

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
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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.

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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

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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 tri-axial 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

Table 1. A summary of studies documenting soil disturbance associated with forest harvesting activities.

Management Prescription	Machinery Used	Area of Cutting Unit Disturbed	Area in Skid Trails	Area Compacted	Degree of Disturbance Expressed in Percentage of Cutting Unit	Slope	Reported by
Thinning	-	40 to 50%	-	20 to 30%	-	-	Froehlich (1973)
-	CAT †	27% (includes roads and landings)	-	-	5% remained slash covered 6% < 1" of soil displaced 16%> 1" of soil displaced	-	Garrison and Rummell (1951)
Clearcut	HD-20 CAT	-	26%	-	-	level	Steinbrenner and Gessel (1955)
Clearcut	CAT	65%	28%	28%	26% slightly disturbed 9% exposed to subsoil	< 20%	Dyrness (1965)
Thinning	CAT RTS ‡	30% 14%	- -	- -	15% mineral soil exposed 7.5% mineral soil exposed	< 25%	McDonald (1971)
Thinning	CAT	29% (does not include roads and landings)	20%	-	16% > 1" of soil displaced	< 60%	Wooldridge (1960)
Clearcut	-	12% primary skid trails 20% secondary skid trails	32%	-	-	-	Hatchell , et al. (1970)
Clearcut	RTS	34%	-	-	25% mineral soil exposed 9% > 4" of soil displaced	level	Zasada and Tappeiner (1969)
Clearcutting and slash disposal	D-8 CAT and TD-6 RTS	78%	-	-	32% < 3" of soil displaced 46% > 3" of soil displaced	-	Edgerton, et al. (1975)

†CAT = crawler tractor
‡RTS = rubber-tired skidder

studies ranged from 14% to 65% of the total cutting unit area. Some investigators specify whether they have included haul roads and landings in their computations, others do not. Total area disturbed by skid trails in the studies reviewed ranges from 20 to 32%. Roads and landings may occupy from 4% (large tractors) to 10% (small tractors) of the cutting unit depending on tractor size (Haupt, 1959). Lull (1959) indicated, in general, primary skid trails occupy approximately 20% of the logged area and that landing sites, secondary skid trails, and fire lines may disturb an additional 20%.

Haupt (1959) reported that the number of stems removed per unit area will influence the amount of mineral soil exposed during logging. Garrison and Rummell (1951) and Lull (1959) indicated that the type of vegetation cover and duff thickness influence the amount of mineral soil exposed and the depth of compaction incurred. Froehlich (1973), in a review of the effects of forest management on soil physical properties in the Pacific Northwest, concluded that under tractor logging 50% of the cutting unit is disturbed and 25% can be considered compacted. On the compacted area he estimated that increases in bulk density ranged from 15% to 50%.

Modern forest harvesting equipment applies heavy loads to soil, although loads are small compared to engineering machinery designed to effect compaction on highway subgrades. Static pressures exerted on the ground are derived by dividing the weight of the machinery by the

total ground contact area. Typical static loads are as follows: low pressure flexible tracked vehicles [0.3 - 0.4 kg/cm^2 (4.3 - 5.8 psi)], crawler tractors [0.5 - 0.6 kg/cm^2 (7.2 - 8.7 psi)], and rubber-tired skidders [0.6 - 0.9 kg/cm^2 (8.0 - 12.3 psi)] (Greacen and Sands, 1980).

Dynamic loads, exerted by machinery in motion, can be several times greater than static contact pressures. Pressures up to five times greater than the static contact pressures have been recorded under the back wheels of operating agricultural tractors (Cohron, 1971). Similarly, in logging operations, the rear axle may support considerably more load than the front, as additional weight from dragging logs is imposed upon the rear of the vehicle. Chancellor (1977) found that actual ground pressure exerted by an unloaded crawler tractor in motion was two to three times the load imposed at rest. Additionally, the extremely stiff suspension of a crawler tractor may cause point loads that exceed by several times the static ground pressure of the vehicle (McDonald, 1971; Miles, 1978). As a tractor negotiates uneven ground, small portions of the tracks will support the full weight of the machine. Grecean and Sands (1980) stated that the dynamic components causing compaction are greatly increased by any pushing (slash piling) or pulling (skidding) activities of a logging vehicle.

Gill and VandenBerg (1967) reported that vehicles with rigid tracks develop vibrational stresses. The peak stresses are correlated with vibration and impact loads from the drive sprockets. Their study showed that impact loading was 50 times as effective as kneading load (similar to tire passage) in generating soil compaction. Lull (1959) indicated that vibrations imposed by crawler tractors contribute greatly to their compacting potential. According to Sowers and Sowers (1970), the compacting influence of vibrations is more important with respect to cohesionless than cohesive soils. Vibrational forces alone are generally not enough to overcome the large cohesive strength in cohesive soils.

The rigid frame of a tracked vehicle will also cause soil disturbance while making sharp turns. When a turn is initiated the operator holds one track stationary while applying power to the other track. This causes the fixed track to skid laterally, often leaving a fan-shaped pattern as duff and soil are displaced. McDonald (1971) calculated that a 45° turn with one track locked increased the area influenced by track contact by 32% in comparison to straight line travel. He stated that turning maneuvers contribute greatly to the amount of bare soil and deep disturbance (". . . mineral soil exposed to a depth of 2 inches or greater"). McDonald also reported, in the same study, that D-6 crawler tractors caused about twice as much

litter displacement, shallow and deep disturbance as a Garrett Tree Farmer (rubber-tired skidder) operating on slopes less than 25%.

The length of time a stress is acting on soil has an effect on how much compaction will occur. According to Li (1956), a definite period of time is required for non-elastic strains to develop completely in a soil after the inducement of stresses. If the loading is instantaneous there may be only enough time for partial compression, whereas an extended load application may induce more compaction. Aboaba (1969) found a roller compacted a soil less deeply at high speeds [greater than 11.3 km/hr (7 mph)] than at lower speeds. Similarly, McDonald (1971) determined that a crawler tractor traveling at 4.8 km/hr (3 mph) would subject a point under its track to stresses for 1.55 seconds. A skidder traveling at 9.7 km/hr (6 mph) would exert stress at a point for only .17 seconds (although loading will occur twice in a period of .68 seconds, once as each wheel passes). The optimum speed of operation, in terms of reducing compaction potential, has not been quantified for forest logging equipment. Velocities are similar when both types of equipment are engaged in securing logs, but are about 50% faster on main skid trails for rubber-tired vehicles (Silversides, 1966).

The studies of Davies, et al. (1973) and Raghaven, et al. (1977) identified wheel slip by agricultural tractors as causing increased compaction. The ability of tracked vehicles to work uphill on steep

terrain is important. Tracked vehicles are normally limited by slopes in excess of 40% (Engelbretson, 1980). Attempting to negotiate steeper slopes may cause additional soil disturbance as vehicles lose traction producing ruts. Garrison and Rummell (1951) reported that slopes exceeding 40% had 2.8 times as much deep soil disturbance (". . . more than 1 inch of soil displaced.") as slopes less than 40%. They found soil ruts ranging from 60 to 120 cm in depth on slopes exceeding 40%. Ruth and Silem (1950) recommended that tractor yarding be limited to slopes not exceeding 35% to prevent excessive disturbance.

Vehicle sinkage is an important factor affecting the depth of soil disturbance. Typically under extremely wet conditions (i.e., approaching saturation) a tracked vehicle or skidder may induce complete shear failure in the soil. This condition may be observed in association with deep ruts. As a logging vehicle sinks into the soil, simultaneously a berm of soil is pushed up adjacent to the bearing surface. This has been termed "pistoning" by civil engineers and is observed in the Proctor test on the wet side of optimum moisture for compaction. Grecean and Sands (1980) and Li (1956) state that this represents shear failure without compaction due to poor drainage in the soil under the load. In this case soil structure is destroyed (puddled) with accompanying infiltration reductions (Chancellor, 1977). As stated earlier, subsequent drying may cause the puddled soil to compact.

Moehring (1970) indicated that considerable soil displacement may occur during logging and site preparation. He termed this phenomenon ". . . erosion by mechanized equipment.", and indicated that surface soil losses may effectively cause a permanent reduction of site potential due to a reduction of potential rooting depth. Brendermuehl (1969) reported growth reductions in a pot study by removing one or more inches of topsoil. Growth reductions were correlated with reduced nitrogen and organic matter contents in the soil volumes. Similarly, Youngberg (1959) observed chlorosis in 75% of Pseudotsuga menziesii seedlings planted on compacted skid trails.

Mace (1971) indicated that winter logging on 30 to 40 cm of snow when soil was frozen 10 to 15 cm deep substantially reduced total soil disturbance. He found less area in the "heavy" (1%) and "medium" (8%) disturbance classes as compared to summer logging where 13% and 33% of the area were in each class, respectively.

Edgerton, et al. (1975) assessed soil disturbance caused by logging and slash disposal operations on pumice soils near Bend, Oregon. The cutover area was logged and piled with TD-6 rubber tired and D-8 tracked vehicles. They noted that soils were moderately to heavily disturbed on 78% of the area. Thirty-two percent of the area had soil disturbance to a depth of less than 7.5 cm, whereas 46% of the area was disturbed to a depth greater than 7.5 cm. They concluded that most of the disturbance was due to trafficking during slash

piling operations. Soil churning and ruts 23 to 30 cm deep were noted on the site. Although they did not partition disturbance caused during road building and harvesting from disturbance incurred during slash piling, the effects are additive.

It should not be assumed that all soil disturbance is harmful. Scarification is a primary goal of slash piling operations in northwestern Montana. However, the amount of area scarified and the severity of soil disturbance is of interest with respect to stocking rates, potential for soil erosion, and possible reductions in productivity due to soil compaction or soil displacement. Slash piling dozers in northwestern Montana are commonly equipped with brush blades to reduce the amount of soil displacement and to avoid the incorporation of soil into slash piles.

Depth of Compaction Caused by Mechanized Forest Harvesting Equipment

Lull (1959), in a review of compaction under forest logging regimens, stated that in general, the depth to which compaction occurs seldom exceeds 30 cm. He also stated that compaction is most severe directly below the bearing surface and indicated that the effect does not extend laterally more than 30-45 cm. As discussed earlier the potential for compression compaction theoretically decreases exponentially with depth. However, the advent of heavier logging equipment may increase the potential for long lasting deeper compaction. It is commonly believed that a reduction in soil compaction can be obtained

by reducing the unit load applied to the soil surface, resulting in a proportional reduction of compacting pressures in the underlying soil. "As machinery has doubled in weight, tire size has been increased to double the area of the foot print." (Taylor, et al., 1980). Low pressure tracked vehicles have been designed with this principle in mind. However, Soehne (1958) concluded that even when surface pressures are equal, pressure bulbs will be larger and reach deeper as the total load increases.

Taylor, et al. (1980) examined Soehne's hypothesis by trafficking bins filled with sandy loam soil. The soil was placed in bins to achieve uniform bulk density with respect to depth. They found bulk density increases decreased with depth (although not exponentially) and were more severe under a heavier load even at approximately equal ground pressures. Bulk density increased .45 g/cm^3 (36%), .35 g/cm^3 (26%), and .35 g/cm^3 (27%) at 18 cm, 30 cm, and 50 cm, respectively under a "heavy load [4136 kg (9,120 lbs)] as compared to .30 g/cm^3 (19%), .30 g/cm^3 (22%), and .28 g/cm^3 (21%) under a "light load" [2380 kg (5,250 lbs)]. They stated that <u>in uniform soils</u> stresses can be predicted at specified depths but that there is no simple relationship between stresses and bulk densities induced. Grecean and Sands (1980) stated that Danfours, et al. (1974) reported compaction under 14.5 metric ton loads at 50 to 60 cm, and concluded that under heavy loads it is largely the load and not the contact pressure that affects the

magnitude of stresses at depths greater than 40 cm. They stated that above this depth (shallower than 40 cm) stresses were reduced by utilizing lighter equipment.

The depth of impact has seldom been evaluated. All studies reviewed that attempted to evaluate soil compaction under logging operations dealt with compaction within 30 cm of the surface. Most studies concentrated on the 0- to 50-cm depth and were carried out on soils low in coarse fragments using core methods. Theoretically, depth of compaction varies with ground pressures exerted and the number of trafficking events (Sowers and Sowers, 1970). However it is also influenced by litter layer thickness, the persistence of litter, soil texture, and soil moisture, making direct comparison between studies difficult. Additionally, a reliable surface reference plane has not been documented in most studies. Typically researchers use the surface of the mineral soil as a reference datum in evaluating compaction. Current research does not address the problem of changes in the datum plane caused by gradual wearing and deepening of skid trails (Miles, 1978). Since bulk density generally increases with depth, it is difficult to know whether measurements are evaluating compaction incurred or merely the natural higher bulk density at depth.

Soil Compaction Incurred During Forest Logging Operations

Representative studies evaluating changes in bulk density under forest logging operations are tabulated in Table 2. Bulk density increases range from 0 to .86 g/cm^3. The increases undoubtedly depend on many variables including soil texture, soil moisture at time of trafficking, number of trafficking events, and litter layer thickness as exemplified in studies by Miles (1978), Steinbrenner (1955), and Froehlich (1978). Although direct comparison between studies is difficult, due to the variation in site characteristics and equipment used, trends are obvious.

Data presented by Steinbrenner (1955) and Miles (1978) illustrate that soils are more susceptible to compaction when trafficked "wet" than when "dry." Increasing the number of trafficking events also increases the degree of compaction incurred (Steinbrenner, 1955; Froehlich, 1976, 1978; and Mace, et al., 1971). In general, the largest percent increase in bulk density occurs during the first few trafficking events (Aulerich, et al., 1974; Froehlich, 1978). However, bulk density may continue to increase dramatically at the surface and as deep as 30 cm as the number of trafficking events increases. This is particularly likely on major skid trails (Youngberg, 1959; Aulerich, et al., 1974; Miles, 1978; and Froehlich, 1978).

Trafficking intensity during slash piling operations might be intuitively compared with one to three trafficking events or with

Table 2. Representative studies evaluating changes in soil bulk density under forest logging regimes.

Equipment/misc.	Method of Evaluation	Soil Texture	Depth Evaluated	Initial Bulk Density g/cm³	Increases in Bulk Density g/cm³ and (%)	Source and Study Location
HD-20 Crawler Tractor	Volumetric 7.5 cm core	Silty clay loam	0-7.5 cm	0.91	Trafficking Events: 1 Trip / 3 Trips / 6 Trips Logged wet (at field capacity): .08 (5) / .13 (14) / .27 (30)	Steinbrenner (1955) S.W.Washington
				0.58	Logged dry: .05 (9) / .06 (10) / .10 (17)	
HD-20 Crawler Tractor	Volumetric 7.5 cm core	Pumice	0-7.5 cm	0.71	Minor Skid Trails: -.02 / Major Skid Trails: .17 (24)	Steinbrenner and Gessel (1955) S.W. Washington
		Silt loam		0.80	0 / .37 (46)	
		Silty clay		1.07	-.02 / .21 (19)	
Crawler Tractor	Volumetric cores	Clay	9-15 cm		On "heavily" used skid trails (at least 30 cm of soil removed or displaced) Control: .87 / Treatment: .71 (82) / Control: .88 / Treatment: .64 (72)	Youngberg (1959) W. Oregon
			15-30 cm		.98 / .86 (87) / .88 / .71 (81)	
"Small" crawler Tractor (thinning operation)	Nuclear densiometer	Clay loam	0-15 cm	1.04	Skid Trail Use: Light .13 (13) / Moderate .17 (16) / Heavy .22 (21)	Froehlich (1976) W. Oregon
Crawler Tractor	Volumetric 100 cm³ cores	Granitic parent material	0-3.5 cm	-	Minor Skid Trail ("dry"): .11 / Major Skid Trail ("dry"): .15 / ("wet"): .65	Miles (1978) N. California
			6.5-10 cm		.10 / .04 / .53	
			13-16.5 cm		.10 / .13 / .35	
			19.5-23 cm		.11 / .18 / .40	
Low ground pressure track vehicle FMC-model 200CA	Double probe nuclear densiometer	Mt. Hood sandy loam 43% moisture (by wt)	0-1 cm	.65	Trafficking Events (1-3) / (6-10) / (15-20) / (50-100) .38(58) / .41(63) / .47(72) / .59(90)	
			at 25 cm	.88	.08(9) / .04(5) / .07(8) / .02(2)	
		Maheur sandy loam 13% moisture (by wt)	0-1 cm	1.09	.12(11) / .15(14) / .16(15) / -	Froehlich (1978) W. Oregon
			at 25 cm	1.06	0 / -.05 / .02(2) / -	
		Umpqua sandy loam 29% moisture (by wt)	0-1 cm	1.06	.03(3) / .02(2) / .03(3) / .27(25)	
			at 25 cm	1.16	.02(2) / -.03 / 0 / .17(15)	
D-6 crawler tractor (after logging and slash piling)	Nuclear Densiometer	Clay	0-10 cm		Control Bulk Density g/cm³: 1.42 / Treatment Bulk Density (1 pass): 1.56 (10) / Control Bulk Density g/cm³: 1.20 / Treatment Bulk Density (3-5 passes): 1.61 (34)	Davis (1978) W. Montana
			0-38 cm		1.45 / 1.45 / 1.56 / 1.67 (7)	
Logged 2-25 years earlier (average of 29 sites)	Saran-clod	Volcanic ash-loess (silt loam)	10 cm	.95	Skid Trails: .21(20)	Kuennen, et al. (1979) N.W. Montana
			20 cm	1.07	.17(15)	
		Glacial till	40 cm	1.63	.07(4)	
Tractor logged	Volumetric core	Medium texture	0-1 cm	.66	Mineral soil exposed: .11 (17) / Compacted: .22 (34)	Dyrness (1965) W. Oregon
Rubber-tired Skidder	Volumetric core	Sandy, developed in Granite	0-15 cm	-	On Skid Trails: Tree Length Skidding: 5% / Full Tree Skidding: 11%	Mace (1970) N. Minnesota
Rubber-tired Skidder	Volumetric core	Cutfoot series sandy loam	0-1 cm	-	Bulk density* (g/cm³) / Skid Trail Use: Light / Medium / Heavy	Mace, et al. (1971)
			1-2 cm		1.28 / 1.40 / 1.40	N. Minnesota
Rubber-tired Skidder	Volumetric core	Sandy loam	Surface few centimeters	.91	Trafficking Events: 1 / 3 / 6 / 10 .13(14) / .24(26) / .30(33) / .32(35)	Hatchell, et al. (1970) Atlantic Coastal Plain
Rubber-tired Skidder	Volumetric (200 cm³ core)	Various loamy sand to silty clay loam	0-5 cm	1.29	Logged "wet" - sampled under wheel ruts: .26(20)	Dickerson (1976) N. Mississippi

*Values represent actual bulk density, not bulk density increases.

results presented for secondary or minor skid trails. On this basis increases in bulk density ranging from 0 to .38 g/cm^3 might be expected in the surface 15 cm as exemplified by the studies of Steinbrenner (1955), Steinbrenner and Gessel (1955), Aulerich, et al. (1974), and Froehlich (1978). Similarly in the 15- to 30-cm depth increment increases of 0 to .11 g/cm^3 are reported by Steinbrenner and Gessel (1955), Miles (1978), Aulerich et al. (1974), and Froehlich (1978).

Persistence and Natural Amelioration of Compacted Soils

Soil compaction may be ameliorated by natural forces including wetting and drying, freezing and thawing, shrinking and swelling, and the growth of plant roots (Chancellor, 1977). Several studies have attempted to determine how long and to what extent compaction persists. Thorud and Frisell (1976) reported complete recovery in the surface 7.5 cm of a sandy loam soil artificially compacted by tampers in northern Minnesota. Soil bulk density decreased .31 g/cm^3 to the pretreatment bulk density after 8.75 years. Most of the recovery took place in the first 5 years. No recovery was measured in the 15- to 23-cm zone which had been increased in bulk density by .14 g/cm^3 (10%).

Hatchell and Ralston (1971) developed a predictive equation, based on 5 years of observations in Virginia. They assumed both a linear relationship of recovery with respect to time and that all soil

textures recovered at the same rate. They predicted 18 years for complete recovery of heavily compacted log decks in a variety of soil textures (loam, silt loam, silty clay loam, and clay loam). Similarly, Dickerson (1976) monitored the recovery of soil compaction for 5 years in the top 5 cm under wheel ruts in northern Mississippi. Using linear regression analysis he predicted that soils compacted to 1.55 g/cm^3 (20% increase) would take 12 years to recover completely.

Akram and Kemper (1979) suggest, based on a lab study, that most amelioration takes place in the first wetting and drying or freeze-thaw cycle. They propose that the relationship is not linear. Moehring (1970) indicated that the amount and type of clay is an important factor influencing compaction persistence. He stated that compaction seemed less permanent in fine textured soils dominated by expanding clays than in non-expanding sands or silts.

Mech, et al. (1967) found that 4 years of wetting and drying cycles, including extreme frost heaving, did not increase porosity in a naturally compacted layer. Similarly, Larson and Allmaras (1971) reported a study by van Ouwerkerk (1968) in which amelioration of compaction was not observed in an artificially compacted sandy loam soil at depths of 7-12 cm, 18-23 cm, nor at 23-28 cm. The study was conducted over 4 years and freezing and thawing occurred at least annually.

Froehlich and Berglund (1976), using a nuclear densiometer, inferred that compaction had persisted in the top 15 cm on 2 of 5 sites, for 6 to 12 years. On these two sites soil bulk density was .08 g/cm^3 (7%) and .17 g/cm^3 (18%) higher than the undisturbed bulk density. Textures of the recovered sites were loam and sandy loam. The unrecovered soils had clay loam and sandy loam textures. At these same sites bulk densities in the 0- to 30-cm depth increment averaged .11 g/cm^3 higher than the undisturbed bulk densities. The authors concluded that compaction had persisted at the 15- to 30-cm depths for as long as 12 years and suggested that 35 to 40 years might be necessary for complete recovery by natural forces. Perry (1964) estimated that complete recovery of infiltration rates might take as long as 40 years on severely compacted logging roads in North Carolina.

Thorud and Duncan (1972) concluded that soil compaction, in the absence of insulating litter and snow, might induce deeper and more severe freezing than on undisturbed plots. Geographic regions which are characterized by deep soil freezing and lack of persistent snow cover increase the likelihood of natural recovery. Larson and Allmaras (1971) concluded that freezing and thawing tends to decrease the porosity in loose soil and increase the pore space in compact soil.

In northwestern Montana, Kuennen, et al. (1979) reported average increased bulk densities on sites that had been logged 2 to 25 years earlier. However, effects were not evaluated based on time since

logging. Soils were similar to those evaluated in this study. Similarly, Cullen (1981) reported ". . . no statistically significant differences attributable to age of harvest unit were found in infiltration, soil water retention, or bulk density." In other words, the effects of soil compaction were not ameliorated over the range of time investigated. Sites were grouped by age as "young" (0-4 years since harvest), "medium" (5-9 years since harvest) and "old" (10-17 years since harvest). Cullen investigated soils similar to those monitored by Kuennen, et al. (1979) and to soils at two sites (AQT and ALT) in this study.

In summary, deeper compaction may persist longer than shallow compaction. Although complete recovery has been hypothesized to take as long as 35-40 years, (Perry, 1964), this is largely based on extrapolation of data and to date has not been conclusively documented in field studies. Recovery rates in differing soil textures and climates are likely to be vastly different. Low clay contents and persistence of snow cover may largely reduce the potential for short term natural recovery in northwestern Montana. The significance of complete recovery as opposed to partial recovery must be evaluated in terms of our knowledge about the effects of compaction on tree growth.

Effects of Mechanized Forest Harvesting Equipment on Soil Porosity

Although increased bulk density is by definition a decrease in total porosity, the effect of compaction on pore size distribution may be of greater significance. Soil pore size distribution has been shown to be an important factor affecting air and water availability to plant roots. The relative proportion of macropores (aeration pores) and micropores (pores which hold water against the force of gravity) vary widely with soil texture and structure (Archer and Smith, 1972; Baver, et al., 1972). Archer and Smith (1972) stated that pore sizes holding water in the plant available range (.1-15 bars) and larger pores are those most significantly influenced by compaction. Macropores tend to be converted to micropores during the compaction process (Hill and Sumner, 1967). For most soil textures increases in bulk density will increase the number and volume of micropores while simultaneously decreasing the number and volume of macropores (Archer and Smith, 1972). An increased proportion of micropores makes a soil behave as if it were of finer texture, therefore plant available water may be increased by compaction (Grecean and Sands, 1980). Continued compaction will, however, ultimately reduce total porosity to a point where the decrease in total porosity dominates over the increase in the proportion of micropores. At this point the available water holding capacity also decreases (Hill and Sumner, 1967). The point at which this occurs is largely dependent upon soil

texture and the distribution of particle sizes. Available water holding capacity may be more easily reduced in well graded soils than in poorly graded soils (Hill and Sumner, 1967).

