The characterization and compaction of forest soils forming in three parent materials in western Montana

by Stephen James Cullen

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Soil Science
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Abstract:
Eighteen forest soil pedons (boralfs and ochrepts) in the Bitterroot, Flathead and Kootenai National Forests were characterized and 54 pedons evaluated for the existence of soil compaction. The soils were examined over a range of parent materials: Tertiary Volcanics, lime- stone dominated glacial till and quartzite dominated glacial till. Characterization data included the amorphous character of surface horizons, texture, Proctor test, Atterberg limits, clay mineralogy, particle size distribution, bulk density, porosity, water holding characteristics, organic matter content, organic carbon content, pH, electrical conductivity, exchangeable cations, cation exchange capacity and calcium carbonate content.

Soil compaction was evaluated in timber harvest units ranging from 3 to 17 years old. Three treatment classes of soil compaction (control, moderate and severe) were established based on evidence of surficial disturbance and the presence of vegetation. Infiltration, bulk density and soil moisture retention data were collected and analyzed by two-way analysis of variance to determine if compaction had occurred as a result of treatment. Additionally, subsites were grouped by age as "young" (0-4 years since harvest), "medium" (5-9 years since harvest) and "old" (10-17 years since harvest). The data were analyzed to determine possible amelioratory effects of time on compaction.

Amorphous character of the surface deposits was strongly expressed in the Flathead and Kootenai National Forests of northwest Montana, while the surface deposits of the Bitterroot National Forest soils in the southwest were not amorphous. Three independent measurements showed that significant changes in the physical properties of the study soils had taken place with treatment. Significant reductions in infiltration and significant increases in bulk density of the surface horizon occurred at all three study sites. Significant reductions in soil water retention at three water potentials occurred in the surface horizon of the limestone and quartzite glacial till sites. With three exceptions, no significant changes occurred in the physical properties of the study subsoils. No significant changes attributable to age grouping were detected in infiltration, soil water retention or bulk density.

Compaction occurred at all three study sites examined. Although the compaction was found only in the surface horizon, the author feels that the effects of the compaction process are expressed throughout the profile in the form of reduced water and gas movement.

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Signature Stephen J. Cullen

Date February 3, 1981

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STEPHEN JAMES CULLEN

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Approved:

Cliff Montagne
Chairperson, Graduate Committee

Dwane H Miller
Head, Major Department

Michael Malone
Graduate Dean

MONTANA STATE UNIVERSITY
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ABSTRACT

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INTRODUCTION

Soil compaction is defined as the process of increasing soil bulk density as the result of applied loads or pressure (Baver et al., 1972). In the timberlands of western Montana, field soil scientists have observed that soil compaction may be inhibiting forest regeneration, productivity and the maintenance of a sustained yield management program.

In western Montana, harvesting, slash disposal and site preparation operations are accomplished in part by either rubber-tired or crawler tractor vehicles. The objective of this study is to measure possible soil compaction in areas which have undergone ground-harvest operations and to characterize the physical and chemical properties of the soils involved in compaction.

REVIEW OF LITERATURE

Successful establishment and maintenance of forest vegetation requires a root penetrable soil substrate capable of supplying aeration, water and nutrients. These capabilities are influenced by changes in soil physical properties which may be associated with compaction.

Effect on Root Growth and Proliferation

Most research on soil bulk density and plant root growth relationships concerns agricultural soils. Trouse and Humbert (1961) used soil core measurements of bulk density to establish bulk density values restricting to sugar cane root penetration. They comment that "the deformations that occur in roots growing in compacted soils that are approaching the critical levels are believed to lower their efficiency in moving air, water, and nutrients into the plant." Veihmeyer and Hendrickson (1948) drew similar conclusions with sunflowers. Roots did not penetrate soil with a bulk density of 1.9 g/cm^3 or greater. The threshold densities for root penetration seemed to be about 1.75 g/cm^3 for sandy soils. They also made the important observation that these critical levels were not the same for all soil materials. The critical level was lower (1.6-1.7 g/cm^3) in clayey soils. In addition to visual root counts, Veihmeyer and Hendrickson used the inability to extract moisture from a soil as an indication of the absence of roots in dense soils. In general, they state, "thus far, pine trees, grape vines, fig trees, and chapparal have shown little or no extraction of moisture from subsoils of about the same high densities reported in this paper."

