The effects of mechanized slash piling on soil bulk density and infiltration rates at five forested sites in northwestern Montana
by Earl William Cassidy, Jr

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Soils
Montana State University

Abstract:
This study evaluates the effects of mechanized slash piling on five important commercial timber producing soils in northwestern Montana. Trafficking occurred when soil moisture was near optimum for compaction according to Proctor tests.

Observers monitored the intensity and areal extent of slash piling, established soil disturbance classes, and quantified slash weight before and after piling. Pre- and post-disturbance bulk density measurements, taken by depth and horizon to 40 cm, showed statistically significant increases ($p = .001$ to $.10$) ranging from .09 to .26 g/cm^3 in the surface horizons and .10 to .13 g/cm^3 subsurface glacial till horizons.

Equilibrium infiltration rates decreased to 60 to 90% of pre-disturbance rates ($p = .001$). Averaged over all five sites 85%, 11%, 3%, <1%, and <1% of the trafficking events were 2, 4, 6, 8, and 10 pass events, respectively. Trafficked area varied from 25 to 48% of the total area on each of the five sites. However, bulk density increases greater than .09 g/cm^3 probably occurred only on 11 to 24% of each site.

Results from a concurrent skidding study imply that similar levels of compaction also occur when slash piling under drier soil moisture conditions. The significance of these disturbance levels to timber productivity in northwestern Montana is unknown.

Two concurrent studies on similar northwestern Montana soils measured skid trail bulk density by the saran clod method. They detected significant bulk density increases in the surface horizon only. This study, determining bulk density by the sand excavation method, documents bulk density increases in both the surface and subsurface horizons. This indicates that the sand excavation method may be a more sensitive bulk density instrument, especially in soils containing a high percentage of coarse fragments.

STATEMENT OF PERMISSION TO COPY

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Montana State University, I agree that the Library shall make it freely available for inspection. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by my major professor, or, in his absence, by the Director of Libraries. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature Earl W. Cassidy

Date 23 October 1981

DEDICATION

This work is dedicated to those who work to understand natural environments and to those who strive, through knowledge, to delineate the tenuous boundary between use and abuse.

THE EFFECTS OF MECHANIZED SLASH PILING ON SOIL BULK DENSITY

AND INFILTRATION RATES AT FIVE FORESTED SITES

IN NORTHWESTERN MONTANA

by

EARL WILLIAM CASSIDY, JR.

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soils

Approved:

Cliff Montagne
Chairperson, Graduate Committee

Dwane G. Miller
Head, Major Department

Michael Malone
Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

September, 1981

ACKNOWLEDGMENTS

Thanks to Dr. Cliff Montagne, my major professor, who understood my need and provided encouragement in my struggles to find a personally rewarding project. Thanks also to other members of my graduate committee, Dr. Larry Munn, Dr. Murray Klages, Dr. Jarvis Brown, and Dr. Steve Custer for your technical expertise and guidance.

Thank you, Dr. Tom Nimlos for your contagious enthusiasm for soils, you got me interested.

I thank those who labored long and hard with me both in the field and in the lab providing companionship and humor and who became my friends. Thank you, Walt Adams, Con Donvan, Terri Jarvis, Nancy Granger, Wendy Williams, and especially Kathy Gallagher.

Thank you, Forest Service soil scientists, Al Martinsen and Lou Kuennen for your help in site selection and willingness to share ideas.

Thank you, Champion Timberlands, for funding this research and thanks especially to Wayne Maahs and Andy Lukes for your support, guidance, and flexibility.

Thanks to Clyde Smith (part logger, businessman, alligator, and friend) for recognizing the importance of this research and for striving to see the job was done correctly.

Thank you, my parents, for your emotional support, and for providing me with my initial opportunities to learn the joy of learning.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

ABSTRACT

This study evaluates the effects of mechanized slash piling on five important commercial timber producing soils in northwestern Montana. Trafficking occurred when soil moisture was near optimum for compaction according to Proctor tests.