Steinbrenner and Gessel (1955) evaluated the effects of tractor logging on porosity in the top 7.5 cm on skid trails at nine sites. They used .05 bars tension to delineate macropores from micropores using 7.5 cm field cores. They reported an average decrease of 53% in macroporosity amd an increase of 5% in microporosity. Average total macropore space was reduced to 6.4%. In a similar study Steinbrenner (1955) demonstrated 44 and 77% reductions in macropore space in soils logged "wet" and "dry" respectively after 10 trafficking events by an HD-20 crawler tractor. Ninety percent of the reduction occurred in the first two passes on the "wet" soil. The decrease was linear in the "dry" soil. In both cases aeration porosity was reduced to slightly less than 10%. Vomocil and Flocker (1961) concluded that air filled porosity values of less than 10% (when the soil is at field capacity) can be expected to restrict root growth. Dickerson (1976) reported macropores were reduced by 68% in wheel rutted soils and 38% in log disturbed soils. He used .06 bars tension to differentiate macropores from micropores. Micropore space increased by 7% in both cases (in the surface 5 cm). Skidding reduced aeration porosity to 4% under wheel ruts and to 9% under log disturbed soils. In a lab study, conducted by Foil and Ralston (1967), soil cores were extracted from

the top 12.5 cm of three soil textures (sand, loam, and clay) and subsequently subjected to static compaction in molds under a 3.5 kg/cm^2 (50 psi) load. Macropores were differentiated from micropores at .06 bars tension. Macroporosity decreased 45, 71, and 82% while microporosity increased 13, 24, and 10%, respectively for the sand, loam, and clay. Aeration porosity was reduced to 11.6, 6.7, and 3.3% of total porosity for each texture, respectively.

Kuennen, et al. (1979), using an air permeameter, evaluated macroporosity on 29 logged soils in northwestern Montana. Soils were similar to those used in this study. They reported average reductions of macroporosity of 40, 56, 30, and 0% at 1, 15, 25, and 30 cm, respectively. Similarly Cullen (1981) demonstrated statistically significant reduction in soil water holding capacity due to logging activities in northwestern Montana (Table 3). He evaluated soil water held at .02, .1, and .33 bars tension at 15 cm depth increments to 45 cm and at the middle of deeper horizons. Cullen reported reductions in water content of all three potentials only in the B2ir ash-loess surface horizon (at 15 cm depth) overlying limestone and quartzite tills. Average magnitudes of reduction in water holding capacity (for all three potentials) ranged from 15.5 to 23.2% (by wt) for the moderately and severely disturbed skid trails respectively, at the limestone till sites. Reductions in water contents of the B2ir horizons at the quartzite till sites similarly decreased by 12.3 to 16.9% (by wt). In

Table 3. Water content at .02, .1, and .33 bars soil water tension of major horizons in soils forming in limestone and quartzite dominated glacial tills and available water holding capacity as influenced by trafficking.

Site	Horizon	Depth (cm)	Water Tension (Bars)	Water content held at indicated tension (percent by weight) Control	Moderately Disturbed Skid Trails	Severely Disturbed Skid Trails
Ash-loess Overlying limestone Till	B2ir	15 cm	.02	82.9	65.3*	59.7**
			.10	78.3	62.0*	55.3**
			.33	73.9	58.6*	53.9**
			Available water holding capacity (.33 bars to 15 bars)	32.2	17.8 (45% reduction)	15.3 (53% reduction)
	IIA2	30 cm	No statistically significant changes in water content nor available water holding capacity at this depth or deeper.			
Ash-loess Overlying Quartzite Till	B2ir	15 cm	.02	57.6	43.1#	43.0#
			.10	50.9	38.6#	38.6#
			.33	47.8	33.4#	30.9#
			Available water holding capacity (.33 bars to 15 bars)	59.2	43.8 (26% reduction)	39.1 (34% reduction)
	IIA2	30 cm	No statistically significant changes in water content nor available water holding capacity at this depth or deeper.			

*Difference from control significant at p = .05.
**Difference from control significant at p = .01.
#Difference from control significant at p = .10.

the same study, Cullen also noted reductions in "available water holding capacities" (AWHC) only in the B2ir horizons measured at 15 cm depth. At the limestone till sites he reported 45 and 53% reductions in AWHC, respectively, on moderately and severely disturbed skid trails. Similarly he reported 26 and 34% reductions in the AWHC of the B2ir horizons (at 15 cm depth) overlying quartzite glacial till. Table 3 (after Cullen, 1981) presents results of both determinations, which are relevant to soils evaluated in this study.

Under "wet" conditions loading may induce puddling which alters or destroys pore continuity with or without changes in bulk density. Foil and Ralston (1967) evaluated bulk density changes with respect to puddling in the lab. Undisturbed soil cores of three textures were wetted to .06 bars tension, allowed to drain for 12 hours, and subjected to kneading (puddling) and subsequent load application (150 psi). Bulk densities were compared to soil cores treated identically except for the puddling treatment. They found bulk density decreased in the Bayboro clay by .19 g/cm^3 and in the Coxville loam by .08 g/cm^3. However, bulk density in the Lakeland loamy sand increased by .10 g/cm^3. They attributed this result to greater capillary retention of water in the finer textured soils, leaving water filled pores to resist compaction. Macropore volume increased by 1 and 2.5% for the clay and loam textures but decreased by 4% in the loamy sand. Micropore volume increased by 5% in all textures.

Because compaction reduces the volume of macropores, infiltration rates and saturated hydraulic conductivity decreases. Since compaction often increases the proportion of micropores, the reduction in unsaturated hydraulic conductivity is usually less extreme (Grecean and Sands, 1980). According to Kemper, et al. (1971) and Sands, et al. (1979) unsaturated water flux may even increase.

In summary, the physical properties of soil affect the rate at which water, nutrients, oxygen, and heat move in response to potential gradients. According to Eavis and Payne (1968),

> .... reduced rates of movement through a porous body are due to the reduced cross-sectional area available for gas movement or to the reduced cross sectional area of the individual pores in the case of water, and is also due to the increased path lengths imposed by the geometric arrangement of the solid material.

Greenwood (1969) states that the distribution of oxygen in soil will be dominated by the surface area of the gas-phase water saturated soil interface and

> ... thus will be critically dependent on the size of the gas filled pores. In consequence, the minimum gas filled pore space necessary to prevent growth from being restricted by lack of oxygen will be greater when the pores are larger than when they are small.

When the soil is loose, the pores are larger (less surface area per unit volume) than when soil is compact. He states "... the minimum gas space necessary to supply sufficient oxygen for growth will be larger in uncompacted soils than in compacted soils."

Effects of Mechanized Forest Harvesting Equipment on Infiltration Rates

Several investigators have evaluated water infiltration rates as affected by logging activities. Infiltration rates are significant with respect to identifying soil erosion potential. If rainfall exceeds a soil's infiltration rate, subsequent overland flow may cause soil erosion. Additionally, small increases in bulk density have been correlated with drastic reductions in infiltration rates. Therefore, infiltration rates may be a more sensitive indicator of soil disturbance than bulk density under light trafficking which characterizes slash piling. Soil surface sealing and pore continuity may also be evaluated by comparative infiltration measurements (Chancellor, 1977).

Steinbrenner and Gessel (1955), evaluated infiltration rates by extracting 7.5 cm core samples of trafficked soils from the field and assessing infiltration in the lab. They reported that an average 15% increase in bulk density resulted in a 93% average reduction in infiltration rate. Using the same methodology, Steinbrenner (1955) recorded 98 and 90% reductions in infiltration rates after 10 trips of an HD-20 crawler tractor over a forest soil logged "wet" and "dry", respectively. Ninety-seven percent of the reduction occurred during the first two trips on the "wet" soil, where bulk density increased only .05 g/cm^3 (5%). The same magnitude of reduction was not measured on the "dry" soil until eight trafficking events had occurred. The

corresponding increase in bulk density was .25 g/cm^3 (43%). Kuennen, et al. (1979) reported an average 50% reduction in field infiltration rates compared to controls on 29 logged sites, 2-25 years old, in northwestern Montana. They evaluated infiltration using double ring infiltrometers.

Johnson and Beschta (1980), using a rainfall simulator infiltrometer, reported a 50% decrease in infiltration rates on clay soils trafficked during tractor logging 3 to 6 years earlier. They attributed this reduction to surface sealing caused by dislodgement of silt and clay particles by raindrops and subsequent plugging of macropores.

Akram and Kemper (1979) found similar drastic reductions in infiltration rates on sieved soils of various textures (sandy loam, clay loam, and silty clay) that had been compacted in the lab by a hydraulic ram. Compacting loads of 50 psi, applied to soils of sandy loam and finer texture at field moisture capacity, reduced infiltration rates to less than .1% of values obtained after these soils had been compacted air dry. These reductions were associated with bulk density increases of .2 to .4 g/cm^3. They found compaction was greatest and infiltration rates least when soil was compacted near its field moisture capacity.

Mace, et al. (1971) reported that an increase in bulk density of .1 g/cm^3 was as effective in reducing infiltration rates as an increase

of .5 g/cm^3. He stated that once the macropore structure is altered, increased compaction reduces infiltration rates very little.

Cullen (1981) reported significant reductions in the total volume of water entering three soil types characteristic of extensive land areas in western and northwestern Montana. Volumes entering soils over a 60-minute period were measured using a double ring infiltrometer. Sites had been logged 3 to 17 years earlier. He reported reductions of 78 and 81% relative to control volumes on moderately and severely disturbed skid trails, respectively. Corresponding increases in bulk density in the surface B2ir horizon overlying limestone till averaged .23 and .36 g/cm^3 for moderately and severely disturbed skid trails, respectively. Similarly, in the ash cap overlying quartzite till, volumes entering were reduced by 75 and 79% on moderately and severely disturbed skid trails, respectively. Corresponding bulk density increases in the surface B2ir horizon overlying quartzite till were .02 and .37 g/cm^3 on moderately and severely disturbed skid trails, respectively. On high clay soils formed in Tertiary volcanic parent materials reductions of 42 and 87%, on moderately and severely disturbed skid trails respectively, were reported. Corresponding bulk density increases measured in the surface A2 horizons of 15 cm depth were .23 and .28 g/cm^3 on moderately and severely disturbed skid trails, respectively.

Effects of Soil Compaction on Plant Growth

Field personnel in northwestern Montana have indicated through qualitative visual observations that soil compaction, incurred during logging, has resulted in the modification of root morphology in young naturally regenerating tree seedlings (Martinsen, 1979; Kuennen, 1979). Additionally, studies in this area have demonstrated increases in bulk density, decreases in macropore space, and reductions in infiltration rates caused by logging equipment (Kuennen, et al., 1979; Cullen, 1981; and Bates, 1981). However, quantitative information relating the physical properties compacted soil to tree growth in northwestern Montana is lacking. Potentially adverse effects of soil compaction have been extrapolated to economically important tree species of northwestern Montana based on more quantitative associations established elsewhere (Table 4). These studies have evaluated this relationship on a variety of differing soil textures and parent materials not commonly found in northwestern Montana. Although correlative associations have been observed for a variety of tree species, many of these are not indigenous to northwestern Montana. Additionally, climatological and environmental settings of the various studies reviewed undoubtedly vary significantly from those found in this area.

Reductions in tree height growth as high as 42% have been reported on severely compacted skid trails (Youngberg, 1959). Froehlich (1976) reported a 21% decrease in height of seedling Pseudotsuga menziesii

Table 4. A summary of studies evaluating soil compaction effects on tree growth.

Tree Species	Type and Duration of Study	Soil Texture	Results	Source and Study Location
Pinus taeda	Field Trees planted 26 years earlier	-	Growth after 26 years Control / Old Road Ruts Mean dbh*: 3.4 cm / 2.5 cm (28%) decrease Mean height: 18.9 m / 15.6 m (13%) decrease Mean volume: .25 m^3 / .12 m^3 (53%) decrease	Perry (1964) N. Carolina
Pseudotsuga menziesii	Field Five plots thinned 7-15 yrs earlier	Clay loam, Loam, Sandy loam	Site Disturbance / Percent of Root Soil Trafficked / Increase in Bulk Density / Percent of trees having slower growth rates after thinning compared to before thinning. Heavy: ≥ 40% / ≥ 10% / 60% (a 30% reduction in basal area growth) Moderate: < 40% / 0 to 10% / 14% (a 14% reduction in basal area growth) Light: < 10% / - / 4% / -	Froehlich and Berglund (1976) W. Oregon
Pseudotsuga menziesii	Field Planted tubling Douglas-fir 5 years earlier	Jory clay loam	Trafficking Events: 0(control) / (1-3) / (6-10) Bulk density (g/cm^3): .92 / .93 / 1.01 (10% increase in top 15-23 cm) Height growth: - / - / (11.2%) decrease	Froehlich (1976) W. Oregon
Pseudotsuga menziesii	Field Planted tubling Douglas-fir 4 years earlier	McCully sandy loam	Bulk density (g/cm^3): .87 / .92 (6% increase) / .97 (11% increase) Height growth: - / (11% decrease) / (21% decrease)	
Pinus taeda	Field Effects on wet logging evaluated 5 years after trafficking on 40 year old trees	Silt loam	Treatment - dragged a load of logs 6 times on 1,2,3,4 sides of trees soil disturbance on number of (n) sides of trees:n = 1 2 3 4 growth volume reduction = 0 13.7% 36.3% 43.4%	Moehring and Rawls (1970) Arkansas
Pseudotsuga menziesii	Field In 1955 planted 2-0 bareroot seedlings. Evaluated after 1 and 2 growing seasons	Clay	Control Plot: B.D.** (.88-.90); Height of seedlings 1955 .94 cm; 1956 2.68 cm Skid Trail Ruts: B.D.** (1.52-1.73); Height of seedlings 1955 .65 cm (31% decrease); 1956 1.55 cm (42% decrease) CONCLUSION: Inadequate aeration. N deficiency caused by low soil moisture and aeration inhibiting mineralization of organic N.	Youngberg (1959) Pacific Northwest
Pinus contorta Pseudotsuga menziesii Alnus rubra Thuja plicata Picea sitchensis Tsuga heterophylla Abies amabilis	Greenhouse Planted seeds in artificially compacted soil. Evaluated after 2 years.	Sandy loam artificially compacted to: 1.32 g/cm^3, 1.45 g/cm^3, 1.59 g/cm^3	B.D.** 1.32 - roots of all species grew through compacted cores 1.45 - Pinus contorta, Pseudotsuga menziesii, and Alnus rubra grew through cores; all others were inhibited 1.59 - no species penetrated compacted cores	Minore, et al. (1969) Pacific Northwest
Pinus taeda	Greenhouse Planted seeds in extracted field cores that were subsequently artificially compacted. Evaluated after 1 year	Lakeland loamy sand, Coxville loam, Bayboro clay	TREATMENTS: cores compacted by (1) 3.5, 7.0, and 10.5 kg/cm^2 static pressure (2) 10.5 kg/cm^3 static pressure and puddled - All treatments reduced size and weight of seedlings - root weight (r^2 = .57) and root length (r^2 = .68) were linearly related (negatively) to soil density in the range .8 - 1.4 g/cm^3 regardless of soil texture - germination not inhibited - many seeds failed to survive because radicle could not penetrate the dense soil	Foil and Ralston (1967) Atlantic Coastal Plain

*dbh = Tree diameter breast high.
**B.D. = Bulk density in g/cm^3.

corresponded to a .09 g/cm^3 (11%) increase in soil bulk density. He proposed that a 1% increase in soil bulk density predicts a .67% decrease in seedling height growth. He also proposed that the relationship appears to be linear as bulk density increases from 0 to 80% relative to control values. Data presented by Perry (1964) indicate that reduction in growth volume is a more sensitive index of compaction effects than is height. He evaluated growth reductions in Pinus taeda planted 26 years earlier on logging roads. He found a 13% reduction in height but a 53% decrease in timber volume. Moehring and Rawls (1970) similarly found volume reductions ranging from 13.7 to 43.4% in Pinus taeda with trampled root zones. Some researchers have indicated that relatively minor increases in bulk density (10%) may decrease productivity (Froehlich, 1976; Froehlich and Berglund, 1976). However the validity of extrapolating these correlations to the soils of northwestern Montana is questionable for additional reasons discussed below. Table 4 presents a summary of studies which have evaluated the effects of soil compaction on tree growth.

Rosenberg (1964) reported that compaction effects on growth are a complex interaction between soil strength, water and nutrient availability and aeration. Russell (1977) further defined the impacts on soil properties stating that compaction reduces the volume of large diameter pores, which may cause greater mechanical resistance or impedance to root extension, reduction of gas exchange between the

soil and atmosphere, and changes in soil water holding characteristics. "All these effects modify root growth, and as they can be experienced simultaneously, when a soil is compacted, it is often difficult to distinguish unequivocally between them." (Russell, 1977).

The majority of studies relating compaction to productivity have investigated compaction effects on root growth of agricultural crops. However, principles derived from agronomic investigations may have considerable applicability to tree species. Russell (1977) stated that ideal conditions for plant growth are not necessarily those which lead to the maximum proliferation of roots. He indicates that very restricted root systems can support considerable shoot growth if other conditions are favorable (e.g., aeration, adequate water, and nutrient levels). However, if these conditions are unfavorable, then soil conditions which restricts the proliferation of roots is a primary factor decreasing shoot growth and yields (Grecean and Sands, 1980). The effects of soil compaction on root growth may have considerably more importance to forest productivity where moisture and nutrient levels are largely beyond the control of the land manager.

Wiersum (1957) found that roots cannot grow into rigid pores which are smaller than the diameter of the root tip. Russell (1977) states that if root extension is not to be limited by mechanical impedance, then one of two conditions must be met. The solid fabric of soil must contain a sufficient number of large continuous pores or

voids between structural units (peds), or soil strength must be low enough to allow roots to push aside soil particles, effectively enlarging pores. Compaction reduces the size of pores and increases soil strength (Carter and Tavernetti, 1968). Soil strength is also greatly influenced by soil moisture (Chancellor, 1977).

Russell (1977) indicated that aeration pores are those having diameters greater than 30-60 um. He also observed that most roots are greater than 50 um in diameter. Therefore soil compaction, which primarily affects aeration pores may have a significant effect on a tree's ability to extend its roots. Although roots of some crops may be able to exert large pressures (e.g., 9 to 13 bars (131 to 191 psi), rate of root growth has been shown to decrease by as much as 50% when continuing pressures exceed .25 to .5 bars (3.7 to 7.4 psi) (Goss, 1977). Root extension may not cease completely however, until the confining pressure equals the turgor pressure of the extending root cells (Russell, 1977). In soils of "low" strength, stresses necessary to enlarge pores may be so small that irrespective of pore size, root penetration occurs easily (Barley, 1954; Gerard, et al., 1972).

Changes in root morphology have been observed when mechanical impedance is a factor. Eavis (1965) using pea seedling roots found that the elongating region behind the root cap became shorter as mechanical impedance increased. The roots behind the elongating region expanded radially, resulting in shorter, thicker roots. The

number of root hairs per unit length of root also increased. Eavis stated that for the root to exert pressure on the soil, the reaction force must be taken by the stationary non-elongating portion of the root. He hypothesized that the anchorage is facilitated by the presence of abundant root hairs and suggests that a profusion of root hairs is indicative of mechanical impedance.

Several authors have indicated that voids occurring between peds are more important to root growth than pores within soil aggregates. Greenland (1979) indicates that while roots may enter some of the larger pores that occur within aggregates, they will have difficulty enlarging them (allowing root extension), unless the soil is close to field capacity. He states that roots are primarily restricted to fissures between aggregates. Russell (1977) noted that roots grow preferentially along planes of weakness in soil, especially if it is compacted. Sands, et al. (1979) demonstrated preferential penetration by Pinus radiata roots into soil pockets of low strength. Foil and Ralston (1967) found that Pinus taeda root penetration was restricted to cleavage planes between structural units in the Bayboro clay (bulk density = 1.31 g/cm^3). Grecean and Sands (1980) indicated that roots preferentially exploit structural planes of weakness in soils of high bulk densities and proposed that loss of growth may not occur if sufficient continuous voids exist in compacted soils. Russell and Goss (1974) observed that interped pores, fissures, and channels are

most easily lost during the compaction process. Baver, et al. (1972) indicated that the importance of puddling may be a reduction of porosity associated with extensive degradation of soil structure. Kuennen (1979) has reported the conversion of subangular blocky structure to platy structure under logging activities in northwestern Montana.

Bulk density measurements alone provide no quantification of soil structure, planes of weakness, nor pore continuity. Therefore the validity of inferring compaction effects on growth from bulk density measurements alone is questionable. Some authors however have reported strong correlations for some species of crops and trees on specific soil textures (Duffy and McClurkin, 1974; Rosenberg, 1964).

In any one soil the extent to which root penetration is restricted may vary closely with its bulk density, but over a wide range of soil textures there may be considerable variation. Veihmeyer and Hendrickson (1948) noted that the maximum bulk density which permitted root penetration of Helianthus annuus (double dwarf sunflower) varied from 1.46 g/cm^3 in clay to 1.75 g/cm^3 in sand. Similarly Zimmerman and Kardos (1961) found appreciable differences in the bulk densities which excluded root penetration of Glycine max (soybeans) and Sorghum sudanese (sudangrass) in a variety of soil textures. They found root penetration and bulk densities were negatively correlated in only 50%

of their comparisons. Lull (1959) and Raney, et al. (1955) concluded that a given bulk density in fine textured soils limits root growth more than the same density in coarse textured soils.

Since soil compaction primarily impacts aeration pores and some soil textures have a greater proportion of their total porosity in large voids, it is not surprising that different soil textures seem to have different "threshold" bulk densities. Foil and Ralston (1967) reported that the Bayboro clay contained 8% macropores (by volume) in its natural undisturbed state. The Coxville loam and Loveland sandy loam had 12.0% (by volume) and 25.6% (by volume) macropores. This represented 16, 24, and 45% of total porosity, respectively.

The work of a few authors has suggested critical "threshold" bulk densities for tree species beyond which roots may not penetrate (Forristall and Gessel, 1955; Minore, et al., 1969). However these investigators are quick to point out that results are probably only valid for the same species, on the same soil, under identical environmental conditions. Foil and Ralston (1967) indicated that root length and weight were linearly related (negatively) to bulk density in the range .8 to 1.4 g/cm^3 regardless of soil texture (loamy sand, loam, and clay). They reported severely restricted root and shoot growth in one year old Pinus taeda seedlings grown in extracted soil cores

compacted to 1.33 g/cm^3 in sandy loam and 1.2 g/cm^3 in loam. Differences in root growth between undisturbed clay textures (bulk density = 1.31 g/cm^3) and compacted cores (bulk density = 1.43 g/cm^3 to 1.49 g/cm^3) were not as pronounced.

Soil strength, defined as resistance to penetration, may be a more significant measure of the mechanical resistance encountered by plant roots than bulk density. Taylor and Gardner (1963) reported the correlation coefficient between root penetration and soil strength was $r^2 = -.96$, whereas a value of $r^2 = -.59$ related root penetration to soil bulk density. Soil strength increases with bulk density at a given moisture content (Chancellor, 1977). Root penetration has been shown to decrease exponentially as soil strength increases (Grecean and Sands, 1980). Although bulk density may or may not decrease as soil moisture increases (depending on the shrink-swell capacity of a soil), soil strength decreases for all but coarse textured soils (Taylor and Bruce, 1968). Taylor and Gardner (1963) indicated that the percentage of cotton taproots penetrating a fine sandy loam (bulk density = 1.60 g/cm^3) was reduced by 50% as soil water potential increased from -.2 to -.67 bars. They attributed this restriction to increasing mechanical impedance, induced by increased soil strength developed as the soil dried. They also presented data substantiating the hypothesis that there exists some "threshold" soil strength, above which roots of a given species cannot penetrate. Their data indicated

that, at less than this "critical" value, the percentage of roots penetrating may be inversely proportional to soil strength. Grecean, et al. (1969) tabulated soil strengths ranging from 8 to 50 bars (113 to 735 psi) as critical limiting values for a variety of crop species. The measurements were made using penetrometers in a variety of soil textures at bulk densities ranging from .9 g/cm^3 to 1.85 g/cm^3 at soil moisture potentials of -.01 bars to -.7 bars.

Grecean and Sands (1980) reported that it is difficult to separate the effects of reduced soil strength from the effects of increased water availability, at soil moisture tensions near field capacity. Both conditions improve root extensibility. They also indicated that trees may be less sensitive to soil compaction than annuals. There is an increased probability that tree roots may encounter wet soil of lower resistance over their relatively extended growing period.

Reduced gas exchange between soil and atmosphere, due to compaction, has been a concern to both agronomists and foresters. As stated earlier, aeration pores are those primarily destroyed during the compacting process. Generally speaking, a value of 10% air filled porosity, measured at field capacity moisture, has been established as critically reducing gas exchange (Vomocil and Flocker, 1961). Below this value detrimental effects on plant growth may be expected (Grable, 1971). However, other workers have indicated that reduction in root growth often occurs before aeration becomes a problem. Taylor and

Burnett (1964) found root impedance occurred more frequently and was more severe within the plant available moisture range, concluding that soil strength was limiting growth and not aeration. Rosenberg (1964) stated that compaction effects on plant growth need not necessarily involve impeded aeration. Warnaars and Eavis (1972) found increased soil strength caused major reductions in the root growth of Pisum sp. (peas), Zea mays (corn), and species of Graminaceae (grasses). However, they reported that aeration progressively limited root growth as aeration porosity was reduced to less than 25%.

Greenwood (1969) stated that

> "... there is no easily measurable parameter (e.g., gas filled pore space, oxygen content, or oxygen diffusion rate) that is really a satisfactory index of soil aeration status because none of these parameters is related to yield in the same way in more than a few soils."

