Volcanic Ash Soils: Sustainable Soil Management Practices, With Examples of Harvest Effects and Root Disease Trends

Mike Curran, Pat Green and Doug Maynard

In: Page-Dumroese, Deborah; Miller, Richard; Mital, Jim; McDaniel, Paul; Miller, Dan, tech. eds. 2007. Volcanic-Ash-Derived Forest Soils of the Inland Northwest: Properties and Implications for Management and Restoration. 9-10 November 2005; Coeur d'Alene, ID. Proceedings RMRS-P-44; Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

***Mike Curran**, Corresponding author, Research Soil Scientist, B.C. Ministry of Forests and Range, Forest Sciences Program, Kootenay Lake Forestry Centre, Nelson B.C., Canada. (also Adjunct Professor, Agroecology, University of B.C.). **Pat Green**, Forest Ecologist, Nez Perce National Forest, Grangeville, Idaho. **Doug Maynard**, Research Scientist, Natural Resources Canada, Canadian Forest Service, Victoria BC, Canada.*

Abstract

Sustainability protocols recognize forest soil disturbance as an important issue at national and international levels. At regional levels continual monitoring and testing of standards, practices, and effects are necessary for successful implementation of sustainable soil management. Volcanic ash-cap soils are affected by soil disturbance and changes to soil properties influence ecosystem responses such as productivity and hydrologic function. Soil disturbance from timber harvesting, reforestation, or stand tending is mainly a result of moving equipment and trees. Compaction and organic matter removal are of primary concern. The severity and extent of disturbance depend on the harvest system, soil and climatic conditions. Ash-cap soils can be susceptible to disturbance and schemes to predict compaction, displacement and erosion hazards are useful for planning forest management operations. On-site effects range from permanent loss of growing sites because of roads, to more subtle changes in soil properties that ultimately influence site productivity. Off-site effects may include erosion and landslides. Soil disturbance during operations should be regulated and monitored to minimize both on- and off-site effects, which can take years or decades to appear. Forest health issues vary on volcanic ash-cap soils. An analysis of Armillaria root disease incidence across the National Forests of the Inland Northwest indicates some potential relationships among root disease, and soil and site factors. The strong relations between presence of susceptible host and development of fungal biomass may be the strongest causal agent, with the soil and site factors supporting the presence of the pathogen and susceptible host. Thicker ash soils of more northerly areas are related to habitat types that historically supported white pine and a higher diversity of less susceptible species. After root disease mortality occurs, these more mesic environments also fill in with other species rapidly, so higher levels of root disease are more difficult to discern. Recommendations are made for soil management and about information needs for soil disturbance and root disease relations.

Key words: volcanic ash-cap soils, forest health, *Armillaria*, root disease, criteria and indicators, organic matter depletion, soil disturbance, soil compaction, sustainability protocols

The Practice of Sustainable Soil Management

Sustainable soil management can be defined as ensuring the biological, chemical and physical integrity of the soil remains for future generations. Sustainability should be addressed throughout all facets of forest management including implementation of individual harvest or stand-tending plans, development of agency or company standards and best management practices (BMPs), and third-party certification. Demonstration of sustainable soil management is promoted through reporting procedures required by applicable sustainability protocols,and by having third-party certification of forest practices and products (Curran and others 2005a).

Sustainability protocols exist at international and national levels. At the international level, the Montreal Process (MP) includes a Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests (Montreal Process Working Group 1997). Some countries have developed their own protocols and procedures designed to track and report progress toward meeting requirements of international protocols such as the MP. For example, the Canadian Council of Forest Ministers recently developed revised criteria and indicators for sustainable forest management (CCFM 2003).

Third-party (eco)certification of forest practices and resulting wood products arose in response to sustainability protocols and the greening of the global marketplace. Organizations such as Sustainable Forestry Initiative (American Forest and Paper Association), Canadian Standards Association, Forest Stewardship Council (FSC), and ISO 1400.1 all have documented review processes and procedures for certification. Protecting streams and natural drainage patterns, maintaining slope stability, and regulating soil disturbance are common elements considered. In addition, most require some adaptive management process to ensure continuous improvement of practices on the ground. Compliance with current soil disturbance standards is often used as a proxy for ensuring sustainability; however, a common approach to standards, and validation of the standards through research are important steps that must not be overlooked when these are used as proxies. Some certification schemes also call for more restrictive standards (e.g., FSC in British Columbia calls for lower disturbance levels than Provincial regulations).

At the local level, when managing harvest-effects on soils, tree growth and long-term productivity, soil disturbance from mechanical operations is of most concern. Soil disturbance occurring at time of operations can have negative, positive, or no detectable effect on growth or hydrologic function. Soil disturbance at the time of operations is often an indicator used in regulating long-term productivity and hydrologic effects. This is because in many NA ecosystems, we need at least 10 to 20 years data to draw conclusions about the effects of various practices on growth or hydrologic function. In discussing evidence for long-term productivity changes, Morris and Miller (1994) indicated slow-growing stands require 20 or more years of growth before long-term productivity consequences can be ascertained. Soil disturbance is the proxy that we can observe and regulate at the time of harvesting and site preparation. However, this proxy also needs to be validated and revised over time in an adaptive management process that includes standards, best management practices, monitoring (compliance, effectiveness and validation), further research and strategic direction and revision over time (Curran and others 2005b). A common approach is needed for describing soil disturbance so that results achieved in different areas are comparable (Curran and others 2005c).

Management and Communication Frameworks for Sustainable Soil Management

Just like ecosystem classification schemes (e.g., Braumandl and Curran 1992) in neighboring BC, organizing soil into mappable or otherwise describable units provides an important framework for communicating management experience, research results, and conservation efforts. Detailed soil or land type maps are available for much of the ash-cap soils in the United States, and reconnaissance-level soil mapping is available in southern BC. Maps designate soil units (e.g., soil series in detailed mapping and soil or land type associations in reconnaissance mapping) based on soil-forming factors of parent material, topography, climate and vegetation, all acting over time, which varies due to geologic events like glaciation and volcanic eruptions. As discussed above, soil disturbance can also be classified and we are working towards a common classification there as well.

Perhaps the most useful way of organizing soil units for forest management is a consideration of their risk of damage from soil disturbance. The most common disturbance of concern in forest management is from machine traffic during harvesting, site preparation, or fuel management treatments. The biggest concerns associated with machine traffic are soil compaction, soil displacement, and soil erosion. In addition, slope stability is a concern on steeper and wetter sites. To identify and mitigate the potential for landslides, terrain mapping and/or terrain stability field assessments are used on sites that exceed certain slope gradients or have indicators of potential slope instability.

Determining the soil disturbance hazards on a given site provides a framework for developing harvesting strategies by alerting the prescription developer to the specific soil disturbance concerns on that site. For example, in BC, soil disturbance default standards under the Forest and Range Practices Act (FRPA) permit up to 5 or 10% net disturbance within a cutblock area (excluding permanent access). In the Interior, the trigger for 5% is when one of the key hazards is Very High. A High rating for any hazard is primarily intended to alert the prescription developer and the operational staff of a hazard that may require special treatment to prevent problems (manage and mitigate the hazard). High compaction hazard also results in more equipment traffic disturbance types being "counted"[1] under FRPA disturbance criteria. The soil disturbance hazards also help identify site conditions that are suitable for construction of excavated and bladed trails (skid roads or backspar trails), and/or temporarily exceeding soil disturbance levels and rehabilitating slope hydrology and forest site productivity. The hazards are defined below, including brief discussions of why they are of concern.[2]

Soil Compaction Hazard

Soil compaction is the increase in soil bulk density that results from the rearrangement of soil particles in response to applied external forces. Soil puddling is the destruction of soil structure and the associated loss of macroporosity that

---

[1] In BC, the term "counted" is used in reference to soil disturbance to recognize the fact that soil disturbance types or their severity vary with soil sensitivity to disturbance. More disturbance types are of concern on more sensitive soils, and less are of concern on more resilient soils (e.g., sandy soils). The net result is that more disturbance types are "counted" towards the total cumulative allowable limit on more sensitive soils.

[2] Soil degradation hazard rating keys for soil compaction, displacement, and erosion are found in Land Management Handbook 47 (Curran et al. 2000) and the *Forest Practices Code of British Columbia, Hazard Assessment Keys for Evaluating Site Sensitivity to Soil Degrading Processes Guidebook.* **The general BCMOF Web site where these and other FPC information can be located is: http://www.for.gov.bc.ca/ (look under legislation).**

results from working the soil when wet. Organic matter is often incorporated during puddling and because organic matter is lighter than mineral particles, soil bulk density may not increase; however, the other properties described below are still negatively affected. The science and rationale for the BC compaction hazard key are laid out in Carr and others (1991).

Soil moisture content is probably the best determinant of compaction hazard at any given time. In British Columbia, the soil compaction hazard key ranks the potential compaction hazard by grouping soil textures that are most susceptible to structural degradation from compaction and puddling, and are most likely to hold moisture and remain wet for longer periods. The soil compaction hazard key is a tool to help with planning of an operation, while careful monitoring of equipment effects on the soil, and hand tests for soil moisture content are the tools that help guide the operation.

