARDAY (1=YES, 0=NO, #.SEA FILE) ,		
0	NEGX = PRINT ERROR MESSAGES WHEN X(I) IS NEGATIVE: 1 MEANS YES.		
29	NUMX = NUMBER OF X VALUES TO READ		
833 P*	X (1)	SNOWPACK	(M**3)*
650 P**	X (2)	SOIL WATER CONTENT	(M**3)**
0.0	X (3)	WATER OUTFLOW	(M**3)
0.0	X (4)	TRANSPIRATION	(M**3)
0.0	X (5)	EVAPORATION	(M**3)
0.0	X (6)	PSN	(KG)
0.0	X (7)	RESPIRATION AUTOTROPHIC	(KG)
1715 P	X (8)	LEAF CARBON	(KG)
36938 P	X (9)	STEM CARBON	(KG)
1715 P	X (10)	ROOT CARBON	(KG)
3000	X (i i)	LEAF/ROOT LITTER CARBON	(KG)
000	X (12)	RESPIRATION DECOMP, C	(KG)
40000	X (13)	SOIL CARBON	(KG)
25	X (14)	AVAILABLE NITROGEN	(KG)
25.7	X (15)	LEAF NITROGEN (1.5% OF X8)	(KG)
100	X (16)	STEM NITROGEN	(KG)
16	X (17)	ROOT NITROGEN (.75% OF X10)	(KG)

APPENDIX A (continued)

300	X (18)	L/R LITTER NITROGEN (1% OF X11)	(KG)
3000	X (19)	SOIL NITROGEN	(KG)
000	X (20)	NITROGEN LOSS	(KG)
0.0	X (21)	LEAF MORTALITY LOSS	(KG)
0.0	X (22)	STEM MORTALITY LOSS	(KG)
0.0	X (23)	ROOT MORTALITY LOSS	(KG)
16.5 P	X (24)	AVERAGE MID-CROWN HT	(m)
1608 P	X (25)	PLOT SIZE	(M**2)
11.6 P	X (26)	RESPIRATION SURFACE	(M**3)
43.20 P	X (27)	AVE DBH - STAND LEVEL (cm) ONLY NEEDED IF	
20.9 P	X (28)	AVE HT - STAND LEVEL (m) NOT USING TREE LIST	
119 P	X (29)	STAND DENSITY	(tree/ha)
51	Numb=	NUMBER OF B CONSTANTS TO READ	
25	B (1)	SPECIFIC LEAF AREA	(M**F2/KG C)
-0.5	B (2)	CANOPY LIGHT EXTINCTION COEFFICIENT	
650 P	B (3)	SOIL WATER CAPACITY	(M**3)
0.0005	B (4)	INTERCEPTION COEFF	(M/LAI/DAY)
10000	B (5)	GROUND SURFACE AREA	(M**2/HA)
0.0007	B (6)	SNOWMELT COEFF	(M/DEG C/DAY)
44	B (7)	LATITUDE	(DEG)
0.8	B (8)	1- SURFACE ALBEDO	
0.5	B (9)	SPRING MIN. PMS	(MPA)
3000	B (10)	RAD. RED LC THRESHOLD	(KJ/M**2/DAY)
0.0016	B (11)	MAX CANOPY AVG. LC	(M/SEC)
2.0	B (12)	LWP AT STOMATAL CLOSURE	(MAP)
0.045	B (13)	SLOPE ABS HD REDUCTION	(M/SEC/ABSHD)
432	B (14)	PSN LIGHT COMP PT.	(KJ/M**2/DAY)
9720	B (15)	PSN I	(KJ/M**2/DAY)
0.0008	B (16)	MAX LC (C02)	(M/SEC)
7.5	B (17)	MIN TEMP. PSN	(DEG C)
37	B (18)	MAX TEMP. PSN	(DEG C)
0.0001	B (19)	LEAF RESPIRATION COEFF	
0.00007	B (20)	STEM RESPIRATION COEFF	
0.00017	B (21)	ROOT RESPIRATION COEFF	
10	B (22)	SAPWOOD TURNOVER (YEARS)	
4.0	B (23)	TEMP. EFFECT MESOPHYLL COND. ADJUSTMENT COEFFICIENT	

APPENDIX A (continued)

