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CONCEPTUAL MODEL FOR PREDICTING FOREST PRODUCTIVITY LOSSES FROM SOIL COMPACTION

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ABSTRACT

A simple, conceptual model for predicting forest productivity losses from soil compaction is presented. Information regarding each component of the model is summarized. Once compacted, most forest soils in the Pacific Northwest are expected to remain compacted and forest growth affected for several decades. Elements within the model which managers are able to manipulate to influence the amount of soil compaction caused by tractive machines are identified.

Reductions in forest productivity following harvesting with tractive machines have been reported for several sites and species in the Pacific Northwest (Froehlich 1979; Wert and Thomas 1981). Estimates of stand growth loss range from 5 to 13 percent. Reports that reduced stand growth persists for at least three decades and that soils remain compacted even longer (Froehlich et al. 1983) have motivated forest managers to protect the soil resource from soil compaction.

Information is not always available for identifying the most efficient methods for protecting the soil resource from compaction, although current research continues to evaluate the problem. Research will not confirm the applicability of existing knowledge to all soil and site conditions, or to provide answers for future problems. Therefore, we are presenting a conceptual model of how forest productivity is reduced by harvesting with tractive machines. The purpose of the model is to assist land managers in making decisions regarding soil compaction. Forest managers should be able to use the model and associated information to determine how they can best minimize the loss of forest productivity from soil compaction on their lands.

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Conceptual Model

Our model of forest productivity losses from soil compaction is intentionally simplistic (Figure 1). Only the major elements (rectangles) and major actions or processes (ovals) have been shown. The basic sequence of events is identified by solid lines and arrows. Machines operating on soils during harvesting or site preparation change several soil properties and the change occurs over some portion of the total area treated. The growth of individual plants is affected by their response to the change in soil properties; plant response is translated into a stand response when the response of the individuals are summed over the entire area. Plant and stand response are only measurable over the time period that the soils remain compacted. Natural recovery rates of compacted soil or tillage determine: the time interval overwhich the soil properties will deviate from their natural condition; the portion of the total area involved (These two loops are identified by dashed lines and arrows); and the overall impact of soil compaction on forest productivity.

The interaction of soils, machines, and plants to produce a change in forest productivity is extremely complex. More information is known about some elements of the model than others. Therefore, the model should be viewed as qualitative rather than quantitative.

Before proceeding with a discussion of the individual elements and processes, a definition of soil compaction may be helpful. Soil compaction is defined as the densification of soil by the application of a dynamic load to a soil, thereby causing a decrease in the air voids within the soil due to changes in the relative positions of soil grains or aggregates (Li 1956). The load is only briefly applied to the soil but may be applied repeatedly, as in the case of a skidder using the same skidtrail a number of times. Bulk density, the weight of soil solids per unit volume of soil, is commonly used to describe the densification that occurs, but several other changes in soil properties occur as well.

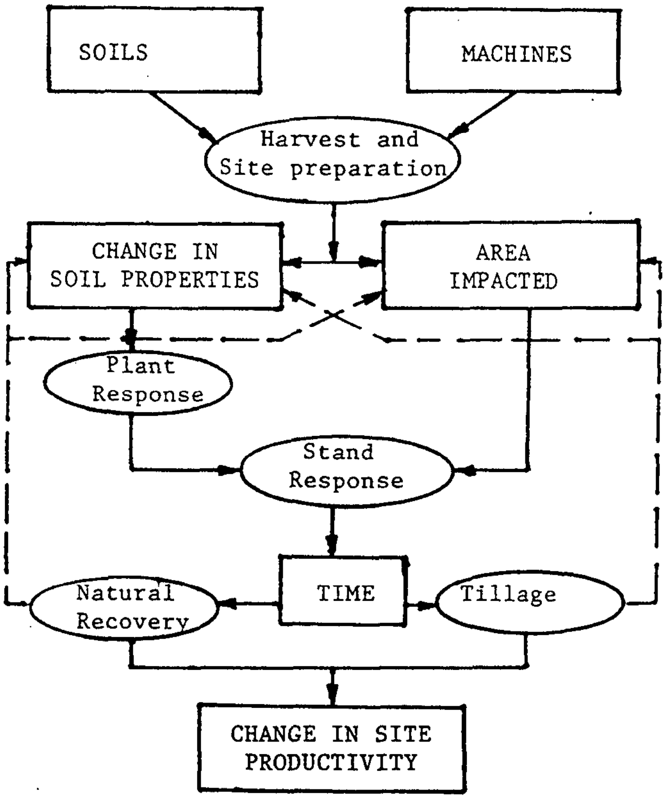

Figure 1.-- Conceptual model of forest productivity losses from soil compaction.