He indicated that minimum gas filled pore space, necessary for optimum growth, depends on pore size, soil texture, soil water content, bulk density, and temperature.

Grecean and Sands (1980) indicated that trees often experience oxygen deficiency at some time during their growing season. They reported that some species are specifically adapted to tolerate low partial pressures of oxygen in the soil. Adaptations include the

development of air spaces in the root stele, whereby oxygen may be transported directly to the roots from aerial parts of the plant (e.g., in Pinus contorta) (Coutts and Phillipson, 1978).

Although it is difficult to predict the effect of soil compaction on root growth, Baver, et al. (1972) suggested the following model. Where mechanical impedance is minor, oxygen content determines root elongation. At high mechanical impedance roots do not elongate regardless of soil oxygen. At a given oxygen content root elongation decreases logrithmically with increased soil mechanical impedance. Additionally, where aeration is not limiting, root elongation at a given bulk density depends on soil moisture tension. The higher the tension, the lower the percentage of root penetration. These authors suggest that only aeration and soil moisture restrict growth in a low density soil (e.g., bulk density = 1.0 g/cm^3) where mechanical impedance is not a factor. Mechanical impedance seems to become more important as bulk density increases (e.g., bulk density = 1.4 to 1.6 g/cm^3). Since poor aeration effects are more strongly expressed at soil matric potentials less than .1 bar, mechanical impedance is the major factor restricting root elongation at or above this matric potential. Moisture stress effects may be linked with mechanical impedance at higher tension values.

Similarly, it is difficult to predict the effect of soil compaction on plant growth because of the variation in species tolerance.

Rosenberg (1964) indicated that the limiting factor(s) depend(s) on soil type, climatic conditions, plant species, and possibly upon stage of plant development existing when roots encounter compacted soil conditions. Rosenberg stated ". . . whether a given density will hamper or improve plant growth depends on whether the soil is looser than or more compact than the optimal density for the season and stage of growth of the crop growing in the soil." Grecean and Sands (1980) proposed that for each soil type and species ". . . there exists a critical albeit ill-defined soil strength above which root penetration effectively ceases." However, if root growth is restricted, this does not necessarily mean that stem growth will also be reduced, providing that air, water, and nutrients are in plentiful supply (Taylor and Bruce, 1968). Conversely, in a dry year the inability of roots to explore additional soil volume may reduce yields. The relationship between root growth, soil strength, and timing of root growth is largely unknown for forest tree species (Greacean and Sands, 1980).

Although compaction usually decreases growth it may also increase growth. Slight compaction may increase water holding capacity and unsaturated hydraulic conductivity, and improve nutrient ion diffusivity. However, there is a point where compaction may become so severe as to destroy pore continuity and increase the tortuosity of diffusion paths (Grecean and Sands, 1980). This critical point is most likely different for each soil texture, climate, and species.

Because of these complexities, extrapolating compaction-growth interactions from one species environment to another is probably not appropriate. However certain trends do exist. Grecean and Sands (1980) surveyed the literature between 1970 and 1977 dealing with the effects of compaction on plant growth and reported as follows: there were 117[24], 12[1], 8[0], and 5[1] studies showing yield reduction, yield increase, both yield reduction and increase, and no effect on yield, respectively. The bracketed numbers refer to the number of tree species.

In the literature reviewed, and with the exception of studies reported by Perry (1964) and Froehlich and Berglund (1976), compaction tree growth interactions were evaluated within 5 years of treatments. This represents an extremely short time frame in comparison to the rotation length of most tree species. Similarly, Hassan (1978) noted the unavailability of long-term studies relating compaction to tree growth. Additionally, most studies have evaluated tree seedling responses rather than compaction effects on mature timber. In comparison to the agricultural setting, soil impacts incurred under logging equipment may be extremely variable in lateral and vertical extent. This may be an important attribute of species tolerance.

MATERIALS AND RESEARCH METHODS

Site Selection

The study area is located approximately 50 km west of Kalispell, Montana, and several kilometers north of Montana Highway 2 (Fig. 1). Five study sites were selected in the Champion Timberlands Pleasant Valley Management District (Fig. 2). U. S. Forest Service Soil Scientists helped in the identification and selection of soil types to be studied. The sites were selected as being representative of extensive timber producing soils in northwestern Montana and on the basis of relative susceptibility or insusceptibility to compaction. It was hypothesized that soils with shallow glacial till horizons would be most susceptible, especially to compacting vibrations, that lacustrine soils would be insusceptible due to their poorly graded particle size distribution, and that the volcanic ash over residuum soils would be insusceptible due to their high coarse fragment content. The five soil types evaluated in this study are as follows:

1. Volcanic ash overlying quartzite glacial till (AQT)
2. Mixed volcanic ash, lake sediments, and glacial till (MIX)
3. Lacustrine sediments (LAC)
4. Volcanic ash overlying limestone glacial till (ALT)
5. Volcanic ash overlying calcareous argillite residuum (AAR)

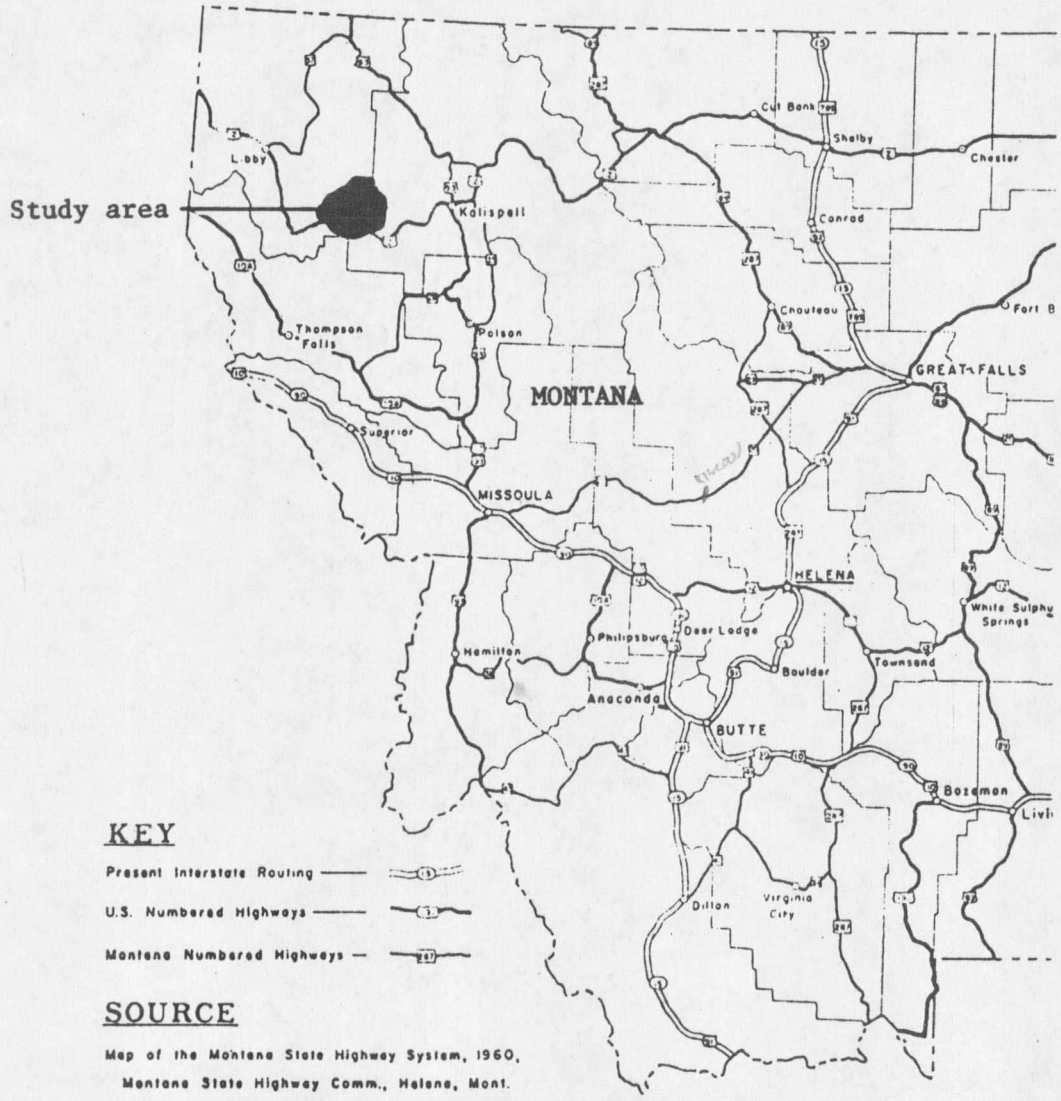


Figure 1. Map showing location of study area.

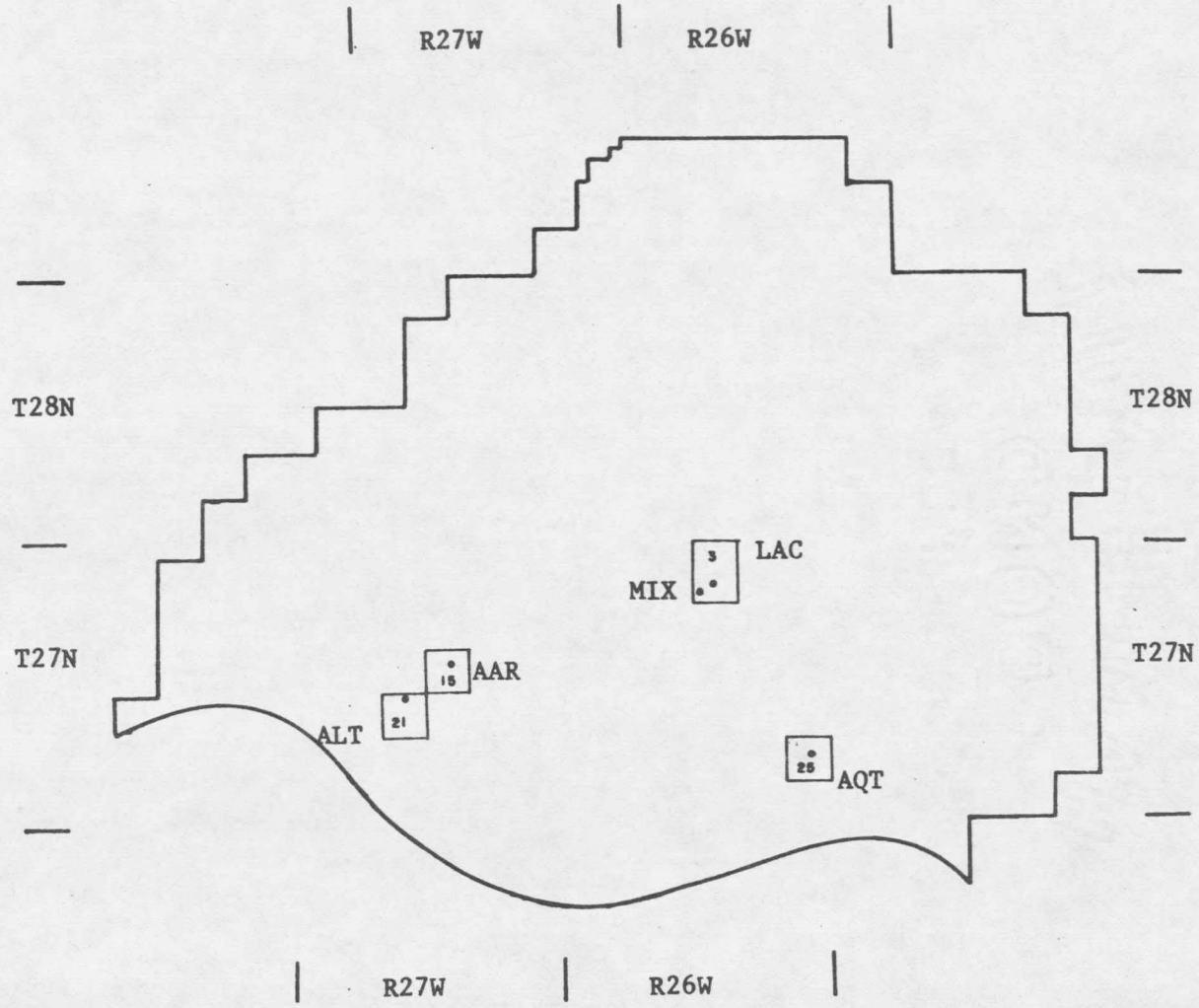


Figure 2. Map showing locations of individual study plots.

Soil Classification and Site Characteristics

Each site was characterized for geomorphology and bedrock geology. A representative soil profile at each site was described and classified according to standards outlined by the Soil Survey Staff (1975). The forest habitat type was identified at each site according to (Pfister, et al., 1977). One hundred measurements of duff thickness (01 and 02 horizons) were accomplished by random sampling throughout the cutting unit at each site. Values reported in the soil profile descriptions for each site are means of these measurements. These data are summarized for each site in Appendix I.

Plot Layout

One 1.08 hectares (2.67 acres) study plot representing each soil type was selected based on soil and topographic uniformity. Sites AQT, ALT, and AAR had no previous logging history. Sites MIX and LAC had been logged 60 to 80 years earlier. Additionally, cattle were frequently seen at these two sites. Old access roads, skid trails, and obvious livestock paths were flagged and avoided during sampling. The study plot at sites AQT, LAC, ALT, and AAR was a 180 x 60 m rectangle oriented with the long axis running upslope. Two designated skid trails were flagged 15 m on each side of the plot center line running parallel to the 180 m axis (Fig. 3). Each plot was divided in half perpendicular to the slope, leaving two rectangular subplots of

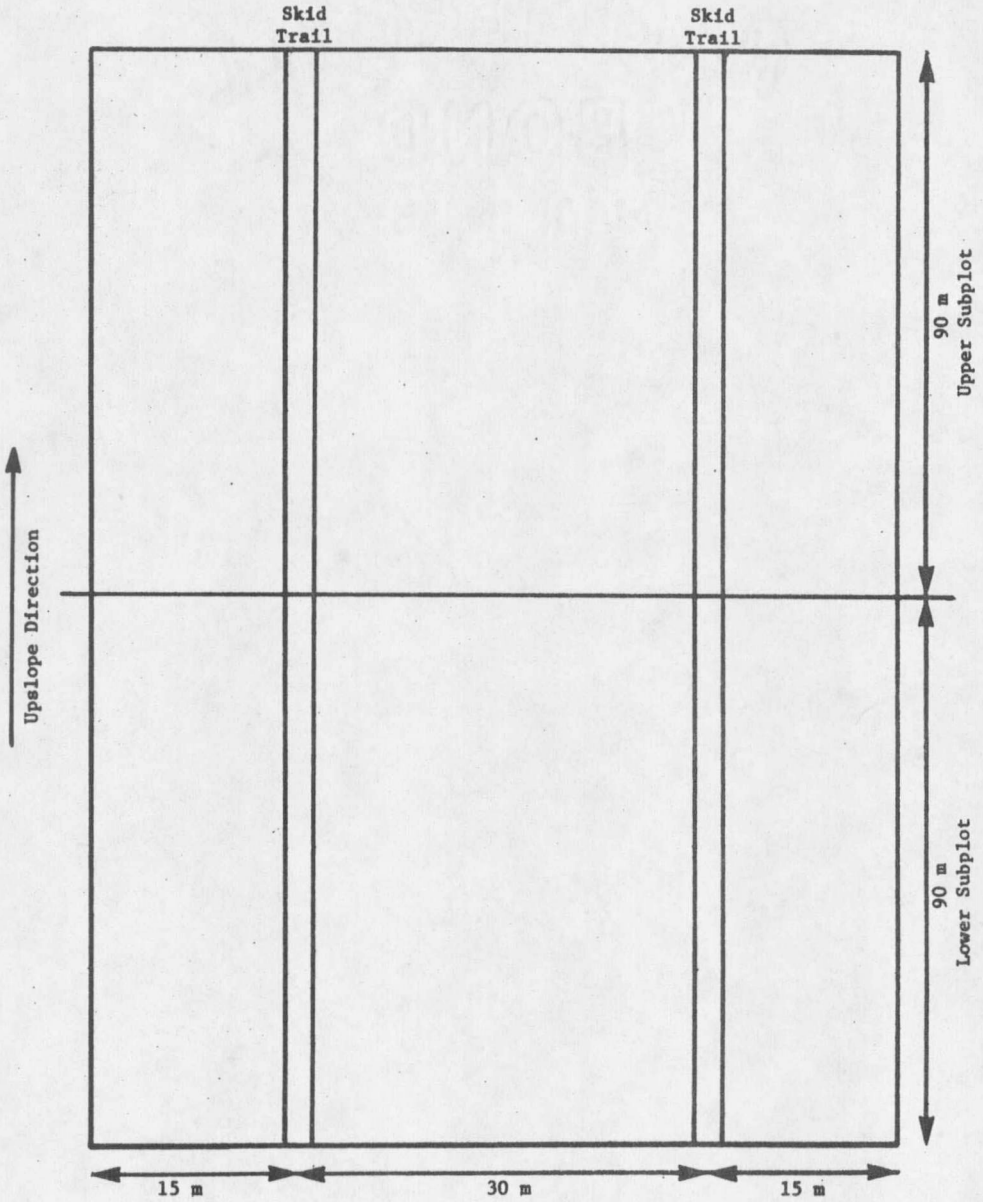


Figure 3. Schematic diagram of plot layout at sites AQT, LAC, ALT, and AAR.

90 m x 60 m dimensions. The entire plot was utilized for slash weight, soil disturbance, and slash piling measurements. Identical subplots were utilized for pretreatment and treatment bulk density and infiltration measurements. Due to the ease of access, the upper subplot was sampled at sites AQT and LAC, and the lower subplot was sampled at sites ALT and AAR.

The study plot at site MIX was a 120 x 90 m rectangle with the long axis oriented perpendicular to the slope. The 120 m axis was bisected parallel to the slope leaving two side by side plots of 60 x 90 m dimensions. On each of these subplots two skid trails were flagged 15 m on each side of the centerline running parallel to the 90 m axis. As a result there were four designated skid trails at this site (Fig. 4). The right hand plot was designated for control and treatment bulk density and infiltration measurements.

Trafficking Associated with Slash Pile Construction

The number of trafficking events associated with slash pile construction was visually monitored for individual slash piles. The construction of 11 to 18 slash piles was monitored at each of the five sites.

A trafficking event is defined as one pass over the ground by the crawler tractor. Moving forward and then backing up on the same path

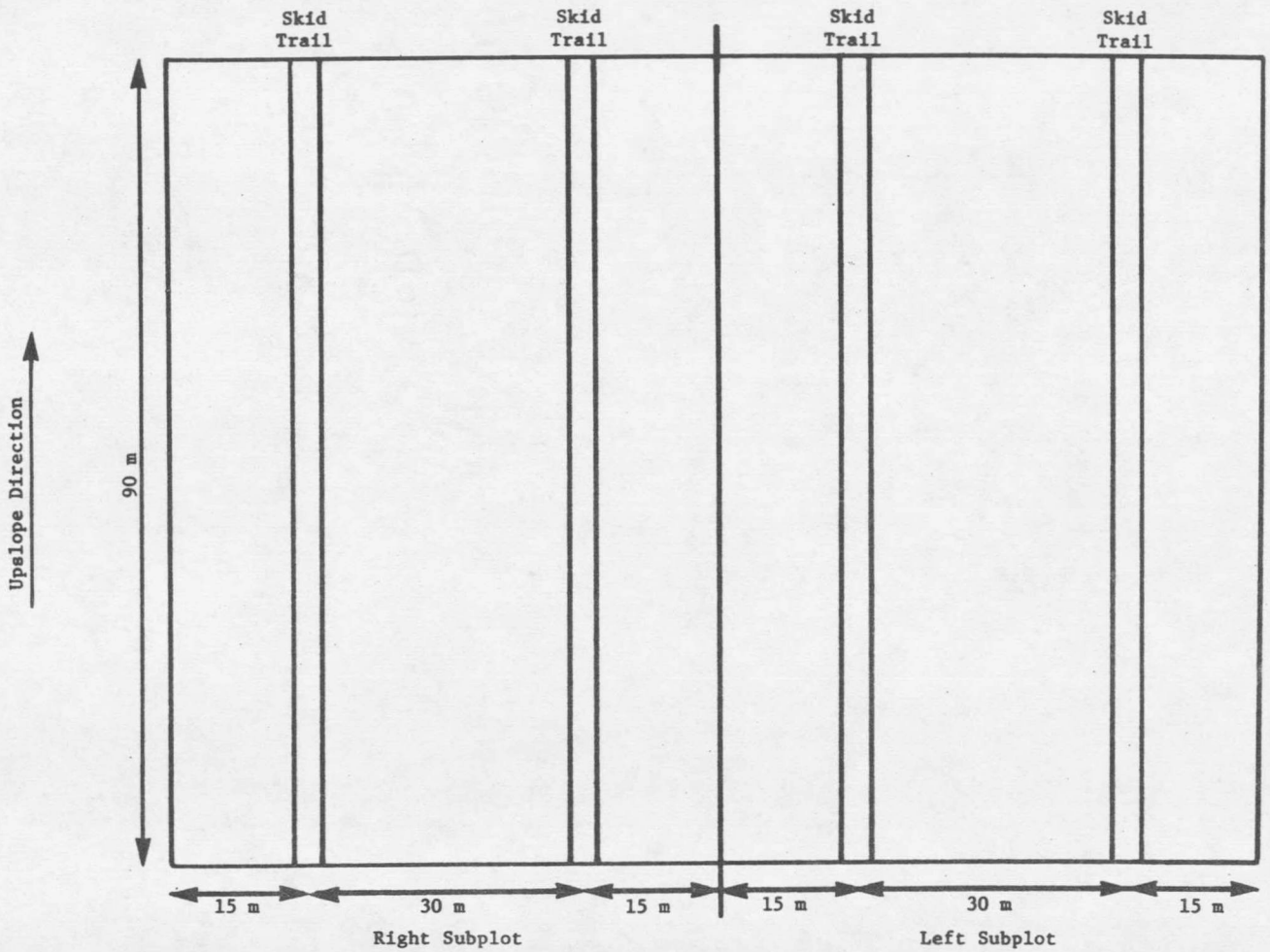


Figure 4. Schematic diagram of plot layout at site MIX.

constitutes two trafficking events. The average intensity of site trafficking on disturbed areas was inferred through these observations.

Site Disturbance Incurred During Slash Pile Construction

After slash piling, site disturbance was quantified by line intercept sampling. Sampling methodology was similar to that utilized by McDonald (1971) in evaluating site disturbance on skid trails. Disturbance was monitored only in the area between skid trails as follows. Starting at the top of each piled unit, a 30 meter tape was stretched between skid trails. The tape was oriented approximately perpendicular to the direction of slope. The number of meters in each disturbance class, intercepted by the tape was recorded to the nearest .3 m. After each transect was evaluated the tape was moved 5 m downslope and the operation repeated. The percentage of transect length occupied by each disturbance class was used as an estimator of the total areal extent of each class. Twelve hundred meters (4000') of transect were inspected at sites AQT, MIX, LAC, and ALT. Seven hundred and sixty meters (2500') of transect were inspected at site AAR. The disturbance classes are similar to those used by Dyrness (1965), Wooldridge (1960), Garrison and Rummell (1951), and McDonald (1971). The evaluation of disturbance and assignment to disturbance classes was based on visual indicators, defined as follows:

Trafficked Areas

1. Litter Disturbed: The presence of crawler tractor tracks impressed into the duff. Mineral soil is not visible. Undisturbed except for the presence of "cat tracks."
2. Slightly Disturbed: Duff has been laterally displaced and bare mineral soil is exposed. Soil disturbance appears less than 2.5 cm deep.
3. Moderately Disturbed: Duff has been laterally displaced and bare mineral soil is exposed. Soil disturbance appears greater than 2.5 cm deep.
4. Trafficked Berm: Displaced duff has been mixed with mineral soil and slash and has been subsequently trafficked as evidence by "cat tracks." The surface of the underlying mineral soil horizon is not visible.

Not Trafficked Areas

1. Undisturbed: No evidence of trafficking.
2. Untrafficked Berm: Displaced duff that has been mixed with mineral soil and slash and mounded but subsequent trafficking is not evident.
3. Miscellaneous: Transect intercepts slash piles or stumps.

Soil Bulk Density Sampling Apparatus Design and Sand Calibration Procedures

The sampling apparatus was constructed using clear 1/8" plexiglass material, measuring 30 cm x 30 cm at the base. Four 5 cm high plexiglass sides were glued vertically around the perimeter making a sampling tray. In the center of this tray a 15 cm circle was inscribed and cut out. A standard laboratory ring stand was positioned inside the sampling tray. A clamp was clamped to the ring stand post. A standard 7.5 cm ring was affixed to this clamp and positioned directly over the hole in the plexiglass. A plastic funnel was situated in the ring and the clamp assembly adjusted vertically until the bottom of its funnel was 8 cm above the base plate (Fig. 5).