Soil compaction and puddling are of concern in timber harvesting operations because of effects on roots and site water relations. Compacted soils have higher penetration resistance that can impede root growth. Compacted and puddled soils both have lower aeration porosity and lower hydraulic conductivity and infiltration rates; however, in some coarser textured soils, compaction may actually increase water holding capacity (these soils typically have lower compaction hazard ratings).

Lower aeration porosity results in reduced gas exchange that can adversely affect oxygen levels in the soil air; this reduces physiologic function of roots, which in turn can lead to root die off under wetter conditions. Lower hydraulic conductivity and infiltration rates of the compacted or puddled soil can result in increased runoff during rainfall and snowmelt events. This can lead to increased net export of water from a cutblock, which can affect downslope sites, natural drainage features, and other resource values due to erosion and sedimentation. Increased water export also means less water may be stored on site to support tree growth during summer drought. Compacted soils can also remain wetter longer, thereby further affecting seedlings because the soil may be colder and have poor aeration.

Monitoring of traditional spring harvesting on three ash-cap influenced soils in the southern Rocky Mountain Trench near Cranbrook indicated that significant declines in aeration porosity occured when evidence of equipment traffic was visible on the ground (e.g., wheel lugmarks on the soil or slight impressions with track grouser marks) (Utzig and others 1992). These sites were typical Trench soils: silt loam to silty clay loam textured surface soils low in coarse fragments, underlain by denser subsoils with more coarse fragments.

The undisturbed soils had aeration porosity values at or above the threshold recommended by the United States Forest Service (USFS) in some of its policy for the Pacific Northwest (i.e., 15% at 10 J/kg water tension referred to in Boyer 1979). Regardless of the severity of disturbance, aeration porosities were less than 15% (fig. 1). Effects on saturated hydraulic conductivity (i.e., water relations) were similar (fig. 2). Bulk density increased in a similar but opposite trend to the aeration porosity and saturated conductivity, as would be expected. The concern about these effects is how extensive the machine traffic disturbance is on fully mechanized harvesting. On the three sites studied, the combined total of the light ruts, 5-cm ruts, and main trail disturbance ranged from 52 to 64% of the entire cutblock area, with lighter machine disturbance covering from about 30 to over 45% (fig. 3).

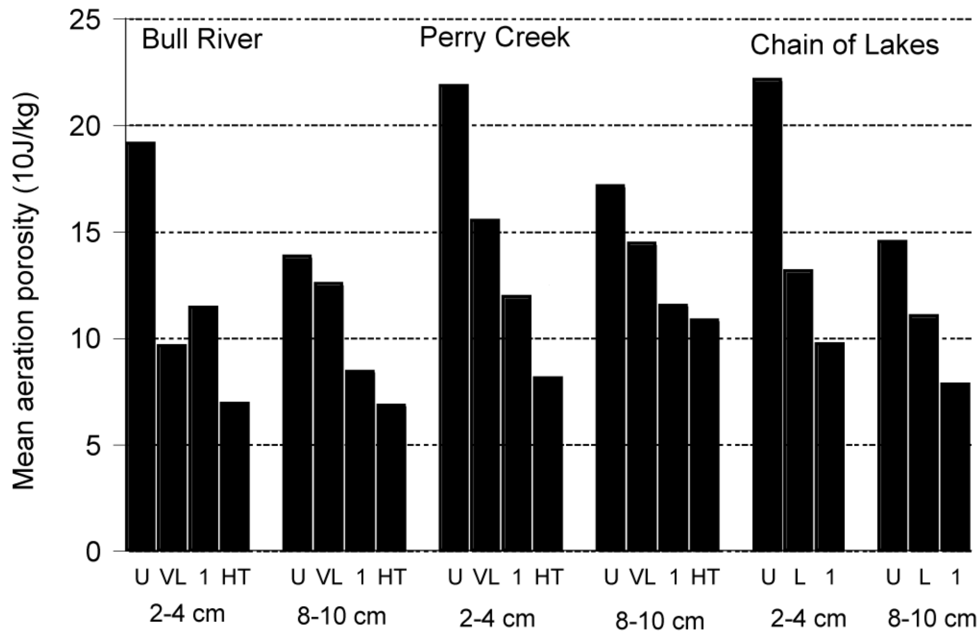

Figure 1—Aeration porosity at 10 J/kg tension for two sample depths at three sites in the southern Rocky Mountain Trench near Cranbrook, BC (Utzig and others 1992). U (undisturbed), VL (very light ruts, <5 cm deep), 1 (ruts 5 cm or deeper), HT (heavy [main] trails).

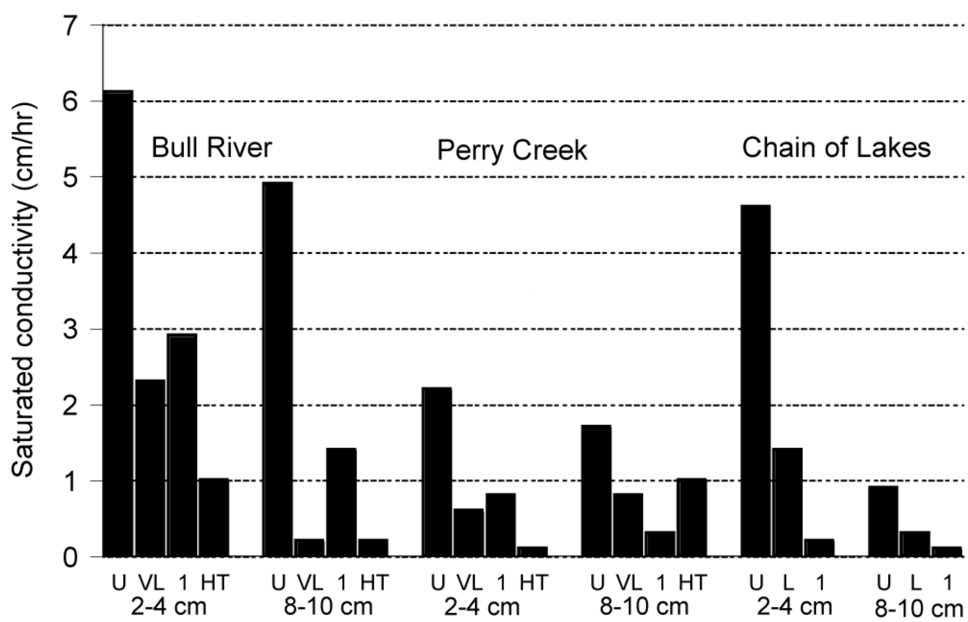

Figure 2—Saturated hydraulic conductivity for two sample depths at three sites in the southern Rocky Mountain Trench near Cranbrook, BC (Utzig and others 1992). U (undisturbed), VL (very light ruts, <5 cm deep), 1 (ruts 5 cm or deeper), HT (heavy [main] trails), from Curran (1999).

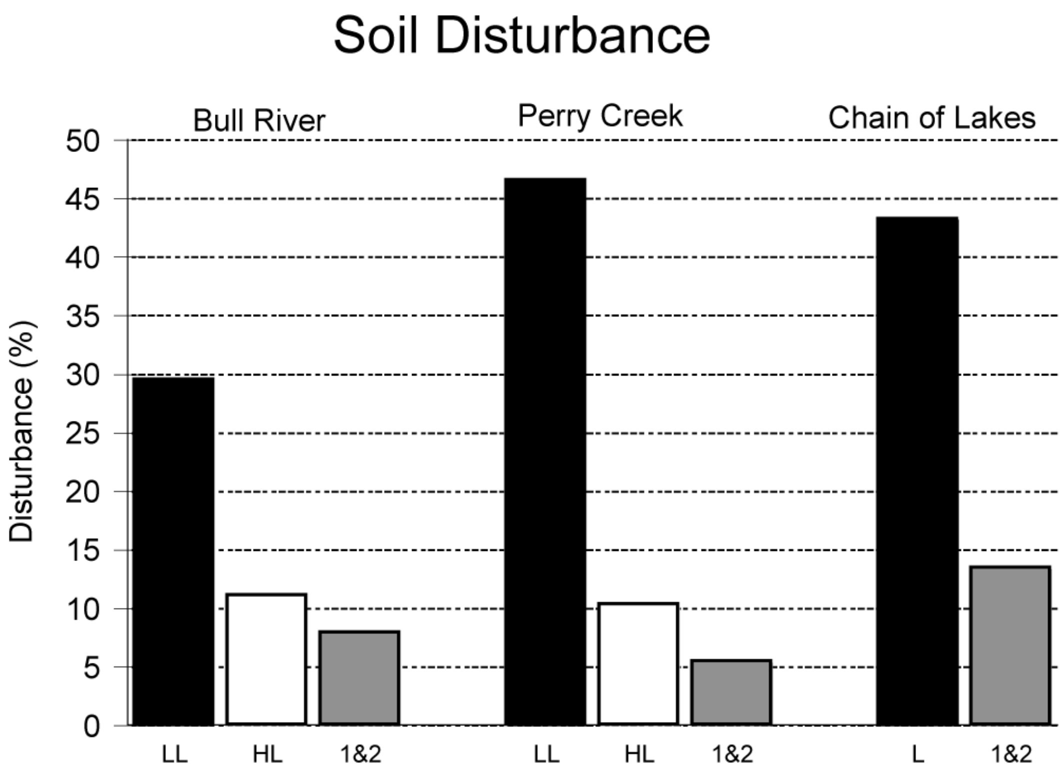

Figure 3—Aerial extent of soil disturbance at three sites in the southern Rocky Mountain Trench near Cranbrook, BC (Utzig and others 1992). LL (very light ruts, <5 cm deep), HL (heavy [main] trails), 1&2 (ruts 5 cm or deeper), and L (very light and heavy, combined) from Curran (1999).