Soils

The variation among soils with respect to their susceptibility to compaction is directly related to their inherent soil strength. The strength of a soil ultimately determines how resistant it is to compaction (Greacen and Sand 1980). When compacted by the same load, a soil of low strength will increase in bulk density more than a soil with high strength.

Soil strength is affected by numerous soil properties, including particle size distribution, gradation, particle roughness, organic matter content, mineralogy of the clay fraction, soil structure, and sometimes soil moisture (Froehlich and McNabb, 1984). Some of these factors also affect bulk density but bulk density and soil strength may not be directly related, particularly when attempting to make comparisons between or among several soils. Therefore, the susceptibility of a soil to compact cannot be inferred from its original or compacted bulk density, although changes in bulk density have been a useful indicator of soil compaction in some situations.

Machines

The large variation in static pressures reported for skidding machines suggest that machines with lower pressures should compact the soil much less than machines with higher pressures. Considerable differences exists, however, between static pressures and the dynamic or actual pressures that machines produce in the soil. Determination of dynamic machine pressures is extremely complex and must also include characteristics of the site over which the machine is operating (Lysne and Burditt 1983). Estimates of dynamic pressures suggest that differences among machines are not as large as the static pressures imply although the pressure can vary across a site. For example, a skidding machine moving uphill causes more compaction than when it is traveling downhill (Sidle and Drlica 1981).

Three types of skidding machines commonly used on the West Coast were compared on four soils in the Sierra-Nevada Mountains of northern California to determine the amount of compaction that they caused (Froehlich *et al.* 1980). The maximum pressure developed by a wheel or leading or trailing portion of track, including the weight of the log load and effects of slope on weight distribution, was significant in predicting soil compaction. But, this pressure accounted for only a small portion of the variation in a multiple regression equation predicting changes in bulk density. The number of machine passes and a cone index measure of initial soil strength were much more important variables.

Most of the densification of a skidtrail occurs in the first few passes of a machine. At least sixty percent of the increase in bulk density expected in a well used skidtrail (20+ passes) occurs after the first 3 to 5 passes. During this time, soil strength increases with densification and the soil is better able to support the machine; further increases in bulk density are small because proportionally more of the energy is absorbed within and between the soil particles.

Soil Changes

Soils with high compacted bulk densities are sometimes assumed to be more susceptible to compaction than soils with low bulk densities. We have results, however, that show all soils will increase in strength regardless of their initial bulk density and that compacted soils with similar strengths can have large differences in bulk density. Therefore, using bulk density as an indicator of the susceptibility of a soil to compact fails to consider the importance of soil strength changes during compaction. Cochran (1971) apparently observed this process when he compacted a naturally low bulk density soil ($0.38\ Mg/m^3$) to a bulk density of $0.62\ Mg/m^3$ and reduced root growth of *Pinus ponderosa* Laws. and *P. contorta* Dougl. which he attributed to particle bridging or interlocking.

More densification of soil is commonly assumed to occur when a soil is moist than when it is dry. Therefore, restricting machine operations to drier soil conditions has been one method adopted for minimizing soil compaction; however, the moisture content of soil in skidtrails may have little affect on the amount of compaction occurring in some soils (Froehlich *et al*. 1980; Froehlich and McNabb, 1984). The compaction of coarse-textured soils with insufficient fines to fill the pore space between large particles and fine-textured soils containing kaolin clay minerals are relatively insensitive to soil moisture conditions below field capacity. Coarse-textured soils containing sufficient fines to fill the space between the larger particles and fine-textured soils with the more expandable clay minerals are moisture sensitive and will compact to higher bulk densities at moisture contents near field capacity than when drier. Identifying soil moisture conditions when densification will be lower, however, is extremely difficult to determine and monitor. Furthermore, it will only be partially effective at reducing the densification of some soils, and ineffective for other soils.