Washed molding sand was air dried and sieved through a #18 screen on a mechanical shaker. Sand that passed the #18 sieve but that was retained on the #200 sieve was then calibrated to determine its packing characteristics. Sand calibration was performed setting the plexiglass plate atop a standard cylindrical 15 cm Proctor mold (volume = 2123.8 cm^3). Sand was poured through the ring stand funnel assembly into the mold until the mold was filled and a cone of sand projected approximately 5 cm above the base plate. This took approximately 2500 grams of sand. The excess projecting above the base plate was "struck off" with a straight edge. The base plate was subsequently removed and the sand formerly held in the 1/8" high circular base plate hole

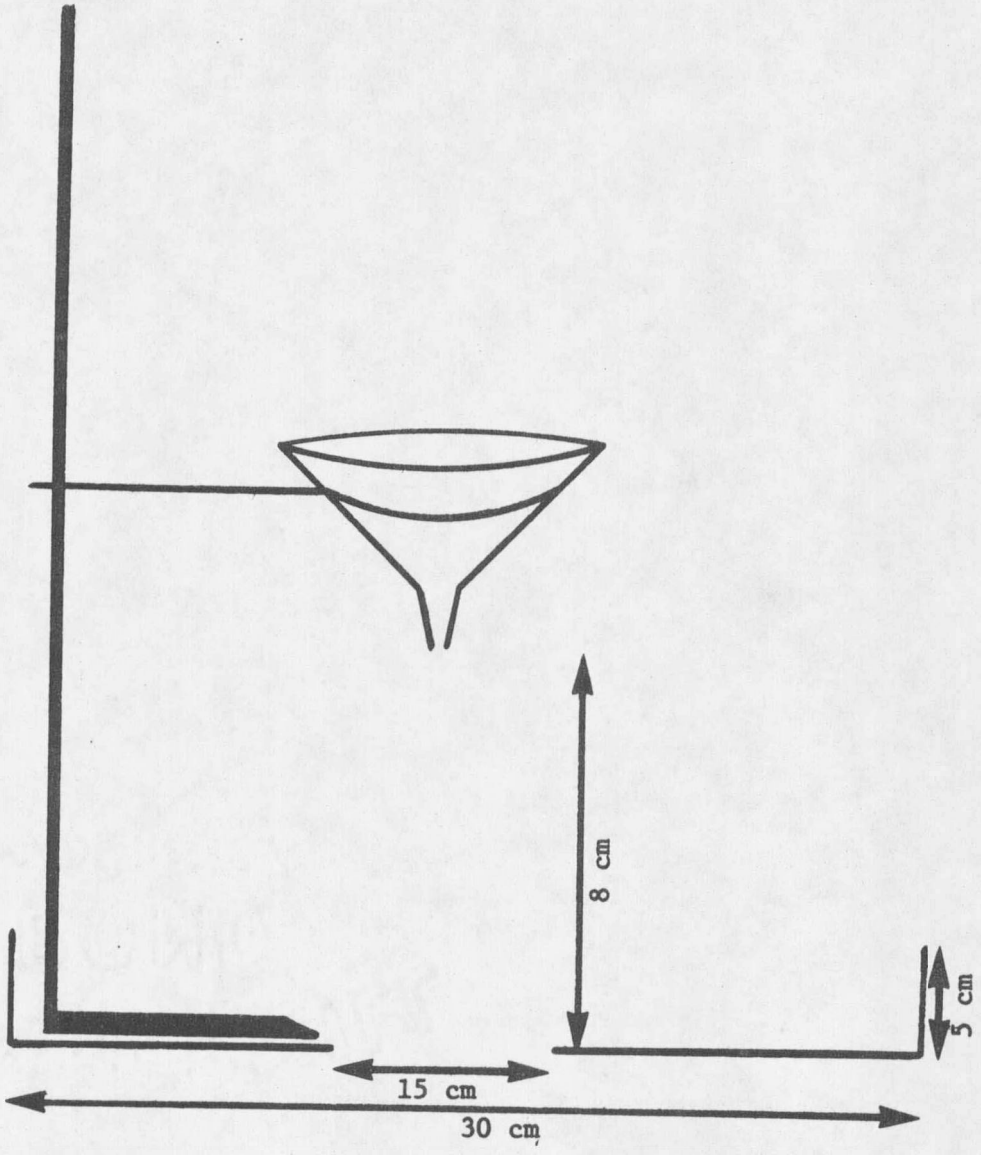


Figure 5. Sand delivery apparatus utilized in bulk density sampling.

was struck off and weighed. This enabled estimation of sand weight held above the theoretical ground surface by the thickness of the sampling tray. Finally, the weight of the sand held in the mold was calculated by subtracting the mold weight. Sand packing characteristics were determined by dividing the weight of sand contained in the mold by the mold volume. Sixty random subsamples were selected from the sand lot for calibration. Sand poured into the mold through the funnel apparatus consistently packed to a bulk density of 1.33 g/cm^3 $\pm$ (.005). On this basis the weight of the sand is directly related to the volume it occupies, e.g.

$$\text{sand weight (g)} \times \frac{1}{1.33(g/cm^3)} = \text{volume } (cm^3)$$

Bulk Density Measurement

Field Sampling

At each site a subplot was selected for bulk density sampling. Pretreatment and treatment sampling was accomplished on the same subplot. Individual sampling points within the subplots were selected by stratified random sampling. The subplots were stratified on the following basis. Sample plots were offset from standing timber and

stumps by 1 m. Treatment bulk density sampling was performed only on trafficked moderately disturbed soils. Churned or severely rutted soils and skid trails were not sampled.

The method used to determine bulk density was a slightly modified version of method A. AASHO T 147-54 (AASHO, 1963a), in which sand is the volumetric displacement medium. This method is referred to as the sand excavation method throughout this work. McLintok (1959) discussed the advantages of this method in stony soils. According to McNabb (1979) this method is the "standard of comparison" in terms of precision. The principle of the method has been illustrated in the previous section on sand calibration procedures. Use in the field is briefly described as follows: The sampling tray was placed on mineral soil after duff removal. A circular hole was excavated through the cutout in the sampling tray base using a garden trowel. Roots projecting into the excavation were clipped using pruning shears. All excavated material (soil, roots, and coarse fragments) was sealed in double plastic bags for transport to the lab. Subsequently as much calibrated sand as necessary to fill the hole was poured into the excavation through the ring stand funnel apparatus and leveled. Sand was poured from plastic bags containing 2500 g of calibrated sand. Sand not occupying the excavation was returned to its container (a plastic bag) and transported to the lab for weighing.

In field sampling excavation depth was normally 10 to 15 cm. Horizon boundaries were not knowingly crossed during the excavation. If a new horizon was encountered while excavating, the boundary determined the depth sampled. On this basis, bulk density was sampled by depth and horizon. After a sample was collected, sand was removed from the excavation, and a 50 cm by 50 cm area dug out to the bottom of the excavation. This datum was located by the small quantity of sand remaining in the hole, which served as a visual depth marker. Subsequently, the area was leveled and the operation repeated for the succeeding depth increment.

Usually three separate depth increments were sampled at each sample point. Total depth evaluated was approximately 0 to 45 cm. At each site 9 to 20 control samples and 5 to 26 treatment samples were taken from each horizon sampled.

Lab Analysis

The sand remaining in each bag (corresponding to one horizon-depth increment sample) was weighed to the nearest gram. From this value, 108 g was subtracted to correct for sand held above the excavation by the 1/8" thick base plate. The volume of the excavated bulk sample is then calculated as outlined in the previous section.

The excavated material was separated into three components: roots, coarse fragments, and fines. A 2 mm sieve was used to

differentiate coarse fragments from fines, and a toothbrush to remove soil adhering to roots and coarse fragments. Each component was weighed, dried at 105°C for 24 hours, and reweighed. The weight of water held by roots and coarse fragments was subtracted from the wet weight of the bulk sample, which allowed a precise determination of treatment soil moisture. Correction for these components of soil moisture would not have been necessary in the large volume samples taken in this study, as the contribution to error was insignificant.

Since this investigator was primarily interested in the bulk density of the fine fraction (the root growth media) the bulk density of the fines only was calculated. This was deduced by subtracting the oven dry weight and volume of roots and coarse fragments from the weight and volume of the excavated bulk sample. The volumes of roots and coarse fragments were calculated based on their oven dry weights assuming bulk densities of .5 g/cm^3 for roots and 2.65 g/cm^3 for coarse fragments. Assuming that weight equals mass, and dividing the mass of the fines by the volume of the fines yields the bulk density of the fine fraction. This method determines soil bulk density at its field moisture state.

Use of the sand excavation method to determine soil bulk density over a range of soil moisture conditions assumes that bulk density remains relatively unchanged with respect to soil moisture. The low

clay contents of the horizons sampled (less than 5%) and the relative physical inertness of volcanic ash (Klages, 1980), make this assumption valid. Additionally, a few informal laboratory measurements indicate that the shrink-swell potential of these silt loam textured soils is negligible.

Infiltration Measurement

At each site, control and treatment infiltration measurements were made within the same subplot used for bulk density sampling. Sample points were randomly located within the subplots, utilizing the same criteria as for bulk density sampling. Only trafficked moderately disturbed points were evaluated. Infiltration rates were determined with double ring infiltrometers (Johnson, 1963). The inner and outer rings were constructed of 1/16" steel and measured 15.2 cm and 35.6 cm in diameter, respectively. The nested rings were driven through the duff and into mineral soil approximately 5 cm, after which duff was removed from the inner ring only. Subsequently, a piece of circular cotton cloth was placed within the inner ring. Both rings were filled with water and allowed to sit for 30 minutes before measurements were initiated.

During measurements, a 75 mm hydraulic head was maintained in both rings, which were refilled to this level after each 5 minute reading. The vertical drop in water level from this datum was measured

to the nearest millimeter. Readings were made at 1 minute, 3 minutes, 5 minutes, and at each 5 minute interval thereafter until 60 minutes total time had elapsed. The last three 5-minute readings were averaged, converted to centimeters, and multiplied by twelve to yield the final equilibrium infiltration rate in centimeters per hour (cm/hr). A constant rate of infiltration was generally reached after approximately 30 minutes.

Slash Weight Quanitification

Slash weight, expressed in tons per acre, was quantified before and after slash piling using a planar intersect technique for inventory of downed woody material (Brown, 1974). The logged area was randomly sampled using the uniform sampling grid method recommended by Brown.

The method is utilized primarily to help land managers practice fuel management, and to estimate slash utilization potential. As a result, duff weights and slash weights in the 0 to .25 inch class were disregarded as being an insignificant component of total slash weight (Brown, 1980).

In the dense slash encountered before piling, sampling plane lengths of 6 feet, 12 feet and 50 feet were used for the .25 to 1, 1 to 3, and greater than 3 inches diameter classes, respectively. In the scattered slash encountered after slash piling, sampling plane lengths of 12, 24, and 100 feet were used for the .25 to 1, 1 to 3, and greater than 3 inches diameter classes, respectively.

Calculations of slash weight were accomplished using formulae developed for species common to the Northern Region of the U. S. Forest Service (Brown, 1974). These are presented as follows:

	Slash size class	Formula used
1.	.25- to 1-inch diameter	$w = 1.825\ nc/N1$
2.	1- to 3-inch diameter	$w = 14.25\ nc/n1$
3.	greater than 3-inch diameter (sound slash)	$w = 4.656\ \Sigma\ d^2c/N1$
4.	greater than 3-inch diameter (rotten slash)	$w = 3.492\ \Sigma\ d^2c/N1$

w = Slash weight in tons/acre

n = Number of pieces intercepted

c = Slope correction factor

d = Diameter of intercepted piece

N1 = Number of sample points (N) multiplied by length (1) of sampling plane (feet)

Statistics

Statistical analyses were performed using the MSUSTAT statistical library interactive programs (Jan 1980 version) developed and described by Lund (1980). Specific statistical tests utilized for each category evaluated are listed as follows:

1. Number of Trafficking Events No statistical analyses were performed

2. Site Disturbance (MSUSTAT program TSINGLE) Means, standard deviation, and 95% confidence intervals are calculated for the percentage of values in each disturbance class.

3. Soil Compaction (MSUSTAT program TGROUPED)

Bulk density control values were compared to treatment values of each horizon-depth increment utilizing the t statistic. Control and treatment groups are tested for homogeneous variance utilizing the F ratio tested at $p = .05$. Groups having heterogeneous variances subsequently are compared using Cochran's t' (Snedecor and Cochran, 1967).

4. Depth of Compaction (MSUSTAT ANOV I)

Individual treatment bulk density values were subtracted from the corresponding mean control bulk density value at each horizon-depth increment. The differences, at each horizon-depth increment, were compared by analysis of variance at $p = .10$ to determine if there were differences with respect to depth.

5. Infiltration Rates (MSUSTAT program NPGROUPED)

The assumption of normally distributed data is suspect based on skewness and kurtosis (as shown by the NP grouped program), and by plotted histograms. Therefore, the distribution free Mann-Whitney rank test, which compares population medians, is utilized.

6. Slash weight (MSUSTAT program TGROUPED)

Slash weight values before and after slash piling are compared utilizing the t statistic. Control and treatment groups were tested for homogeneous variance utilizing the F ratio tested at p = .05. Groups having heterogeneous variances are compared using Cochran's t' (Snedecor and Cochran, 1967).

Standard statistical symbols are used throughout this report as follows:

1. n = Number of samples
2. $\bar{x}$ = Mean
3. s = Standard deviation
4. .95 CI = 95% confidence interval
5. p = Probability value (expressed as a decimal, e.g., .01) that differences were due to chance.
6. NS = No statistically significant differences.

Soil Physical and Chemical Characterization

Equal volume soil samples were collected from each horizon of twelve soil profiles representative of the characteristic pedon described at each of the five study sites (Appendix I). Samples were collected from Bates' 1980 backhoe pits (Bates, 1981), thus all sampling was done within a 30 m x 180 m area adjacent to the cutting units in this study. Bulk samples were air dried and crushed in a flail type soil grinder.

Representative subsamples of material passing a 2 mm sieve were selected for chemical and physical analysis by the quartering method (ASTM, 1979b). Physical and chemical characterization data for each site are presented with soil profile descriptions in Appendix I.

Analyses were made for pH and electrical conductivity on a 1:2 (soil:water) dilution. Percent organic matter was determined using the Sims-Haby colorimetric method (Sims and Haby, 1971). Available phosphorus was determined using Olsen's sodium bicarbonate extraction technique (Olsen, et al. 1954). Cation exchange capacity was determined by sodium replacement both at the naturally occurring pH of the soil horizon (Singh, 1978) and at pH = 8.2 (Chapman, 1965a). Exchangeable bases (Ca, Mg, Na, and K) were estimated by ammonium acetate extraction (Chapman, 1965b). No correction was made for soluble salts, as it is well known that these acid forest soils are characteristically low in soluble salt content (Ottersberg, 1977; Klages, 1980). The minor elements, copper, iron, manganese, and zinc were determined by the DTPA-TEA extraction of Lindsay and Norvel (1969) as modified by the Montana State University Soil Testing lab.

Particle size classes were determined by the hydrometer method (Day, 1965). Sieve analyses were performed on soil horizons that were found within 40 cm of the soil surface according to AASHO (1963b). Horizons were classified as poorly graded or well graded according to the Unified Soil Classification System (AASHO, 1963c) (Appendix I).

Soil available water holding capacity was calculated as the difference between water (% by wt) held at .33 bar tension and water (% by wt) held at 15 bars tension. Moisture contents were determined on ground samples that passed a 2 mm sieve, using a pressure chamber apparatus similar to that described by Richards (1972). A porous ceramic plate was used as the suction control "membrane" for .33 bar determinations. A dialysis membrane was used in the 15 bar measurements. Textural class was determined according to the Soil Survey Staff (1975).

The clay mineralogy of each horizon was determined utilizing X-ray diffraction. Clay samples were prepared according to Theisen and Harward (1962). X-ray diffraction patterns were interpreted according to Whittig (1965). Relative abundance of clay minerals was estimated by determining the area under the peaks produced by the X-ray pattern and employing weighting factors according to Klages (1980) as follows:

1. Trace = Less than 5% of total clay
2. Low = 5 to 25% of total clay
3. Medium =25 to 50% of total clay
4. High = 50 to 75% of total clay
5. Very High = 75 to 100% of total clay

Study Scenario

Study plots were located, assessed for uniformity, and laid out during July, 1979. Undisturbed bulk density sampling was also conducted during July, August, and September of 1979. Preliminary soil profile descriptions were completed during this time.

In May and June of 1980 soil moisture was monitored every two weeks to approach theoretically "optimum" soil moisture for compaction as determined by Bates' Proctor tests (Bates, 1981). Prior to logging in early July, 1980, control infiltration measurements were made at sites AQT, MIX, and LAC. Because of difficult access, infiltration measurements were not made at sites ALT nor AAR. In early July all plots were clearcut and logs were skidded down designated skid trails only. Cull logs and unmerchantable timber remained standing until knocked down during slash piling operations. Operators were told to stay on designated skid trails unless they were unable to reach a merchantable log. Trafficking between skid trails was minimized on this basis. After skidding was completed, but before slash piling commenced, weight measurements of downed logging slash were made. The few remaining standing stems were deemed insignificant in comparison to total downed slash. Subsequently, slash piling (the treatment) was initiated utilizing a Caterpillar D6-D crawler tractor equipped with a brush blade. Slash piling was accomplished by the same operator at

each site to minimize operator variability. Upon completion of slash piling soil disturbance was evaluated and disturbance classes established. In late July, treatment infiltration measurements were made at sites AQT, MIX, and LAC. Subsequently, treatment bulk density sampling was initiated. Both infiltration measurements and bulk density sampling were conducted on the moderately disturbed trafficked areas. In both cases, skid trails and obviously churned or rutted soils were avoided. In August, downed slash which had not been consolidated into piles was quantified as a measure of slash piling efficiency. Detailed profile descriptions and soil sampling for physical and chemical analysis were made during September, 1980.

RESULTS AND DISCUSSION

Trafficking Associated with Slash Pile Construction

The following is a description of mechanized slash piling operations observed in this study. This scenario may be representative of slash piling operations in general. The bulldozer operator was instructed to proceed "as usual" according to the modus operandi for slash piling on each of the five clearcut sites. Slash piling was always initiated from the highest point in the cutting unit and proceeded downslope. This enabled the operator to gather material and efficiently roll it downhill, ultimately to be consolidated into a pile. Typically slash was moved downslope 20 to 40 meters before consolidation. The operator usually initiated construction of several piles (2 to 5) simultaneously, as he evaluated terrain and slash volume while in motion. The size of slash piles was primarily influenced by the volume of slash readily retrievable and the capacity of the crawler tractor to densify large volumes of slash with respect to the terrain. Efficiency of motion and judgment determined how far the operator traveled to retrieve slash for a given pile. Travel was more laterally extensive in "light" than in "heavy" slash volumes. The location of slash piles within the sites was also largely a result of operator judgment as influenced by slash volume, terrain, and his

perception of efficient movement. Completed slash piles were roughly circular or elliptical in shape.

Piling operations occurred in two phases, a piling phase and a densification phase. The distinction is somewhat arbitrary with considerable overlap between the two operations. To initiate pile construction the operator proceeded forward pushing slash ahead with the brush blade. The brush blade was carried at or slightly above the ground surface as slash was gathered. The blade was lifted and slash deposited as forward motion ceased. As the first gathering event was completed, the operator backed out an ill-defined distance on the same path. This represents two trafficking events. He then either advanced again on the same path, densifying the pile (a total of four trafficking events) or turned and gathered additional slash, advancing toward the pile from a different angle. As many as ten trafficking events over the same soil were recorded at one site, as the operator repeatedly backed off and advanced to facilitate crushing and pile consolidation.

The operator preferred to work downslope when possible and especially in the initial stages of slash pile formation. However, to achieve a compact pile of circular proportions uphill pushing against a considerable load was initiated at some time during pile construction. The D-6D crawler frequently lost traction during the densification

phase, especially when working upslope, with subsequent churning of surface horizon.

Characteristically, losing traction denoted the end of a pushing event associated with the final stages of densification. That is, the operator often proceeded forward until he could no longer gain traction. Most churning took place within 3.7 m (the length of a D-6D crawler) of the slash pile circumference (Caterpillar, 1978). Deep churning, however, was judged to be a minor component of slash piling operations. Final consolidation was often achieved by driving once around the slash pile circumference, breaking off protruding cull logs or hooking them with the brush blade and forcing them into the pile. This event was not counted in quantifying the amount of trafficking. One pass trafficking events also occurred when the operator traveled from one location to another. These were not recorded, as they were not directly related to slash pile construction and are assessed as an insignificant component of slash piling trafficking.

The construction of 11 to 17 slash piles at each site was monitored by visual reconnaissance in an attempt to quantify the intensity of trafficking at each site. This was difficult in that several piles were often constructed simultaneously. Frequently the operator would combine two or three smaller piles into one large pile. Although pile combination was observed at all sites, it was particularly prevalent at site LAC, which was dominated by small diameter Pinus contorta

stems. Associated trafficking events were summed as if they had occurred on one slash pile. 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. Means for individual sites are presented in Table 5. Raw data are available in Appendix II.

The results are best described as semi-quantitative, due to difficulties in partitioning trafficking events between piles and in quantification of the "ill-defined" backing distance. Of importance is the fact that 93 to 98% of all trafficking events at each site were 2 or 4 pass events. Averaged over all five sites, 96% of total trafficking were 2 or 4 pass events. It is clear that slash piling trafficking intensity is substantially less severe than trafficking on skid trails where 50 to 100 trafficking events are common (Froehlich and Berglund, 1976).

Site Disturbance From Mechanized Slash Piling

Means, standard deviations, and .95 confidence intervals for percentages of area in each disturbance class at each site are presented in Table 6. Raw data are available in Appendix III.

Data are intended to illustrate the range of site disturbance incurred during slash piling operations. Definitions of each disturbance class were presented on page 65. Comparisons between sites were not attempted due to the variation in site factors, (e.g.,

Table 5. Mean trafficking intensity associated with slash pile construction.

	Number of Trafficking Events					
	2	4	6	8	10	Site
Mean Number of Trafficking Events in Each Trafficking Category	86%	11%	2%	1%	0	AQT (40) *
	86%	10%	4%	< 1%	0	MIX (40)
	85%	10%	3%	1%	< 1%	LAC (40)
	77%	16%	7%	< 1%	0	ALT (40)
	90%	8%	1%	< 1%	0	AAR (25)
	85%	11%	3%	< 1%	< 1%	Average for All Five Sites

*The number in parenthesis indicates the number of transects utilized to determine the data base at each site.

Table 6. Areal extent and severity of site disturbance incurred during slash piling operations at the five study sites.

Site	Statistics	Disturbance Class (Area in each class is recorded as a percentage of the total slash piled area)								
		Trafficked †					Not Trafficked			
		Litter Disturbed (%)	Slightly ‡ Disturbed (%)	Moderately ‡ Disturbed (%)	Berm (%)	Total (%)	Untrafficked* Berm (%)	Undisturbed (%)	Miscellaneous (%)	Total (%)
AQT (40)**	$\bar{x}$	.5	7.9	2.6	14.4	25.4	63.2	1.6	9.6	74.4
	s	1.2	4.3	3.5	6.4	-	9.4	5.1	6.4	-
	.95 CI	(.1-.9)	(6.5-9.3)	(1.4-3.7)	(12.6-16.8)	-	(60.2-66.2)	(0-3.2)	(7.5-11.6)	-
MIX (40)	$\bar{x}$	8.1	14.3	5.0	11.9	39.3	44.8	11.7	4.0	60.5
	s	7.0	9.3	5.6	7.9	-	14.9	10.2	6.6	-
	.95 CI	(5.9-10.3)	(11.3-17.3)	(3.2-6.8)	(9.4-14.4)	-	(40.0-49.5)	(8.4-15.0)	(1.9-6.1)	-
LAC (40)	$\bar{x}$	3.6	15.8	6.8	14.2	40.4	52.6	5.8	1.3	59.7
	s	3.9	7.1	6.0	7.6	-	10.2	5.6	4.0	-
	.95 CI	(2.3-5.8)	(13.5-18.0)	(4.8-8.6)	(11.8-16.7)	-	(49.4-55.9)	(4.0-7.6)	(0-2.5)	-
ALT (40)	$\bar{x}$	1.6	12.3	6.2	17.7	37.8	54.9	1.3	6.1	62.3
	s	3.1	8.0	5.6	6.7	-	11.4	2.3	8.3	-
	.95CI	(.6-2.6)	(9.7-14.8	(4.4-8.0)	(15.6-19.8)	-	(51.3-58.5)	(.5-2.0)	(3.5-8.8)	-
AAR (25)	$\bar{x}$	8.2	12.4	11.6	15.7	47.9	39.7	6.8	5.8	52.3
	s	6.2	7.4	6.7	10.1	-	15.6	7.0	10.1	-
	.95 CI	(5.7-10.8)	(9.3-15.4)	(8.8-14.3)	(11.5-19.9)	-	(33.3-46.2)	(3.9-9.6)	(1.6-10)	-

†Area subjected to potentially compacting stresses.
‡Most likely sites of potentially severe soil compaction.
*Soil buried beneath may have been subject to compacting stresses prior to burial.
**The number in parenthesis indicates the number of transects utilized to determine the data base at each site.

stand volume, number of stems/hectare, and percent slope).

Summation of mean values for all disturbance classes except undisturbed and miscellaneous indicates that 84 to 93% of the five logged areas were subjected to disturbance during slash piling operations. Disturbance, as used here, means displacement of duff or mixing of duff, slash, and mineral soil. Disturbance does not imply direct trampling of material unless specified. The category "untrafficked berm" is included in this summation. This mounded material has been displaced (disturbed) although it was not possible to determine if the soil beneath had been trafficked before burial. This category is the largest disturbance class, values range from 40 to 63% of total site area.