Observers monitored the intensity and areal extent of slash piling, established soil disturbance classes, and quantified slash weight before and after piling. Pre- and post-disturbance bulk density measurements, taken by depth and horizon to 40 cm, showed statistically significant increases ($p = .001$ to $.10$) ranging from .09 to .26 g/cm^3 in the surface horizons and .10 to .13 g/cm^3 in subsurface glacial till horizons. Equilibrium infiltration rates decreased to 60 to 90% of pre-disturbance rates ($p = .001$). Averaged over all five sites 85%, 11%, 3%, <1%, and <1% of the trafficking events were 2, 4, 6, 8, and 10 pass events, respectively. Trafficked area varied from 25 to 48% of the total area on each of the five sites. However, bulk density increases greater than .09 g/cm^3 probably occurred only on 11 to 24% of each site. Results from a concurrent skidding study imply that similar levels of compaction also occur when slash piling under drier soil moisture conditions. The significance of these disturbance levels to timber productivity in northwestern Montana is unknown.

Two concurrent studies on similar northwestern Montana soils measured skid trail bulk density by the saran clod method. They detected significant bulk density increases in the surface horizon only. This study, determining bulk density by the sand excavation method, documents bulk density increases in both the surface and subsurface horizons. This indicates that the sand excavation method may be a more sensitive bulk density instrument, especially in soils containing a high percentage of coarse fragments.

INTRODUCTION

Many of the most productive forest soils in northwestern Montana are characterized by 20-50 cm of surficial volcanic ash-loess deposits overlying a variety of glacial debris derived from Precambrian metasediments. Forest Service soil scientists and land managers in northwestern Montana have expressed concern over possible soil compaction occurring in these soils due to mechanized logging operations. Field observations by these personnel indicate that potentially detrimental compaction may be taking place in both the surficial ash-loess and in the subsurface glacial tills. Studies elsewhere suggest that subsurface compaction may be extremely slow to ameliorate. Compaction persistence for as long as 40 years has been hypothesized. Recent studies in the southeastern and Pacific northwestern regions of the United States have shown that soil compaction decreases yields in economically important tree species. Yield reduction estimates range from one to two site classes on severely compacted sites.

Theoretical and field research show that compaction is primarily a surficial phenomenon, occurring at depths less than 30 cm. There is however, documentation of ruts as deep as 120 cm produced in soils logged during extremely wet moisture conditions. The structural degradation of these soils (puddling), subsequent potential compaction upon drying, and the advent of heavier logging equipment have caused renewed interest in deeper compaction. Field scientists have also expressed concern about the potential for compaction in cohesionless, skeletal, glacial till subsoils induced by vibration of logging equipment.

Virtually all forestry related compaction studies to date evaluate soil compaction of primary and secondary skid trails, logging roads, and landings. They are the sites of obvious potential impact since trafficking is concentrated at these locations. Additionally, field and laboratory studies demonstrate that substantial increases in soil bulk density may occur during the first few trafficking events. This fact has intensified interest in possible compaction on less heavily trafficked areas, such as the additional land trafficked during slash piling operations. Few studies have quantified the additional area trafficked during slash disposal operations, and none have quantified the severity and areal extent of soil compaction incurred.

In northwestern Montana, logging slash is commonly piled and burned as a means of scarifying the soil (to expose a mineral soil seed bed), to facilitate access for tree planting crews, and to reduce fire hazard. This is usually accomplished by tracked vehicles equipped with brush blades, e.g., D-6 crawler tractors. Slash is either "windrowed" or consolidated into piles. Since dense piles burn more efficiently, extra trips may be made over the ground to produce a more compact slash pile.