Currently, there is no quantitative method for classifying soils according to their potential to impair plant growth. Based on the increase in soil strength caused by compaction, the differences among soils are not as large as those suggested by initial or compacted bulk densities. Therefore, all soils should be considered susceptible to compaction until determined otherwise.

Area Compacted

The area in compacted skidtrails often range between 18 and 40 percent of the total harvest area from a single entry (Froehlich 1974). Repeated entries for thinnings or partial cuts tend to increase the area in skidtrails. Reducing the area in compacted skidtrails to about 10 percent by preplanning or designating their location appears to be a feasible method of reducing the detrimental effects of soil compaction (Froehlich *et al*. 1981). To be effective, all trees must be chokered and winched to the designated skidtrail. Harvesting by this method have costs similar to traditional logger's choice in skidtrail location (Froehlich *et al*. 1981). The time needed to pull winch line from a designated skidtrail to a log tends to be offset by shorter travel times because designated skidtrails follow more direct routes.

Plant Response

Decreased tree height and volume growth have often been associated with increases in bulk density, particularly in the Pacific Northwest. For seedlings and young saplings, the relationship has been consistent regardless of species, soils or site conditions (fig. 2). The consistency of this relationship is surprising considering that, in addition to bulky density increasing, mechanical impedance to root penetration, aeration, nutrient and water availability and mycorrhizae growth may also be affected (Froehlich and McNabb, 1984).

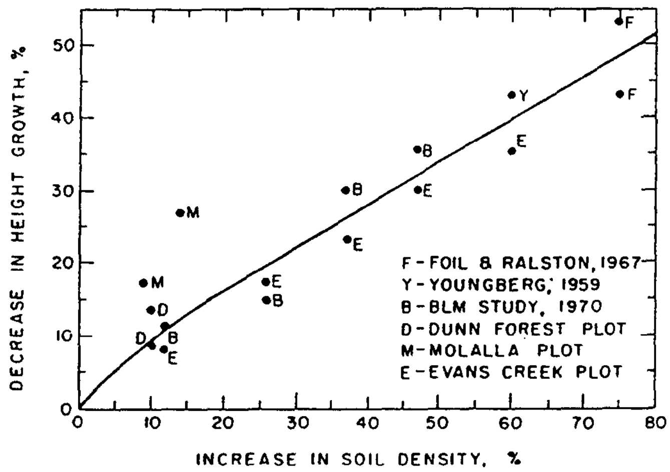

Figure 2--Relationship between an increase in bulk density and a decrease in seedling height growth for several soils and species (Froehlich and McNabb, 1984).

Because of the numerous soil properties affected, the relationship between bulk density and plant growth must be viewed as an association rather than a true cause and effect relationship. The association may not apply to specific sites where the densification does not place the plant under an abnormal stress (Froehlich and McNabb, 1984).

Growth of saplings and poles are also commonly reduced by soil compaction, although the relationship is not as consistent as that presented for younger trees. For the larger trees, only a portion of the root system is in compacted soils and both the amount of densification and its areal extent around a tree must be considered.

Stand Response

Both plant response to changes in soil properties and the area over which the changes occur must be combined in arriving at stand response to soil compaction (fig. 1). Current measurements of stand response to soil compaction have been made over a specific number of years; no measurements have been made at different time intervals within the same stand to determine if the impact on stand growth is decreasing. Stem analysis of trees growing on compacted soils indicates that tree growth is initially reduced by compaction but after several years, the growth rate may either be similar to trees of equivalent size on noncompacted soil or continue to grow at a slower rate (Wert and Thomas 1981; Froehlich et al. 1983). As a result, the long-term response of individual trees to soil compaction is uncertain but the effect on stand growth has been measured up to three decades after compaction.

Time

The persistence of compacted soil over time determines its affect on stand response and the long-term effect on forest productivity. How long soils remain compacted is determined by natural recovery rates or tillage operations or both.

Natural Recovery Processes

Natural recovery rates are generally slow, particularly in the Pacific Northwest. Freezing and thawing of compacted soils and shrinking and swelling during wetting and drying cycles are the major mechanical means of loosening compacted soil. The activity of flora and fauna is also an important process working to loosen compacted soil, although it is normally slow and probably dependent on mechanical processes to aid its effectiveness.

