HARVESTING EFFECTS ON SOILS, TREE GROWTH, AND LONG-TERM PRODUCTIVITY

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ABSTRACT

Soil disturbance related to timber harvesting, reforestation, or stand tending is mainly a result of moving equipment and trees. Compaction and organic matter removal are of primary concern. Severity and extent of disturbance depend on harvest system, soil and climatic conditions. On-site, long-term effects range from permanent loss of growing sites to 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 is regulated and monitored to minimize both on- and off-site effects, which can take years or decades to appear. At national and international levels, sustainability protocols recognize forest soil disturbance as an important issue. At the regional level, continual monitoring and testing of standards, practices, and effects, is necessary for the successful implementation of sustainable soil management. In western forests, few studies are old enough to conclusively predict the long-term effects of harvest-induced soil disturbance on tree growth. Results from existing long- and short-term studies have demonstrated a full range of possible productivity outcomes. The net effect depends on which growth-limiting factors have been influenced by disturbance. Refinement of policies will occur as existing studies like the Long-term Soil Productivity (LTSP) network reach critical, predictive stand ages. In the interim, some regional trends are apparent: deeply developed, moderately coarse textured soils appear less sensitive to disturbance. Conversely, shallower and/or finer textured soils appear more sensitive.

KEYWORDS: Criteria and indicators, organic matter depletion, soil disturbance, soil compaction, sustainability protocols.

INTRODUCTION

For forest productivity, sustainable development can be defined as ensuring the biological, chemical and physical integrity of the soil remains for future generations. Sustainability must 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. Sustainable development is promoted through reporting procedures required by applicable sustainability protocols, and by having third-party certification of forest practices and products.

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).

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Third-party (eco) certification of forest practices and resulting wood products has arisen in response to sustainability protocols and the greening of the global market place. 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. Some call for more restrictive standards than others (e.g., FSC in British Columbia calls for lower disturbance levels than Provincial regulations).

When managing harvest effects on soils, tree growth and long-term productivity at the local level, managers usually focus on reducing soil disturbance from mechanical operations. Soil disturbance occurring at time of harvest 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 North American ecosystems, we need at least 10 to 20 years of data to draw conclusions about the effects of various practices. 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, site preparation, etc. A common approach is needed for describing soil disturbance so that results achieved in different areas are comparable (Curran et al. in prep.).

In this paper, we discuss effects of harvest induced soil disturbance on subsequent tree growth. Long-term productivity implications are explored along with some soil considerations in harvest planning and continuous improvement schemes. More detailed discussion of these effects and practical interpretations are provided in the literature that has been cited, guidebook materials available from government agencies like the B.C. Ministry of Forests (http://www.gov.bc.ca/for), the USDA Forest Service (http://www.fs.fed.us/), various University extension websites, and related products like the new Forestry Handbook for B.C. (soils chapter by Krzic and Curran, in press).

HARVESTING EFFECTS ON SOILS

Soil disturbance can be defined as any physical, biological, or chemical alteration of the soil caused by forestry operations. The examples of soil disturbance we provide here are primarily related to harvesting activities. Effects on tree growth may be inconsequential, beneficial or detrimental, depending on the net effect on growth-limiting factors and hydrologic properties. Soil disturbance can be considered in the context of: (1) the necessary permanent access network and (2) disturbance that occurs within individual harvest areas that will be reforested and managed as forest land.

Permanent Access Network (Roads, Trails, Landings)

The permanent access network is part of the infrastructure required to transport timber and manage forest land. Standards are in place for transportation system development because it represents a permanent removal of growing sites from the land base, and can have long-term effects both on- and off-site. Effects can include drainage interception and disruption, as well as erosion and sediment delivery to streams, which can affect other resource values, and can also cause property damage and possibly loss of life in catastrophic events. These are all good reasons to minimize the amount of forest land lost to permanent access.

In-Block Disturbance (Area to be Reforested)

Most in-block soil disturbance is the result of harvest equipment and dragging logs. Effects of soil disturbance depend on harvest method and season of operation. Ground-based harvesting typically creates more disturbance than aerial or cable. Wet season harvest is typically more disturbing than dry season harvest, or winter condition harvest (where that option exists). Severity and extent of in-block disturbance can be controlled or minimized through careful harvest planning and practices. Guidelines, regulations and standards often limit types and extent of disturbance and commonly focus on compaction and displacement.

Fully mechanized harvest activities, where feller-buncher and grapple skidder operations are allowed off main skidtrails, can result in high amounts of soil disturbance. Examples of the type and amounts of soil disturbance that can occur from this type of harvest are shown in figure 1. Total machine traffic coverage on the soil ranged from 49% to 62 %. The amount of concentrated disturbance complied with the guidelines at the time of harvest. Repair of concentrated disturbance is often possible with rehabilitation techniques; however, extensive off-trail disturbance is more problematic if it has damaged the soil. The main concern with off-trail traffic is compaction.