Soil mechanics theory and laboratory investigations have established clear relationships between soil moisture and soil susceptibility to compaction for most soil textures. This relationship has been verified by numerous investigators in field trials with logging equipment. Most slash piling operations in northwestern Montana take place during the "dry" summer season (July-October). Theoretically, most soil textures are least susceptible to compaction when relatively "dry". However, due to economic considerations and in the interest of maximum efficiency, slash may be piled any time equipment is available, irrespective of soil moisture. On this basis, it was decided to evaluate slash piling operations under theoretically highly susceptible "wet" soil moisture conditions to determine the potential for severe impacts. A similar study was conducted simultaneously on adjacent sites (same soils) by another investigator (Bates, 1981). This complementary study evaluated skid trail soil compaction by crawler tractor and rubber-tired skidders under "wet" and "dry" soil moisture conditions. Since soil trafficking was rigorously controlled in this concurrent study, it is believed that Bates' "dry" compaction results for skid trails can be reasonably extrapolated to slash piling operations under "dry" conditions.

This study was initiated by the Plant and Soil Science Department at Montana State University in cooperation with Champion Timberlands.

The objectives of this study are to characterize, quantify, and evaluate impacts on soil caused by slash disposal operations on five different soils characteristic of extensive land areas important to timber production in northwestern Montana. This study provides base line data on several parameters not previously evaluated in northwestern Montana, with respect to mechanized slash piling. Specific objectives are as follows:

1. Quantify the area trafficked during slash piling operations.
2. Establish classes of disturbance caused by trafficking performed during theoretically compaction susceptible soil moisture conditions.
3. Quantify the degree and depth of compaction in the most severe disturbance class.
4. Evaluate the effect of disturbance on water infiltration rates in the most severe disturbance class.
5. Quantify the amount of slash removed during piling operations.

LITERATURE REVIEW

Mechanics of Soil Compaction

Compaction is the increase in soil density as a result of applied loads or pressure (Baver, et al., 1972). Li (1956) defined compaction as the process of densification of soil by static or dynamic load application causing a decrease in air voids due to changes in the relative positions of soil grains. Water seldom has time to drain away during the compacting process, thus compaction is a reduction in the volume of air voids.

The compaction process has been summarized by soil mechanics engineers as a reduction in the voids ratio (Sowers and Sowers, 1970). The voids ratio (e) is defined as follows:

$$e = \frac{\text{volume of voids}}{\text{volume of solids}} \qquad [1]$$

The minimum voids ratio occurs at the state of minimum porosity (maximum density).

Proctor (1933) pioneered the study of moisture-density relationships, for engineering purposes. He developed the concept of an "optimum moisture content" at which maximum density may be achieved under a given load. For any given soil and load, theoretical maximum density is defined for <u>each moisture content</u>, as the point where all air has been expelled from the soil. Achievable maximum density is somewhat less than this due to air trapped in voids that cannot be expelled during the compaction process.

The mechanism for reducing the voids ratio occurs differently in cohesive soils than in non-cohesive soils. In cohesive soils densification occurs through plastic distortion and reorientation of particles and their associated water films. In cohesionless soils densification occurs through sliding of particles over one another or through breaking of particles at their points of contact (Sowers and Sowers, 1970).

Cohesion is defined as a bonding of particles due to attractive forces between particles arising from physicochemical mechanisms (Baver, et al., 1972). Forces contributing to cohesion include: van der Waal's forces, electrostatic forces as defined by Coulomb's Law, linking through cation bridges and their associated spheres of hydration, cementing agents, (e.g., organic matter and iron and aluminum oxides), and surface tension generated by the curved menisci at air-water interfaces present in unsaturated soils (Baver, et al., 1972). In an elementary sense, cohesion is a function of the number of moisture films and their thicknesses. Cohesive strength is associated with the soil's clay content. Clays have extremely large surface areas, which influences the number of cohesive moisture films that can develop (Baver, et al., 1972).

Friction, generated at points of contact between soil particles, is also an important factor resisting soil compaction. Li (1956) stated that frictional forces resisting soil movement are dependent upon the surface area of the particles, the normal pressure between the two surfaces, and the nature of the surfaces; which influences the coefficient of friction (e.g., smooth surfaces provide less resistance than rough surfaces).