In the Pacific Northwest, the mild climate reduces the possibility of freezing and thawing cycles to effectively loosen compacted soil, particularly at depths below 2 to 4 inches. West of the Cascade Mountains freezing temperatures generally are not low enough or persist for sufficient time to freeze the soil to an appreciable depth. Even at the higher elevations where colder temperatures are more common, the winter snowpack generally insulates the soil from the severe cold. Furthermore, agronomic studies of freezing and thawing in the upper Midwest, where soils may freeze to a depth of several feet, have found the process to be relatively ineffective at rapidly loosening compacted soils (Froehlich and McNabb, 1984). Similarly, a recent study to determine the persistence of soil compaction in central Idaho indicates that natural recovery of the soil may take 40 to 70 years (Froehlich et al. 1983).

Shrinking and swelling of compacted soil caused by wetting and drying requires very specific soil and climatic conditions. To be effective, soils must contain expandable clay minerals, i.e, montmorillonites, and undergo several, severe wetting and drying cycles annually. Most Pacific Northwest soils are not susceptible to natural recovery by shrinking and swelling because montimorillonitic clay minerals are not common and the region undergoes only one major wetting and drying cycle annually.

The ineffectiveness of natural recovery processes in loosening compacted soils means that soils will remain compacted for a substantial portion if not the entire rotation of future, managed forests.

Tillage

Tillage should accelerate the recovery of compacted soils. Several implements including rock rippers, large disks, slashrakes, and winged rippers for tilling soils have been evaluated (Andrus and Froehlich 1983). Most implements either fail to till soil to an adequate depth (disks and slashrakes) or create relatively narrow slits of disturbed soil unless several passes are made (rock rippers). A winger ripper, a nearly flat shoe approximately 18 inches wide mounted on a long shank, appears most successful. Three winged rippers mounted on a tool bar pulled by a large crawler tractor can loosen about 80 to 90 percent of the soil in a compacted skidtrail to a depth of 18 inches.

Tillage is a promising technique for ameliorating compacted soil. The cost is less than $200/mile (1982) of skidtrail (Andrus and Froehlich 1983). The tillage operation, however, must effectively loosen the compacted soil which is not only a function of the implement used and the depth of tillage, but the soil texture and moisture content at the time of the operation. As a result, short-term changes in seedling survival or growth following tillage have ranged between -9 and 73 percent (Andrus and Froehlich 1983). More research and longer term studies are needed to determine the long-term effectiveness of the practice.

Reducing Site Productivity Losses

Management practices for reducing site productivity losses from soil compaction can emphasize reclamation by tillage, prevention of soil compaction, or both. The slow natural recovery of compacted soil suggests that managers should minimize changes in soil properties caused by tractive machines, decrease the area over which the machines operate, or till the soil after it is compacted (fig. 1).

Management practices based on grouping soils into compactibility classes or defining critical soil moisture contents will have limited effectiveness at reducing compaction. This is because the difference in susceptibility to compaction among soils is not as large as those suggested by their bulk density. All Pacific Northwest forest soils have increased in soil strength when compacted, regardless of their initial bulk density. Depending on soil texture and clay mineralogy, soil moisture content will have a variable but limited affect on the amount of densification occurring in moderately used skidtrails. Therefore, all soils should be considered susceptible to compaction.

Harvesting timber from a limited number of preplanned or designated skidtrails by yarding all logs with chokers and winch line to a machine setting in the skidtrail is an effective method of reducing the proportion of the area in compacted soil. The same skidtrails should be used for all harvest entries because the area in compacted skidtrails normally increases with multiple harvest entries. The effectiveness of using grapple skidders on designated skidtrails has not been determined.

Tillage is probably an economical means of reducing forest productivity losses from soil compaction, particularly when large volumes of soil are loosened efficiently. Tillage of designated skidtrails may not be desirable or cost-effective when the area to treat is small or after intermediate harvest entries.

Additional research is needed to determine the amount of compaction caused by machines designed to reduce soil compaction or feller-bunchers, grapple skidders, and forwarders making a few passes, and the effect that compaction from a few passes of a machine has on tree growth.

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