Area directly trafficked during slash piling ranges from 25% to 48% of the total logged area on the five sites investigated. Trafficked area, as evidenced by crawler tracks, represents the area subjected to potentially compacting stresses. In the opinion of this investigator, slightly and moderately disturbed trafficked areas represent the most likely sites of potentially severe compaction. In these classes litter had been at least partially displaced and crawler tracks were impressed into bare mineral soil. The summation of area in these two categories ranges from 11 to 24% of the total site area on the five sites.

It is probable that some area buried beneath the untrafficked berm has also been trafficked. If the percentages reported for each disturbance class are also representative of trafficking intensity on the soil obscured by untrafficked berm, the values would increase as follows. Area trafficked would range from 41 to 67%; slightly and moderately disturbed areas would range from 17 to 35%.

The significance of area disturbed by slash piling lies in the fact that it is additive to area occupied by skid trails. If 27% of a logged area is in skid trails, an average of values reported by Steinbrenner and Gessel (1951), Dyrness (1965), Wooldridge (1960), and Hatchell (1968), adding 84 to 93% disturbance by slashing implies that approximately 100% of a cutting area is disturbed by skidding and slash piling operations. This value is comparable to the total value (i.e., 78%) reported by Edgerton, et al. (1975).

Mineral soil exposed in the moderately and severely disturbed classes accounts for 11 to 24% of the logged area. This range of values is additive to the 20% average value of mineral soil exposed on skid trails (the average of values reported by Garrison and Rummell, 1951; McDonald, 1971; Wooldridge, 1960; Zasada and Tappeiner, 1969). As a result 31 to 44% of a clearcut-slash piled logging site may be denuded to bare mineral soil by skidding and subsequent slash piling. Approximately 50% of the total site denudation may be attributed to slash piling operations.

Soil Compaction From Mechanized Slash Piling

After slash piling, moderately disturbed trafficked areas were selected at random, within the same subplots as controls, for bulk density determinations. Ten to 20 control bulk densities were compared with 5 to 26 treatment bulk densities by horizon-depth increment at each site. Treatment sampling points were within 35 meters of control sampling points. It was not possible to determine precisely the number of trafficking events that occurred at each treatment sample point. However, since 96% of all site trampling involved 2 to 4 trafficking events, it is probable that this is the level trafficking intensity usually evaluated for changes in bulk density. Additionally, it was observed that bare mineral soil was usually exposed after 2 to 4 trafficking events. Skid trails, rutted areas, and soils obviously churned or mixed were not evaluated. Moderately disturbed areas were selected because (as stated earlier) they represented the greatest potential for soil compaction. Less severely disturbed areas probably experienced compaction to a lesser degree (these areas were not evaluated).

Bulk density data presented assumes that the ground surface is a fixed datum plane that is unmodified by trafficking. However, implicit in the definition of moderate disturbance is the fact that at least 2.5 cm of mineral soil has been scraped away or displaced. Although quantification of the precise depth of soil scalping was not attempted

in this study, this investigator believes the average magnitude of displacement ranged approximately from 2 to 10 cm.

Mean control and treatment bulk densities, changes in bulk densities, and levels of statistical significance are tabulated by depth and horizon for all sites in a summary table (Table 7). Raw bulk density data for each site are presented in Appendix IV.

Results from this study are compared and discussed with results reported in similar studies by Bates (1981) and Cullen (1981). Bates evaluated skid trail soil compaction on the same soil types on adjacent plots. His study compares trafficking under "wet" soil moisture conditions (1.12 to 2.19 x field moisture capacity) with trafficking under "dry" conditions (.37 to 1.00 x field moisture capacity). Soil moisture conditions were generally substantially wetter at each site (5-30% by wt) in the Bates' study than those measured when treatments in this study were initiated (Table 8). Although Bates utilized both a D-6D crawler tractor and a 518 rubber-tired skidder for trafficking, comparisons are made with the tracked vehicle only. The tracked vehicles used in both studies are identical except for blade type. In the skidding study, the tractor was equipped with a straight blade rather than a brush blade. Additionally, logs were dragged behind the tractor to simulate skidding. Bates employed 0, 1, 2, 4, and 8 trafficking events during "dry" trafficking and 0, 1, and 8 events during

Table 7. Bulk density changes associated with moderate disturbance caused by slash piling at the five study sites.

Site	Horizon Sampled	Average † Depth Increment Sampled (cm)	Control Bulk Density (g/cm^3) $\bar{x}$	s	n	Treatment Bulk Density (g/cm^3) $\bar{x}$	s	n	Change in Bulk Density (g/cm) $\bar{x}$	s	%	Statistical Significance p-value
AQT	A21 & A22	0-12	.62	.07	13	.81	.16	15	+.19	.05	31	.010
	A22 †	13-24	.70	.07	13	.86	.13	9	+.16	.04	23	.001
	II A21‡	12-37	1.06	.18	13	1.18	.16	19	+.12	.07	11	.020
MIX	A21	0-12	.96	.09	19	1.12	.10	13	+.16	.03	17	.001
	A21	12-25	1.29	.12	18	1.38	.10	13	+.09	.04	7	.036
	A22	26-37	1.46	.13	20	1.45	.18	8	-.01	.06	<1	.894
LAC	A21	0-12	1.06	.14	19	1.16	.10	26	+.10	.04	9	.010
	A22	14-24	1.24	.14	17	1.36	.11	17	+.12	.04	10	.008
	A22	25-35	1.42	.11	16	1.52	.06	9	+.10	.04	7	.019
	A23	33-42	1.59	.09	5	1.64	.06	7	+.05	.04	3	.244
ALT	A21	0-12	.72	.11	12	.81	.09	19	+.09	.04	13	.015
	A22	12-24	.76	.05	10	1.02	.14	5	+.26	.05	34	.025
	II A2	15-39	1.24	.12	10	1.34	.16	18	+.10	.06	8	.106
AAR	A21	0-12	.56	.06	18	.65	.10	12	+.09	.03	16	.003
	A22	14-26	.59	.05	15	.69	.05	12	+.10	.02	17	.001
	A22	28-40	.64	.04	12	.74	.08	12	+.10	.03	16	.005

†When average control and treatment depth increments are within 2 cm the shallower mean depth increment is reported for both control and treatment samples.

‡IIA21 control 26-38 cm depth increment is compared with treatment 12-37 cm depth increments.

Table 8. A comparison of three studies evaluating soil compaction, induced by forest harvesting equipment, in northwestern Montana.

Soil type	Horizon†	This Study (Sand Excavation Method)					Skid Trail Study After Bates (1981) (Saran Clod Method)										Skid Trial Study After Cullen (1981) (Saran Clod Method)			
							Wet					Dry								
		Depth‡	SM‖	TI¶	Δ B.D.§	Stat*	Depth	SM	TI	Δ B.D.	Stat	Depth	SM	TI	Δ B.D.	Stat	Depth	TI	Δ B.D.	Stat
		cm	%		g/cm^3	p	cm	%		g/cm^3	p	cm	%		g/cm^3	p	cm		g/cm^3	p
AQT	A216&A22	0–12	26	2–4	+.19	.010	16	57	1	—	NS	13	13	2	—	NS	5	Mod	—	NS
									8	+.47	.05			4	+.20	.05		Sev	+.37	.01
	A22	13–24	27	2–4	+.16	.001								8	+.19	.05	15	Mod	—	NS
																		Sev	+.16	.10
	IIA21	12–37	15	2–4	+.12	.020	25	23	1	—	NS	36	11	2	-.31	.05	30	Mod	-.17	.10
									8	—	NS			4	-.20	.05		Sev	—	NS
														8	—	NS				
MIX	A21	0–12	24	2–4	+.16	.001	10	34	1	+.19	.05	8	15	2	—	NS				
	A21	12–25	20	2–4	+.09	.036			8	+.18	.05			4	+.30	.05				
														8	—	NS				
	A22	26–37	17	2–4	--	NS	27	35	1	—	NS	22	13	2	—	NS				
									8	--	NS			4	—	NS				
														8	—	NS				
LAC	A21	0–12	20	2–4	+.10	.010	6	35	1	—	NS	9	19	2	—	NS				
									8	+.25	.05			4	—	NS				
														8	—	NS				
	A22	14–24	18	2–4	+.12	.008	21	27	1	—	NS	19	12	2	—	NS				
		25–35	15	2–4	+.10	.019			8	—	NS			4	—	NS				
														8	—	NS				
	A23	33–42	14	2–4	—	NS	36	19	1	—	NS	40	10	2	—	NS				
									8	—	NS			4	—	NS				
														8	—	NS				
ALT	A21&A22	0–12	46	2–4	+.09	.015	11	50	1 (25–30)	—	NS	11	27	2	—	NS	5	Mod	+.23	.01
																		Mod	+.44	.01
	A22	12–24	43	2–4	+.26	.025				.50	.05			4	+.20	.05				
														8	+.18	.05	15	Mod	+.44	.01
																		Sev	+.40	.01
	IIA2	15–39	21	2–4	+.13	.105	32	26	1	—	NS	26	17	2	—	NS				
									8	—	NS			4	—	NS	30	Mod	—	NS
														8	—	NS		Sev	-.16	.10
AAR	A21	0–12	55	2–4	+.09	.003	6	59	1	—	NS	16	28	2	—	NS				
									8	+.28	.05			4	—	NS				
														8	—	NS				
	A22	14–26	56	2–4	+.10	.001	19	61	1	—	NS	27	27	2	—	NS				
	A22	28–40	54	2–4	+.10	.005			8	—	NS			4	—	NS				
														8	.43					

† Horizon sampled for changes in bulk density.

‡ Mean depth evaluated for changes in bulk density.

‖ Soil moisture (% by weight) at trafficking, Cullen did not know soil moisture at trafficking.

¶ Trafficking intensity (number of trafficking events). Cullen estimated trafficking intensity as Mod (Moderate) and Sev (Severe).

§ Change in bulk density incurred by trafficking.

* Level of statistical significance recorded as the p-value (NS means not significant). Bates rejected at $p \geq .05$, Cullen rejected at $p \geq .10$.

"wet" trafficking. Treatments are similar enough to warrant comparisons.

Bates evaluated soil bulk density utilizing a saran-clod method modelled after Brasher, et al. (1966), whereas this study employed the "sand excavation method." Therefore, actual soil bulk densities are not directly comparable. However, relative treatment effects (increases and decreases) are comparable. Bates sampled at the middle of each soil horizon. In thick horizons (greater than 30 cm) Bates took one sample whereas this study took two, one in each 15 cm depth increment. Averaging bulk density values reported for two depth increments in the same horizon (e.g., 0-12 cm and 13-24 cm) gives values that are approximately comparable to those obtained by Bates for the middle of the horizon (e.g., 16 cm). Comparisons are made on this basis throughout this work.

Cullen (1981) evaluated bulk density increases in 3 to 17 year old skid trails on two similar soils in northwestern Montana (e.g., volcanic ash-loess overlying quartzite and limestone tills). These soils are comparable to those evaluated in this study at sites AQT and ALT, respectively. He sampled moderately and severely disturbed skid trails. Differentiation was based on visual parameters. Soil moisture at the time of treatment, trafficking equipment, and number of trafficking events are not known. In the opinion of this author both classes

of disturbance represent substantially more trafficking than experienced under slash piling. Cullen also employed the "saran-clod method" and sampled at 5 cm and 15 cm in the surface ash-loess horizons, and at 30 cm in the IIA2 till horizons. Although he sampled deeper horizons, the results will not be discussed here.

The results of all three studies are summarized in Table 8. All bulk density increases and decreases and depths at which they were sampled, as discussed in the text, are mean values. These studies are among the first rigorous attempts to quantify changes in bulk density under logging regimes in northwestern Montana.

Bates "dry" treatment results are extrapolated to slash piling operations in an attempt to predict the magnitude and extent of likely bulk density increases under more realistic soil moisture conditions (Table 9). As stated in the Introduction, most, but not all slash piling operations are performed in summer when soils are comparatively dry. Table 9 is a summary table for all sites of predicted soil bulk density increases that are expected to occur at different soil moisture conditions (expressed as a percentage of .33 bar soil moisture (by wt)). Soil moisture at sites AQT, MIX, and LAC approaches the theoretically optimum soil moisture for compaction determined by Proctor tests (ASTM, 1979a) as modified by Bates (1981). Bates corrected for coarse fragments in determining optimum soil moisture for compaction. In

Table 9. Predicted bulk density increases and percentage of site area within which bulk density increases may be found due to slash piling at two levels of soil moisture.

Site	Horizon Depth Increment* (cm)	Proctor Test Method C Optimum Moisture for soil compaction** (after Bates, 1981) % by wt	Soil Moisture Condition: Moderately Wet to Saturated (this study) — Soil Moisture % by wt	Predicted Bulk Density Increase† g/cm^3	Predicted Site Area Impacted %	Soil Moisture Condition: Dry to Moderately Wet (after Bates, 1981) — Soil Moisture % by wt	Predicted Bulk Density Increase† g/cm^3	Predicted Site Area Impacted %
AQT	A21 & A22 (0-24)	31 (.89)	26 (.74)	.19	23-47	13 (.37)	.20	2-8
	IIA2 (12-37)	11 (1.00)	15 (1.36)	.12	23-47	11 (1.00)	-----unknown-------	
MIX	A21 (0-25)	21 (1.00)	22 (1.05)	.13	23-47	15 (.71)	.30	2-8
	A22 (26-37)	16 (1.00)	17 (1.06)	No change expected		13 (.81)	No change expected	
LAC	A21 (0-12)	22 (.81)	20 (.74)	.10	23-47	14 (.52)	No change expected	
	A22 (14-35)	20 (.91)	16 (.72)	.11	23-47	12 (.55)	No change expected	
	A23 (33-42)	12 (.71)	14 (.82)	No change expected		10 (.59)	No change expected	
ALT	A21 & A22 (0-24)	35 (.97)	45 (1.25)	.18	23-47	27 (.75)	.20	2-8
	IIA2 (15-39)	18 (.95)	21 (1.11)	.13	23-47	17 (.89)	-----unknown-------	
AAR	A21 (0-12)	31 (.84)	55 (1.49)	.09	23-47	28 (.76)	No change expected	
	A22 (14-40)	31 (.97)	55 (1.72)	.10	23-47	27 (.84)	No change expected	

*Horizon depth increment within which the predicted bulk density increase is expected.
**Values in parenthesis are the equivalent of soil moisture (% by wt) as the percentage of field moisture capacity (expressed as a decimal).
†Assuming a trafficking intensity of two and four passes.

general, Proctor optimum moisture for compaction approximates the field moisture capacities (assumed to be water content (% by wt) at .33 bars tension) of these soils (Appendix I). Included is the percentage of site area within which the predicted bulk density increases are expected.

Bulk density values in the "dry to moderately wet" category are from Bates' "dry" 2 and 4 pass skid trail data, and values in the "moderately wet to saturated" category are from this slash piling study (Table 8).

The percentage of site area within which bulk density increases are expected are calculated by the method illustrated in the following hypothetical example. If an average .25g/cm^3 bulk density increase occurred after 4 trafficking events, then a .25g/cm^2 increase is expected on all site area that has been trafficked 4 times. Since area trafficked averages 25 to 48% at the five sites (Table 6) and 4 pass events represent 8 to 16% of all trafficking events (Table 5), the product (2 to 8%) equals site area that has incurred 4 trafficking events. Therefore, 2 to 8% of the site area is expected to incur a .25g/cm^3 bulk density increase. These calculations are conservative because bulk density charges are theoretically not confined to the vertical area directly beneath the tractor track. Compacting stresses also extend but diminish laterally in concentric zones as predicted by the Boussinesque equation (Chancellor, 1977; Craig, 1974). Lull

(1959) estimated that compaction could extend laterally 30 to 45 cm on each side of the applied load. Since the D-6D track is 45 cm wide, the total area impacted could be 2 or 3 times that estimated. However, magnitudes of compaction in these lateral zones would be diminished in comparison to those incurred directly beneath the track. Table 9 also illustrates relative magnitudes of bulk density increases that are likely when trafficking occurs under "wetter" versus "drier" soil moisture conditions.

Bulk Density Changes at Site AQT

Data evaluated for this site indicate that statistically significant changes in bulk density occurred in both surface ash and subsurface till horizons, as a result of mechanized slash piling (Table 7). The average magnitudes of measured increases are: .19 g/cm^3 (31%), .16 g/cm^3 (23%), and .12 g/cm^3 (11%). for A21 and A22 horizons (0-12 cm), A22 horizons (13-24 cm) and IIA21 horizons (12-37 cm), respectively. Associated levels of statistical significance are $p = .01$, $p = .001$, and $p = .02$, respectively.

Because of the thinness of the A21 horizon (1 cm), A21 and A22 horizons are evaluated together in the 0-12 cm depth increment. It is felt that evaluation of a 1 cm thick horizon by the sand excavation method would lead to excessive sampling error.

We noted that IIA2 till material was never found at less than 22 cm in the control group whereas it was found at 9 to 15 cm depths in 9 of 19 treatment points evaluated. While this may be due to site variability, it is probably a result of superficial soil scalping. In view of the previous discussion on soil displacement three alternative approaches to evaluation are presented (Table 10).

1. Control bulk densities at the 26-38 cm depth ($\bar{x}$ = 1.06 g/cm^3) are compared with treatment bulk densities ($\bar{x}$ = 1.18 g/cm^3) at approximately the same depth (25-37 cm). Analysis indicates that bulk density increased .12 g/cm^3 (11%), (p = .10).
2. Control bulk densities at the 26-38 cm depth ($\bar{x}$ = 1.06 g/cm^3) are compared with treatment bulk densities at the 12-26 cm depth ($\bar{x}$ = 1.21 g/cm^3). This comparison attempts to compensate for a changing datum plane caused by soil displacement and assumes that 14 cm of soil has been scraped away. This analysis also indicates that bulk density has increased The magnitude of increase is .15 g/cm^3 (14%), (p = .03).

Table 10. Bulk density changes in the IIA21 horizon at site AQT evaluated at three depth increments.

Horizon Sampled	Average Depth Increment Sampled (cm)	Control Bulk Density (g/cm^3)			Treatment Bulk Density (g/cm^3)			Change in Bulk Density (g/cm)			Statistical Significance	Conclusions
		$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	%	p-value	
IIA21	26-38 cm	1.06	.18	13				+.12	.07	11%	.10	Bulk density has increased
	25-37 cm				1.18	.16	10					
IIA21	26-38 cm	1.06	.18	13				+.15	.07	14%	.03	Bulk density has increased
	12-26 cm				1.21	.12	9					
IIA21	12-26 cm				1.21	.12	9	+.04	.07	3%	.60	Treatment bulk density is independent of depth in the interval 12-37 cm
	25-37 cm				1.18	.16	10					

3. A comparison is made of treatment effects measured in IIA21 material evaluated at 12-26 cm ($\bar{x}$ = 1.21 g/cm^3) with deeper IIA21 material evaluated at 25-37 cm ($\bar{x}$ = 1.18 g/cm^2). Since treatment effect on bulk density was found to be independent of depth in the interval 12-37 cm (Table 10), treatment bulk densities at 12-26 cm and 25-37 cm were combined and compared together with the control IIA21 at 26-38 cm ($\bar{x}$ = 1.00 g/cm^3). This final result was reported in the first paragraph on this section and is presented in the summary table for all sites (Table 7).

Results are compared with those of Cullen (1981) and Bates (1981) (Table 8). Cullen reported statistically significant increases in bulk density in the ash horizon at 5 cm (.37 g/cm^3) and 15 cm (.16 g/cm^3) on severely disturbed skid trails.

Under "dry" conditions (13% by wt) Bates reported increases of .20 g/cm^3 and .19 g/cm^3, in the surface ash, after 4 and 8 trafficking events, respectively. No compaction in the subsurface IIA2 till horizon was detected. Extrapolating his results to slash piling under "dry" conditions predicts bulk density increases in the surface ash horizons that have been trafficked at least four times. Therefore, on similar soils, 2 to 8% of site area may be expected to incur an average .20 g/cm^3 bulk density increase in the surface 0-24 cm (Table 9). This

investigator concludes that slash piling on AQT soils under "dry" conditions will not induce changes in bulk density over a large portion of the site.

At soil moisture conditions approaching theoretically optimum moisture for compaction (26% by wt), 23 to 47% of site area may be expected to incur a .18 g/cm^3 bulk density increase in the surface 0-24 cm. The .18 g/cm^3 value is an average of increases found in the 0-12 cm and 12-24 cm depth increments. Within the 13 to 26% (by wt) soil moisture range compaction susceptibility does not appear to be significantly influenced by soil moisture (i.e., bulk density increases are approximately equal).

However, after 8 trafficking events at 57% (by wt) soil moisture content, Bates reported a .47 g/cm^3 bulk density increase. This is approximately 3 times the increase reported at 13% (by wt) moisture for 8 passes (Table 8). The trend is that compaction susceptibility increases with increasing soil moisture but that the relationship is not strong within the 13 to 26% (by wt) moisture range. This result is in accord with Li's hypothesis that cohesionless soils are more susceptible to compaction near saturation (Li, 1956). Cullen (1981) demonstrated that the ash horizons on these soils are cohesionless.

A comparison of the three studies with respect to bulk density changes in the IIA2 quartzite till leads to different conclusions. Bates did not find increases in bulk density in the IIA2 horizons regardless of soil moisture (skidded "wet" or "dry") and the number of trafficking events (1 to 8). In fact, he found statistically significant decreases after 2 to 4 events under the "dry" treatment, at 36 cm depth. Although Cullen (1981) reported statistically significant decreases on moderately trafficked skid trails at 30 cm depth in the IIA2 horizon, he dismissed them as unreasonable. In contrast, this study indicates that statistically significant increases in bulk density (.12 g/cm^3 (11%)) have occurred in the IIA2 horizon near theoretically optimum moisture conditions (Table 9).

While differences in soil moisture at trafficking may explain these differences, in the opinion of this investigator differences in sampling methodology (sand excavation method versus saran-clod method) offer a more likely explanation. Obtaining large clods for analysis, using the saran-clod method, is extremely difficult due to the high coarse fragment content in the till horizons.

Bates' and Cullen's clods ranged from 9 to 209 cm^3 in volume, including roots and coarse fragments. In contrast, the volume of material, excluding roots and coarse fragments used to evaluate bulk density in this study averaged 800 cm^3, and ranged from 417 cm^3 to

1372 cm^3. Theoretically, a much more representative sample is obtained with the larger volume sample. As a result, the "sand excavation method" may be a more sensitive measuring instrument in soils containing a larger percentage of coarse fragments. On this basis, prediction of soil compaction in the IIA2 till horizons, under "dry" soil moisture is not attempted, and is listed as unknown in Table 9.

Bulk Density Changes at Site MIX

Control bulk densities for this site were taken under two different soil moisture conditions. Thirteen to 15 samples were taken from each horizon evaluated during the summer of 1979 and 5-6 additional samples during the spring of 1980. Analysis indicates that there is no statistically significant difference in bulk density values between "wet" and "dry" controls (Table 11). As a result "wet" and "dry" control bulk densities are combined and used in comparison with treatment values (Table 7).

At this site statistically significant increases in treatment bulk densities were found within the 0 to 25 cm depth increment. Average increases are .16 g/cm^3 (17%) and .09 g/cm^3 (7%) for A21 (0-12 cm) and A21 (12-25 cm) horizon-depth increments, respectively. Associated p-values are $p = .001$ and $p = .036$, respectively. Mean bulk density increases were not found in the A22 (26-37 cm) horizon-depth increment (Table 7).

Table 11. Comparison of "dry" and "wet" control bulk densities at site MIX.

Horizon Sampled	Average Depth Increment Sampled (cm)	Mean Soil Moisture (% by wt)	Dry Control Bulk Density (g/cm^3) $\bar{x}$	s	n	Wet Control Bulk Density (g/cm^3) $\bar{x}$	s	n	Change in Bulk Density (g/cm^3) $\bar{x}$	s	%	Statistical Significance p-value	Conclusions
A21	0-12	8	.94	.10	13				+.07	.04	7	.12	NS†
	0-12	33				1.01	.04	6					
A21	13-24	4	1.27	.12	13				+.09	.06	5	.15	NS
	12-25	24				1.36	.10	5					
A21	23-35	3	1.45	.13	15				+.05	.07	3	.47	NS
	26-37	20				1.50	.13	5					

†NS means no significant difference in bulk density values between "wet" and "dry" controls.

Bates (1981) reported similar increases, on skid trails logged "wet" (34% by wt), in the A21 horizon at 10 cm depth (Table 8). He reported statistically significant increases of .19 g/cm^3 (18%) and .18 g/cm^3 (17%) for 1 and 8 trafficking events, respectively. Bates did not report statistically significant increases in the A22 horizon at the 27 cm depth; nor in deeper horizons.

Under "dry" soil moisture conditions (15% by wt) Bates found statistically significant bulk density increases of .30 g/cm^3 (29%) after 4 trafficking events in the surface A21 horizon at 8 cm. Bulk density increases were not found in deeper horizons.