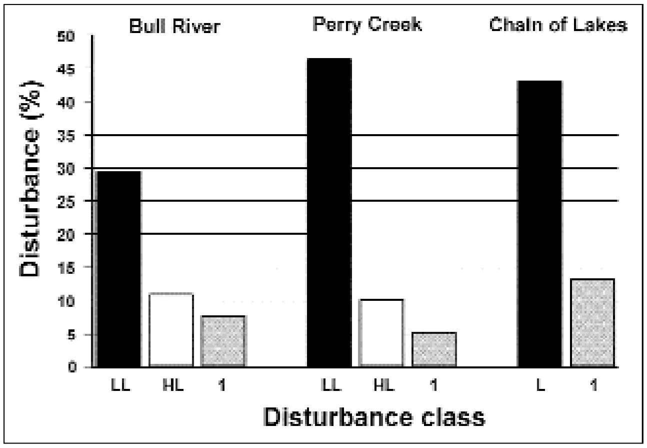

Figure 1—An example of soil disturbance coverage from mechanized harvesting in the Southern Rocky Mountain Trench British Columbia, 1991 (Curran 1999). (LL = light traffic trails; HL = heavy traffic trails – main skid roads; 1 = 5 & 10 cm deep ruts; L at Chain of Lakes includes both LL and HL.)

Figure 2—Close-up of an example of significant compaction from a heavy traffic trail at the Perry Creek site (see Fig. 1). Note the coarse platy structure that often results from heavy compaction of these study soils.

Compaction and Puddling

Compaction and puddling result in alteration and/or loss of soil structure with the affected soil often appearing coarse platy or massive (figure 2). Guidelines define thresholds for compaction severity and spatial extent, beyond which it is generally thought to have a long-term effect on forest productivity or hydrologic function. Compaction results from the weight and vibration of heavy equipment and dragging of logs. Important effects of compaction on forest soils are:

1. Soil density and strength are often increased,
2. Soil macro-porosity is often decreased, and
3. Soil infiltration is often decreased.

Bulk density increases are often measured in terms of total soil or fine fraction bulk density. Neither of these may be a true measure of other effects (e.g., soil porosity and penetration resistance) because trafficking sometimes incorporates considerable amounts of organic matter in the soil. Incorporation of forest floor and other organic material into a soil can result in increased puddling of soils due to clay-sized particles settling under wet conditions, or being smeared by equipment traffic.

Penetration resistance can be a good measure of relative compaction and conditions of high soil strength can restrict root growth. However, penetrometer readings are dependent on soil moisture content at the time and observations are affected by soil texture, and the amount of coarse fragments and roots. Figure 3 shows how compaction increases soil strength as measured by penetration resistance. Soil moisture content often varies between disturbance types due to differences in hydrologic properties (discussed below). However, while strength is affected by soil moisture and clay content, soils in areas severly disturbed invariably test higher than undisturbed soil, regardless of soil moisture. Figure 3 also demonstrates that most compaction occurs in the top 20 cm. Compaction increases with increasing traffic, and most compaction occurs during the first trips over the same piece of ground; as few as three passes can result in most of the compaction.

Perhaps the most important compaction effect is alteration of soil porosity, due to the collapse or distortion of large macro-pores. Soil compaction increased bulk density on a loam soil resulting in an overall decrease in aeration porosity and slight increases in available and unavailable water (figure 4). Less biological activity occurs as aeration porosity decreases. Once aeration porosity drops below 10% (at 0.01 MPa tension in a standard laboratory test) gas diffusion in the soil is essentially zero (Xu et al. 1992). This is thought to be a result of the tortuous nature of remaining large soil pores and restrictions in the necks between pores.

Another potential result of soil compaction is altered hydrologic function. Saturated hydraulic conductivity can decrease substantially in compacted soils (fig. 5). Infiltration decreases in compacted soil can result in increased surface runoff and consequently less water storage. Soil compaction may or may not impact plant growth detrimentally. Gomez et al. (2002), Powers (1999) and Powers et al. (in review) found that for sandy soils and drier sites, compaction actually improved growth by improving water availability. Interestingly, soil microbial activity may be unaffected by soil compaction. Unless soils are poorly drained, microbial activity probably continues unabated in

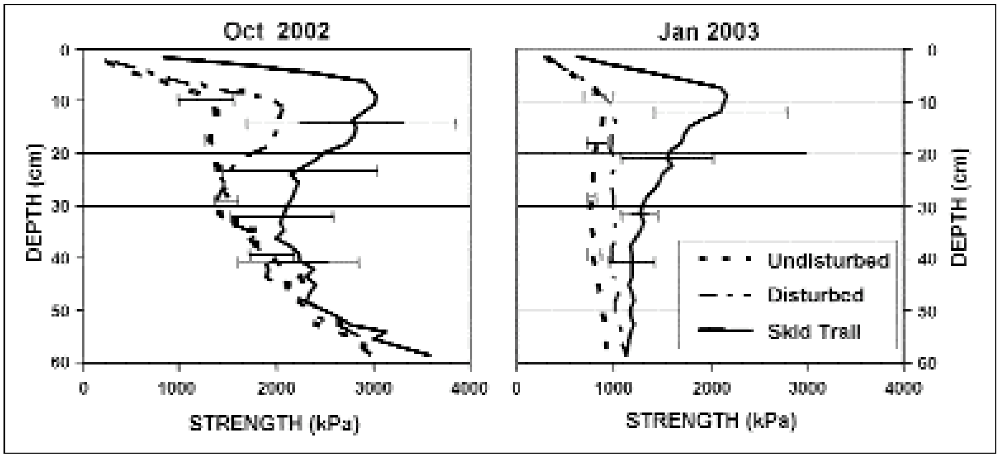

Figure 3—Iron Canyon soil monitoring to determine disturbance severity following second harvest. Penetrometer profiles by disturbance class, October 2002 (21% soil moisture), and January 2003 (45 % soil moisture) (Unpublished data on file at the USFS, PSW Research Station, Redding, California.)