Frictional forces and cohesive forces are commonly considered together in assessing a soil's shear strength. Baver, et al. (1972) defined shear strength in soil as the maximum internal resistance to slipping or sliding of soil over soil. This is given by Coulomb's Law as:

$$S = C + p \cdot \tan\phi \qquad [2]$$

where: S = shear strength

C = cohesive force

p = effective pressure normal to the shear plane

$\tan\phi$ = coefficient of friction, where ϕ is the angle of internal friction.

Shear strength is the soil strength that must be overcome to allow compaction to occur. The equation effectively integrates the two components resisting compaction, cohesion and friction, which are expressed through a combination of physicochemical and physical factors, respectively. The relative contribution of each component to soil strength is influenced by the soil's water content and particle size distribution.

Engineers frequently evaluate soil shear strength in the lab using the tri-axial shear test (Baver, et al., 1972). This test is carried out on soil cores in which the confining pressure from all sides can be regulated. It is noteworthy that compression compaction can be produced in soils by increasing the confining pressure. However, engineers typically assess shear strength as shear strength at failure. This is induced by applying an additional vertical stress until the soil shears or fails along some diagonal plane. Kumar and Weber (1974) separated the compaction of an unsaturated soil in a triaxial cell into two phases; compression by confinement and compression by a deviator or vertical shear stress. They found that compression with shear induced more compaction than compression without shear. In terms of the definition of shear strength presented earlier, it must be made clear that compaction initially takes place through the reorientation of grains which is shear at the particle level but not shear failure in terms of a soil's inability to support a load.

Trafficked forest soils are subjected not only to compacting compression but also to shearing deformations (Grecean and Sands, 1980). Under compression compaction the largest stresses occur where the load contacts the soil or slightly below (Baver, et al., 1972;

Chancellor, 1977). In this case stresses generally decrease exponentially with depth. However, if shearing to failure takes place, the largest stresses develop at some ill-defined distance below the load (Chancellor, 1977). That is, the potential for deeper soil compaction is increased. Greacen and Sands (1980) state that shearing deformation may produce twice as much compaction in a soil as compression compaction.

Factors Affecting Compaction Susceptibility

Water Content

Numerous investigators have demonstrated that water content is the most significant factor influencing compaction susceptibility. In some soils the moisture density relationship is well defined, whereas in other soils the relationship is less apparent. Water content affects both the cohesive and frictional components of soil strength. It affects the distance between soil particles and the attractive forces associated with the air-water menisci in both cohesive and cohesionless soils.

In cohesive soils, the distance between particles influences the physicochemical factors previously listed. The magnitude of attractive and repulsive forces generated between soil particles is influenced by the distance between particles (Baver, et al., 1972). At low moisture contents capillary tension between particles increases contact pressure, friction, and thereby shear strength by pulling soil particles together (Akram and Kemper, 1979). Cohesive forces resisting compaction increase, as percent clay and water content increase, to a maximum at somewhat below the soil's plastic limit (Baver, et al., 1972). Shear strength in this moisture range is attributed to the development of abundant moisture films (Baver, et al., 1972). However, as water content exceeds the plastic limit, shear strength decreases dramatically, becoming minimal as the liquid limit is approached. Once a soil becomes plastic there is little internal friction and water films become too thick to allow strong attractive forces between particles (Baver, et al., 1972). Similarly, Akram and Kemper (1979) indicated that cohesive soils are most susceptible to compaction at their field moisture capacities. They observed considerable shear strength and resistance to compaction in cohesive soils at one-half field moisture capacity. As a result Proctor curves are generally well defined in cohesive soils.