The predicted areal extent of compaction due to slash piling at two soil moisture contents for the surface A21 and A22 horizons (0-25 cm) is as follows (Table 9). Under "dry" soil moisture conditions (15% by wt), 2 to 8% of the slash piled area is expected to incur a bulk density increase of .30 g/cm^3. At soil moisture approaching theoretically optimum moisture for compaction (21% by wt), 23 to 47% of the site is expected to incur a bulk density increase of .13 g/cm^3 (an average of increases in the 0-25 cm depth increment, Table 7).

Data from both studies (Table 8) indicated that compaction is probable within the moisture range (13-34% by wt). Within this moisture range the relationship between soil compaction susceptibility

and soil moisture content is not obvious. It appears that MIX soils are compaction susceptible at both high and low ends of the range. This phenomena has also been noted in field tests for cohesionless fine sands (Sowers and Sowers, 1970).

Bulk Density Changes at Site LAC

Control bulk densities were taken when the soil was relatively "wet" (spring, 1980) and relatively "dry" (summer, 1979) for the first three horizon-depth increments. Analysis indicates that there is no statistically significant difference in bulk density between "wet" and "dry" controls for these horizon-depth increments (Table 12). As a result "wet" and "dry" control bulk densities are combined and used in comparison with treatment bulk densities.

Data evaluated for this site indicate that statistically significant bulk density increases have occurred to the (25-35 cm) depth increment. Average increase magnitudes are as follows: .10 g/cm^3 (9%), .12 g/cm^3 (10%), and .10 g/cm^3 (7%) for A21 (0-12 cm), A22 (14-24 cm), and A22 (25-35 cm) horizon-depth increments, respectively. Associated levels of statistical significance are $p = .01$, $p = .008$, and $p = .019$, respectively. Statistically significant increases were not found in the A23 (33-43 cm) horizon-depth increment.

In contrast to this study, Bates (1981) did not find statistically significant increases in bulk densities except in the surface

Table 12. A comparison of "dry" and "wet" control bulk densities at site LAC.

Horizon Sampled	Average Depth Increment Sampled (cm)	Mean Soil Moisture (% by wt)	Dry Control Bulk Density (g/cm^3) $\bar{x}$	s	n	Wet Control Bulk Density (g/cm^3) $\bar{x}$	s	n	Change in Bulk Density (g/cm^3) $\bar{x}$	s	%	Statistical Significance p-value	Conclusions
A21	0-12	9	1.05	.12	13								
									+.04	.07	4	.60	NS †
A21	0-13	36				1.0	.17	6					
A22	13-26	6	1.26	.14	12								
									-.06	.07	5	.43	NS
A22	14-24	27				1.20	.12	5					
A22	26-35	5	1.40	.08	10								
									+.04	.06	3	.58	NS
A22	25-35	21				1.44	.15	6					
A23	33-42	14	Dry controls only										

†NS means no significant difference in bulk density values between "wet" and "dry" controls.

A21 horizon after 8 trafficking events (Table 8). He reported an average increase of .25 g/cm^3 (20%) at 6 cm depth in this horizon. Surface horizon soil moisture conditions were considerably wetter (35% by wt) when his treatments were carried out than in this study (20% by wt). Differences in conclusions may be due to sampling methodology or to differences in sample sizes. Bates used a treatment sample size (n=6) to draw his conclusions. This study evaluated 17 and 16 treatment points at two A22 depth increments (13-24 cm) and (24-34 cm) respectively. Similarly, in this study, the conclusion that increases in bulk densities did not occur in the A23 horizon is based on a relatively small data base. Only 5 controls and 6 treatment points were evaluated for the A23 horizon. Using the sand excavation method made it extremely difficult to differentiate A22 from A23 horizons at this site. These two horizons grade into each other and the sampling method employed relies on changes in color or strength for horizon differentiation. It is possible that some of the horizons encountered at 25 to 35 cm identified as A22 are actually A23 horizons. This possible source of error may have led to the inclusion of erroneously high bulk density values in the data base established for the A22 horizons. Bates (1981) located the centers of A23 horizons at depths ranging from 22 to 50 cm. This substantiates the possibility of erroneous horizon identification.

Bates did not find statistically significant increases in bulk densities in the A21, A22, nor A23 horizons under "dry" trafficking (Table 8). This was true regardless of trafficking intensity (1 to 8 events). Therefore, increases in bulk density resulting from slash piling are not expected under dry soil moisture conditions (10 to 14% by wt) (Table 9).

At soil moistures approaching theoretically optimum moisture for compaction (20 to 22% by wt) slash piling should induce increases in bulk densities of approximately .11 g/cm^3 in the A21 and A22 horizons (0-34 cm) (Table 9). This increase is expected throughout 23 to 47% of the slash piled area. Deeper soil compaction is not anticipated.

The Proctor test optimum moisture value is approximately 21% for the A21 and A22 horizons, respectively. This value, predicting maximum compaction susceptibility, is supported by bulk density data collected at this site. In this study treatment soil moistures were within 5% (by wt) of this value. Bates found that, as soil moisture varied 7 to 10% above or below this value, bulk density did not change (Bates, 1981). It is also possible that the sand excavation method yields more precise data than the saran-clod method, and hence detected bulk density changes.

Bulk Density Changes at Site ALT

Data indicate that statistically significant changes in bulk density occurred in both surface ash and subsurface till horizons. Average increases are .09 g/cm^3 (13%), .26 g/cm^3 (34%), and .10 g/cm^3 (8%) for A21 and A22 horizons (0-12 cm), A22 (12-24 cm), and IIA21 (15-39 cm) depth increments. Associated levels of statistical significance are $p = .02$, $p = .035$, and $p = .105$, for each horizon-depth increment, respectively.

Paralleling data at site AQT, IIA2 till material at this site was found in only 1 of 11 cases in the control at the 12-24 cm depth increment. In the treatment samples IIA2 till was found in 8 of 18 cases in the 14-26 cm) depth increment. This implies that either superficial material has been displaced during slash piling operations, or that the site is extremely variable. As for site AQT, three approaches for the analysis of data are suggested for this depth increment (Table 13).

1. Control bulk densities for the IIA21 (27-38 cm) horizon-depth increment are compared with the treatment A21 bulk densities of approximately the same depth (27-39 cm). Analysis indicates that average bulk densities have increased .12 g/cm^3 (10%) significant at $p = .035$.

Table 13. Bulk density changes in the IIA21 hoizon at site ALT evaluated at three depth increments.

Horizon Sampled	Average Depth Increment Sampled (cm)	Control Bulk Density (g/cm^3) x	s	n	Treatment Bulk Density (g/cm^3) x	s	n	Change in Bulk Density (g/cm^3) x	s	%	Statistical Significance p-value	Conclusions
IIA21	27-38	1.24	.12	9								
								+.13	.05	10	.035	Bulk density has
IIA21	27-39				1.37	.12	10					increased
IIA21	14-26				1.29	.21	8					
								-.05	.08	4	.555	Bulk density has not
IIA21	27-39	1.24	.12	9								increased
IIA21	14-26				1.29	.21	8					
								+.08	.08	6	.350	Treatment bulk density is independent
IIA21	27-39				1.37	.12	10					of depth in the interval 14-39 cm

2. Treatment bulk densities in the IIA21 (14-26 cm) depth increment are compared with control bulk densities at the (27-39 cm) depth increment. This analysis attempts to compensate for the possible displacement of surface material and puts comparisons on an equal depth basis (assumes that 14 cm of surface material has been displaced). This method indicates that the bulk density of the till horizon has not changed, which is different than the conclusions regarding compaction of IIA2 material at site AQT.

3. Treatment bulk densities for the IIA2 (14-26 cm) horizon-depth increment are compared with treatment bulk densities at the IIA2 (27-39 cm) depth increment. Analysis indicates that there is no statistically significant difference in treatment effect with respect to depth. As a result, IIA2 treatment bulk densities are combined for both depths and compared with control bulk densities. This result was reported in the first paragraph and in the summary table (Table 7).

In the surface ash-loess horizons, more soil compaction was measured in the second (12-25 cm) than first (0-12 cm) depth increment.

This phenomena is in contrast to that observed at site AQT which has a similar ash cap. The ash cap at site AQT was trafficked with soil moisture at 27% (by wt). In contrast soil moisture at this site (ALT) averaged 43% (by wt) at treatment. It is possible that shear failure occurred in the second depth increment, although there was no visual evidence (ruts) to support this hypothesis.

In contrast to this study, Bates (1981) found statistically significant increases in bulk densities only in the surface ash horizon (at 11 cm depth). This was observed regardless of soil moisture ("wet" or "dry") at treatment. He also reported average increases of .50 g/cm^3 (76%) at "wet" soil moisture (50% by wt) after an estimated 20-35 trafficking events. Cullen (1981) similarly observed that compaction had persisted on skid trails. He reported statistically significant bulk density increases of .23 g/cm^3 on moderately disturbed skid trails and .36 g/cm^3 on severely disturbed trails (at 5 cm depth). He also reported statistically significant increases of .44 g/cm^3 and 40 g/cm^3 (at 15 cm depth) under moderately and severely disturbed skid trails, respectively. Neither Cullen nor Bates reported increases in bulk densities in the subsurface glacial till horizons.

Under "dry" conditions (27% by wt) Bates (1981) found an average bulk density increase of .20 g/cm^3 in the surface A21 horizon after 4 trafficking events. It is predicted that this increase would be

found, in the surface 0-25 cm, on 2 to 8% of the site area when slash piled "dry" (Table 9).

Another approach which predicts slash piling soil compaction at relatively dry soil moisture is presented as follows. The surface ash and till horizons at sites AQT and ALT are similar. The surface horizons at both sites are characterized by amorphous volcanic ash-loess deposits. Ash horizon thickness is approximately 31 cm at both sites. The ash cap at site AQT averages 31% coarse fragments (by wt) whereas the ash at site ALT average 20% coarse fragments (by wt). The difference in coarse fragment content should theoretically make the ash at site ALT somewhat more susceptible to compaction. The IIA21 horizons at site AQT are formed in quartzite till and have 63% coarse fragments (by wt). The IIA21 horizons at site ALT are formed in limestone till and contain 38% coarse fragments (by wt). The upper till horizon boundary at both sites is found at approximately the same depth (Appendix I). Theoretically, the till at site ALT is somewhat more compaction susceptible due to a lower percentage of coarse fragments (Li, 1956). Additionally, Bates' "dry" treatments at site ALT were performed when soil moisture was 27% (by wt) in the ash horizons and 17% (by wt) in the IIA2 till horizons. These values correspond to soil moistures of 26% (by wt) in the ash horizons and 15% (by wt) in the till horizons measured at site AQT during treatment slash piling.

Since increases in bulk density were recorded for site AQT in both the ash depth increment (0-25 cm) and in the IIA21 (12-37 cm) depth increment it is hypothesized that soil compaction is also likely in the corresponding horizons at this site. The predicted bulk density increases are approximately .18 g/cm^3 in the ash and .12 g/cm^3 in the till. The predicted bulk density increase in the ash (.18 g/cm^3) corresponds almost exactly to the value reported by Bates (.20 g/cm^3) at this site (ALT) under 4 trafficking events "dry." Although Bates did not find compaction in the IIA2 till horizon at this site, it is hypothesized that a bulk density increase of .12 g/cm^3 will occur when these ALT soils are slash piled at 27% (by wt) soil moisture. This increase is expected to occur over 23 to 47% of the site in the IIA2 (14-39 cm) depth increment (Table 9).

Soil compaction is also predicted under wetter conditions. With soil moisture at 45% (by wt), which is 10% (by wt) higher than Proctor optimum moisture for compaction (35% by wt), a .18 g/cm^3 bulk density increase is predicted in the ash horizons (0-25 cm depth). The .18 g/cm^3 value is the average of bulk density increases in the A22 (0-17 cm) and A22 (13-25 cm) depth increments (Table 8).

In the IIA2 horizon at 21% (by wt) soil moisture (which is within 3% of "optimum moisture") a .13 g/cm^3 bulk density increase is expected.

Therefore, soil compaction in both ash and till horizons is expected to occur in 23 to 47% of the slash piled site (Table 9).

Data indicate that soil compaction is probable in the ash horizon within the soil moisture range 27 to 46% (by wt). However, variation in soil compaction susceptibility within this moisture range is not obvious. It is probable that compaction susceptibility in this horizon parallels compaction susceptibility in the ash horizon at site AQT, which increased with soil moisture in the range 13 to 57% (by wt). Compaction susceptibility, in relation to soil moisture, for the IIA2 till horizon is not predicted due to the narrow range of soil moisture values monitored (17 to 21% by wt).

Bulk Density Changes at Site AAR

Data for this site indicate that statistically significant increases in bulk densities occurred as deep at the (28-40 cm) depth increment. Magnitudes of measured increases were .09 g/cm^3 (16%), .10 g/cm^3 (17%), and .10 g/cm^3 (16%) for the A21 (0-12 cm), A22 (14-26 cm), and A22 (28-40 cm) horizon depth increments, respectively. Associated levels of statistical significance are $p = .003$, $p = .001$, and $p = .005$, respectively (Table 7).

Under "wet" soil moisture conditions (60% by wt), Bates (1981) found average bulk density increases of .28 g/cm^3 in the A21 horizon

(at 6 cm depth) after 8 trafficking events (Table 8). Bulk density increases were not found in the underlying A22 horizons nor in deeper horizons.

Bates reported bulk density differences in undisturbed A21 horizons with respect to soil moisture conditions. He found average control bulk densities of .58 g/cm^3 at 59% moisture (by wt) and .78 g/cm^3 at 28% moisture (by wt). Thus bulk density apparently decreased by .20 g/cm^3 under "wet" soil moisture conditions. As a result in this slash piling study reported bulk density increases may be underestimating the actual increases. However, a few informal lab measurements do not verify this reported shrink-swell phenomena. Additionally, Bates did not report this phenomena in the deeper A22 horizon, which has identical soil texture and similar clay mineralogy (Appendix I).

Under "dry" soil moisture conditions (28% by wt) Bates, with one exception, did not find statistically significant bulk density increases in the A21 nor A22 horizons. This was true regardless of the number of trafficking events. He reported a bulk density increase of .43 g/cm^3 in the A22 horizon (at 27 cm depth) which had been trafficked 8 times. However, this result is based on a sample size of one, which makes the accuracy suspect. Extrapolating these results to slash piling operations during dry summer conditions indicates that compaction hazard is negligible (Table 9).

Compaction under wet soil moisture conditions (55% by wt) is also predicted for the A21 and A22 horizons within the 0-40 cm depth increment. It is anticipated that a .11 g/cm^3 bulk density increase will be incurred over 23 to 47% of the slash piled area. The .11 g/cm^3 value is an average of bulk density increases for the 0-40 cm depth increment. The moisture-density relationship within the soil moisture range 20 to 60% (by wt) is not clear. Bates (1981) reported that compaction did not occur at 28% (by wt) soil moisture. Soil moistures for both the skid trail and slash piling studies ranged from 55 to 61% (by wt). It appears that soil susceptibility to compaction increases as soil moisture increases.

The three depth increments sampled at this site each average approximately 65% coarse fragments (by wt). The high percentage of coarse fragments probably reduces compaction susceptibility at this site in comparison to the surface ash-loess caps at sites AQT and ALT.

It is well documented in the literature that magnitudes of bulk density increases, induced by trafficking, decrease with depth. This is attributed to the attenuation of compacting stresses as depth increases (Chancellor, 1977; Lull, 1959). To test this hypothesis, bulk density changes for each horizon-depth increment at each site were compared by analysis of variance. The hypothesis that the magnitude of bulk density increase decreased with depth was tested at $p = .10$. Results are presented in Table 14.

Table 14. Treatment soil compaction with respect to depth at the five study sites.

Site	Horizon Evaluated	Mean Depth Evaluated (cm)	Mean Bulk Density Change* (g/cm^3)
AQT	A21 & A22	0-12	+.19[a]
	A22	13-24	+.16[a]
	IIA21	12-26	+.15[a]
	IIA21	25-37	+.12[a]
MIX	A21	0-12	+.16[a]
	A21	12-25	+.09[a]
	A22	26-37	-.01[b]
LAC	A21	0-12	+.10[a]
	A22	14-24	+.12[a]
	A22	25-35	+.10[a]
	A23	33-42	+.05[b]
ALT	A21 & A22	0-12	+.09[a]
	A22	12-24	+.26[b]
	IIA21	14-26	+.05[a]
	IIA21	27-39	+.13[a]
AAR	A21	0-12	+.09[a]
	A22	14-26	+.10[a]
	A22	28-40	+.10[a]

*At each site mean bulk density increases are not statistically significant (at $p \leq .10$) if followed by the same letter.

At all sites bulk density increases did not decrease with depth in the surface 25 cm. This was true for both till and nontill horizons. In the third depth increment (approximately 26-42 cm) bulk density increases were not statistically different from the upper two depth increments (0-12 cm and 13-25 cm) in three of five sites. The magnitude of bulk density increases decreased statistically only in the A22 (26-37 cm) depth increment at site MIX and in the A23 (33-42 cm) depth increment at site LAC.

Changes in Infiltration Rates Associated with Slash Piling Operations

Dramatic decreases in equilibrium infiltration rates were measured after slash piling at the three sites evaluated (AQT, MIX, and LAC). Decreases are highly significant at $p = .001$ at these sites. Since infiltration measurements were made on the same disturbance class as bulk density measurements, the associated bulk density changes in the surface horizons are also presented (Table 15). Raw data are presented in Appendix V.

The average decrease at site AQT was 9.0 cm/hr (60% decrease). This is associated with an increase in bulk density of .21 g/cm^3 (31%) in the surface ash horizon measured at the 0-12 cm depth increment. At site MIX average infiltration decreased by 8.9 cm/hr (83%). The corresponding increase in bulk density is .16 g/cm^3 (17%) in the surface A21 horizon measured in the 0-12 cm depth increment. Similarly,

Table 15. Changes in equilibrium infiltration rates and associated bulk density changes in the surface horizons caused by slash piling operations at sites AQT, MIX and LAC.

Site	Equilibrium Infiltration Rate		Decrease in Infiltration Rate		Statistical Significance	Associated Bulk Density Change in the Surface Horizon		
	Control (cm/hr)	Treatment (cm/hr)	(cm/hr)	(%)	(p-value)	Horizon	Depth (cm)	Bulk Density Change (g/cm^3)
AQT	15.2	6.2	9.0	60	.001	A21	0-12	+.21
MIX	10.7	1.8	8.9	83	.001	A21	0-12	+.16
LAC	15.4	1.6	13.8	90	.001	A21	0-12	+.10

at site LAC average infiltration rates decreased 13.8 cm/hr (90%). The associated bulk density increase in surface A21 horizon 0-12 cm depth increment is .10 g/cm^3 (9%).

Data are compared with infiltration rates presented by Cullen (1981) on 3 to 17 year old moderately and severely disturbed skid trails on similar soil profiles in northwestern Montana (Table 16). Cullen also reported major reductions in infiltration rates in the volcanic ash surface horizons overlying quartzite and limestone tills. He monitored infiltration rates with double ring infiltrometers of the same diameters as those used in this study. Additionally, he ran measurements for the same length of time as in this study, i.e., 60 minutes.

He reported 75% and 80% reduction in infiltration rates on moderately and severely disturbed skid trails overlying quartzite till. Final infiltration rates were 8.9 cm/hr and 7.9 cm/hr on the two skid trails, respectively. Similarly, he found 78% and 81% reduction in infiltration rates on moderately and severely disturbed skid trails overlying limestone till. Associated increases in bulk density relative to the control values ranged from .02 g/cm^3 to .37 g/cm^3 for moderately and severely disturbed skid trails at 5 cm depth and from .12 g/cm^3 to .44 g/cm^3 at the 15 cm depth. It is clear that significant reductions in infiltration rates can occur in association with small increases in soil bulk density.

Table 16. A comparison of studies investigating median equilibrium infiltration rates in the surface horizons of similar parent materials in northwestern Montana.

Study Type	Soil	Degree of Trafficking	Median Infiltration Rate (cm/hr) Control	Treatment (% decrease)		Statistical Significance p-value
This study	Ash Overlying Quartzite Till	2-4 events	14.4	4.8 (67)		.001
				Moderately Disturbed	Severely Disturbed	
Skid Trail †	Ash Overlying Quartzite Till	Unknown	36.1	8.9 (75)	7.4 (80)	.01
	Ash Overlying Limestone Till	Unknown	38.5	8.3 (78)	7.3 (81)	.01

† Infiltration rates on skid trails trafficked 3 to 17 years earlier (after Cullen, 1981).

Cullen reported no significant differences in treatment effects with respect to time since logging. The significance of persistent reductions in infiltration rates is not known. It is possible that overland flow would occur from reductions of this magnitude. However, measuring infiltration rates with small rings (less than 30 cm) tends to overestimate infiltration capacity as does the gravitational head induced by the ponded water (Bertrand, 1965; Philip, 1958; Hills, 1970). The results are consistent with those reported by Steinbrenner (1955), Steinbrenner and Gessel (1955), Mace, et al. (1971), and Cullen (1981).

Slash Weight Remaining after Mechanized Slash Piling

Average slash weights before mechanized piling varied considerably between sites, ranging from 44 to 66 tons/acre (98.6 to 147.8 metric tons/hectare). However, mean slash weights remaining after the completion of piling operations varied little between sites, ranging from 9 to 12 tons/acre (20.2 to 26.9 metric tons/ hectare). Means, standard deviations and .95 confidence intervals are presented for each site in Table 17. Raw data are available in Appendix VI.

The weight of slash removed at each site was quantified to determine slash piling efficiency. The volume of slash remaining after piling has significance with respect to: maintaining microsites for natural regeneration, providing protection from soil erosion, reduction

Table 17. Slash weights before piling, after piling, and slash weight removed by mechanized slash piling at the five study sites.

Site	Statistics†	Slash Weight Before Piling (tons/acre)	Slash Weight After Piling (tons/acre)	Weight of Slash Removed (tons/acre)	Statistical Significance (p-value)
AQT	$\bar{x}$	51.43	9.05	42.38	
	s	25.22	3.45	4.02	.0001
	.95 CI	(43.51-59.35)	(7.94-10.16)	(34.37-50.39)	
	n	42	40	-	
MIX	$\bar{x}$	46.38	10.09	36.29	
	s	37.15	6.14	5.32	.0001
	.95 CI	(35.80-56.90)	(8.25-11.75)	(25.73-46.86)	
	n	50	50	-	
LAC	$\bar{x}$	44.04	8.97	35.07	
	s	31.21	4.41	4.98	.0001
	.95 CI	(35.18-52.90)	(7.56-10.38)	(25.17-44.96)	
	n	50	50	-	
ALT	$\bar{x}$	55.96	12.16	43.81	
	s	23.41	6.88	4.22	.0001
	.95 CI	(48.49-63.43)	(9.72-14.60)	(35.39-52.33)	
	n	40	33	-	
AAR	$\bar{x}$	66.14	11.70	54.44	
	s	35.60	5.81	6.27	.0001
	.95 CI	(54.90-77.38)	(9.64-13.76)	(41.94-66.94)	
	n	41	33	-	

† $\bar{x}$ = Mean
s = Standard deviation
.95 CI = 95% confidence interval
n = Number of transects sampled

of fire hazard, stability of soil microbial populations, and facilitating movement of tree planting crews.

It is hypothesized that the volume of slash removed may have significance with respect to the level of site disturbance and severity of soil compaction incurred on a logged unit. During the first forward trafficking event the crawler tractor usually rode over a portion of downed slash. As a result the overridden slash probably shelters the soil from compacting vehicle weight and vibration. The second forward event was typically initiated both to gather material missed on the first pass and to densify the slash pile. If this event were eliminated, site disturbance and soil impacts would likely be somewhat mitigated. The advantages, if any, must be weighed against desired site preparation and scarification. It is clear that both the operators' and land managers' perceptions of a good piling job influence the intensity of slash piling operations at a given site.

CONCLUSIONS

The effects of mechanized slash piling on site disturbance, soil bulk density, and infiltration rates were evaluated at five study sites in northwestern Montana. The trafficking intensity which characterizes slash piling is as follows: 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. Ninety-six percent of all trafficking events were 2 and 4 pass events. Trafficking intensity appears to be relatively independent of the weight of slash removed at these sites within the range of slash weights evaluated (35 to 54 tons/acre). The number of stems per acre and their diameters are probably important factors influencing slash piling trafficking intensity.

Eighty-four to 93% of the site area was disturbed during slash piling operations. Forty to 63% of the site area was displaced mounded berm material, and 11 to 24% of the site was exposed to bare mineral soil. Soil displacement or scalping was noted in the surface horizons and it is estimated that 10-15 cm of the surface horizon may be displaced during slash piling operations. However, this was found only on 11 to 24% of the area.

Area directly trafficked by the D6D crawler tractor ranged from 25 to 48% of total site area. However, since much of the site is obscured by berm material, these values are conservative. It is deduced that 41

to 67% of the area may have experienced trafficking. Although all trafficked area is subjected to potentially compacting stresses, it is the opinion of this author, that the greatest bulk density increases are likely only in those areas from which duff has been removed, i.e., 11 to 24% of site area. These values are similarly conservative in that they do not account for the additional area covered by displaced berm nor bulk density increases that probably occur laterally from the track-soil surface interface.