50.0	B (24)	DECOMPOSITION TEMPERATURE OPTIMUM	
0.085	B (25)	Q10=2.3 CONSTANT FOR EXPONENTIAL RESPIRATION SURFACE	
0.044	B (26)	MAXIMUM CAN AVE LEAF NITROGEN CONC	(% x 2.2 C/CH20)
0.0132	B (27)	MINIMUM CAN AVE LEAF NITROGEN CONC	
0.80	B (28)	MAX LEAF NITROGEN RETRANSLOCATION FRACTION (DIM)	
0.03	B (29)	SOIL/LITTER DECOMPOSITION RATE FRACTION (DIM)	
0.5	B (30)	N/C DECOMP RELEASE FRACTION (DIMS	
26.5	B (31)	MAXIMUM LEAF AREA INDEX, ALL SIDES (DIM)	
6.0	B (32)	LEAF TURNOVER RATE (YR)	
0.25	B (33)	LEAF LIGNIN FRACTION (%/100)	
1.0	B (34)	SOIL WATER LEAF/ROOT ALLOCATION FACTOR (DIM)	
1.0	B (35)	NITROGEN AVAIL LEAF/ROOT ALLOCATION FACTOR (DIM)	
0	B (36)	DATE OF SPRING LEAF GROWTH (YEARDAY)	
365	B (37)	DATE OF FALL LEAF CROP (YEARDAY)	
20.0	B (38)	MOBILE N RETENTION TIME (YR)	
2.5	B (39)	ATMOSPHERIC DEPOSITION N (KG/HA/YR)	
5.0	B (40)	BIOLOGICAL FIXATION N (KG/HA/YR)	
0.00	B (41)	STEM TURNOVER COEFF	
0.80	B (42)	ROOT TURNOVER COEFF	
0.35	B (43)	LEAF GROWTH RESP	
0.30	B (44)	STEM GROWTH RESP	
0.35	B (45)	ROOT GROWTH RESP	
50	B (46)	DECOMPOSITION TEMPERATURE OPT (DEG)	
0.03	B (47)	SOIL/LITTER C DECOMP FRACTION (DIM)	
0.4	B (48)	DECOMPOSITION RATE SCALAR (DIM)	
225.0	B (49)	STEM CONVERSION FACTOR FROM VOLUME TO CARBON	
0.25	B (50)	LEAF CONVERSION FACTOR FROM SAPWOOD AREA TO LEAF AREA	
0.5	B (51)	K = LEAF SHADING COEFFICIENT	
0	NUMIZP=	NUMBER OF Z VARIABLES TO PRINT:	CAN BE 0
0	NUMIGP=	NUMBER OF G VALUES TO PRINT:	CAN BE 0

* Value used here was determined by subtracting value given by TREEBGC snowpack from SNOWMELT value. TREEBGC constantly underestimated the result obtained from the more sophisticated SNOWMELT model.

** In this case, soil water-holding capacity for Fort Rock 10 (610 M3/ha) was increased 6 percent to simulate increased capacity under old-growth (D. Page-Dumroese, pers. comm.).

P Indicates value changes for each run.

APPENDIX B

Model calibration: Regression equations, their r^2s and standard errors are as follows.

Old Growth Volume for all plots in cubic feet:
$\ln(ft^3) = -6.657 + 1.9307 \ln Dbh + 1.1633 \ln H$

Where:
Dbh = diameter breast height in inches
H = height in feet
$r^2 = .99$,
standard error 0.14.

Old Growth Dbh as function of the diameter outside bark of a 20-inch stump

Fort Rock $Dbh = -0.679 + 0.8982DS$ $r^2 = 0.97$ se = 0.78 in
Sugar Cast $Dbh = -0.8208 + 0.9134DS$ $r^2 = 0.97$ se = 0.78 in
Bend R D $Dbh = -0.1988 + 0.8998DS$ $r^2 = 0.98$ se = 0.72 in

Old Growth Height (H) as a function of DBH:
Fort Rock $\ln H = 4.8137 - 9.3759/Dbh$ $r^2 = 0.47$ se = 0.09
Sugar Cast $\ln H = 4.8492 - 7.3156/Dbh$ $r^2 = 0.40$ se = 0.08
Bend R D $\ln H = 5.035 -11.746/Dbh$ $r^2 = 0.44$ se = 0.09