These results are consistent with monitoring studies of nearby sites in northern Washington, Idaho, and Montana (Kuennen and others 1979; Laing and Howes 1988, Svalberg 1979). In the Washington study, based on the literature at the time, Laing and Howes (1988) predicted a "conservative estimate of 35% volume reductions over the next rotation" for detrimentally compacted areas (42% of the cutblock area in their study). On similar sites in Northern Idaho and Montana, Kuennen and others (1979) suggested that changes in soil physical properties resulting from compaction can decrease the ability of trees to compete with pine grass. It is not clear whether these type of effects would be realized on our soils; however, in the absence of long-term data to the contrary, we need to continue to monitor tree growth on these sites. Light compaction is also being studied as part of the North American Long-term Soil Productivity Study (LTSP).

In summary, the implications for site water storage, runoff, and tree growth are of concern when random skidding causes these types of disturbances. It is therefore inferred that, under certain soil conditions (e.g., harvesting under wetter than optimum soil conditions), detrimental compaction can occur before soil disturbance criteria for ruts or trails are reached. Harvesting strategies recommending dispersed skidding traffic need to recognize this risk and "tread lightly." Compaction is a long-lived phenomenon; natural freeze-thaw and wet-dry cycles have not been observed to ameliorate machine-induced compaction at depth. In the ash-cap soil locations, where summer drought is one of the factors most limiting to tree growth, and in the absence of long-term data to the contrary, prevention of widespread "below the FRPA depth limit" compaction is probably the best bet and can be achieved economically.

Soil Displacement Hazard

Soil displacement is the mechanical movement of soil materials by equipment and movement of logs. It involves excavation, scalping, exposure of underlying materials, and burial of fertile surface soils. Three aspects of displacement can produce soil degradation:

- Exposure of unfavourable subsoils, such as dense parent material, gravelly subsoil, and calcareous (high pH) soils.
- Redistribution and loss of nutrients.
- Alteration of slope hydrology, which can lead to hydrologic effects (discussed under compaction, above).

Soil development is often shallow and many of the nutrients that are limiting to tree growth are often biocycled and concentrated in the upper soil horizons throughout the British Columbia Interior. A similar affect occurs on shallow ash-cap soils that overlay less fertile subsoils. Most of the soil nutrients are often concentrated in the forest floor and top 20 cm of mineral soil (table 1). Therefore, we don't want to displace this fertile topsoil away from seedlings, or reduce the rooting volume of these vital topsoil layers.

Table 1—Typical nutrient distribution in British Columbia Interior soils.

	Nutrients in kg ha^{-1} (% of total)		
Soil layer	**Nitrogen**	**Phosphorus**	**Potassium**
Forest floor	1450 (44%)	112 (82%)	224 (73%)
0-20 cm	1050	13	56
20-40 cm	820	8	25
Total	3320	133	305

Forest Floor Displacement Hazard

Forest floor displacement is the mechanical movement of the upper organic materials by equipment and movement of logs. It involves excavation, scalping, mineral soil exposure, and burial of the forest floor. The effects of forest floor displacement range from beneficial to detrimental, depending on site factors (e.g. mineral soil characteristics) and how far the forest floor is displaced from the seedlings.

Forest floors typically represent a major component of the nutrient capital on a forest site. In the British Columbia Interior, it is not uncommon for the forest floor to contain over 50% of the soil nitrogen and 80% of the phosphorus (table 1). Given that many Interior sites are considered nitrogen deficient, conservation of the forest floor is important. On deeper ash-cap or older, richer soils, much of the nutrient capital occurs in the mineral topsoil and forest floor displacement may be of less concern.

Two aspects of forest floor displacement can produce soil degradation:

- Redistribution and loss of nutrients (e.g. chemically bound and unavailable in the mineral soil, and accelerated decomposition of organic matter).
- Exposure of unfavourable rooting medium.

A review of forest floor displacement and implications for tree growth in the Southern British Columbia Interior found that while there were a few trends in soil nutrient levels, it was difficult to relate displacement to any negative effects on tree growth (Hickling 1997). In cooperation with Pope and Talbot Ltd., we installed long-term monitoring plots on various disturbance types including some associated with stumping (Hickling 1998).

Most forest operations were well below the forest floor displacement limits originally set in the FPC, so determining the forest floor displacement hazard is no longer officially required for harvest planning and permitting. However, use of this hazard interpretation is supported and recommended for planning dispersed skidding on steeper slopes, rehabilitation of soil disturbance, and root rot treatments. Forest floor displacement is also more of a concern on calcareous soils due to the higher pH of the mineral soil

Surface Soil Erosion Hazard

Surface soil erosion is the wearing away of the earth's surface by water and includes splash, rill, and gully erosion. It has on-site impacts (soil loss, nutrient loss, lower productivity) and off-site impacts (water quality, sedimentation, habitat impacts). The surface soil erosion hazard key focuses on on-site erosion and conservation of the fertile topsoil layers near developing seedlings. The science and rationale for the British Columbia key were laid out in Carr and others (1991), and the rating weightings tested in the Nelson Forest Region by Commandeur (1994), resulting in modifications to the final key currently in use. Other assessments may be used for haul road erosion and sediment delivery to streams. Haul roads and landings are of concern because erosion and drainage diversions can lead to sedimentation and stability problems. They require careful layout and attention to erosion hazard on haul roads and minimizing erosion and sedimentation during construction and maintenance.

Defining Soil Disturbance

A technical definition of soil disturbance is any disturbance that changes the physical, chemical, or biological properties of the soil (Lewis and others 1991). It is not always negative. Foresters commonly prescribe purposeful soil disturbance as site preparation for seedling planting and establishment; these disturbance types are often not counted in standards (e.g., under FRPA in British Columbia). By controlling how we harvest a site, we can create more "site preparation" type disturbance and keep most of the potentially detrimental disturbance confined to travel corridors; these main trails may then be rehabilitated after harvesting, as appropriate. Whenever planning soil disturbance, the preservation and restoration of natural drainage patterns should be the primary goal (necessary repetition).

The strategies described in this document strike a balance between "favourable" and "detrimental" disturbance by limiting the amount of "counted" soil disturbance. Regionally applicable soil disturbance standards recognize that some level of disturbance is necessary to permit access to timber. Counted disturbance usually includes main trails and ruts/impressions of certain dimensions, and under some schemes (e.g., FRPA in British Columbia) also include wide or deep gouges into the soil. Those developing and implementing a harvesting strategy need to recognize that on more sensitive sites, disturbance types that "count" may be created more easily and may be counted sooner (e.g., in Interior British Columbia 5-cm ruts and impressions on High and Very High Compaction hazard, as opposed to 15 cm on other soils; when Erosion, Displacement, or Compaction hazards are Very High). On sites with lower hazard ratings, less disturbance categories may be counted.

The actual effect of a given soil disturbance on tree growth will depend on the most growth-limiting factors on a given site and how these factors change over the course of a rotation. In the British Columbia Interior, common growth-limiting factors include: competing vegetation, soil moisture (drought or excess), soil temperature, summer frost, rooting substrate (volume), soil nutritional problems (e.g., calcareous soils), and root rot. The net effect on growth will also depend on whether soil disturbance has introduced a new limitation, such as reduced soil aeration from compaction. Long-term effects could include increased susceptibility to blowdown because of poor rooting in detrimentally disturbed soil.

Regional ecology guides often summarize common growth-limiting factors for various ecosystems (Braumandl and Curran 1992), and a model has been developed for comparing disturbance effects on growth-limiting factors when deciding on site preparation prescriptions (Curran and Johnston 1992; Sachs and others 2004).

Regardless of the actual tree growth effects, a number of soil disturbance types are also of concern because of potential effects on site and slope hydrology and the potential for downslope impacts. On-site hydrology changes are difficult to study but we need to err on the conservative side considering that much of British Columbia is not flat and summer drought is often one of the most growth-limiting factors on many sites (effects on hydrology may confound tree growth on apparently "undisturbed" microsites in tree growth studies). Similar hydrologic concerns have been voiced by other researchers in the local area (Kuennen and others 1979).

Synthesis of Above Knowledge and Principles in Our Forest Practices

Machine-Based Practices

Forest harvest, site preparation, and fuel management treatments are most commonly accomplished through the use of machinery. In the case of timber harvest or fuels, this may occur through aerial, cable, or ground-based equipment. Because ground-based harvesting typically creates the most disturbance, it is discussed below but the principles remain the same for the other methods.