Mean bulk density increases measured under trafficked bare mineral soil ranged from .09 to .26 g/cm^3 (7 to 34%) in the surface 25 cm at all sites. Deeper compaction was also found at 3 of 5 sites to 40 cm, wherein bulk density increases ranged from .10 to .13 g/cm^3 (8 to 17%). Although the data indicate that compaction tends to decrease with depth, the differences in magnitudes with respect to the depths evaluated (0-40 cm) are not statistically significant at sites AQT, ALT, and AAR. Of interest are the average bulk density increases (.10 to .13 g/cm^3) in the subsurface glacial till horizons. These results differ from those of Cullen (1981) who concluded that compaction probably did not occur and certainly did not persist in the till horizons. Bates (1981) similarly did not find compaction in the subsurface till horizons. Both these investigators monitored soil bulk density by the saran-clod method under skid trail operations, which impose a more severe trafficking regime than slash piling. As a result it is proposed that the

sand excavation method may be a more sensitive bulk density instrument than the saran-clod method especially in soils containing a high percentage of coarse fragments.

Although all soils evaluated incurred bulk density increases as a result of mechanized slash piling, the greatest mean increases were found in the surface horizons at sites AQT and ALT. These volcanic ash-loess influenced surface horizons have low coarse fragment contents and were the most compaction susceptible of the soils investigated in this study. These soils had the lowest pretreatment bulk densities and, therefore, the lowest bearing capacities. The soils at site LAC had the highest initial bulk densities and incurred the smallest bulk density increases. Although the soils at site AAR are volcanic ash-loess influenced, their high coarse fragment content probably reduces their compaction susceptibility. Soil particle size distribution does not appear to significantly influence the soil compaction susceptibility of these cohesionless soils under mechanized slash piling. The greatest bulk density increases were found at sites AQT (poorly graded) and ALT (well graded). Site LAC (poorly graded) had the smallest mean bulk density increase. Duff layers are thin on all sites (ranging from 2.3 to 5.6 cm), and differences in thickness do not appear to affect the compaction susceptibilities of underlying soil horizons.

In these cohesionless silt loam textured soils, soil compaction susceptibility generally increases with soil moisture content although

the moisture-density relationships are not well defined. In the opinion of this investigator slash piling operations will not induce large bulk density increases over a wide range of soil moisture conditions of these nor similar soils. However, the effects of structural degradation (puddling) and destruction of pore continuity associated with trafficking at saturated soil moisture conditions on timber productivity are yet to be evaluated in northwestern Montana.

Bulk density increases incurred by slash piling were 32 to 64% less than those incurred by eight trafficking events. The trafficking intensity imposed by eight pass skidding operations induced on the order of .2 to .3 g/cm^3 greater increase in bulk density than slash piling.

Infiltration rates were reduced 60 to 90% at the three sites evaluated. Corresponding bulk density increases ranged from .10 to .21 g/cm^3 in the surface horizons. It is clear that small bulk density increases are associated with major reductions in soil infiltration rates.

The effects of these magnitudes of soil compaction on tree species indigenous to northwestern Montana have not been evaluated.

It is not known whether potential soil impacts would be more significant at sites which have incurred the greatest bulk density increases (AQT and ALT) or at those sites having higher pretreatment

bulk densities, which are further increased by compaction (MIX and LAC). Although soil compaction in general decreases growth, it has also been shown under some conditions to increase growth. The reductions in infiltration rate, and apparent disruption of pore continuity may have more long term significance to timber productivity and soil erosivity than the small bulk density increases incurred by slash piling. Reduced soil water holding capacity by compaction is more likely under skidding than under slash piling operations, although soil displacement or scalping may potentially reduce the water holding capacity of the profile in either case. The persistance of soil compaction on these cohesionless soils is likely due to their low shrink-swell potentials and the persistance of snow cover in northwestern Montana. Mechanized slash piling reduced slash on these sites from (44 to 66 tons/acre) to (9 to 12 ton/acre). It is proposed that less intensive slash piling may reduce potential soil impact.

RECOMMENDATIONS FOR FUTURE STUDY

1. Before informed management decisions can be made regarding alternative harvesting plans, site preparation methods, or reclamation procedures, it is important to ascertain the significance of soil compaction to timber species indigenous to northwestern Montana. Field studies of regeneration productivity and root morphology on skid trails and slash pile units of various ages are recommended. Trees are tolerant of extremely varied biological conditions, thus while compaction effects may be expressed in young seedlings, the effects may not be apparent nor significant in mature timber.
2. The development of a laboratory test that more closely models the field compaction process under timber harvesting equipment than the standard Proctor tests now utilized as a predictive tool is needed.
3. The effects of soil puddling on timber productivity and regeneration should be quantified. Structural degradation and disruption of pore continuity may have more biological significance than the small bulk density increases typically found in puddled soils.
4. A study of the effects of coarse fragment content, size, and shape on compaction susceptibility in the cohesionless volcanic ash-loess influenced soils common in northwestern Montana is recommended.

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APPENDICES

APPENDIX I

SOIL PROFILE DESCRIPTIONS,

PHYSICAL AND CHEMICAL CHARACTERIZATION,

AND SITE CHARACTERISTICS AT THE FIVE STUDY SITES

SITE AQT

CLASSIFICATION: Andic Dystric Eutrocrept, loamy skeletal, mixed, frigid
LOCATION: SW1/4, NE1/4, Sec25, T27N, R26W, MPM
PHYSIOGRAPHIC POSITION: Midslope, 1298 m Elevation
SLOPE: 15%
ASPECT: 74° NE
HABITAT TYPE: Abies grandis/Linnaea borealis (Xerophyllum tenax phase)
PARENT MATERIAL: Volcanic ash overlying quartzite till
DRAINAGE: Well drained

O1 4.3-2.0 cm Essentially undecomposed forest litter

O2 2.0-0 cm Decomposed forest litter

A21 0-1 cm Light brownish gray (10YR 6/2) dry, silt loam, very dark grayish brown (10YR 3/2) crushed moist; weak fine subangular blocky structure; soft (dry), very friable (moist), non-sticky and non-plastic (wet); many very fine and fine roots, common medium and coarse roots; 10% gravels by volume; abrupt smooth boundary.

A22† 1-31 cm Light yellowish brown (10YR 6/4) dry, silt loam, yellowish brown (10YR 5/6) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; soft (dry), very friable (moist), non-sticky and non-plastic (wet); many very fine and fine roots, common medium and coarse roots; 10% gravels by volume, medium acid (5.8); abrupt smooth boundary.

IIA21 31-58 cm Light gray (10YR 7/2) dry, very gravelly silt loam, light brownish gray (10YR 6/2) crushed moist; weak coarse subangular blocky structure breaking to weak fine subangular blocky structure; slightly hard (dry), friable (moist), non-sticky and non-plastic (wet); few very fine, fine, medium and coarse roots; 50% gravels, 15% cobbles, and 5% stones by volume; very strongly acid (5.0); abrupt smooth boundary.

IIA22 58-84 cm Light gray (10YR 7/2) dry, very gravelly silt loam, light brownish gray (10YR 6/2) crushed moist; very weak medium subangular blocky structure breaking to very weak fine subangular blocky structure; slightly hard (dry), friable (moist), non-sticky and non-plastic (wet); few very fine, fine, medium and coarse roots, 60% gravels, 15% cobbles, and 5% stones by volume; strongly acid (5.4); abrupt smooth boundary.

IIB2 84-100+ cm White (10YR 8/2) dry, very gravelly silt loam, pale yellow (10YR 7/4) moist; moderate medium subangular blocky structure breaking to moderate fine subangular blocky structure; slightly hard (dry), friable (moist), non-sticky and non-plastic (wet); few very fine, fine, medium and coarse roots; 60% gravels, 15% cobbles, and 5% stones by volume; very strongly acid (5.0); boundary not reached.

†This horizon is commonly called a Bir horizon in northwestern Montana.

SITE AQT

Horizon	Horizon depth	Particle Size Analysis				Textural class	Bulk density	1/3 Bar water	15 Bar water	Available water holding capacity
		Sand	Silt	Clay	>2mm					
	cm	(% wt)			(% vol)		(g/cc)	(% wt)		
A21	0-1	ND[‡]								
A22[†]	1-31	28	66	6	10	silt loam	.66	35	10	25
IIA21	31-58	40	58	2	70	silt loam	1.06	11	2	9
IIA22	58-84	45	54	1	80	silt loam	ND	7	1	8
IIB2	84-100[+]	30	69	1	80	silt loam	ND	12	1	11

Horizon	Organic matter	(1:2) soil:water dilution		Extractable Cations				Cation Exchange Capacity[§] NaOAc (pH=8.2)	NaCl (Natural pH)	P	Extractable minor elements			
		pH	e.c.	Ca	Mg	Na	K				Fe	Mn	Cu	Zn
	(% wt)		(mmhos/cm)	(meq/100g)						(ppm)	(ppm)			
A21	ND													
A22	2.5	5.8	.10	3.0	.5	.2	.5	21.4	9.0	23.0	51	51	1	1
IIA21	.5	5.0	.04	1.3	.4	<.1	<.1	3.7	2.8	5.0	24	2	<1	<1
IIA22	<.1	5.4	.02	1.2	.3	<.1	<.1	2.9	2.3	.6	16	2	<1	<1
IIB2	<.1	5.0	.02	.7	.2	<.1	<.1	2.3	1.6	.6	33	<1	1	<1

Horizon	Kaolinite	Estimated abundance					Interstratified Vermiculite-Chlorite	Interstratified Smectite-Vermiculite Chlorite
		Illite	Chlorite	Vermiculite	Smectite	Amorphous		
A21	ND							
A22	Trace	Trace				Very high	Trace	
IIA21	Low	Very High					Trace	Trace
IIA22	Low	High						Low
IIB2	Low	Very High						

[†]This horizon is commonly called a Bir horizon in northwestern Montana.

[‡]ND means not determined.

[§]Cation exchange capacity determined by sodium replacement (NaOAc) at pH = 8.2 and by (NaCl) at the natural pH of the soil horizon.

SITE MIX

CLASSIFICATION: Typic Eutroboralf, loamy, skeletal, mixed frigid
LOCATION: SW1/4, SW1/4, Sec3, T28N, R26W, MPM
PHYSIOGRAPHIC POSITION: Lower slope, 1112 m Elevation
SLOPE: 8%
ASPECT: 26°N
HABITAT TYPE: Pseudotsuga menziesii/Linnaea borealis (Calamagrostis rubescens phase)
PARENT MATERIAL: Mixed volcanic ash and lake sediments over mixed glacial till
DRAINAGE: Moderately well drained

O1 2.3-.8 cm Essentially undecomposed forest litter

O2 .8-0 cm Decomposed forest litter

A21 0-21 cm Light yellowish brown (10YR 6/4) dry silt loam, dark yellowish brown (10YR 4/4) moist crushed; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; slightly hard (dry), friable (moist), non-sticky and non-plastic (wet); many very fine, fine, medium, and coarse roots; 5% gravels by volume; very strongly acid (4.9); clear smooth boundary.

A22 21-36 cm Pale brown (10YR 6/3) dry, silt loam, borwn (10YR 5/3) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; slightly hard (dry), friable (moist), non-sticky and non-plastic (wet); common very fine, fine and medium roots, few coarse roots; 10% gravels by volume, strongly acid (5.3); clear smooth boundary.

IIA21 36-53 cm White (2.5Y 8/2) dry, gravelly silt loam, light gray (2.5Y 7/2) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; slightly hard (dry), friable (moist), non-sticky and non-plastic (wet); few very fine, fine, medium, and coarse roots; 15% gravels and 5% cobbles by volume; medium acid (5.6); abrupt smooth boundary.

IIA22 53-75 cm White (2.5Y 8/2) dry, gravelly silt loam, light yellowish brown (2.54Y 6/4) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; hard (dry), friable (moist), slightly sticky and slightly plastic (wet); few very fine, fine, medium, and coarse roots; 15% gravels and 5% cobbles by volume; medium acid (5.6); abrupt smooth boundary.

IIB21t 75-110 cm Very pale brown (10YR 7/4) dry, gravelly silt loam, brownish yellow (10YR 6/6) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; hard (dry), firm (moist), slightly sticky and slightly plastic (wet); common thin clay films on ped faces; few very fine, fine, medium, and coarse roots; 15% gravels and 5% cobbles by volume; medium acid (5.9); clear smooth boundary.

IIB22t 110-145+ cm Brownish yellow (10YR 6/6) dry, gravelly silt loam, yellowish brown (10YR 5/6) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; hard (dry), firm (moist), slightly sticky and slightly plastic (wet); common, moderately thick clay skins on ped faces; 15% gravels and 5% cobbles by volume neutral (6.7); boundary not reached.

SIT MIX

Horizon	Horizon depth	Particle Size Analysis				Textural class	Bulk density	1/3 Bar water	15 Bar water	Available water holding capacity
		Sand	Silt	Clay	>2mm					
	cm	------- (% wt)----			(% vol)		(g/cc)	---------- (% wt)		----------
A21	0-21	34	61	5	5	silt loam	.96	21	5	16
A22	21-36	34	62	4	10	silt loam	1.46	16	3	13
IIA21	36-53	28	68	4	20	silt loam	ND†	12	2	10
IIA22	53-75	19	70	11	20	silt loam	ND	17	6	11
IIB21t	75-110	19	61	20	20	silt loam	ND	18	6	12
IIB22t	110-145+	15	65	20	20	silt loam	ND	21	7	14

Horizon	Organic matter	(1:2) soil:water dilution		Extractable Cations				Cation Exchange Capacity§ NaOAc	Cation Exchange Capacity§ NaCl	P	Extractable minor elements			
		pH	e.c.	Ca	Mg	Na	K	(pH=8.2)	(Natural pH)		Fe	Mn	Cu	Zn
	(% wt)		(mmhos/cm)	----------				(meq/100g)----------		(ppm)	------ (ppm) ----			
A21	1.7	4.9	.06	1.8	.6	.1	.2	8.3	4.4	29	91	23	<1	<1
A22	1.0	5.3	.04	2.0	.6	.1	.3	5.7	4.8	28	75	<1	<1	<1
IIA21	.4	5.6	.02	1.4	.4	<.1	<.1	3.2	2.5	6	20	<1	<1	<1
IIA22	.8	5.6	.03	2.2	.7	<.1	<.1	4.8	4.8	2	23	7	1	<1
IIB21t	.3	5.9	.05	4.2	1.7	.2	.2	7.8	7.0	2	30	11	2	<1
IIB22t	<.1	6.7	.06	5.4	2.1	.3	.4	8.3	8.3	3	19	8	2	<1

Horizon	Kaolinite	Estimated abundance					Interstratified Vermiculite-Chlorite	Interstratified Smectite-Vermiculite Chlorite
		Illite	Chlorite	Vermiculite	Smectite	Amorphous		
A21	Low	Very High					Low	
A22	Low	Very High					Low	
IIA21	Low	Very High						Low
IIA22	Low	Very High						Low
IIB21t	Low	Very High						Low
IIB22t	Low	Very High						Low

†ND means not determined.

§Cation exchange capacity determined by sodium replacement (NaOAc) at pH = 8.2 and by (NaCl) at the natural pH of the soil horizon.

SITE LAC

CLASSIFICATION: Eutric Glossoboralf, loamy, mixed frigid
LOCATION: SW1/4, NE1/4, Sec3, T28N, R26W, MPM
PHYSIOGRAPHIC POSITION: Valley bottom, 1051 m Elevation
SLOPE: 5%
ASPECT: 40°N
HABITAT TYPE: Pseudotsuga menziesii/Linnaea borealis (Calamagrostis rubescens phase)
PARENT MATERIAL: Volcanic ash influenced lacustrine deposits
DRAINAGE: Somewhat poorly drained

O1 5.3-3.0 cm Essentially undecomposed forest litter

O2 3.0-0 cm Decomposed forest litter

A21 0-15 cm Pale brown (10YR 6/3) dry, silt loam, brown (10YR 5/3) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); many very fine, fine, and medium roots, common coarse roots; 5% gravel by volume; very strongly acid (5.0); clear smooth boundary.

A22 15-32 cm Very pale brown (10YR 7/3) dry, silt loam, brown (10YR 5/3) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); many very fine, fine, and medium roots, common coarse roots; 5% gravel by volume; strongly acid (5.2); clear wavy boundary.

A23 32-52 cm Light gray (2.5Y 7/2) dry, silt loam, light brownish gray (2.5Y 6/2) crushed moist; moderate coarse angular blocky structure breaking to moderate medium and fine angular blocky structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); common very fine, fine, and medium roots, few coarse roots; 5% gravel by volume; medium acid (5.7); abrupt wavy boundary.

B2t 52-100 cm Pale yellow (2.5Y 7/4) dry with common fine prominent mottles of red color (2.5YR 5/6) dry, silt loam, light olive brown (2.5Y 5/4) crushed moist; strong very coarse angular blocky structure breaking to strong medium and fine angular block structure; slightly hard (dry), firm (moist), sticky and plastic (wet); many moderately thick clay films on ped faces; many very fine, common fine, and few medium and coarse roots ramifying planes of weakness; 10% gravel by volume; slightly acid (6.5); gradual smooth bounary.

C 100-120^{+} cm White (2.5Y 8/2) dry with common fine prominent mottles of red color (2.5YR 5/6) dry, silt loam, light yellowish brown (2.5Y 6/4) crushed moist; massive structure with varves observable; slightly hard (dry), firm (moist), sticky and plastic (wet); many moderately thick clay films located between varves; few very fine, fine, medium, and coarse roots; 10% gravel by volume; neutral (6.9); boundary not reached.

SITE LAC

Horizon	Horizon depth	Particle Size Analysis Sand	Silt	Clay	>2mm	Textural class	Bulk density	1/3 Bar water	15 Bar water	Available water holding capacity
	cm	(% wt)			(% vol)		(g/cc)	(% wt)		
A21	0-15	15	78	7	5	silt loam	1.06	27	5	22
A22	15-32	22	73	5	5	silt loam	1.24	22	4	18
A23	32-52	16	78	6	5	silt loam	1.59	17	2	15
B2t	52-100	6	78	16	10	silt loam	ND†	23	6	17
C	100-120+	4	78	18	10	silt loam	ND	27	6	21

Horizon	Organic matter	(1:2) soil:water dilution pH	e.c.	Extractable Cations Ca	Mg	Na	K	Cation Exchange Capacity§ NaOAc (pH=8.2)	NaCl (Natural pH)	P	Extractable minor elements Fe	Mn	Cu	Zn
	(% wt)		(mmhos/cm)	(meq/100g)						(ppm)	(ppm)			
A21	1.4	5.0	.07	2.0	.6	.1	.3	8.3	5.2	46	75	4	<1	<1
A22	1.0	5.2	.06	1.8	.6	.1	.3	6.1	4.8	44	70	4	<1	<1
A23	.2	5.7	.03	1.7	.5	.2	<.1	3.6	3.2	.2	22	<1	<1	<1
B2t	.2	6.5	.07	4.6	1.7	.4	.1	13.0	7.2	<.2	24	6	1	<1
C	.1	6.9	.07	4.4	1.5	.5	.1	7.4	7.4	<.2	13	4	1	<1

Horizon	Kaolinite	Estimated abundance Illite	Chlorite	Vermiculite	Smectite	Amorphous	Interstratified Vermiculite-Chlorite	Interstratified Smectite-Vermiculite Chlorite
A21	Med	High					Trace	
A22	Low	Very High					Trace	
A23	Low	Very High					Trace	
B2t	Low	Very High						Low
C	Low	Very High						Low

†ND means not determined.

§Cation exchange capacity determined by sodium replacement (NaOAc) at pH = 8.2 and by (NaCl) at the natural pH of the soil horizon.

SITE ALT

CLASSIFICATION: Typic Eutroboralf, loamy-skeletal, mixed, frigid
LOCATION: NW1/4, NE1/4, Sec21, T27N, R27W, MPM
PHYSIOGRAPHIC POSITION: Midslope, 1341 m Elevation
SLOPE: 22%
ASPECT: 34°NW
HABITAT TYPE: Abies lasiocarpa/Linnaea borealis (Linnaea borealis phase)
PARENT MATERIAL: Volcanic ash overlying limestone till
DRAINAGE: Well drained

O1 5.6-3.0 cm Essentially undecomposed forest litter

O2 3.0-0 cm Decomposed forest litter

A21 0-2 cm Light gray (10YR 7/1) dry, silt loam, grayish brown (10YR 5/2) crushed moist; weak medium subangular blocky structure breaking to weak medium and fine subangular blocky structure breaking to weak medium and fine subangular blocky structure; soft (dry), very friable (moist), non-sticky and non-plastic (wet); many very fine, fine, medium and common coarse roots; 10% gravel by volume; abrupt smooth boundary.

A22 2-31 cm Yellowish brown (10YR 7/6) dry, silt loam, yellowish brown (10YR 5/6) crushed moist; weak coarse subangular blocky structure breaking to weak medium and fine subangular blocky structure; soft (dry), very friable (moist), non-sticky and non-plastic (wet); many very fine, common fine, medium, and coarse roots; 10% gravel by volume; slightly acid (6.1); abrupt smooth boundary.

IIA21 31-47 cm Light gray (10YR 7/2) dry gravelly silt loam; pale brown (10YR 6/3) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; slightly hard (dry), friable (moist), slightly sticky and slightly plastic (wet); few very fine, fine, medium, and coarse roots; 15% gravel and 5% cobbles by volume; medium acid (6.0); clear smooth boundary.

IIA+B 47-67 cm Light gray (2.5Y 7/2) dry, gravelly silt loam, light yellowish brown (2.5Y 6/4) crushed moist; moderate coarse subangular blocky structure breaking to moderate medium and fine subangular blocky structure; slightly hard (dry), friable (moist), slightly sticky and slightly plastic (wet); few thin clay films on ped face; few very fine, fine, medium, and coarse roots; 15% gravel and 5% cobbles by volume; medium acid (6.5); abrupt smooth boundary.

IIB2t 67-105 cm Light yellowish brown (2.5Y 6/4) dry, very gravelly silt loam, light olive brown (2.5 5/4) crushed moist; strong coarse subangular blocky structure breaking to strong medium and fine subangular blocky structure; hard (dry), firm (moist), sticky and plastic (wet); common, thin to moderately thick clay films on ped faces; few very fine, fine medium, and coarse roots; 25% gravel and 5% cobbles by volume; slightly acid (6.4); abrupt smooth boundary.

IICca* 105-120+ cm White (2.5Y 8/2) dry, very gravelly silt loam, light yellowish brown (2.5Y 6/4) crushed moist; massive structure; slightly hard (dry), friable (moist), slightly sticky and slightly plastic (wet); few very fine, fine, medium, and coarse roots; 25% gravel and 5% cobbles by volume; mildly alkaline (7.4); violently effervescent, lime disseminated but also occurring in seams 1-5 mm thick; boundary not reached.

†This horizon is commonly referred to as a Bir horizon in northwestern Montana.

*In some pits this horizon was reached as shallow as 80 cm. Additionally in some pits this horizon appears as a lithologic discontinuity as coarse fragment content may be as low as 10% by volume.

SITE ALT

Horizon	Horizon depth	Particle Size Analysis				Textural class	Bulk density	1/3 Bar water	15 Bar water	Available water holding capacity
		Sand	Silt	Clay	>2mm					
	cm	(% wt)			(% vol)		(g/cc)	(% wt)		
A21	0-2	ND[†]								
A22[†]	2-31	24	74	2	10	silt loam	.66	36	8	28
IIA2	31-47	29	67	4	20	silt loam	1.06	19	3	16
IIA+B	47-67	24	68	8	30	silt loam	ND	20	4	16
IIB2t	67-105	15	67	18	30	silt loam	ND	25	7	18
IICca	105-120[+]	18	64	18	30	silt loam	ND	30	4	26

Horizon	Organic matter	(1:2) soil:water dilution		Extractable Cations				Cation Exchange Capacity§ NaOAc	NaCl	P	Extractable minor elements			
		pH	e.c.	Ca	Mg	Na	K	(pH=8.2)	(Natural pH)		Fe	Mn	Cu	Zn
	(% wt)		(mmhos/cm)	(meq/100g)						(ppm)	(ppm)			
A21	ND													
A22	2.5	6.1	.10	7.7	.5	.2	.6	20.5	11.8	35	50	17	<1	<1
IIA2	.9	6.0	.05	6.8	.5	.1	.1	10.0	10.0	2	17	6	<1	<1
IIA+B	.5	6.0	.03	6.6	1.2	<.1	.1	10.4	10.0	.2	14	3	1	<1
B2t	.6	6.4	.09	14.0	1.5	.1	.3	13.5	15.2	.6	20	12	2	<1
Cca	1.0	7.4	.09	34.0	.6	.1	<.1	9.6	9.5	.2	8	2	2	<1

Horizon	Kaolinite	Estimated abundance					Interstratified Vermiculite-Chlorite	Interstratified Smectite-Vermiculite Chlorite
		Illite	Chlorite	Vermiculite	Smectite	Amorphous		
A21	ND							
A22	Trace	Trace				Very High	Trace	
IIA2	Low	Very High	Trace	Low				
IIA+B	Low	Medium	Low	Low	Trace			
IIB2t	Low	Medium	Low	Low	Low			
IICca	Low	Very High	Low	Low	Trace			

[†]This horizon is commonly called a Bir horizon in northwestern Montana.

[‡]ND means not determined.