Stem Carbon (ST):
$ST_p = VOL_i * 225$

Where:
VOL_{ip} = volume of the ith individual summed over the pth plot.
225 = conversion of wood from volume to carbon

All-sided Leaf Area (LA):
$LA_i = BA_i/0.0001 * \%SW_i * 0.25 * 2.6$

Where:
LA_i = all-sided leaf area of the ith tree in ml
BA_i = basal area of ith tree in m^2
0.0001 = conversion of basal area to cm^2
$\%SW_i$ = percent of basal area that is sapwood of the ith tree
0.25 = conversion from sapwood basal area to 1-sided leaf area of ith tree
2.6 = conversion from 1-sided leaf area to all-sided leaf area of the ith tree

Leaf Carbon for plot (LC_p):
$LC_p = \text{sum } LA_i /25$

Where:
sum LA. = Leaf area of ith trees on pth plot
25 = specific leaf area in m^2/kg carbon

All-sided Leaf Area Index for plot (LAI_p)
$LAI_p = \text{sum } LA_i/PA$

Where:
PA = area of plot over which LA_i was summed.
Total Plot Respiration Surface votume (RS) (from R. Korol):
$RS = SWV_i + SV_i$

Where:
SWV_i = sapwood volume of ith tree
= volume of ith tree * %SW * 0.1 (assume 0.1 living cells)

SV_i = surface volume of ith tree
$= VOLA_i - VOLD_i$
$VOLA_i$ = living surface volume = $(3.1416*r^2*H_i)/3$

APPENDIX B (continued)

Where:
$r = Dbh_i/2 * 0.01$
H_i = Height of ith tree
$dr = r-0.005$ (assumes bark 0.5 cm thick)

Sapwood Area regression (Hunt and others, 1991):
$S = (-0.27 + 0.835d)^2$

Where:
S = sapwood area in cm^2

d = diameter at 1.3 M in cm

Individual Old-Growth Crown Coverage (Moeu, 1981):

$\ln(CW_i) = 1.62365 + 1.081371n(D) - 0.680981n(H) + 0.297861n(CL)$

Where:
CW_i = diameter of ith tree crown in feet
D = diameter at breast height in inches
H = height of tree in feet
CL = length of crown in feet (assumed for open grown ponderosa pine old-growth to be 50% of height)

and Crown Cover for plot (CC):
CC = sum of $((CW_i/2) * 3.1416 * 0.0929)$/plot area

GLOSSARY

A1 horizons-Surface soil layer with maximum organic matter accumulation.

AC horizons-A transitional layer in a young soil occurring between a weathered horizon with organic matter accumulation and an unweathered horizon with very little organic matter.

Acclimative trait-Ability of tree to adjust the trait to match the environment, based on physiological rather than genetic processes.

Achlorophyllous plants-Plants lacking chlorophyll so they cannot produce an independent food source.

Alfisols-Soils with moderate to high base saturation and a clay horizon.

All-sided LAI-Surface area of needles in m^2/m^2 of ground surface.

Alluvium-Sand, mud, and other sediments deposited in land by streams.

Amelioration-An action designed to repair specific damages.

Ammonification-Conversion of other forms of nitrogen into derivatives of ammonia. This form of nitrogen is not leached from the soil and is highly available for plant use.

Andesites-Dark, gray rocks, consisting essentially of oligoclase or feldspar with augite, hornblende, hypersthene or biotite.

Andosols-Volcanic ash influenced inceptisol.

Assimilation-Act of absorbing nutrients, carbon, etc., into plant body.

Balance point-In reference to carbon, where carbon fixed (photosynthesis) and carbon used (respiration) are in balance.

Basal area-Cross-sectional area of stems; provides a good measure of tree density and weight.

Basalt-Volcanic rock that is hard, heavy, and dark.

Base concentration-Quantity of base-reacting plant nutrients.

Broadcast burning-Burning forest fuels as they are; no piling windrowing, etc.

Bulk density-Weight of soil per unit volume, usually expressed in g/cc, e.g. volcanic ash soil (0.6g/cc), glacial till soil (1.0g/cc). Soils with a density over 1.0g/cc are generally considered dense enough to impede root penetration.