In cohesionless soils small amounts of water produce capillary tension which increases shear strength. However, as more water is added, additional strength is not developed due to the lower surface area of cohesionless soils. In fine sand and silt size particles, water films may become thick with respect to irregularities on the surfaces of particles which may result in the densification of particles under light loads. However, in coarse sands and gravels, films may never become thick enough relative to surface roughness to produce "lubrication" (Li, 1956). Compression compaction in these soils is usually achieved only by fracturing particles at their points of contact, which accounts for their high shear strengths (Sowers and Sowers, 1970). Similarly Li (1956) states, on the basis of lubricating film thickness, that the compaction susceptibility of coarse particles is relatively insensitive to water content. He reports that saturation is the optimum moisture content for densification in coarse soils. However maximum densities have been achieved in fine sands at extremely low moisture contents (Sowers and Sowers, 1970). Vibrational forces, which may momentarily decrease friction between particles, are also very effective in compacting cohesionless soils (Means and Parcher, 1963; Chancellor, 1977). Engineers frequently use vibration producing equipment to compact cohesionless soils whereas heavy loads are necessary to overcome the cohesive forces resisting compaction in cohesive soils.

Proctor curves for cohesionless soils similarly reflect insensitivity of maximum achieveable density to moisture content (Sowers and Sowers, 1970). McNabb (1979) presented Proctor curve data for the Tolo series of Oregon. This soil is a non-plastic, silt loam developed in volcanic ash. He found relatively flat compaction curves, typical of cohesionless soils, irrespective of moisture content. Although he varied hammer drops from 5 to 35 per layer, he found the soil to be relatively incompressible (e.g., maximum density achieved was 1.0 g/cm^3). Bates (1981) presented similar data for the volcanic ash-loessial surface horizons of northwestern Montana. Grim (1962) indicates that allophanic materials, which are common in the surface horizons of many soils in northwestern Montana, are variable with respect to their shear strengths.

In saturated soils or in soils wetter than optimum moisture for compaction, compression compaction is minimized by pore water pressure, whereas the potential for shear failure is greatly increased. Li (1956) indicated that shear failure may result in the compaction of soil directly under the load, while simultaneously loosening it at the sides. The result is no net change in the voids ratio. Larson and Allmaras (1971) stated that soils which have been subjected to shear failure while wet may puddle. The term puddling has been interpreted differently by various investigators. Bodman and Rubin (1948) investigated pore space destroyed by compression compaction and shear deformation in the Yolo silty clay loam. They used the term puddling to describe both phenomena. As moisture was increased to field capacity they observed that pore space destroyed by compression alone increased dramatically, as did pore space destroyed by shear under pressure. Chancellor (1977) defined soil puddling as shear and deformation at saturation. He stated that bulk density will not increase but that permeability will decrease due to a loss of pore continuity and soil structural damage. Kohnke (1968) defined puddling as the orienting of clay particles so that they lie parallel to each other and as the filling of large pores with soil particles. Lambe (1960) presented a model of puddling with reference to particle orientation occurring on the wet side of optimum moisture content.

The significance of puddling may not become apparent until a soil has dried. In parallel orientation, aligned particles may shrink, when dried, to a bulk density greater than that achieved by compaction at optimum moisture content. Larson and Allmaras (1971) demonstrated a .2 g/cm^3 increase from this phenomena. Moehring (1970) stated that macropore volume is reduced and a dense crust, similar to a thin compacted zone, is formed upon drying.

Soil Texture

Li (1956) reported that well graded soils are more resistant to compaction because of increased particle (frictional) contacts. "Well graded soils have grain-size distributions that plot as smooth and regular concave curves with no sizes lacking, or no excess of material in any size range" (AASHO, 1963a). Thus, for a given load and moisture content, less compaction would be anticipated from a well graded soil than from a poorly graded soil (Chancellor, 1977). However, highest densities under heavy loads are achieved in well graded soils as the fines can be forced into voids between larger particles (Ingles, 1974).

Bodman and Constantin (1965) found higher attainable bulk densities in various mixtures of sand and silty clay than in either 100% sand or 100% silty clay. When the proportion of sand was increased to greater than 80% of the mixture, maximum bulk density decreased. They attributed this result to insufficient fine material which was unable to fill the voids between the coarser sand particles.