Based on the environmental framework described in the preceding section, a given harvesting strategy should meet the following four requirements:

1. Be site specific and responsive to the soil sensitivities on site and downslope.
2. Offer a reasonable amount of independence from climatic interruptions,.
3. Incorporate rehabilitation, if necessary, to lower disturbance below guidelines.
4. It must instill enough confidence at all levels of approval and operations.

In the 1990s we worked on a number of trials with Industry and District staff, to address concerns about managing harvesting soil disturbance. Trials have addressed tree growth on rehabilitated skid roads (Dykstra and Curran 1999), haul roads (Curran, unpublished data), and landings (Bulmer and Curran 1999a). Memos were circulated and a special publication (Curran 1999) summarized simple field tests developed during operational trials of seasonal harvesting constraints (i.e., "how wet is too wet?" and "how much frost is enough frost?"). Other research trials have been successful in demonstrating the feasibility of rehabilitating soil disturbance (Bulmer and Curran 1999b). Combined, these trials were designed to test tree growth on rehabilitated disturbance and develop strategies to reduce the dependency on weather conditions and reduce shutdown of operations during wetter conditions. Research and practical innovation are still ongoing, and further field guides will be produced as warranted (e.g., we are developing a simpler soil texture key at this time).

Based on industry innovation, practical experience, and research trials, we have identified four key strategies that we feel meet the above criteria:

a) close trail spacing with rehabilitation,
b) closely spaced temporary spur (haul) roads with rehabilitation,
c) combination designated and dispersed (random) skidding, and
d) hoe-chucking, Interior style (i.e., forwarding to wider spaced trails).

These strategies may or may not include fully mechanized harvesting, either with cut-to-length feller-processors and forwarders, or with feller-bunchers and grapple skidders. The strategies also may offer the opportunity to reduce site preparation costs by creating disturbance during the harvesting or rehabilitation phases. Each strategy is described in more detail in Curran (1999). Other harvesting strategies have been described for meeting soil disturbance standards under site conditions in western Washington and Oregon by Heninger and others (1997). Again, the objective is to match equipment capabilities to site sensitivity to disturbance. Ground-based equipment may be restricted to designated trails or allowed to travel overland depending on the soil and climatic conditions.

Studies on ash-cap influenced and similar soils in southern Interior British Columbia have shown that large amounts of soil disturbance can occur during mechanical root removal for root disease management (Quesnel and Curran 2000; Curran, unpublished data). Tree growth responses to these disturbances vary with site growth limiting factors and over time. On two sites on similar climate in southern British Columbia, stump removal treatments had differing effects (fig. 4). On an ash-cap influenced soil at Phoenix, soil disturbance either increased or did not negatively affect tree growth; whereas on a soil on the Gates Creek site that had more clay (12% versus 4%), there was a clear negative trend with tree growth and disturbance severity. The long-term growth trend at the Gates Creek site is interesting as it clearly demonstrates the need for long-term tree growth response data (fig. 5).

Insect and Disease

Some forest insects and pathogens are opportunistic organisms that cause primary damage to stressed host trees. Stress may occur due to soil disturbance effects on tree growing environment, climate change resulting in temperature or moisture stress, other biotic or abiotic environmental factors, or multiple interacting factors. Interacting factors that contribute to pest outbreak are complex. For

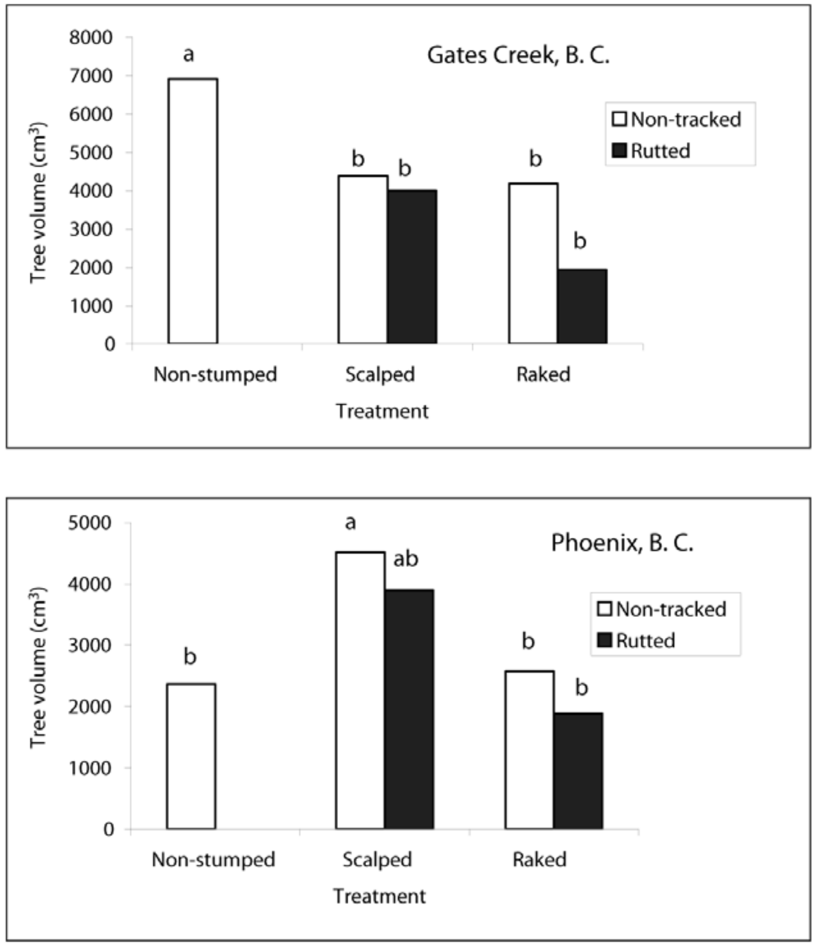

Figure 4—Fifteen-year volume of Douglas-fir seedlings growing in different disturbance types on the Canadian Forest Service Gates Creek and Phoenix stumping trial sites in southern British Columbia, which are gravelly sandy loam textured with 12% clay at Gates Creek and 4% clay at Phoenix (Curran and others 2005a adapted from Wass and Senyk 1999).

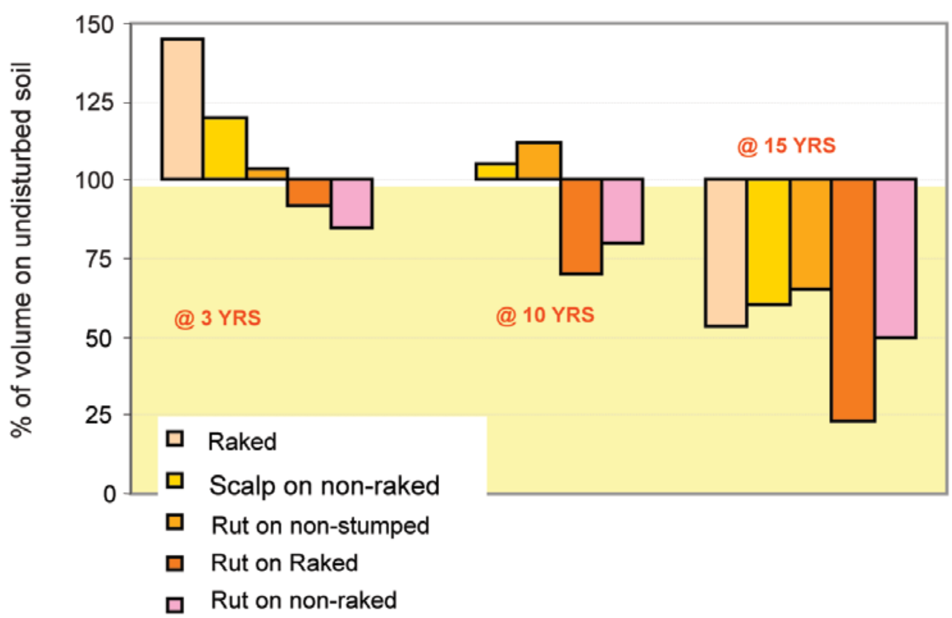

Figure 5—Comparison of relative growth of Douglas-fir on a stump removal trial in southern British Columbia at 3, 10 and 15 years since treatment. All data is relative to the undisturbed condition (Curran and others 2005a adapted from Wass and Senyk 1999).

example, large areas of bark beetle infestations are sometimes attributed to climate change and/or root disease interactions (Partridge and Miller 1972). However, insect attack is also dependent upon inherent dynamics of insect behavior. The following text focuses on root disease organisms in Inland Northwest.