Carbon deficit-Insufficient carbon (photosynthetic products) to support required maintenance respiration and growth.

Cation exchange capacity-Capacity of soil to attach specific quantities of cation-based nutrients to electrically charged surfaces.

Chlorophyllous hosts-Host plants that have chlorophyll and the capacity to independently meet photosynthetic food requirements.

Climax series-Vegetation classification system that indicates the ability of a site to support specific climax vegetation over the long term, e.g. the Douglas-fir or the ponderosa pine climax series.

Cohesion-Ability of soil particles to attract one another, e.g. those with high cohesion resist erosion; those with low cohesion are highly erodible.

Colluvium-A heterogeneous mass of rock detritus or soil material emplaced by gravitational material on or at the foot of slopes.

Compacted tills-Soils based on glacial deposition products. These soils were overlain by glaciers and the weight of the ice severely compacts them, usually sufficient to make them resistant to root penetration.

Compaction-The act of increasing bulk density of the soil. Compacted soils usually have reduced ability to support vegetation because of reduced water/air exchange and the reduced ability for roots to penetrate them.

Cryandepts-Soils developing in volcanic pumice and ash with a mean annual temperature between 37° and 46.4°F.

Debris torrent failure-Mass of rock, soil and other debris that has moved rapidly downslope; because of high water content it has behaved like a water torrent or avalanche.

Displacement-Act of physically moving soil horizons off the site, i.e., essentially rendering the soil component unavailable for future vegetation.

Dry ravel-Movement of dry soil material downslope.

Ectomycorrhizal (activities, tips)-A specific type of mycorrhizal relationship characterized by a short root (tip) that includes a large amount of fungal tissue in the outer layers, surface and adjacent to the root, termed the mantle. Many of the fungi that form this type of root-invasive structure are those that form typical mushroom fruiting bodies seen on the forest floor. This is the primary type that occurs on conifers. The ability to form ectomycorrhizal roots is critical to the ability of conifers to thrive in relatively infertile, dry or competitive environments.

Evapotranspiration-The process of water loss by leaf surface evaporation and the replacement of that water from soil back to stem and leaf. The more leaf surface available, the greater the water removal from the soil. Dependent on rates of gas exchange at the leaf, which can be controlled by opening and closing plant “breathing” apertures (stomates) by some plants.

Fauna-See: soil fauna-flora.

Feeder root pathogens-Pathogens that attack the small (less than 2mm) roots (feeder roots) of plants.

Forest floor-Organic horizons overlaying mineral soil base in forests; includes plant organic litter (leaves, small stems, etc.), humus, and soil wood.

Free-living-Ability to live free in bulk soil without being dependent on infection of a plant to survive.

Glacial till-Soil produced from glacial input and movement.

Growth respiration-Respiration that directly supports additional growth, as opposed to that required to support maintenance of existing plant body.

Heartwood-Dead structural wood in tree stems, roots, and branches.

Heat capacities-Quantity of heat required to raise the temperature of one gram of soil one degree.

Humus-Highly decomposed soil organic matter, usually black in color and decomposed to the point that the original source is no longer identifiable.

Hyphae-Individual fungal strands.

Immobilization-Process of binding plant nutrients into organic compounds; when so bound they cannot move within the soil profile and are not available for plant use.

Inceptisols-Soils having altered horizons that have lost bases or iron and aluminum but retain weatherable minerals and do not have horizons enriched with silicate clays or mixtures of aluminum and organic carbon.

Individualized process model-Physiological process model designed to simulate individual plants.

Interception-Ability of plant leaves and canopies to attach rain water, allowing it to be evaporated so it does not get to the soil.

Invertebrate-Small animals lacking a backbone.

Leaching-Process of dissolving and moving nutrients through the soil profile and off the site.

Limit of stability-Balance point between assimilation and respiration of trees in a stand.

Litter-Small organic debris derived primarily from above-ground parts of plants, leaves, small stems, etc.

Loamy-Soil material that contains 7 to 27% clay, 28 to 50% silt, and less than 52% sand.

Loess-Fine soil particles transported to the site via wind.

Low grade pathogens-Weak pathogens that plants of normal vigor are able to defend themselves from. May invade damaged or low vigor individuals.