They also present evidence refuting the idea that root penetration ceases due to lack of oxygen. They state that "roots penetrated the saturated noncompacted soils from which most of the air had been expelled by heating." Hopkins and Patrick (1969) believe that aeration is not the most limiting factor in root penetration, but that it is important to optimum root growth and proliferation. In soils with high bulk densities, compaction may worsen already poor soil aeration and thus restrict plant root growth.

Taylor and Gardner (1963) found, in laboratory studies with cotton, that the most critical limiting factor to root penetration was soil strength. They state, "to penetrate a soil mass, a plant root must exert a root growth pressure greater than the resistance of the soil through which it is growing." Taylor and Gardner (1963) demonstrated that soil strength increases with increasing bulk density. Thus, for a given soil material, an increase in bulk density will increase the amount of pressure required by a plant root to penetrate the soil. These results are supported in later work by Taylor et al. (1966). Minore et al. (1969) studied the effect of high soil density on the rooting habit of seven northwestern tree species in the greenhouse. Seedlings were allowed to grow for two years in soil columns compacted to bulk densities of 1.32, 1.45 and 1.59 g/cm^3. Roots of western red cedar and western hemlock could not penetrate soil of density 1.45 g/cm^3, but roots of red alder, lodgepole pine and Douglas-fir could penetrate. No roots penetrated soil densities greater than 1.59 g/cm^3. Forristall and Gessel (1955) report that a density of 1.5 g/cm^3 restricts red alder root growth in loam soils while Douglas-fir and western hemlock root growth was restricted at a bulk density of 1.25 g/cm^3 in the same soil.

Effect on Infiltration

When considered over a large area with no boundary effects, infiltration refers to the downward movement of water into the soil profile (Baver, 1972). Infiltration is one of the most important phases of water movement in the hydrologic cycle of a forest environment. Hills (1971) states that infiltration data relate closely to overland flow development. It is well known that erosion potential increases with increasing overland flow (Baver et al., 1972). Trimble and Weitzman (1953) found soil losses on heavily used, poorly permeable skid roads twice as great as losses on more permeable, lightly used skid roads.

Field infiltration measurements are subject to a high amount of natural variability. Thus, detectable differences in soil infiltration must be large to overshadow this natural variation.

Previous research indicates that infiltration is the factor most clearly affected by compaction. Soil compaction reduces macropore space inducing slow water entry and poor aeration. Trimble and Weitzman (1953) reported that it took 619 times longer for a given quantity of water to enter a forest soil skid road than a similar undisturbed soil.

Steinbrenner (1955) reported that after four passes with a tractor, moist soil was only very slowly permeable to water. The mean infiltration rate on primary skid trails was one-tenth that on undisturbed soil on nine loblolly pine soil sites of various textures on the Atlantic coastal plain (Hatchell et al., 1970). Five years after tractor logging a Douglas-fir timber stand on a silty clay loam in Utah (Tackle 1962), the tractor skid road infiltration rate was five percent of the rate on an undisturbed site. Mace et al. (1971) indicate that sites harvested on early spring snow underwent reductions in infiltration rates similar to those harvested in the summer (approximately 50%). However, the area disturbed was reduced by 30%. In areas with a pyroclastic influence in the soil surface horizon, Steinbrenner and Gessel (1955) observed an average reduction in permeability on skid roads of 92.3%.

Effect on Soil Aeration and Porosity

Adequate aeration is essential for the emerging seedling, as well as the growing plant, to carry on normal respiration activities. In poorly aerated soils, root growth is inhibited. This limits the amount of root surface area available for nutrient and water uptake and can lead to a reduction in total plant growth (Taylor and Ashcroft, 1972).