Environmental Factors Affecting the Distribution and Activity of Root Diseases

Biophysical Setting—Armillaria root disease (primarily caused by *Armillaria ostoyae*) and Annosus root disease (caused by *Heterobasidion annonsum*) are widely distributed in western conifer forests. Off-site plantings, wounded trees, and trees growing on compacted soils or in areas with drainage problems are particularly likely to be affected by Armillaria root disease (Goheen and Otrosina 1998; Wiensczyk and others 1997). Douglas-fir dominated stands in northern and central Idaho and northeastern Washington experience substantial mortality from Annosus root disease, especially on dry sites (Schmitt and others 2000). However, in southern interior BC, Morrison and others (2000), found significantly higher rates of *Armillaria* sp. infection on dry sites than moist or wet sites; and once infected, trees on drier sites were less able to resist infection and were more likely to show aboveground symptoms.

Laminated root rot, (caused by *Phellinus weirii*), occurs mainly in hemlock, western red cedar and grand fir habitat types on the Lolo National Forest, but infrequently in Douglas-fir and subalpine fir habitat types, while Armillaria and Annosum root disease are distributed more widely (Byler and others, 1990). Hagle and others (1994) similarly found root disease most severe in grand fir habitat types, and low severity disease ratings occurred most often on Douglas-fir habitat types. Declines in disease severity were noted after 160 years as the more susceptible species died out of the stand. They suggest that grand fir habitat types are most likely to support grand fir and Douglas-fir as seral and climax species, and these are the most susceptible species.

On the Lolo National Forest, Byler and others (1990), found higher probabilities of Armillaria root disease on Douglas-fir habitat types on southerly aspects. Moderate slopes had a higher incidence than either flat or very steep slopes.

Soil Physical Properties—In another study, *Armillaria* spp. infection levels decreased with increasing clay content, which is correlated with moisture-holding ability (Wiensczyk and others, 1997). This is consistent with the hazard rating system of Froelich and others (1977). In the Wiensczyk study, sandy soils were more highly correlated with *Armillaria* spp. activity in black spruce than were silty soils, and as moisture regime increased (based on mottles and gleying), *Armillaria* spp. frequency decreased. This may be due to reduced growth of *Armillaria* rhizomorphs in finer textured and moister soils, or to improved tree vigor. Sand, large soil pores, and high bulk density were also positively correlated with Annosum root disease in loblolly pine plantations (Alexander and others, 1975). It is thought that rapid infiltration in sandy soils allowed easy translocation of root rot spores. Baker and others (1993) also found that low silt in the A horizon was an important predictor of *H. annosum* infection. Blenis and others (1989) also found clay loam to be least favorable for Armillaria root disease and sandy loam the most favorable. The pathogen is known to be sensitive to low levels of oxygen and high levels of carbon dioxide.

Soil Chemical Properties—*Armillaria ostoyae* infection levels were found to increase with increasing phosphorous in the A horizon (Wiensczyk and others 1997). However, phosphorous in ash-cap surface soils is often held in unavailable form and may not locally contribute to infection. Reduced phosphorous may limit tree root elongation, which could reduce the likelihood of underground contact with *A. ostoyae*.

Rishbeth (1951) found *H. annosum* infection rates from stumps to be lower in acid than alkaline soils. He attributes this to competing fungi in more acid soils. Baker and others (1993) found *H. annosum* infection incidence to be lower in acid soils, as did Blenis and others (1989).

Soil Microbiology—Root microflora, such as Actinomycetes and fungi (e.g., *Trichoderma* spp., *Phlebiopsis* spp., *Bjerkandera* spp., *Hypholoma* sp., etc.), can have fungistatic effects on root pathogens (Hagle and Shaw 1991; Holdenreider and Greig 1998; Nelson 1964, 1973;Nelson and Thies 1985, 1986; Raziq 2000). It has been suggested that mixed stands with fewer potential host species, and interruption of succession with shrub and other non-susceptible species reduce *H. annosum* inoculum (Johansson and Marklund, 1980) by supporting enhanced populations of Actinomycetes. Chapman and Xiao (2000) confirmed the ability of a saprophytic fungus, *Hypholoma fasciculare*, to out-compete *A. ostoyae* on a variety of nonliving substrates, such as stumps. Veech and Boyce (1964) also found higher levels of soil fungi, Actinomycetes, and bacteria than in areas of higher *H. annosum* infection. Greig (1962) also found development of *Annosum* root disease to be lower in plantations established on areas formerly occupied by hardwoods than on second-rotation conifer plantations. This "diversity of soil microflora" is hypothesized to be more typical of natural disturbance regimes than stands affected by fire suppression and emphasis on one or two susceptible crop species, like grand fir and Douglas-fir.

Ectomycorrhizal fungi associated with tree roots are known to be important for moisture and nutrient relationships of the host tree (Harvey and others 1986, 1987). Decayed soil wood promotes this association. Root pathogens may interact directly with mycorrhizae so that biomass and energy reserves of all parties are reduced (Graham 2001; Sharma and others 1992), but sometimes pathogen effects on the host tree are reduced (Morin and others 1999). This complex interaction suggests we need to sustain a continuous supply of the organic materials that support healthy mycorrhizal populations.

Relation to Properties of Volcanic Ash—Surface soils formed in volcanic ash tend to be silty in texture, have high porosity, and low bulk density, and low inherent nutrient status, and low nutrient-holding capacity (McDaniel and others 2005). They may adsorb phosphorus and hold it in an unavailable form. Acidity is typically slightly acid to neutral. Tree roots are often concentrated in the volcanic ash layer, suggesting that root contact could be common and distance from stump inoculation point to live root would be short. This would make it easier for infections to spread. High moisture-holding capacity suggests that drought-induced stress during summers would be somewhat mitigated, but that this capacity would be reduced by compaction or displacement. Volcanic ash is highly correlated with grand fir, cedar, hemlock, and subalpine fir habitat series, and to a lesser extent with Douglas-fir.

Management Effects—Fire exclusion, harvest of less susceptible pine and larch, and declines in white pine due to exotic blister rust (*Cronartium ribicola*) have all contributed to the increase in more susceptible Douglas-fir and grand fir, and moisture and nutrient stress, increasing the prevalence of root disease in the range of volcanic ash soils. More studes are needed to determine the effects of partial harvest and soil compaction/displacement on root disease in managed stands.

Climate Change, Root Disease, and Management on Volcanic Ash-cap Soils

Climate change can result in mature trees that are maladapted to their environment, which can increase vulnerability to pathogens (Ayres and Lombardero, 2000), as well as other disturbances like fire or insects. In the Interior Northwest, increasing temperatures and reduced summer moisture (McKenzie and others 2004; Mote and others 2003) increase stress on trees in marginal sites (thin ash-cap, compacted soils), which may make them more susceptible to root diseases. Physiological models to predict how tree defenses would alter with climate change are lacking. Effects of climate change on root disease and competing organisms are not known.

Fire suppression and subsequently more severe fires may increase the rate of root disease by providing more fire-scarred tree wounds as entrance points (Otrosina and Garbelotto 1997). Fire exclusion leading to dominance of susceptible true firs and high levels of root disease would also lead to increased susceptibility to fire and large insect outbreaks. Higher density stands due to fire exclusion could increase the likelihood of belowground spread of the pathogen from tree to tree. Longer periods of high heat and drought could suppress spore germination and stump colonization for longer periods in the summer, although Bendz-Hellgren and Stenlid (1998) found no effect of temperature on stump colonization by *H. annosum*.

Management Opportunities:

- Limit management induced stress by confining soil compaction and displacement to limited areas and rehabilitating them after use.
- Provide connections for species to move in response to changed climatic context (maintaining continuity of species in space, while allowing for movement).
- Use species and density management to allow forest species to use disturbance as stepping stones for migration.
- Introduce and sustain species resistant to root disease.
- Root removal has been proposed to control *Armillaria* root disease (Roth and others 2000), but some studies have concluded that inoculum removal cannot be complete enough to change the dynamics of root disease development (Reaves and others 1993). The associated soil disturbance, particularly in ash-cap soils, is likely to have deleterious physical effects.

The issue of soil restoration to recover suitable moisture and air relationships is complicated by other factors. Soil disturbance associated with roads, skid trails, and precommercial thinning (Hessburg and others 2001) was correlated with incidence of black stain root disease (caused by *Leptographium wageneri*) in southwest Oregon. Alternatively, subsoiling to alleviate soil compaction may result in root damage and dieback of any residual trees, attracting root feeding beetles that carry black stain root disease. Kliejunas and Otrosina (1997) and

Otrosina and others (1996) found higher levels of ergosterol in subsoiled areas, which indicated higher levels of fungal decomposer activity. This was attributed to soil displacement and root severing. This suggests managers should limit the extent of compacted areas as much as possible and avoid subsoiling near trees to avoid both above and below ground damage. Stump removal could have similar effects in adjacent live trees.

Analysis of North Idaho Root Disease Trends in Relation to Soil and Site Factors

Sue Hagle (Pathologist, USDA Forest Service, Region 1) rated stands within randomly selected subcompartments for root disease activity using photo interpretation on a scale of 0 to 9 (Hagle and others 2000). On the three Idaho National Forests (Idaho Panhandle, Clearwater, and Nez Perce) analyzed here, 1,204 plots were available, but 11 of these did not have geologic information and 29 did not have soil survey information. The stand polygons were interacted with geospatial layers including soil survey map units, lithology, mean annual precipitation, elevation, aspect, latitude, longitude, and slope.