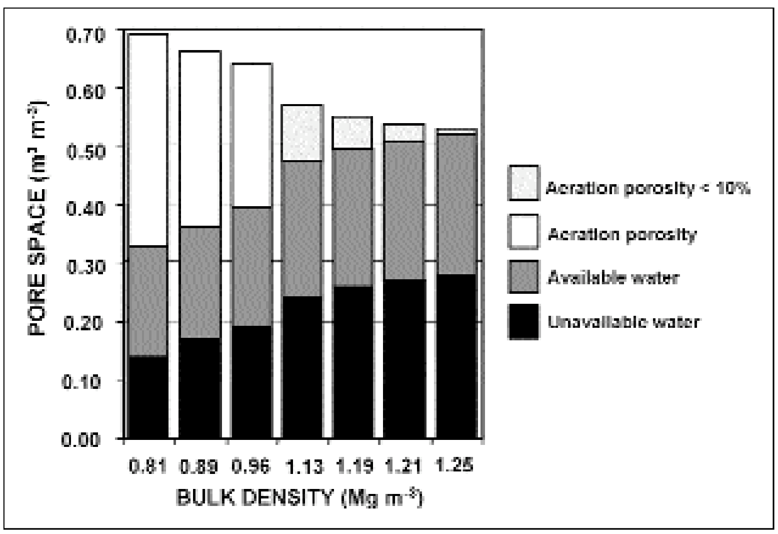

Figure 4—Effect of soil compaction on pore size distribution and water availability, Cohasset Loam studied by Siegel-Issem et al. (2005).

small soil pores and micro-aggregates that are not reduced by compaction (Shestak and Busse 2005).

Severity and extent of compaction are determined by both controlling and manageable factors (modified from Lewis et al. 1989).

Controlling factors are those inherent to the harvest site and include:

- texture,
- coarse fragments,
- forest floor depth/type,
- soil depth, and
- mineralogy.

Manageable factors can be controlled through harvest planning and include:

- machine traffic,
- machine type/dynamic loading,
- seasonal soil conditions (wetness, snow, frozen soil), and
- machine operator awareness, training, and skill.

Various hazard, or risk (hazard times consequence) rating schemes have been developed to evaluate the susceptibility of soils to compaction. One example that focuses on controlling site factors is the B.C. Ministry of Forests compaction hazard key (Curran et al. 2000).

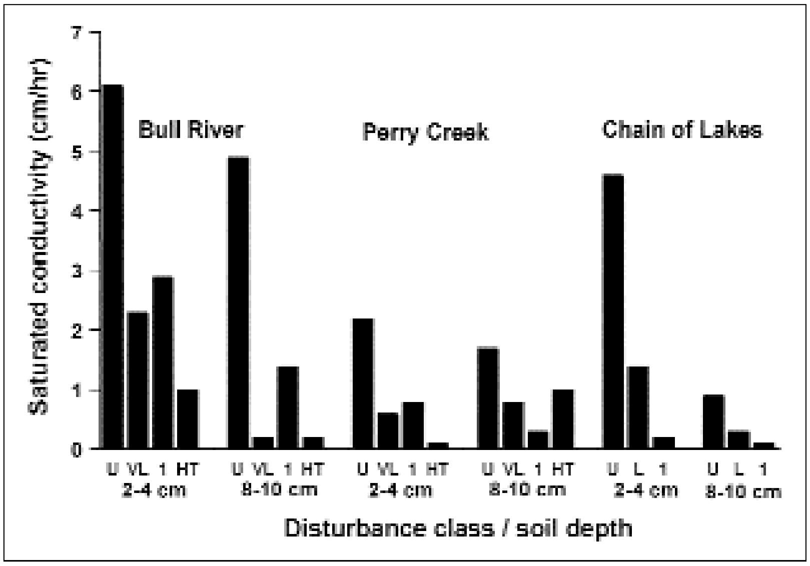

Figure 5—Saturated hydraulic conductivity on soil disturbance types from the mechanized harvesting study shown in Fig. 1 (Curran 1999). (U = undisturbed; VL = light traffic trails; HT = heavy traffic trails – main skid roads; 1 = 5 & 10 cm deep ruts).

Figure 6—Photo of old 1960's era skid trail in the Iron Canyon study site before the recent harvest study. Note lack of tree growth on this trail.