Macroclimates-Regional climate.

Macropore-Large soil pores that transmit air and water to plant roots.

Maintenance respiration-Respiration (energy use) required to meet the normal maintenance of the plant body as it presently exists.

Mass wasting-Large landslump erosion events.

Microbes-Generally inclusive of all forms of bacteria, fungi, and algae that inhabit natural ecosystems. Some fungal structures may be large, i.e., mushrooms, shelf fungi, mat structures, etc.

Microclimate-Climate in immediate vicinity of an individual plant.

Mollisols-Soils characteristically

Morphology-Unique physical structure.

mpa-Millipascal-a unit of pressure.

Mycorrhizal (fungi)-Includes all morphological types of mycorrhizae inclusive of ectomycorrhizae, as described, and endomycorrhizae, where the fungus is deeply embedded in the root and does not form short roots with a mantle.

Mycorrhizosphere-Soil adjacent (within 2mm) to and affected by products from mycorrhizal structures.

Narrow sapwood-Sapwood making up less than 50% of the basal area of a cross-section bole area.

Nitrification-Conversion of other forms of nitrogen into nitrate. Nitrate is highly soluble in water and easily moved through the soil profile and off site. It is also highly available for plant use.

Nitrogen-fixing-Ability of microbes to remove nitrogen from the atmosphere and convert it to forms that are stored in soils and used by plants and microbes.

Nitrogen-fixing plants-Plants that are symbiotically infected by nitrogen-fixing microbes, thereby potentially acquiring the ability to use nitrogen directly from the atmosphere. These plants are nodulated, e.g. legumes, and the bacteria are contained within the nodules.

Non-symbiotic nitrogen fixation-Nitrogen fixation resulting from bacterial populations that do not infect plants but acquire energy for the fixation process as a byproduct or leakage product from a variety of decomposer organisms or in plant rhizospheres or mycorrhizospheres.

Nutrient cycles-Characteristic pathways of nutrients from various soil components or air into vegetation systems and back again.

Ordinating-Arranging things according to predetermined patterns of moisture or temperature (low to high or vice versa).

Pathogenesis-The act of establishing a pathological (damaging) relationship between plant and microbe.

PE-See: production efficiency.

Percent sapwood (%SW)-Percent of basal area of tree bole that is composed of living cells.

Phenology-Predetermined, climate driven changes in development, e.g. germination, bud burst, flowering, etc.

Phenotypic plasticity-Ability to adjust and change (physiologically) to meet changing environments without changing genetic makeup.

Plant available water capacity-Amount of water storage in the soil that can be utilized by the plant community it supports.

Podzolization-Leaching of the upper layers of soil, accumulation of materials in the lower layers with the accompanying development of characteristic horizons.

Pollen counts-Method of counting and identifying pollen contained in ancient bog sediments that provides information on the vegetation existing at the time the deposit was formed.

Prescribed fire-Method of intentional use of fire by prescription to achieve specific forest and soil management objectives.

Production efficiency (PE)-Grams of biomass produced /m^2 of leaf area.

Pumice-Coarse deposits of volcanic ash that occur very near the volcano because of relatively large size (compared to what is usually considered ash).

Radiation frosts-Surface freezing due to rapid loss of heat from the soil to the atmosphere.

Regressions-Statistically valid relationships between one or more values and any other specific value of interest, may be positive or negative.

Remediation-Methods to remedy, offset, cure, or ameliorate a created problem.

Residuals of measured %SW-Statistical term for difference between a measured and predicted value plotted on the predicted value.

Respiration-Process of breaking down energy-containing materials and utilizing the energy released to perform physiological work.

Respiration volume-Volume of living wood m^3.

Rhizomorph-Grouping of fungal hyphae into a root-like structure.

Rhizoplane-Root surface.

Rhizosphere-Region surrounding roots (within 2mm) that is heavily influenced by root leakage products that normally supports an active, diverse microbial population including decomposers, mycorrhizal fungi, non-symbiotic nitrogen fixers, and root pathogens.

Rotation-Refers to each generation of a managed forest; regeneration to harvest is a rotation.

Rhyolite-Acid, volcanic rock.

Sapwood-Living wood in stems, roots, and branches that translocates water and nutrients.