Soil survey map units were classified into four classes based on volcanic ash depth:

1: No described volcanic ash influence
2: Thin or mixed ash
3: Andic subgroups
4: Thick ash (Andosols)

Where soil type varied by aspect, aspect was used to refine the ash depth factor.

Geologic groups were developed based on literature describing associations between root disease and rock type (Garrison and Moore 1998; Moore and others 2004). This process was complicated by different scales, notation, and depth of description of available geologic maps. We tried to identify potential strong associations by spatial exploration of root disease activity and geologic formation. Patterns that appeared strong in one area were not consistent in other areas. The resulting groups used are:

2 = Granitics, predominantly Cretaceous, but also Jurassic (292 samples).
3 = Recent metamorphics (younger than Belt Age) (21 samples).
4 = Belt age metamorphics, but not including Belt quartzites described under 11. (666 samples). These were expected to have higher inherent fertility.
5 = Tertiary and more recent sediments (3 samples).
6 = Seven Devils volcanics of Triassic and Permian age (20 samples). These sites were omitted from this analysis because they are thought to be anomalous. They had very high root disease activity ratings. Trends and significance were similar with and without these samples.
7 = Undifferentiated, such as glacial deposits or alluvium (65 samples).
8 = Other volcanics (2 samples).
9 = Limestone no samples.
10 = Belt age sediments no samples.
11 = Belt quartzites (Middle Wallace quartzites, Striped Peak formation, Revett quartzite, and Prichard quartzite (94 samples). These were expected to have the lowest inherent fertility.

Each stand was additionally assigned to a moisture and temperature gradient class after McDonald and others (2000) using the habitat type information associated with each stand polygon:

Understory: Moisture Regime	
No data	0
Dry grass	1
Dry shrub	2
Dry herb	3
Moist herb	4
Wet herb	5
Wet fern	6
Wet shrub	7

Overstory: Temperature Regime	
No data	0
Cold fir	1
Cool fir	2
Cedar hemlock	3
Douglas-fir	4
Ponderosa pine	5
Pinyon juniper	6

The following tables and plots display exploratory analysis of the association of root disease activity (using an 8 class ranking system) and categorical environmental variables. Shown are the median, interquartile range, extremes, and possible outliers. No pattern is apparent for aspect class and root disease ranking,

Root Disease and Ash Depth

Thin or mixed ash is associated with higher incidence of root disease (table 2). Low root disease activity associated with areas of no volcanic ash are usually in very dry steep slopes or poorly drained areas where soils are formed in mixed alluvium.

Soils with no ash influence have significantly lower root disease activity, but Andic soils and Andosols do not differ significantly.

Table 2—Ash-cap depth as related to root disease ranking.

Ash Depth	N	Mean Root Disease Ranking*	95% C.I.
1 – None	25	2.2	1.5-2.9
2 – Thin or mixed	198	3.6	3.3-3.9
3 – Andic	247	3.2	2.9-3.4
4 – Andosol	638	3.0	2.9-3.2

*See Hagle and others (2000) for detailed root disease activity scale.

Geologic Group

No strong trends were noted, however there were some differences among lithologic groups.

Recent metamorphics showed greater root disease activity than in undifferentiated deposits (table 3). The great variability in recent sediments (group 5) suggests a need for further refinement of this class. Belt age metamorphics (group 4) showed relatively low root disease activity, with numerous samples, and were significantly less than granitics, recent metamorphics, and Belt quartzites. Undifferentiated rock types (recent deposits) also showed low root disease activity. The Belt Age quartzites, anticipated to be naturally low in potassium and with high levels of root disease activity, were significantly higher than other Belt metamorphics and undifferentiated rock types, but did not differ from granitics, recent sediments, or recent metamorphics.

Table 3—Influence of geologic group on disease incidence.

Geologic Group	N	Mean Root Disease Ranking*	95% C.I.
2 – Granitics	292	3.5	3.3-3.7
3 – Metamorphics (not Belt Age)	21	3.9	2.8-4.9
4 – Belt Age Metamorphics/not quartzites	666	2.9	2.8-3.0
5 – Tertiary and more recent sediments	3	4.3	.5-8.1
7 – Undifferentiated (recent glacial deposits or alluvium)	65	2.9	2.5-3.3
8 – Other volcanics	2	3.5	NA
11 – Belt quartzites	94	3.5	3.1-3.9

*See Hagle and others (2000) for detailed root disease activity scale.

Root Disease and Forest

The Idaho Panhandle National Forest had the lowest disease ranking, followed by the Clearwater National Forest, and then Nez Perce National Forest (table 4). These differences could be caused by drier soils, changes in geology, soil nutrition, or other inherent site physical, chemical, or biological properties.

Table 4—National Forest and incidence of disease.

National Forest	N	Mean Root Disease Ranking*	95% C.I.
4 – Idaho Panhandle	639	2.7	2.6-2.9
5 – Clearwater	331	3.4	3.2-3.6
17 – Nez Perce	173	4.0	3.7-4.3

*See Hagle and others (2000) for detailed root disease activity scale.

Root Disease and Potential Vegetation (Habitat Type Group)

Potential Vegetation is an indicator of soil moisture and temperature regimes and constrains whether susceptible species are likely to occur as seral or climax on the site. When habitat types (Cooper and others 1991) are grouped according to Jones (2004), it is evident that those habitat types most likely to support susceptible grand fir or Douglas-fir and show higher levels of root disease activity (data not shown). The occurrence and severity of root disease depends strongly on the abundance of a susceptible host. Sites with a longer history of dominance by suitable host species will likely have accrued higher levels of fungal biomass. Drier grand fir and Douglas-fir habitat types, which are more likely to support more ponderosa pine, show lower levels of root disease activity. It is interesting to note that some extremely high values of root disease activity are associated with more moist cedar or western hemlock habitat type groups. It is possible that these sites are capable of very high levels of inoculum where seral white pine has been eliminated for long periods.

Moisture and Temperature Regime

Using the moisture and temperature indices defined by McDonald and others (2000), we compared disease ranking against moisture indicator (understory association) and temperature indicator (overstory series).

Sites with moderately dry moisture regimes (dry shrub) had the highest root disease activity, and differed from dry grass and dry shrub, but not moist herb (table 5). This may be due to the high incidence of susceptible Douglas-fir on these moisture settings.

Sites with moderately warm temperature regimes (Douglas-fir) had the highest root disease activity, and differed significantly from cold fir and ponderosa pine. Cool fir temperature regimes had higher root disease than cold fir, cedar hemlock, and ponderosa pine (table 6). Again, the presence of susceptible host species is highly correlated with these temperature regimes.

Table 5—Root disease ranking as related to understory moisture indicator.

Moisture Regime	N	Mean Root Disease Ranking*	95% C.I.
1 – Dry grass	12	2.2	1.1-3.2
2 – Dry shrub	89	3.4	2.9-3.8
3 – Dry herb	303	2.9	2.7-3.1
4 – Moist herb	734	3.2	3.1-3.3
5 – Wet herb	1	3	NA
6 – Wet fern	1	0	NA
7 – Wet shrub	1	1	NA

*See Hagle and others (2000) for detailed root disease activity scale.

Table 6—Root disease ranking as related to temperature regime.

Temperature Regime	N	Mean Root Disease Ranking*	95% C.I.
1 – Cold fir	366	3.0	2.8-3.2
2 – Cool fir	153	3.6	3.3-3.9
3 – Cedar hemlock	528	3.1	2.9-3.2
4 – Douglas-fir	90	3.5	3.0-3.9
5 – Ponderosa pine	3	1.3	0-4.2

*See Hagle and others (2000) for detailed root disease activity scale.

Association of Root Disease Ranking with Numeric Variables

The most ecologically significant correlations appear to be that root disease activity is positively associated with steep slopes, southerly latitude, westerly longitude, potential for host species (based on habitat type cover tables), and decreasing annual precipitation.

Conclusions

Ash-cap soils are susceptible to disturbance; schemes to predict compaction, displacement, and erosion hazards are useful in forest management application. Whether more or less disturbance should be permitted on ash-cap soils is a controversial topic and it is likely more important to focus on the individual site hazards because ash-cap soils can vary considerably in their state of weathering, texture, depth and inter-mixing with other soil materials. Machine traffic can be managed and as demonstrated in Bulmer and others (this proceedings), and mitigated through rehabilitation in a set of harvest (machine-traffic) strategies that consider site.

Regarding root disease on ash-cap soils, this preliminary coarse-scale investigation suggests some potential relationships among root disease (primarily *Armillaria* in Idaho) and soil and site factors. The strong relationship between presence of susceptible host and development of fungal biomass may be the strongest causal agent, and the soil and site factors promote the presence of the susceptible host.

Thicker ash soils of more northerly areas are related to habitat types that historically supported white pine and a higher diversity of less susceptible species. These more mesic environments also fill in with other species rapidly after root disease mortality occurs, so higher levels of root disease activity are more difficult to discern (Hagle, personal communication, 2006).