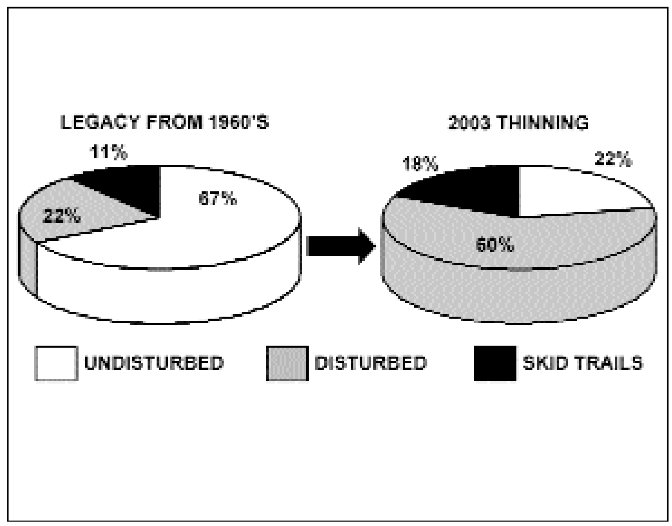

Figure 7—Iron Canyon soil disturbance monitoring pre- and post-harvest showing increase in disturbance following the second harvest entry (Unpublished data on file at the USFS, PSW Research Station, Redding, California.)

Effects of soil compaction can persist for decades (Froehlich et al. 1985), so concern about cumulative effects is important when planning harvest activities. Figure 6 shows there are no trees growing in a heavily used skid trail about 40 years following initial logging. Successive harvest entries can add to already existing compaction and displacement. Figure 7 shows changes from pre- to post-harvest for the area shown in fig. 6. Skid trail coverage nearly doubled, general disturbance increased nearly threefold, and undisturbed ground fell to one-third its previous extent. Lacking careful supervision, cumulative impacts will occur during ground-based operations.

Displacement

Displacement is the removal of mineral topsoil and forest floor layers from tree-growing sites. It is also a result of machine traffic or dragging of logs. Most organic matter and nutrients needed to sustain plant growth are in the developed topsoil, which varies in depth depending on local soil development. Displacement can result in a loss of available nutrients and effective rooting volume. In addition, it can expose subsoils that are less favourable growing sites (e.g., dense or coarse parent materials). Loss of water-holding capacity, exposure of subsurface seepage, increased runoff, and drainage diversion can also occur and affect off-site values as well. Thus, displacing topsoil an appreciable distance may lower site productivity through loss of available nutrients and effective rooting volume. Dyck and Skinner (1990) found that the overall productivity of a plantation where topsoil had been windrowed was only two-thirds that of an adjacent, non-windrowed plantation.

Severity and extent of displacement are also influenced by controlling and manageable factors (modified from Lewis et al. 1989).

Controlling factors include:

- slope,
- topography,
- soil depth, and
- subsoil type.

Manageable factors include:

- amount and extent of excavation,
- machine size/type,
- seasonal soil conditions (wetness, snow, frozen soil), and
- machine operator awareness, training, and skill.

Few hazard or risk (hazard times consequence) rating schemes are available to evaluate soil susceptibility to displacement. Examples that focus on controlling site factors are the B.C. Ministry of Forests soil displacement and forest floor displacement hazard keys (Curran et al. 2000).

Best Management Practices Components: Harvesting Effects on Soils

Careful planning is required to manage effects of harvest activities on soils. Planning should be based on guidelines and standards that limit specific kinds of soil disturbance and reduce potential for cumulative effects on productivity and hydrologic function. Disturbance from in-block disturbance is often regulated based on inherent sensitivity of the site/soil, with corresponding disturbance criteria and limits that are normally set for temporary access and soil disturbance in the area to be reforested. The most manageable factor may be operator training, awareness, and skill. Managing soil disturbance requires the following best management practice (BMP) components:

BMP components include:

1. site characterization,
2. detailed soil inventory,
3. harvesting strategies to meet soil disturbance standards based on the local soil susceptibility to disturbance,
4. considerations for climatic constraints (e.g., wet soils), or opportunities (e.g., snowpack),
5. monitoring of resulting soil disturbance,
6. restorative treatments for disturbance that is either over prescribed limits or preferably, pre-planned for rehabilitation, and
7. communication and information exchange (feedback loops) amongst the various level above, to enable continuous improvement of standards and practices.

Each of these components is discussed below.

Site characterization (1), and soil mapping of the area (2) are done either during the planning phase for the harvest cycle (e.g., methods in British Columbia described in Curran et al. 2000), or as a ground-checked resource inventory of the entire management area (this is more commonly done in the US Pacific Northwest area). With appropriate interpretations, soil mapping alerts harvesters about the amount of care needed to avoid excessive soil disturbance, when to schedule operations, and what portions of an area are most or least operable in wet weather.

Harvesting strategies (3) have been described for meeting soil disturbance standards under site conditions in western Washington and Oregon by Heninger et al. (1997) and for Interior British Columbia by Curran (1999). The objective is to match equipment capabilities to site sensitivity to disturbance, while providing considerations for climatic constraints (4) (e.g., avoiding wet soils), or opportunities (e.g., using a snowpack to reduce compaction and/or displacement).