Important microbiological processes depend on adequate aeration. The microbial population is drastically affected by changes in soil aeration (Brady, 1974). Organic matter oxidation is reduced when sufficient oxygen is not present. Many microbial transformations are reduced, and some processes are eliminated (Alexander, 1977). Alexander also points out that when aeration is lacking, "new microbiological processes come into play, some of which may be deleterious to plant development; for example, N_2 or CH_4 is evolved, organic inhibitors appear, and sulfide, ferrous, and manganous ions accumulate . . .". Russell (1973) states that plants may be weakened sufficiently by the accumulation of toxic substances to become more susceptible to pests and insects. Mitchell and Mitchell (1973) state that many plant root diseases increase under conditions of poor soil aeration. Baker and Cook (1974) hold that under conditions of poor soil aeration, oxygen content decreases and carbon dioxide content increases near plant roots. They state that ". . . high carbon dioxide levels may favor the pathogen over less tolerant microorganisms."

Additionally, high concentrations of carbon dioxide inhibit root growth and may reduce water adsorption, causing a water stress condition (Baker and Cook, 1974). Mattson and Addy (1975) report conclusions that link outbreaks of phytophagus insects to soil-plant systems in which soil moisture regimes are less than optimal.

The same physical qualities that permit rapid infiltration also favor adequate aeration. The transfer of both water and gas in the soil are dependent largely on the porosity and pore size distribution.

Porosity is defined as the total soil volume not occupied by solids. Soil porosity is inversely related to soil bulk density by the following relationship:

$$e = 1 - \frac{B.D.}{P.D.} \times 100,$$

where e = total soil porosity, B.D. = bulk soil density and P.D. = particle density (Baver et al., 1972). 2.65 g/cm^3 is the accepted normal value of particle density in most soils. Thus, if the bulk density is known the porosity can be readily calculated.

There are essentially two types of pores in a soil with structural development: pores between aggregates and pores within aggregates (Baver, 1972). At high soil water potentials, the interaggregate pores are filled with water. This water is not held very tenaciously; it exists only during the wettest part of the year in well drained soils of western Montana. At these times hydraulic conductivities are highest and water movement in the soil is greatest. As the soil water potential decreases during drier parts of the year, interaggregate pores drain and the hydraulic conductivity decreases exponentially. A concommitant decrease in the flux of water occurs. Thus, interaggregate pores are very important in moving large quantities of water during seasonal and acute periods of high rainfall. Steinbrenner (1955) states that "the process of soil compaction brings the solid particles closer by breaking down the macroscopic pores, thus reducing the capacity of soil for air. Soil air is an important factor in tree growth; therefore, any reduction in the macroscopic pore space of the soil could result in a less favorable growing site."

Effect on Available Water Holding Capacity

Available water holding capacity is related to other soil physical properties such as structure, texture, porosity and clay mineralogy. The available water holding capacity of a soil is defined as the amount of water held in the soil between field capacity and the permanent wilting point (Taylor and Ashcroft, 1972). Hyder and Sneva (1956) found that compacting a sandy loam soil with a heavy roller improved available water holding capacity. Rashid and Khalid (1977) concluded that compaction up to 1.51 g/cm^3 bulk density can benefit wheat growth in areas with coarse-textured soils and where water is not available in sufficient quantities.

Factors Which Influence Susceptibility to Compaction

All soils are susceptible to compaction to a greater or lesser degree. Li (1956) describes the compaction process as follows:

> If applied stresses exceed the shearing strength of the soil local failure begins and the load starts to sink into the soil. As the load sinks, the soil under the load is pushed downward and outward. This motion will mobilize more and more resistance, consisting not only of the increased resistance due to lateral confinement from depth, but also that due to the increase in soil density that results from the settlement motion itself, provided the soil is not completely saturated. The settlement stops when equilibrium between stresses and resistance is reached.
>
> If the resistance of the soil is relatively high compared with the stresses, the load will cause very little settlement. . . . If the resistance is extremely low in comparison with the stresses, the load will cause a complete shear failure of the underlying soil by sinking deep and fast and

> replacing the volume of soil by pushing it in an outward direction. This completely disturbed state may result in compaction of the soil under the load and loosen the soil on the sides. The total net reduction in voids is questionable--energy is spent in compacting one portion of the soil and, at the same time, loosening another portion. Both compacting and loosening involve movement of particles and require energy to overcome the frictional resistance.