Recommendations

Sustainable soil management on ash-cap soils needs to follow protocols developed for all sites whereby an adaptive management / continuous improvement process needs to be supported by research, best management practices, and strategies that include all types of monitoring (compliance, effectiveness and validation).

Development of a common approach to describing soil disturbance and soil disturbance hazards will go a long way toward more effective sharing of management experiences on ash-cap soils.

More work is needed on the long-term effects of cumulative aerial extent of soil disturbance and on soil disturbance categories to refine these and hazard rating systems.

For the root disease work, more site-specific evaluation of soil properties, stand history, and geologic parent materials, both mineralogical composition and weathering state, would help to sort out these relationships.

Acknowledgments

The authors thank Dr. R.E. Miller, emeritus research scientist at USDA Forest Service, Pacific Northwest Research Station for his review of the manuscript, and Sue Hagle, pathologist for USDA Forest Service Region 1 for her helpful advice and review of the root disease part of this paper.

References

Alexander, S. A.; Skelly, J. M.; Morris, C. L. 1975. Edaphic factors associated with the incidence severity of disease caused by Fomes *annosus* in loblolly pine plantations in Virginia. Phytopathology. 65(5): 585-591.

Ayres, M. P.; Lombardero, M. J. 2000. Assessing the consequences of global change for forest disturbance from herbivores and pathogens. The Science of the Total Environment. 262(3): 263-286.

Baker, F. A.; Verbyla, D. L.; Hodges, C. S.; Ross, E. W. 1993. Classification and regression tree analysis for assessing hazard of pine mortality caused by *Heterobasidion annosum*. Plant Disease. 77(2): 136-139.

Bendz-Hellgren, M.; Stenlid, J. 1998. Effects of clear-cutting, thinning, and wood moisture content on the susceptibility of Norway spruce stumps to *Heterobasidion annosum*. Canadian Journal of Forest Research. 28: 759-765.

Blenis, P. V.; Mugala, M. S.; Hiratsuka, Y. 1989. Soil affects *Armillaria* root rot of lodgepole pine. Canadian Journal of Forest Research. 19: 1638-1641.

Boyer, D. 1979. Guidelines for soil resource protection and restoration for timber harvest and post-harvest activities. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, Watershed Management.

Braumandl, T. F.; Curran, M. P., eds. 1992. A field guide for site identification and interpretation for the Nelson Forest Region. Victoria, BC Min. Forests, Land Management Report No. 20. 311 p.

Bulmer, C.; Curran, M. 1999a. Retrospective evaluation of log landing rehabilitation on coarser textured soils in southeastern British Columbia. BC Min. Forests, Nelson Forest Region Extension Note No. EN-042. 4 p.

Bulmer, C; Curran, M. 1999b. Operational trials of soil rehabilitation. BC Min. Forests, Nelson Forest Region Draft Extension Note. 10 p.

Byler, J. W.; Marsden, M. A.; Hagle, S. 1990. The probability of root disease on the Lolo National Forest, Montana. Canadian Journal of Forest Research. 20: 987-994.

Carr, W. W.; Mitchell, W. R.; Watt, W. J. 1991. Basic soil interpretations for forest development planning: Surface soil erosion and compaction. BC Min. Forests, Land Management Report No. 63. 17 p.

Canadian Council of Forest Ministers. 2003. Defining sustainable forest management in Canada. Criteria and indicators. 2003. Available: http://www.ccfm.org/2000pdf/CI_Booklet_e.pdf. Accessed November 2003.

Chapman, B.; Xiao, G. 2000. Inoculation of stumps with Hypholoma fasciculare as a possible means to control *Armillaria* root disease. Canadian Journal of Botany. 78: 129-134.

Commandeur, P. 1994. Rainfall simulation, soil infiltration, and surface erosion on skidroad surfaces, Nelson Forest Region. BC Min. Forests, Research Branch. Canada - BC FRDA Report 228. 28 p.

Cooper, S. V.; Neiman, K. E.; Steele, R.; Roberts, D. W. 1991. Forest Habitat Types of Northern Idaho: a Second Approximation. INT-GTR-236. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 143 p.

Curran, M. 1999. Harvest systems and strategies to reduce soil and regeneration impacts and costs. In: Impact of machine traffic on soil and regeneration. Proceedings of FERIC's Machine Traffic/Soil Interaction Workshop; 1999 February; Edmonton, Alberta. FERIC Special Report No. SR-133: 75-11.

Curran, M .P.; Johnston, M. A. 1992. Overview of the SYTEPREP computer-based system (System To Evaluate Prescription Effects on potential Productivity). BC Min. Forests, Nelson Forest Region, Research Summary (Extension Note) RS-006. 2 p.

Curran, M.; Davis, I.; Mitchell, B. 2000. Silviculture prescription data collection field handbook: Interpretive guide for data collection, site stratification, and sensitivity evaluation for silviculture prescriptions. B.C. Min. Forests Land Management Handbook No. 47. 156 p. Includes forms FS39A and B. Available: http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh47.htm. Accessed December 2004.

Curran, M. P.; Heninger, R. L.; Maynard, D. G.; Powers, R. F. 2005a. Harvesting effects on soils, tree growth and long-term productivity. In: Productivity of Western Forests: A Forest Products Focus. GTR-PNW-642. U.S. Department of Agriculture, Forest Service, Pacific Northwest Station: 3-15. Available: http://www.fs.fed.us/pnw/publications/GTR-642/GTR642a.pdf.

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

Curran, M. P.; Miller, R. E.; Howes, S. W.; Maynard, D. G.; Terry, T. A.; Heninger, R. L.; Niemann, T.; Van Rees, K.; Powers, R. F.; Schoenholtz, S. H. 2005c. Progress towards more uniform assessment and reporting of soil disturbance for operations, research, and sustainability protocols. J. For. Ecol. Mange. 220(1-3): 17-30.

Dykstra, P. R.; Curran, M. P. 1999. Tree Growth on Rehabilitated Skid Roads in Southeastern British Columbia.. BC Min. Forests, Nelson Forest Region, Extension Note EN-046. 6 p.

Froelich, R. C.; Kuhlman, E. G.; Hodges, C. S.; Weiss, M. J.; Nichols, J. D. 1977. Fomes *annosus* root rot in the South: guidelines for prevention. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, Southeastern Forest Experiment Station and Southeastern Area, State and Private Forestry. 17 p.

Garrison-Johnston, M.; Moore, J. A. 1998. Nutrient management: a summary and review. Intermountain Forest Tree Nutrition Cooperative. Supplemental Report 98-5. 47 p.

Goheen , D. J.; Otrosina, W. J. 1998. Characteristics and consequences of root diseases in forests of western North American. PSW-GTR-165. U.S. Department of Agriculture, Forest Service, Southern Research Station: 3-7.

Graham, J. H. 2001. What do root pathogens see in mycorrhizas? New Phytologist. 149: 357-359.

Greig, B. J. W. 1962. *Fomes annosus* (Fr.) Cke. and other root-rotting fungi in conifers on ex-hardwood sites. Forestry. 35(2): 164-182.

Hagle, S.; Byler, J.; Jeheber-Matthews, S.; Bath, R.; Stock, J.; Hansen, B.; Hubbard, C. 1994. Root disease in the Coeur d'Alene River Basin: an assessment. In: Proceedings of Interior Cedar-Hemlock White Pine Forests: Ecology and Management; 1993 March 2-4; Spokane Washington. Pullman, WA: Washington Date University: 335-344.

Hagle, S.; Johnson, T. L.; Stipe, L. E.; Schwandt, J. W.; Byler, J. W.; Kegley, S. J.; Bell Randall, C. S.; Taylor, J. E.; Lockman, I. B.; Sturdevant, N. J.; Williams, S. B.; Marsden, M. A.; Lewis, L. G. 2000. Succession function of forest pathogens and insects, Volume 1: Methods. FHP Report No. 00-10. U.S. Department of Agriculture, Forest Service, Forest Health Protection, Northern Region. 97 p.

Hagle, S. K.; Shaw, C. G. III.1991. Avoiding and reducing losses from Armillaria root disease. In: Shaw, C. G. III; Kile, G. A., eds. Armillaria Root Disease. Agricultureal Handbook No. 691. U.S. Department of Agriculture, Forest Service, Washington, DC: 157-173.

Harvey, A. E.; Jurgensen, M. F.; Larsen, M. J.; Schlieter, J. A. 1986. Distribution of active mycorrhizal short roots in forest soils of the Inland Northwest: Effects of site and disturbance. Research paper INT-374. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 8 p.

Harvey, A. E.; Jurgensen, M. F.; Larsen, M. J.; Graham, R. T. 1987. Decaying organic materials and soil quality in the Inland Northwest: a management opportunity. Gen. Tech. Rep. INT-225. U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 15 p.

Heninger, R .L.; Terry, T.; Dobkowski, A.; Scott, W. 1997. Managing for sustainable site productivity: Weyerhaeuser's forestry perspective. Biomass and Bioenergy. 13(4/5): 255-267.

Hessburg, P. F.; Goheen, D. J.; Koester, H. 2001. Association of black stain root disease with roads, skid trails, and precommercial thinning in Southwest Oregon. Western Journal of Applied Forestry. 16(3): 127-135.