Monitoring of resulting soil disturbance (5) follows established methods of measuring the occurrence of specific disturbance types along transects. A working group of the NW Forest Soils Council is currently working towards common disturbance criteria to facilitate comparison and exchange of soil disturbance information (Curran et al. in prep.). Classification systems that are considered to meet desirable criteria, including visually identifiable disturbance types, have been successfully used by the British Columbia Ministry of Forests (Forest Practices Code Act 1995) and Weyerhaeuser Company (Scott 2000), and are currently under developmental use in the U.S. Forest Service Region 6 (Pacific Northwest Region). These classification systems are successfully combined in monitoring protocols to determine severity and areal extent of soil disturbance after operational harvesting (B.C. Ministry of Forests 2001, Heninger et al. 2002).

Restorative treatments for disturbance (6) are required either when disturbance levels are over prescribed limits or preferably, in areas that were pre-planned for rehabilitation.

Figure 8—Decompaction of a logging trail before soil replacement during rehabilitation treatment. (Weyerhaeuser example)

Figure 9—Re-spreading slash onto logging trail as final stage of rehabilitation. (Weyerhaeuser example)

On the right sites, and with appropriate technique, rehabilitation can be an economical and environmentally responsible way to achieve logging efficiency without compromising long-term forest productivity or hydrologic function. (In fact, it can be hard to tell a trail or road existed previously without digging in the soil.) Techniques have been described in the literature, and prescribed in standards or policy guidelines (e.g., B.C. Ministry of Forests 1997), field cards and videos (e.g., Curran 1998). Procedures for successful rehabilitation usually involve both construction and deconstruction phases.

Construction usually includes:

- stockpiling of topsoil for later re-spreading,
- construction of the structure involved out of the subsoil.

Drainage control needs to be considered during construction, to control runoff during harvest but also during and after rehabilitation.

Rehabilitation involves:

- removing large cribbed-in (incorporated) woody debris,
- de-compaction through some form of tillage (e.g., Fig. 8),
- replacement of topsoil layers,
- covering with logging slash similar to the surrounding cutblock area (Fig. 9),
- re-vegetation similar to surrounding cutblock area, and
- use of erosion control mulches or seeding if erosion or sedimentation are concerns.

Rehabilitation of disturbed soils can fully restore the growth potential to that of undisturbed soil, provided the rehabilitation activities are done at the right time. However, not all soils, or all soil disturbances, are conducive to rehabilitation. For example, soil rehabilitation resulted in variable effectiveness in ameliorating compacted soils in a study on Vancouver Island (Maynard and Senyk 2004). In deep, well-drained soils, tilling reduced bulk density to below levels of undisturbed soils and in the short-term improved growth. In contrast, under wetter site conditions rehabilitation decreased survival and growth of seedlings. Other examples where rehabilitation is difficult or very costly include wet clayey-textured soils or where extensive rutting covers the entire harvest area. Rehabilitation is best used as a pre-planned activity for main trails and other temporary access like spur roads and landings that are not needed until the next harvest cycle.

Communication and information exchange (feedback loops) amongst the various levels above, should enable continuous improvement of standards and practices (7 from list on page 8) and be part of an adaptive management system used by each agency responsible for managing soil disturbance and its effects on site productivity and hydrologic function. Strategic databases are needed where disturbance types are tracked in relation to actual tree growth effects on long-term monitoring and research sites. Components for this process are discussed by Curran et al. (in prep.).

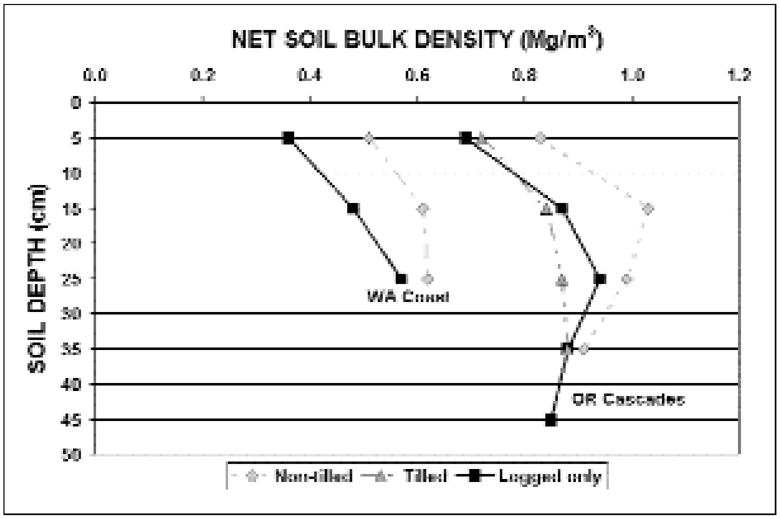

Figure 10—Net soil bulk density (Mg/m^3) for a Weyerhaeuser study of tree growth on tilled and non-tilled logging trails (Heninger et al. 2002)

RESULTING TREE GROWTH EFFECTS

Soil disturbance effects on tree growth depend on the growth-limiting factors influencing trees on a given growing site. Disturbance may both positively or negatively influence a tree's growing environment, with the net result being determined by which factor is most limiting to growth.

Growth limiting factors that are often positively influenced by harvesting soil disturbance include:

- competing vegetation,
- soil moisture,
- soil temperature, and/or
- air temperature (frost).

Growth limiting factors that are often negatively influenced include:

- aeration,
- soil penetration resistance,
- soil moisture availability or storage, and/or
- soil nutrients (e.g., nitrogen falling below critical thresholds).