Engineers have attempted to develop compactibility indexes for cohesive soils based on the Atterberg limits. In cohesive soils maximum attainable density increases as the plasticity index decreases. Similarly, optimum moisture content for compaction decreases as the plasticity index decreases (Lee, 1974; Ring et al., 1962). In a field study Hatchell, et al. (1970) found compaction was greater in loamy sand or sandy loam than in clay loam or clay. They stated that this may have resulted from fine textured soils having nearly saturated pores when wet and an extremely hard condition when dry, thus resisting density changes in either extreme. Final density was positively correlated with percentage of silt and negatively correlated with percentage of clay. These authors also observed that soils which are normally dense (sands) attained a higher compacted density than those which have low natural density (clays and silts). However, they speculated that soils of naturally high porosity may sustain relatively more damage under the same load than soils of low initial porosity.

Soil Organic Matter

Soil organic matter reduces compaction susceptibility (Grecean and Sands, 1980). Sands, et al. (1979) found that increased organic matter reduced compaction under a given load. Bodman and Constantin (1965) found that the addition of organic matter increased the water content at which maximum bulk density was achieved. Free, et al. (1979) found that soils containing the most organic matter were compacted to a lesser degree by the same force, at a constant moisture content. Similarly, Larson and Allmaras (1979) demonstrated that the addition of organic matter improved soil structure and aggregate stability which subsequently reduced compaction susceptibility. Grecean and Sands (1980) indicated that the maintenance of organic matter in forest soils low in clay is important for adequate water retention and transmission, as a source of nutrients, and as a factor resisting compaction. Lull (1959) emphasized that an intact litter layer may mitigate soil compaction during logging operations by providing a buffering cushion.

Coarse Fragments

The effect of coarse fragments in mitigating soil compaction in the field has not been documented. However, engineering laboratory studies indicate that coarse fragments greater than 4 mm may have a significant effect on the bulk density of the fines within the mixture.

Li (1956) presented data derived from Proctor curves indicating that the percentage of gravel greater than 4 mm can significantly reduce the compacted bulk density of finer materials. Li did not report the soil texture nor the size and shape of gravels used in his determinations. He found that additions of gravel up to 40% (by wt) progressively decreased the bulk density of the fines from 1.83 to 1.76 g/cm^3. As the gravel content was increased to 60% and 80% the bulk density of finer material further decreased to 1.65 g/cm^3 and 1.47 g/cm^3, respectively.

Gordon, et al. (1964) examined the variation of optimum moisture content with respect to rock fragment content (greater than 4 mm) in which they varied rock fragments from 0% to 65% (by wt). They reported, for material without plastic fines, that the optimum moisture content remained unchanged regardless of rock fragment content. For materials having plastic fines and greater than 50% rock fragments (by wt) optimum moisture content shifted ". . . well to the wet side of optimum." The Highway Research Board (1960) reported that at less than 25% coarse fragments (by wt), aggregate merely displaced fines having little effect on compaction.

McNabb (1979) feels that stresses may be directly transmitted through coarse fragments compacting the fines. However, Li (1956) indicated that gravels may group together or bridge to form voids sheltering fine materials from compacting stresses. His data indicated that this effect may occur above approximately 30% to 40% coarse fragment content (by wt).

Disturbance Caused by Mechanized Forest Harvesting Equipment

The literature deals primarily with site area disturbed by skidding operations in association with clear cuts and thinning management prescriptions. To the author's knowledge no studies have rigorously evaluated soil disturbance caused by slash piling operations.

The extent and severity of soil disturbance depends upon several interrelated factors. These may be divided into three major categories: site factors, type and layout of harvesting operations, and machinery effects. Site factors include soil texture, soil moisture at the time of trafficking, vegetation parameters, (e.g., stand density, timber type, and duff thickness), and percent slope (Lull, 1969). Site disturbance caused by timber harvesting operations is greatly influenced by the timber harvesting prescription and the location and number of haul roads and skid trails. Machinery utilized in harvesting coupled with operator efficiency may likewise produce considerable differences in the amount of area disturbed (McDonald, 1971).

A summary of studies evaluating site disturbance by crawler tractors and rubber-tired skidders, in association with harvesting activities, is presented in Table 1. Areal disturbance in these