Hickling, J. S. 1997. Some effects of forest floor displacement on soil properties and lodgepole pine productivity in the Boundary Forest District. University of Vancouver, British Columbia. Thesis.

Hickling, J. S. 1998. Effects of forest floor displacement on soil properties and seedling productivity in the Boundary Forest District: Long-term productivity plots. Year two Establishment Report. Prepared for Forest Renewal BC, Pope and Talbot Ltd., and BCMOF, Nelson Region. 35 p.

Holdenreider, O.; Greig, B. J. W. 1998. Biological methods of control. In: Woodward, S.; Stenlid, J.; Karjalainen, R.; Hüttermann, A., eds. *Heterobasidion annosum*: Biology, Ecology, Impact and Control. CAB International, Wallingford, Oxon, UK. Chapter 13.

Johansson, M.; Marklund, E. 1980. Antagonists of *Fomes annosus* in the rhizosphere of gray alder (*Alnus incana*) and Norway spruce (*Picea abies*). European Journal of Forest Pathology. 10(80): 385-395.

Jones, J. 2004. Potential natural vegetation types for Idaho. Data on file at Nez Perce National Forest headquarters.

Kliejunas, J. T.; Otrosina, W. J. 1997. Progress report: effects of subsoiling study, Milford Ranger District, Plumas, National Forest. Report Number R97-01. U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. Forest Pest Management, State and Private Forestry. 10 p.

Kuennen, L.; Edson, G.; Tolle, T. V. 1979. Soil compaction due to timber harvesting activities. Soil, Air, and Water Notes 79-3. U.S. Department of Agriculture, Forest Service, Northern Region.

Laing, L. E.; Howes, S. W. 1988. Detrimental soil compaction resulting from feller buncher and rubber-tired skidder harvest operation: a case study. In: Degradation of forested lands: "Forest soils at risk" Proc. 10th BC Soil Sci. Workshop; 1986 February; BC Min. Forests, Land Management Report 56: 191-195

Lewis, T., Carr, W. W.; Timber Harvesting Subcommittee. 1989. Developing timber harvesting prescriptions to minimize site degradation - Interior sites. BC Min. Forests Land Management Handbook - Field Guide Insert. BC Min. Forests Land Management Report No. 62.

McDaniel, P. A; Wilson, M. A.; Burt, R.; Lammers, D.; Thorson, T. D.; McGrath, C. L.; Peterson, N. 2005. Andic soils of the Inland Pacific Northwest, USA: properties and ecological significance. Soil Science. 170: 300-311.

McDonald, G. I.; Harvey, A. E.; Tonn, J. R. 2000. Fire, competition and forest pests: landscape treatment to sustain ecosystem function. In: Neuenschwander, L. F.; Ryan, K. C.; Gollberg, G. E.; Greer, J. D., eds. The Joint Fire Science Conference and Workshop, Vol. II. Boise, ID, USA: 195–211.

McKenzie, E.; Gedalof, A.; Peterson, D. L.; Mote, P. 2004. Climate change, wildfire, and conservation. Conservation Biology. 18(4): 890-902.

Montréal Process Working Group. 1997. First approximation report on the Montréal Process, 1997. The Montréal Process Liaison Office, Canadian Forest Service, Ottawa, ON.

Moore, J. A.; Hamilton Jr., D. A.; Xiao, Y.; Bryne, J. 2004. Bedrock type significantly affects individual tree mortality for various conifers in the Inland Northwest, U.S.A. Canadian Journal of Forest Research. 34: 31-42.

Morin, C.; Samson, J.; Dessureault, M. 1999. Protection of black spruce seedlings against Cylindrocladium root rot with Ectomycorrhizal fungi. Canadian Journal of Botany. 77: 169-174.

Morris, L. A.; Miller, R. E. 1994. Evidence for long-term productivity changes as provided by field trials. p. 41-48 In: Dyck, W. J. and others, eds. Impacts of forest harvesting on long-term site productivity. London: Chapman and Hall: 41-48.

Morrison, D. J.; Pellow, K. W.; Norris, D. J.; Nemec, A. F. L. 2000. Visible versus actual incidence of *Armillaria* root disease in juvenile conifer stands in the southern interior of British Columbia. Canadian Journal of Forest Research. 30: 405-414.

Mote, P. W.; Parson, E. A.; Hamlet, A. F.; Keeton, W. S.; Lettenmaier, D.; Mantua, N.; Miles, E. L.; Peterson, D. W.; Peterson, D. L.; Slaughter, R.; Snover, A. K. 2003. Preparing for climate change: the water, salmon, and forests of the Pacific Northwest. Climatic Change. 61: 45-88.

Nelson, E. E. 1964. Some probable relationships of soil fungi and zone lines in the survival of *Poria weirii* in buried wood blocks. Phytopathology. 54: 120-121.

Nelson, E. E. 1973. Observations on the formation of zone lines in wood by *Poria weirii*. Res. Note PNW-210. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 4 p.

Nelson, E .E.; Thies, W. G. 1985. Colonization of *Phellinus weirii*-infested stumps by *Trichoderma viride*. 1: Effect of isolate and inoculum base. European Journal of Forest Pathology. 15: 425-431.

Nelson, E. E.; Thies, W. G. 1986. Colonization of Phellinus weirii-infested stumps by Trichoderma viride. 2: Effects of season of inoculation and stage of wood decay. European Journal of Forest Pathology. 16: 56-60.

Otrosina, W. J.; Sung, S.; White, L. M. 1996. Effects of subsoiling on lateral roots, sucrose metabolizing enzymes, and soil ergosterol in two Jeffrey pine stands. Tree Physiology. 16: 1009-1013.

Otrosina, W. J.; Garbelotto, M. 1997. Root disease and exotic ecosystems: implications for long-term site productivity. In: Proceedings of the 9th International Conference on Root and Butt Rots of Forest Trees; 1997 September 1-7; Carcans-Maubuisson, France : Institut National de la Recherche Agronomique: 275-283.

Partridge, A. D.; Miller, D. L. 1972. Bark beetles and root rots related in Idaho conifers. Plant Disease Reporter. 58: 498-500.

Quesnel, H.J.; Curran, M.P. 2000. Shelterwood harvesting in root-disease infected stands - post-harvest soil disturbance and compaction. Forest Ecology and Management: 62: 89-113.

Raziq, F. 2000. Biological and integrated control of Armillaria root rot. In: Fox, R. T. V., ed. Armillaria root rot: Biology and control of honey fungus. Andover, Hants., UK: Intercept Ltd: 183-201.

Reaves, J. L; Shaw, C. G.; Roth, L. F. 1993. Infection of ponderosa pine trees by *Armillaria ostoyae*: residual innoculum versus contagion. Northwest Science. 67: 156-162.

Rishbeth, J. 1951. Observations of the biology of Fomes *annosus*, with particular reference to East Anglian pine plantations. II. Spore production, stump infection, and saprophytic activity in stumps. Annals of Botany. 5(57): 14-21.

Roth, L. F.; Shaw III, C. G.; Rolph, L. 2000. Inoculum reduction measures to control Armillaria root disease in a severely infested stand off ponderosa pine in south-central Washington: 20 year results. Western Journal of Applied Forestry. 15: 92-100.

Sachs, Don; Heineman, Jean; Mather, Jean; Curran, Mike; Simard, Suzanne. 2004. Expert system for site preparation and vegetation management in southern Interior British Columbia. Model. Available: http://www.myacquire.com/spvegman/expertsystem/. Accessed November 17, 2005.

Schmitt, C. L.; Parmeter, J. R.; Kliejunas, J. T. 2000. *Annosus* root disease of western conifers. Forest Insect and Disease Leaflet 172. U.S. Department of Agriculture, Forest Service. 9 p.

Sharma, A. K.; Johri, B. N.; Gianinazzi, S. 1992. Vesicular-arbuscular mycorrhizae in relation to plant disease. World Journal of Microbiology and Biotechnology. 8(6): 559-563.

Svalberg, T. 1979. Compaction study results, Preliminary draft. (Unpublished mimeo.) Libby, Montanta: U.S. Department of Agriculture, Forest Service, Kootenai National Forest.

Utzig, G. F.; Thompson, S. R.; Curran, M. P. 1992. Soil compaction from random skidding in southeastern British Columbia. Contract report to BCMOF, Nelson Forest Region. 45 p.

Veech. J .A.; Boyce Jr., J. S. 1964. Soil microorganisms in two Georgia slash pine plantations with annosus root rot. Plant Disease Reporter. 48(11): 873-874.

Wass, E. F.; Senyk, J. P. 1999. Tree growth for 15 years following stumping in interior British Columbia. Technology Transfer Note 13, Nat. Res. Victoria, British Columbia, Canada: Can. For. Serv., Pacific Forestry Center.

Wiensczyk, A. M.; Dumas, M. T.; Irwin, R. N. 1997. Predicting *Armillaria ostoyae* infection levels in black spruce plantations as a function of environmental factors. Canadian Journal of Forest Research. 27: 1630-1634.