Tree growth effects reflect the tremendous variability of climates and growing sites in the Pacific Northwest and it can be difficult to draw strong conclusions regarding specific types and severity of soil disturbances and tree growth. It is often necessary to monitor sites across the range of management and environmental conditions, and document results in a database used to continually improve guidelines, standards and management practices. Some examples are presented below to illustrate the above statements.

In a Weyerhaeuser study comparing tilled and non-tilled skid trails, bulk density for logged-only, non-tilled, and tilled skid trails by depth and areas (Washington and Oregon) are plotted in figure 10 (Miller et al. 1996 and Heninger et al. 2002). Compared to the logged-only plots, the non-tilled skid trails showed increased bulk density at both geographic locations. The Oregon Cascades tilled skid trails were rehabilitated to almost the same bulk density as the logged-only control for that area. Thus, tillage recovered the bulk density to that of undisturbed soil. There are significant differences between locations in undisturbed soil bulk densities. The next question would be: does this affect tree growth?

In the Washington study, there were no significant differences in Douglas-fir heights among any of the disturbance classes from year 2 through 18 (Fig. 11) (Miller et al. 1996). In the Oregon study, Douglas-fir (Heninger et al. 2002), height growth was reduced on OR skid trails for about 7 years after planting (Fig. 12). Up to age 7 years, the total heights were diverging between treatments. Seedlings on the non-tilled skid trails averaged 15% less in total height. Height growth (slope of line) from year 7 through 10, showed fairly consistent growth rate among the treatments, and was non-significant. Trees on non-tilled skid trail ruts were always shorter than those on logged-only control plots. Trees on tilled skid trails averaged 2% taller than those on logged-only plots. Thus, soil productivity, as measured by total tree height was recovered by tillage. Working through the data, considering time to attain 1.4-m breast height: LO = 4.0 years; NR = 4.7 years; an average difference of 0.7 years to attain breast height. Therefore, trees on the non-tilled skid trails are about one year behind in total height

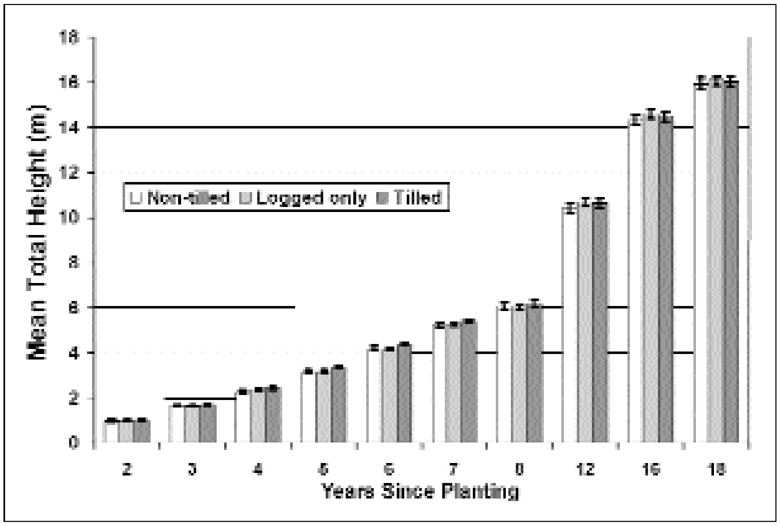

Figure 11—Mean total height of Douglas-fir in Washington for the Weyerhaeuser study of tree growth on till and non-tilled logging trails (Miller et al. 1996).

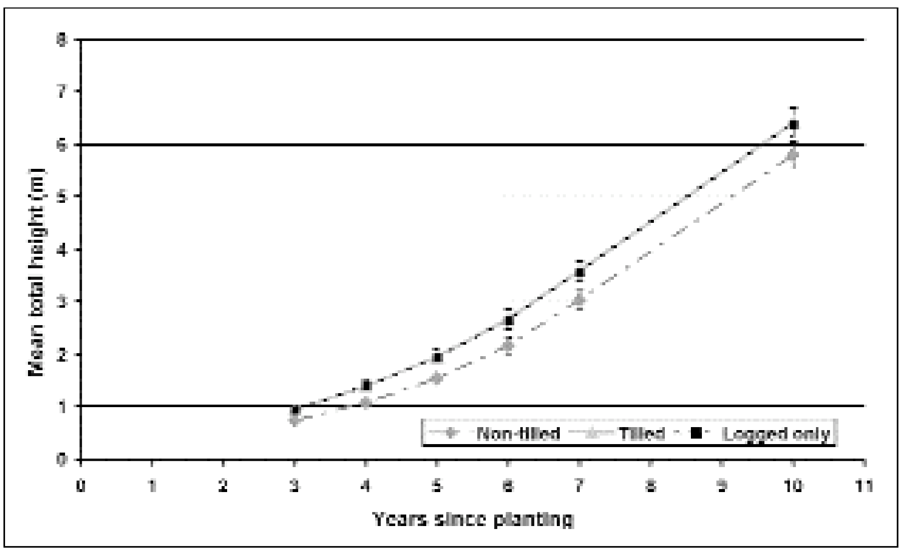

Figure 12—Mean total height of Douglas-fir in Oregon for the Weyerhaeuser study of tree growth on tilled and non-tilled logging trails (Heninger et al. 2002).

and diameter, because it took them one extra year to attain breast height. This difference has been maintained through age 10. The Oregon site has a finer-textured soil than the Washington site and has a longer summer dry period (the effect of the summer dry period is exacerbated by soil compaction). Our hypothesis is that the roots have grown through the compacted skid trail ruts, and are now growing in non-disturbed soil, thus growth rates are now equal. However, the full extent of the impacts on site productivity will surely be magnified if the area in skid trails increases appreciably. Absolute growth will be depressed if roots have little access to friable soil. So, we need to question how common this trend is and hence whether disturbance criteria need to be modified if longer-term data confirms these apparent trends on these site conditions.