The soil properties having the greatest affect on the rate and degree of soil compaction are texture, coarse fragment content, structure, moisture content at time of compaction, and organic matter content (Lull, 1959). Although each factor has been studied separately, complete understanding of soil susceptibility to compaction is complicated by the interaction of these factors. In addition to soil properties, land use factors such as type of equipment being used (crawler tractor or rubber-tired vehicle), type of operation (log skidding, slash piling, etc.), number of vehicular passes, and the harvesting technique of the logger also influence the amount of compaction which occurs at any given site.

Texture

Krynine (1951) demonstrated that maximum densities, achieved by several methods of laboratory and field compaction, decrease with decreasing particle size. This occurred in order from gravel to clay size. In the same study, maximum densities for the coarse textured samples were obtained using heavy smooth-wheel rollers, whereas maximum densities were attained in the fine textured soils using tamping (sheepsfoot) rollers. As pointed out by Means and Parcher (1963), the coarse textured soils are cohesionless and require the vibration of the smooth-wheel rollers to achieve compaction. Cohesionless soils are very low in clay content and their strength and resistance to deformation and compaction depend on grain size, shape, mineralogy, and clay content (Schroeder, 1975). Clays cannot be compacted by vibration (Means and Parcher, 1963). The tamping action of the sheepsfoot roller provides the required pressure to compact the clays.

Huberty (1944) observed the highest densities and greatest reduction in water penetration on soils with a wide range of particle sizes. Raney et al. (1955) found that plowpans and compaction-induced hardpans exist most commonly in soils of medium texture such as loam, sandy loam and silt loam soils. Soils with a wide range of particle sizes can be reoriented so that small particles pack into the voids between the larger particles (Means and Parcher, 1963).

Clay influences the susceptiblity of soils to compaction by affecting shear strength. Depending on the clay mineralogy of a soil and, in some cases, the water content, it may either fracture or exhibit plastic flow upon application of a force. The shear strength of soils can be partly attributed to the cohesive forces between soil particles (Brown, 1977). Because of this, the amount and type of clay present is important when evaluating soil strength. In a clay soil containing 55% clay, shear strength more than doubled between soil water tensions of -1 and -10 bars while loam with 27% clay was nearly insensitive to the same changes in water potential (Brown, 1977). Trask and Close (1958) and Langston et al. (1958) showed that at water contents somewhat less than saturation there was decreasing shear strength from montmorillonite to illite to kaolinite. When the clays were very wet, the order of decreasing shear strength was reversed (Trask, 1959). Allophanic materials are variable with regard to their shear strength, depending on their exchangeable cation composition (Grim, 1962).

Coarse Fragments

Li (1956) concluded that "the influence of gravel content upon compaction is important because it hinders the compaction of fine grained soil fractions." Li presented data showing that at 35% gravel content by weight, soil could be compacted to a density 97% as dense as a similar soil without gravels. A soil with 60% gravels by weight could only be compacted 92% as dense as a soil with no coarse fragments. In explanation, Li notes that gravels, when grouped together, tend to form voids in the soil which may be empty or only partially filled with soil fines. As the gravel content increases, the chance of forming such voids also increases. In this study, Li did not specify the type of soil or gravels that he worked with. It is interesting to note that one of the standard Proctor Tests, which determine the optimum moisture content and maximum density for a given compactive effort, is based on using soil materials which pass a 3/4" sieve. Inclusion of coarse fragments excluded by this sieve in the laboratory test may make the results more representative of field conditions.