Scalping-Physical removal of surface soil horizons to facilitate planting and to reduce competition for post-planting resources.

Scarification-Physical disturbance of surface soil horizons, usually to improve germination and early survival of natural (seed-based) regeneration.

Slump-earth flow-Movement of large, unstable earth masses.

Soil-borne pathogens-Plant pathogens that occur naturally in soil.

Soil fauna-Usually refers to small animals contained in soil.

Soil flora-Refers to small plants (fungi, bacteria, algae, etc.) that occur in soil.

Soil organic matter-Includes all normal soil organic components (litter, humus, wood, etc.).

Soil structure-Refers to physical structure, especially large pores and aggregations that facilitate air and water movement or storage.

Soil wood-Deposits of decayed wood buried in the soil profile.

Stocking-Refers to numbers of tree stems in a given unit area (acre/hectare).

Stomates-Breathing apertures of plants, some plants can control open and closure.

Symbionts-Partners in a relationship where all partners derive benefits from association.

Symbiotic N-fixers-Bacteria that invade plant roots to form nodules where the bacteria utilize energy provided by the plant and, in return, supply nitrogen to the plant.

Temporal sense-Relationship with time, either short- or long-term.

Texture-Balance of silt, clay and sand that produced fine or coarse grained soils with specific characteristics.

Terrestrial-Refers to land-based life forms, ecosystems, etc.

Thermal conductivity-The rate at which one calorie of heat is conducted through one centimeter of soil under a constant temperature difference of 1°C.

Thermal contact coefficients-The products of the thermal conductivity and the heat capacity by volume.

Thermal diffusivities-The thermal conductivity divided by the heat capacity by volume.

Transformations-Directed change of form.

Transpiration-Water loss through vegetation to the atmosphere.

Typic Vitrandepts-Soils with large amounts of ash and pumice and very low amounts of their weathering products.

Volcanic ash-Fine grained (as opposed to coarse grained pumice) volcanic deposits with the appearance of glass shards.

Water-holding capacity-Maximum amount of water that a soil can hold over an extended period without gravity induced loss.

Water-repellant layers-Layers of soil that are resistant to water penetration, characteristic of intensely burned soils; thought to occur as a result of condensation of volatilized organic matter on soil particles.

Water use efficiency (WUE)-Grams of biomass produced/gram of water transpired.

Wide sapwood-Sapwood making up more than 50% of the basal area of a tree bole.

Woody residue-Woody plant products, (logs, stems, boles, large branches, etc) residual from normal mortality, harvesting, windstorms, insect and disease outbreaks, etc., occurring on or suspended above the soil surface.

WUE-See: water use efficiency.

Harvey, Alan E.; Geist, J. Michael; McDonald, Gerald L; Jurgensen, Martin F.; Cochran, Patrick H.; Zabowski, Darlene; Meurisse, Robert T. 1994. Biotic and abiotic processes in eastside ecosystems: the effects of management on soil properties, processes, and productivity. Gen. Tech. Rep. PNW-GTR-323. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 71 p. (Everett, Richard L., assessment team leader; Eastside forest ecosystem health assessment; Hessburg, Paul F., science team leader and tech. ed., Volume III: assessment.)

In ecosystems characteristic of eastside regions of Oregon and Washington, the productive zone in soil is usually in the upper 1 or 2 meters. The biological processes driving both soil productivity and root development are concentrated in limited organic horizons, and they have evolved historically in a natural system that includes mostly modest surface disturbance. Typical disturbances include erosional, seismic or tip-over events, and modest surface heating by periodic wildfire. This combination of properties and processes produces soils with an extremely wide range of productivity potential, but productivity can be highly sensitive to disturbances from heavy machinery or fire, when fuel accumulations are well beyond historical norms. Limited moisture-holding capacity and nitrogen storage often impose a need for carefully balancing developing vegetation with available soil resources.

Keywords: Soil management strategy, soil productivity, soil sustainability, soil damage, soil moisture, soil microbiology, soil-disease interaction, soil-climate interaction, soil wood, coarse woody debris, organic matter, water storage and use, nutrient cycling, nitrogen fixation, ectomycorrhizal activity, carbon cycling, harvest effects, fire effects, fertilizer effects, forest health, physical properties, chemical properties.

Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, Oregon 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, OR 97208