LONG-TERM PRODUCTIVITY

Factors that limit early tree growth and establishment are often different from those that influence long-term productivity. Changes occur as a stand grows and matures, particularly around the time of canopy closure, when the

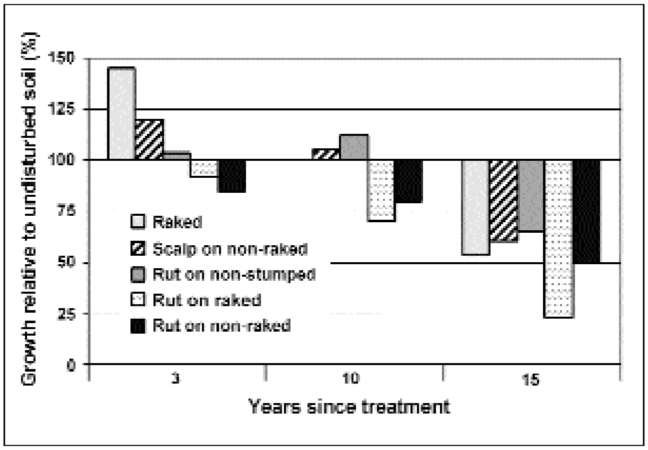

Figure 13—Comparison of relative growth of Douglas-fir on a stump removal trial in southern British Columbia at 3, 10 and 15 years since treatment. All data is relative to the undisturbed condition (adapted from Wass and Senyk 1999.

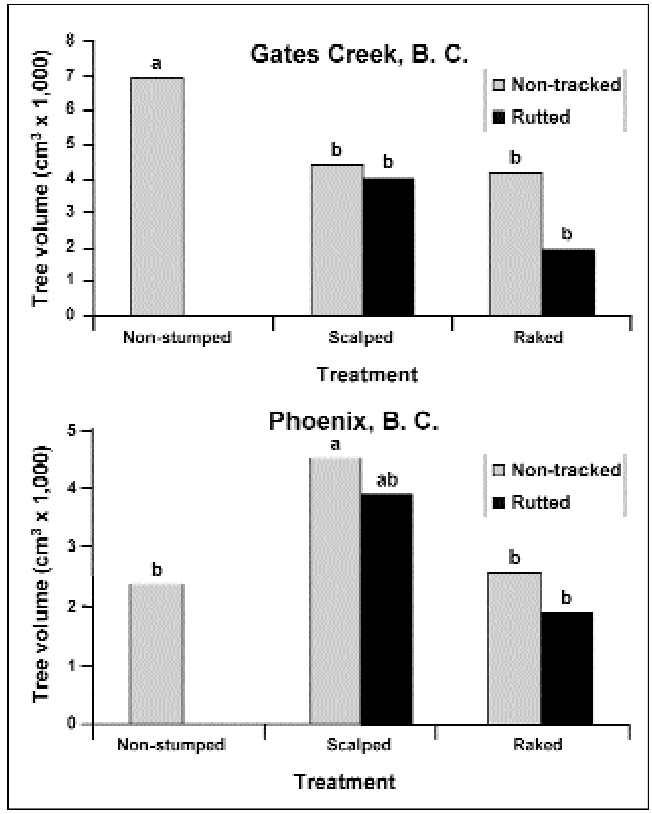

Figure 14—Fifteen-year volume of Douglas-fir seedlings growing in different disturbance types on the Canadian Forest Service Gates Creek and Phoenix stumping trial sites in southern B.C., which are gravelly sandy loam textured with 12% clay at Gates Creek and 4% clay at Phoenix (adapted from Wass and Senyk 1999).

trees are influenced less by microclimate and competing vegetation, and more by regional climatic conditions and a site's ability to provide adequate nutrients and moisture. Effects that are initially positive or negative may reverse over time. The time required to verify long-term effects on productivity is probably longer in slower growing subalpine or droughty areas. For example, on a relatively clayey site in southeastern British Columbia, short-term growth was enhanced on some disturbance types (Fig. 13). However, in the longer-term (15 years), tree growth was poorer on all soil disturbances compared to the undisturbed areas (Wass and Senyk 1999). It is clear that validation takes time and long-term monitoring/data is essential.

Some trends are becoming apparent. Deeply developed soils in humid climates appear to be less sensitive to disturbance whereas shallow, often younger and drier soils are more sensitive. Volcanic ash-influenced soils are often c o nsidered less sensitive than other soils, but data are still forthcoming.