Structure

Soil structure also effects the degree to which a soil can be compacted and the subsequent effect on plant growth and water relations. Well aggregated soils generally have low bulk densities and good permeability. As a result of compaction, aggregates are crushed, interaggregate porosity reduced and permeability diminished (Lull, 1959; Baver et al., 1972). Intense rain storms can break down the structural units in a soil and form a dense, impervious crust in the soil surface. Crusting is a form of compaction in which the energy of raindrops acts on bared mineral soil. Baver (1972) states, "this type of structure degradation is least common with those aggregates that are stabilized with humus or iron compounds." It is an important point that crusting or puddling is associated with soils of low organic matter content and weak structure. Baver (1972) asserts that though the direct effect of crusting is confined to the immediate surface layer, "the structure of this layer may be broken down to limit the air and moisture relations of the entire profile." Taylor and Ashcroft (1972) give evidence that mechanical manipulation of soil reduces aggregate stability and suggest work on soil with machinery only at soil moisture contents where soil strength is optimized.

Moisture Content

Much research has been done on the effect of moisture content on compaction. Engineering studies show that the most compaction for the least expense occurs when the soil is slightly below its plastic limit (Lull, 1959). Because the plastic limit varies with the soil texture and type of clay present (Grim, 1962), it follows that the optimum moisture content at which soils compact will vary accordingly. Optimum water content tends to increase as the texture becomes finer (Felt, 1965). The less dense the initial soil sample, the greater moisture content required to reach maximum density (Lull, 1959) for a given compactive effort. For materials containing very little or no fines, moisture content has almost no effect on density (Li, 1956).

Moisture affects the size of the double layer between colloidal particles (Taylor and Ashcroft, 1972), the surface tension on non-colloidal particles, and subsequently the shear strength and ease of movement of soil particles with respect to each other (Li, 1956). Water lubricates the particles and allows their reorientation with respect to each other. This effect is operative up to the optimum moisture content for compaction. Thereafter, the incompressibility of water prevents reorientation and packing and the density is reduced because the density of water has a greater weight in the overall density of the soil-water mixture.

Li (1956) points out that the optimum moisture content for a given compactive effort is valid only for that effort. Each compaction pressure has its own optimum moisture content. It is difficult to relate the standard laboratory Proctor test to field conditions where the compactive effort may differ substantially. However, the Proctor test can serve as an index to the relative compactibility of soils. In working with 14 forest soils in California, Howard et al. (1979) state, "the Proctor maximum dry bulk density is a sensitive empirical way of ranking the soils based on their susceptibility to compaction."

Organic Matter

Alderfer and Merkle (1941) demonstrated that total organic matter content is closely related to aggregate size and stability. Thus, any reduction in organic matter content will result in loss of aggregate stability and a subsequent increase in a soils's potential for compaction. Howard et al. (1979) concluded that organic carbon was clearly the most important soil characteristic of California forest soils for predicting maximum soil densities and inferred that the same could be concluded regarding compaction. Organic carbon content and soil organic matter are directly correlated (Allison, 1965). Thus, soil organic matter content can be used to predict a soils compactibility. Working with four soils in New York, Free et al. (1947) concluded that soil samples containing the most organic matter would be compacted the least at given moisture contents and compactive efforts. Also, the soils with high organic matter content were compacted to their maximum densities at higher moisture contents. In addition to improving soil structure and water relations, forest humus and litter may offer a cushioning effect to provide underlying soil some protection from compaction (Lull, 1959).

RESEARCH METHODS

Site Selection

Study sites with a range of parent materials, soil properties and environmental conditions were selected in the Bitterroot, Flathead and Kootenai National Forests. These soils are widespread and produce significant amounts of timber in the Northern Region; they are of critical importance to forest management and planning. Bitterroot National Forest sites are located in the West Fork of the Bitterroot River drainage. These soils are formed in clay-rich Tertiary Volcanic parent materials which are often overlain by a thin layer of silty material. Flathead and Kootenai National Forest sites are located in glacial till and are overlain by a layer of volcanic ash. One group of pedons are in limestone dominated glacial till. The second group of pedons is in quartzite dominated glacial till. Study site locations are depicted in figure 1.

Soils in this study were located only on the above three parent materials. Each parent material defines a site. Within each site, three subsites were located. Each subsite was located in and adjacent to a timber harvest unit. In choosing subsites, an attempt was made to minimize the effect of the variability of the natural soil landscape. Comparative soil profiles within each study site were chosen based on soil morphology and geomorphic setting. Every attempt was made to keep soil and geomorphic properties within a given study subsite