The actual effects of site disturbances on tree growth depend on many factors, like texture. In British Columbia, our longer-term data currently available are from older studies such as that discussed for figure 13. Figure 14 contrasts 15-year Douglas-fir volume on the Gates Creek site shown in Figure 13 with a less clayey site at Phoenix. Both sites have sandy-loam textures, but clay content varies from 4% at Phoenix to 12% at Gates Creek. This also demonstrates the need for a database that covers the specific soils within the operating area covered by the guidelines. In our example, current compaction hazard ratings for the two sites would be the same, but the soils clearly behaved differently.

Figure 15 shows the importance of texture in the results from the Long-term Soil Productivity (LTSP) sites in California. In the clayey and loam textured study sites there is clearly a negative affect of compaction on 10-year biomass, whereas on the sandy sites there is actually a positive effect. This is considered to be due to compaction increasing the water-holding capacity on the sandy sites. Ten-year findings from the oldest LTSP sites in California, Idaho, the Lake States, and the Southern Coastal Plain support the conclusion that impacts of soil compaction on tree growth depend mainly on soil texture and degree of soil drought (Powers et al., in prep.). Studies like the LTSP are producing more long-term data every year. Over time, we will have indicators of soil disturbance conditions that affect tree growth under specific conditions.

Long-term productivity is dependent on the amount of permanent access and the net effect of in-block disturbance on future yield. Timber supply modeling takes into account these two factors. However, we need to improve data upon

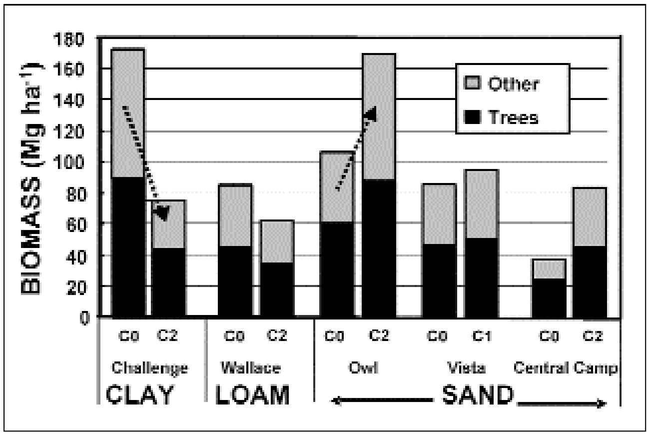

Figure 15—The importance of texture on the LTSP sites in California (C0 = no compaction, C1 = moderate compaction, C2 = severe compaction) (Powers et al. in review).

which in-block soil disturbance projections are based. Many tree growth studies are based on individual tree data from specific disturbance types. Data are needed on an areal (or extent) basis across a cut-block to fully integrate the net effect of on-site disturbance. The LTSP study is an area-based controlled experiment on compaction and organic matter levels that ideally should be paired with operational disturbance types and rehabilitation at each installation. Powers et al. (1998) proposed operationally feasible soil-based indicators for weighing the likely impacts of management on potential site productivity. Among their recommendations were to develop: soil maps highlighting soil types apt to be sensitive to disturbances, soil physical indic a t o r s such as resistance to penetration, and chemical/microbial indicators of nutrient supply, such as mineralizable nitrogen. These indicators need testing and implementation through continued testing, refinement and augmentation of existing soil disturbance standards.

SUMMARY

Harvesting Effects on Soils

Most soil disturbance caused by machine traffic is in the form of compaction and displacement. Compaction often results in increase in bulk density and decreases in penetrability, amount and size of pore space, aeration porosity, infiltration, and hydrologic conductivity. Displacement often results in loss of topsoil and exposure of subsoils. Off-site effects from soil disturbance can include erosion, sediment delivery and loss of life and property loss (not discussed in detail in this paper).

Effects on Tree Growth

Soil disturbance effects on tree growth depend on the nature of the disturbance in relation to the inherent site conditions/sensitivity such as soil texture and climate. Results can range from positive, through no-effect to negative, depending on which growth-limiting factor is affected.

Effects on Long-Term Productivity

Growth-limiting factors change as a stand ages and crown closure occurs. Early effects may reverse over time. Studies like the LTSP will permit better prediction of long-term effects and development of indicators that can be used in managing disturbance at the time of harvesting.

Best Management Practices

A number of soil considerations are required in harvest planning. An adaptive management approach needed to continually improve understanding of management effects on our soils. One needs to:

1. Know the soils upon which operations are planned (through survey of site information),
2. Know what practices should be planned (organize this knowledge based on a soil disturbance classifica tion, and a soil risk rating system),
3. Understand potential effects of these practices (both on- and off-site), and
4. Adapt planned practices (BMPs) over time as more knowledge becomes available.

Site-specific knowledge needs to be part of an adaptive management process for continual improvement of practices (sustainability). A lack of data often results in more restrictive policies, erring on the conservative side. Overly conservative policies and practices cost in terms of economics and social benefit from the forest resource. Conversely, policies that are not conservative enough may cost us in terms of environmental values and long-term productivity and hydrologic function. We need to constantly refine and adapt our guidelines, standards, practices and tools as more information becomes available. To meet these needs, linked databases that track the results of implementation, effectiveness, and validation monitoring are essential.

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