§Cation exchange capacity determined by sodium replacement (NaOAc) at pH = 8.2 and by (NaCl) at the natural pH of the soil horizon.

SITE AAR

CLASSIFICATION: Entic Eutrandept, medial, skeletal, mixed frigid
LOCATION: SW1/4, NE1/4, Sec15, T27N, R27W, MPM
PHYSIOGRAPHIC POSITION: Upper slope, 1712 m Elevation
SLOPE: 25%
ASPECT: 10° SW
HABITAT TYPE: Pseudotsuga menziesii/Vaccinium globulare (Xerophyllum tenax phase)
PARENT MATERIAL: Volcanic ash over calcareous argillite residuum
DRAINAGE: Well drained

O1 4.8-2.5 cm Essentially undecomposed forest litter

O2 2.5-0 cm Decomposed forest litter

A21† 0-16 cm Brown (10YR 5/3) dry, gravelly silt loam; very dark grayish brown (10YR 3/3) crushed moist; weak medium subangular blocky structure breaking to weak fine subangular blocky structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); .5 cm of charcoal present; many very fine, common fine, medium, and coarse roots; 20% gravel and 5% cobbles by volume; strongly acid (5.5); abrupt smooth boundary.

A22 16-58 cm Brownish yellow (10YR 6/6) dry, gravelly silt loam, dark yellowish brown (10YR 4/6) crushed moist; weak coarse subangular blocky structure breaking to weak medium and fine subangular blocky structure; soft (dry), very friable (moist), non-sticky and non-plastic (wet); many very fine, common fine, medium, and coarse roots; 20% gravel and 5% cobbles by volume; strongly acid (5.4); abrupt smooth boundary.

IIA2 58-110 cm Pale brown (10YR 6/3) dry, very gravelly silt loam, brown (10YR 5/3) crushed moist; weak very fine granular structure; soft (dry), very friable (moist), non-sticky and non-plastic (wet); common very fine, few fine, medium, and coarse roots; 35% gravels and 15% cobbles by volume; strongly acid (5.3); abrupt smooth boundary.

IIB2 110-120+ cm Very pale brown (10YR 7/4) dry, very gravelly silt loam; yellowish brown (10YR 5/6) crushed moist; moderate medium subangular blocky structure breaking to moderate fine subangular blocky structure; soft (dry), very friable (moist), slightly sticky and slightly plastic (wet); few very fine and fine roots; 35% gravels nad 15% cobbles by volume; medium acid (5.6); boundary not reached.

†These horizons are commonly referred to as Bir horizons in northwestern Montana.

SITE AAR

Horizon	Horizon depth	Particle Size Analysis				Textural class	Bulk density	1/3 Bar water	15 Bar water	Available water holding capacity
		Sand	Silt	Clay	>2mm					
	cm	------- (% wt)----			(% vol)		(g/cc)	---------- (% wt)		----------
A21†	0- 16	29	65	6	25	silt loam	.56	37	11	26
A22†	16- 58	36	61	3	25	silt loam	.64	32	8	24
IIA2	58-110	48	50	2	50	silt loam	ND‡	19	4	15
IIB2	110-120+	35	59	6	50	silt loam	ND	15	3	12

Horizon	Organic matter	(1:2) soil:water dilution		Extractable Cations				Cation Exchange Capacity§ NaOAc (pH=8.2)	NaCl (Natural pH)	P	Extractable minor elements			
		pH	e.c.	Ca	Mg	Na	K				Fe	Mn	Cu	Zn
	(% wt)		(mmhos/cm)	----------				(meq/100g)----------		(ppm)	------ (ppm) ----			
A21	6.0	5.5	.15	5.6	.6	.1	.7	23	14	44	81	70	2	<1
A22	3.3	5.4	.10	2.8	.4	.1	.5	17	10	20	45	64	<1	<1
IIA2	1.0	5.3	.05	3.2	.5	.1	.2	10	8	9	33	12	<1	<1
IIB2	.3	5.6	.04	4.8	1.0	.1	<.1	9	9	2	20	3	1	<1

Horizon	Kaolinite	Estimated abundance					Interstratified Vermiculite-Chlorite	Interstratified Smectite-Vermiculite Chlorite
		Illite	Chlorite	Vermiculite	Smectite	Amorphous		
A21	Trace	Trace				Very High	Trace	
A22	Trace	Trace				Very High	Trace	
IIA2	Low	High					Low	
IIB2	Low	High	Low	Low			Trace	

†These horizons are commonly called Bir horizons in northwestern Montana.

‡ND means not determined.

§Cation exchange capacity determined by sodium replacement (NaOAc) at pH = 8.2 and by (NaCl) at the natural pH of the soil horizon.

Sieve Analysis Data For Selected Horizons At The Five Study Sites

Site	Horizon	Sample Depth (cm)	Number of Samples[†]	Total sample weight (g)	percent (by wt) finer than 50.8 mm	38.1 mm	25.4 mm	19.0 mm	9.5 mm	4.76 mm	2.0 mm	.42 mm	.074 mm	Classification[‡]
AQT	A22	1- 31	4	3431	86.8	84.6	77.2	66.9	60.0	54.8	48.4	35.0	21.0	Poorly graded
	IIA21	31- 58	4	5148	92.8	87.5	76.9	68.7	53.0	38.5	28.3	20.4	13.5	Poorly graded
MIX	A21	0- 21	3	2468	100.0	98.1	96.9	95.3	89.6	85.4	80.6	69.5	35.1	Poorly graded
	A22	21- 36	3	2768	100.0	97.0	95.2	93.6	88.9	86.0	79.8	71.3	34.2	Poorly graded
	IIA21	36- 53	3	3495	100.0	100.0	96.5	95.3	86.9	81.4	75.7	68.0	27.1	Poorly graded
LAC	A21	0- 15	2	2954	100.0	100.0	99.1	99.1	98.9	98.7	98.3	94.5	33.2	Poorly graded
	A22	15- 32	1	3032	100.0	98.3	96.7	96.2	94.4	92.4	89.7	81.6	36.5	Poorly graded
	A23	32- 52	2	4133	100.0	99.7	96.6	95.8	91.3	89.1	86.3	79.7	21.5	Poorly graded
ALT	A22	2- 31	3	1913	100.0	100.0	99.4	99.1	95.4	92.3	80.8	81.1	45.7	Well graded
	IIA2	31- 47	3	4405	93.0	85.0	76.5	74.3	65.8	58.2	50.7	40.3	13.1	Well graded
AAR	A21	0- 16	2	3094	100.0	100.0	95.2	87.3	65.9	49.3	37.7	21.7	9.9	Well graded
	A22	16- 58	2	3652	100.0	98.6	94.3	85.0	62.6	48.0	37.3	23.2	11.6	Well graded
	IIA2	58–110	4	4378	97.2	93.5	82.4	75.0	60.6	48.4	37.7	25.0	14.4	Well graded

[†]When number of samples is greater than one, means are reported.

[‡]Gradation characteristics are classified according to the Unified Soil Classification System (AASHO, 1963c).

APPENDIX II

FIELD DATA FOR NUMBER OF TRAFFICKING EVENTS AT EACH SLASH PILE AND OF SLASH PILES CONSTRUCTED AT THE FIVE STUDY SITES

Site	Number of Trafficking Events	Number of Slash Piles Evaluated																
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
AQT	2	35	27	22	25	12	19	27	30	19	27	60	28	12	6	23	—	—
	4	5	6	5	4	2	1	3	5	0	3	9	2	0	0	3	—	—
	6	2	1	0	2	0	0	0	1	0	1	3	0	0	0	0	—	—
	8	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	—	—
	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	—	—
MIX	2	23	22	13	43	23	19	30	40	17	12	18	—	—	—	—	—	—
	4	5	4	2	7	1	1	3	4	3	0	1	—	—	—	—	—	—
	6	1	0	1	5	0	0	1	1	0	0	2	—	—	—	—	—	—
	8	0	0	0	0	0	0	0	1	0	0	0	—	—	—	—	—	—
	10	0	0	0	0	0	0	0	0	0	0	0	—	—	—	—	—	—
LAC	2	39	22	52	23	16	10	20	27	19	51	27	57	33	50	21	—	—
	4	7	3	6	2	2	2	2	3	1	7	2	10	2	6	2	—	—
	6	3	3	1	3	2	0	2	1	0	0	0	2	0	1	0	—	—
	8	0	0	0	3	1	0	0	1	0	0	0	0	0	2	0	—	—
	10	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	—	—
ALT	2	11	15	15	10	15	13	16	26	16	11	9	30	25	25	15	22	20
	4	4	2	4	4	4	2	3	6	2	2	2	8	6	5	2	3	4
	6	0	1	2	0	1	2	0	1	1	1	1	1	6	3	3	2	1
	8	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AAR	2	20	17	5	15	10	18	12	14	15	15	21	19	25	18	18	—	—
	4	1	0	0	2	0	2	1	2	1	0	4	4	3	3	0	—	—
	6	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	—	—
	8	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	—	—
	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	—	—

APPENDIX III

FIELD DATA SHOWING

PERCENT AREA DISTURBED ON

EACH MEASUREMENT TRANSECT FOR EACH STUDY SITE

Site AQT

Transect number	Disturbance Classes: Trafficked: Litter disturbed (%)	Trafficked: Slightly disturbed (%)	Trafficked: Moderately disturbed (%)	Trafficked: Trafficked berm (%)	Not Trafficked: Untrafficked berm (%)	Not Trafficked: Undisturbed (%)	Not Trafficked: Miscellaneous (%)
1	2	15	0	15	53	7	8
2	1	15	2	14	55	4	9
3	0	2	0	11	75	0	12
4	2	8	0	17	61	3	9
5	0	4	0	9	76	0	11
6	0	12	0	12	66	0	10
7	0	15	0	5	66	0	14
8	0	9	0	26	58	0	7
9	0	6	0	22	72	0	0
10	0	5	4	19	67	5	0
11	3	9	4	20	64	0	0
12	0	8	3	10	79	0	0
13	0	12	0	12	67	0	9
14	0	7	0	11	61	0	21
15	0	12	0	8	61	0	19
16	0	0	6	10	72	0	12
17	0	3	7	16	62	0	12
18	0	11	12	16	50	0	11
19	0	8	0	14	67	0	11
20	0	15	3	35	31	0	16
21	6	7	3	12	42	30	0
22	2	9	0	18	61	10	0
23	0	13	0	11	76	0	0
24	0	12	0	11	77	0	0
25	0	5	6	6	77	0	6
26	0	16	13	7	55	0	9
27	0	6	0	11	62	0	21
28	3	10	5	11	60	0	11
29	0	7	3	12	64	0	14
30	0	6	10	23	61	0	0
31	0	3	0	21	62	0	14
32	0	4	0	24	57	0	15
33	0	11	2	18	59	0	10
34	0	8	0	21	61	0	10
35	2	4	0	19	62	4	9
36	0	0	0	17	72	0	11
37	0	8	8	4	66	0	14
38	0	6	3	6	61	0	24
39	0	2	5	20	61	0	12
40	0	3	4	14	68	0	11

Site MIX

Transect number	Disturbance Classes: Trafficked: Litter disturbed (%)	Trafficked: Slightly disturbed (%)	Trafficked: Moderately disturbed (%)	Trafficked: Trafficked berm (%)	Not Trafficked: Untrafficked berm (%)	Not Trafficked: Undisturbed (%)	Not Trafficked: Miscellaneous (%)
1	10	8	0	17	33	27	5
2	24	10	2	30	22	7	5
3	12	12	10	21	45	0	0
4	2	13	19	11	43	12	0
5	3	15	19	9	34	20	0
6	6	9	4	4	77	0	0
7	23	17	0	6	29	25	0
8	10	8	17	0	49	16	0
9	25	6	6	5	33	25	0
10	13	20	0	0	39	28	0
11	0	0	0	20	64	0	16
12	2	0	0	17	42	28	11
13	6	17	0	5	31	32	9
14	4	1	2	22	48	11	12
15	5	6	7	6	64	2	10
16	2	13	0	17	31	6	31
17	7	31	0	15	25	6	16
18	16	15	4	4	26	23	12
19	4	31	0	17	18	18	12
20	15	15	0	15	28	23	4
21	8	18	0	7	61	6	0
22	12	36	2	12	24	12	2
23	14	19	5	8	51	3	0
24	13	8	9	6	43	21	0
25	0	24	0	11	65	0	0
26	9	6	3	8	70	4	0
27	1	0	5	6	72	16	0
28	2	22	9	2	54	11	0
29	13	20	13	4	48	2	0
30	4	8	5	20	63	0	0
31	11	5	7	8	40	26	3
32	0	12	13	20	49	6	0
33	3	16	0	26	37	10	8
34	20	6	0	5	42	25	2
35	3	30	12	3	45	7	0
36	14	5	6	14	56	5	0
37	3	26	6	7	58	0	0
38	5	15	5	26	45	4	0
39	0	19	11	22	47	1	0
40	0	29	0	20	47	0	4

Site LAC

Transect number	Disturbance Classes: Trafficked: Litter disturbed (%)	Trafficked: Slightly disturbed (%)	Trafficked: Moderately disturbed (%)	Trafficked: Trafficked berm (%)	Not Trafficked: Untrafficked berm (%)	Not Trafficked: Undisturbed (%)	Not Trafficked: Miscellaneous (%)
1	5	17	9	44	25	0	0
2	2	15	0	17	56	10	0
3	0	16	3	10	65	6	0
4	1	14	6	9	63	7	0
5	0	12	7	13	64	4	0
6	0	8	0	28	64	0	0
7	0	16	2	14	66	2	0
8	2	12	0	20	57	0	9
9	4	6	2	21	64	3	0
10	2	13	6	15	64	0	0
11	4	21	2	7	66	0	0
12	0	6	17	11	51	9	6
13	2	13	13	15	53	4	0
14	0	26	7	14	53	0	0
15	7	20	4	18	45	6	0
16	0	14	0	14	57	15	0
17	0	14	2	14	69	1	1
18	1	18	0	15	59	3	4
19	0	16	4	13	65	0	2
20	4	16	5	6	62	7	0
21	6	20	4	8	42	20	0
22	0	19	2	24	55	0	0
23	0	25	2	17	50	6	0
24	0	26	13	0	46	15	0
25	0	20	15	4	49	0	12
26	7	19	5	6	42	21	0
27	15	15	7	13	44	6	0
28	5	31	4	9	51	0	0
29	9	10	0	19	35	7	20
30	11	10	2	17	52	8	0
31	5	19	17	10	46	3	0
32	2	3	20	15	54	6	0
33	0	35	8	9	43	5	0
34	9	22	7	20	35	7	0
35	7	7	13	14	56	3	0
36	4	5	8	10	55	18	0
37	4	19	14	2	53	8	0
38	6	2	23	23	37	9	0
39	12	13	11	16	41	7	0
40	6	17	5	15	51	6	0

Site ALT

Transect number	Disturbance Classes: Trafficked: Litter disturbed (%)	Trafficked: Slightly disturbed (%)	Trafficked: Moderately disturbed (%)	Trafficked: Trafficked berm (%)	Not Trafficked: Untrafficked berm (%)	Not Trafficked: Undisturbed (%)	Not Trafficked: Miscellaneous (%)
1	0	19	0	15	64	0	2
2	0	23	21	12	38	6	0
3	0	3	7	13	68	0	9
4	0	7	7	16	46	0	24
5	0	12	17	23	47	0	1
6	0	19	17	8	56	0	0
7	0	3	11	14	68	0	4
8	0	18	8	14	60	0	0
9	0	16	4	25	55	0	0
10	5	23	14	30	26	2	0
11	2	13	2	7	49	7	20
12	3	6	9	29	43	0	10
13	0	12	3	29	36	0	20
14	0	45	3	13	39	0	0
15	0	7	16	8	62	0	7
16	0	15	3	19	55	0	8
17	0	7	8	22	63	0	0
18	0	8	10	12	50	0	20
19	2	11	7	18	48	0	14
20	5	21	7	20	42	0	5
21	0	16	11	21	34	4	14
22	2	8	2	14	70	3	1
23	0	10	10	11	53	0	16
24	0	12	3	24	61	0	0
25	0	11	0	25	64	0	0
26	0	12	1	20	50	0	17
27	0	22	0	27	51	0	0
28	0	16	2	19	63	0	0
29	0	11	4	9	54	0	22
30	2	4	0	27	60	7	0
31	11	15	2	13	57	2	0
32	0	10	3	10	77	0	0
33	10	2	12	26	48	2	0
34	11	10	10	16	50	3	0
35	0	4	9	23	64	0	0
36	3	6	0	18	70	3	0
37	0	3	2	8	64	0	23
38	6	3	0	23	55	0	13
39	2	10	3	11	69	5	0
40	0	18	0	16	66	0	0

Site AAR

Transect number	Disturbance Classes: Trafficked: Litter disturbed (%)	Trafficked: Slightly disturbed (%)	Trafficked: Moderately disturbed (%)	Trafficked: Trafficked berm (%)	Not Trafficked: Untrafficked berm (%)	Not Trafficked: Undisturbed (%)	Not Trafficked: Miscellaneous (%)
1	0	16	5	30	41	8	0
2	5	14	3	14	51	8	5
3	12	18	4	10	36	8	12
4	20	5	12	15	34	8	6
5	22	2	3	8	28	8	29
6	7	24	13	25	25	6	0
7	17	5	15	10	25	20	8
8	6	10	7	12	24	0	41
9	7	16	8	15	35	13	6
10	7	12	17	13	36	4	11
11	6	8	16	12	58	0	0
12	11	13	2	14	57	0	3
13	8	16	7	25	40	4	0
14	15	8	15	6	53	0	3
15	9	12	11	15	36	3	14
16	11	0	15	2	72	0	0
17	0	6	25	8	56	5	0
18	7	3	15	2	60	13	0
19	12	12	23	7	46	0	0
20	7	5	14	5	69	0	0
21	3	27	3	30	29	8	0
22	14	21	12	28	17	8	0
23	0	13	15	15	49	8	0
24	0	26	5	40	22	3	4
25	0	17	24	31	28	0	0

APPENDIX IV

FIELD DATA

SHOWING CONTROL AND TREATMENT

BULK DENSITIES AT THE FIVE STUDY SITES

SITE AQT

	Control					Treatment				
	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)
	0-13	.65	11	766	44	0-12	.70	23	761	29
	0-12	.51	14	632	38	0-12	.66	30	803	20
	0-13	.57	13	599	55	0-12	.71	41	1020	14
	0-13	.67	11	491	15	0-13	.70	38	1111	13
	0-12	.57	12	459	10	0-11	1.05	9	680	52
	0-13	.62	16	855	21	0-12	1.05	12	824	48
A21 &	0-12	.60	18	708	23	0-11	.67	25	986	7
A22	0-13	.56	15	759	19	0-11	.78	13	735	27
	0-12	.78	8	761	57	0-12	.97	15	715	62
	0-14	.67	13	1002	20	0-12	.75	38	869	38
	0-13	.66	13	783	22	0-11	.91	39	910	38
	0-12	.55	18	402	53	0-12	.61	25	596	43
	0-14	.61	14	652	24	0-11	.76	33	678	15
						0-12	.76	33	924	33
						0-12	1.07	22	1447	13
	15-28	.71	12	719	44	13-23	.80	27	416	18
	14-23	.65	15	901	13	13-22	.86	39	625	29
	14-28	.72	13	635	51	13-24	.85	37	863	33
	14-26	.60	11	420	32	14-25	.77	24	811	24
	14-26	.88	17	869	30	12-25	.86	39	946	42
A22	15-24	.74	16	893	22	13-24	.80	22	462	48
	13-22	.71	10	796	30	12-25	1.16	13	634	45
	14-33	.63	15	723	54	13-22	.94	14	981	28
	13-26	.64	14	770	14	14-25	.73	24	505	45
	15-22	.73	14	607	20					
	14-26	.69	16	831	23					
	13-21	.67	6	447	31					
	12-22	.69	7	671	43					
	30-43	.86	8	419	83	11-24	1.23	8	1168	48
	24-36	1.05	5	842	60	9-23	1.25	11	855	61
	31-44	1.06	5	631	67	13-25	1.28	7	763	64
	28-41	.86	6	748	74	12-26	1.10	21	721	66
	28-38	1.06	8	810	72	13-27	1.47	11	1314	31
	26-40	1.19	4	879	47	10-25	1.09	15	632	72
	23-37	.84	7	491	71	13-26	1.16	28	589	77
IIA2	25-40	.86	6	771	68	15-31	1.08	24	577	80
	28-41	1.15	7	942	75	12-26	1.27	11	907	52
	23-33	1.10	4	562	53	25-37	1.11	18	1120	56
	28-36	1.03	8	591	62	24-38	1.51	14	1372	48
	22-33	1.49	7	746	65	26-38	1.02	12	871	41
	24-37	1.17	6	897	60	27-38	.96	11	680	78
						26-36	1.21	8	807	57
						25-38	1.27	10	950	57
						22-37	1.25	17	901	51
						23-37	1.30	17	704	65
						26-37	1.07	21	674	66
						21-35	1.09	20	645	54

SITE MIX

	Control					Treatment				
	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)
	0-12	1.06	10	1551	3	0-13	1.30	17	1621	9
	0-11	.85	8	1039	6	0-12	1.12	20	1345	24
	0-12	.94	8	1295	10	0-12	.96	30	1117	8
	0-11	.89	8	849	9	0-11	.98	27	1008	8
	0-12	1.04	7	1320	6	0-10	1.13	32	723	7
	0-12	.83	8	1178	12	0-12	1.05	26	1213	18
	0-13	1.02	6	1390	8	0-12	1.10	28	1414	5
A21	0-11	1.08	6	1083	11	0-13	1.08	21	1496	4
	0-11	1.04	6	1122	6	0-13	1.21	25	1619	11
	0-12	.97	10	1214	9	0-13	1.17	20	1427	4
	0-12	.88	8	1071	15	0-14	1.21	20	1816	10
	0-11	.79	12	949	9	0-11	1.08	30	817	11
	0-11	.80	10	914	12	0-13	1.15	15	1782	5
	0-14	1.05	28	1376	20					
	0-13	1.02	26	1350	16					
	0-12	1.05	30	1277	18					
	0-13	1.02	32	1468	12					
	0-12	1.00	44	1216	30					
	0-12	.93	35	1177	15					
	13-23	1.18	5	1191	15	13-26	1.23	21	1716	11
	12-25	1.35	3	1583	15	12-25	1.35	17	1427	12
	13-22	1.15	4	700	51	12-25	1.21	16	1429	30
	11-23	1.25	4	1504	13	11-24	1.27	28	1358	8
	12-25	1.25	4	1714	25	11-26	1.41	21	1644	17
	12-22	1.11	5	1181	8	12-24	1.39	26	1371	13
	13-25	1.27	6	1452	33	12-24	1.37	24	1621	4
	11-24	1.35	4	1841	10	13-26	1.46	20	1622	14
A22	12-22	1.25	5	1060	23	13-23	1.31	13	853	57
	12-24	1.31	4	1509	9	13-26	1.50	19	1558	29
	12-24	1.09	7	1304	20	14-24	1.48	18	1035	19
	12-24	1.44	3	1325	11	11-24	1.46	20	1622	14
	11-25	1.47	4	1877	30	12-26	1.50	19	1558	29
	13-25	1.41	22	1533	14					
	13-21	1.34	25	724	13					
	13-24	1.41	23	1373	25					
	13-25	1.19	23	1457	31					
	12-24	1.43	27	1306	16					
	24-34	1.64	2	1288	13	26-39	1.64	16	1740	13
	25-32	1.42	3	828	43	26-38	1.65	17	1460	26
	22-33	1.49	3	1074	21	26-37	1.58	17	1398	31
	24-35	1.66	2	1498	20	25-38	1.40	16	1490	43
	25-37	1.58	3	1676	17	27-37	1.29	20	1294	22
	23-35	1.47	3	1446	32	25-36	1.12	17	1285	27
	25-36	1.49	3	1356	26	25-36	1.43	18	1398	36
	24-34	1.28	2	1194	50	26-37	1.50	15	1233	35
	23-33	1.36	3	1014	37					
A22	25-34	1.40	3	1185	8					
	25-38	1.64	2	1441	25					
	24-34	1.30	5	1206	27					
	25-34	1.28	6	1068	58					
	25-38	1.39	3	1832	17					
	22-33	1.30	5	1206	23					
	25-33	1.38	18	756	34					
	22-34	1.37	19	1563	17					
	25-35	1.55	17	1324	34					
	26-34	1.51	26	1202	36					
	25-38	1.68	19	1670	14					

SITE LAC

	Control					Treatment				
	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)
	0-13	.99	18	1366	4	0-12	1.07	21	1497	0
	0-12	1.09	6	1322	1	0-12	1.15	21	1451	0
	0-12	1.02	10	1494	6	0-13	.96	20	1317	1
	0-12	1.27	6	1986	1	0-13	1.17	23	1896	1
	0-13	.90	8	956	4	0-12	1.28	21	2055	0
	0-13	1.05	14	1299	1	0-12	1.25	22	1507	0
	0-12	1.13	7	2016	0	0-13	1.00	25	1197	0
	0-12	1.13	9	1049	2	0-12	1.04	21	1479	2
A21	0-13	.91	6	1316	12	0-13	1.22	16	1969	2
	0-12	.82	9	1032	2	0-14	1.22	17	1477	1
	0-13	1.13	7	1543	1	0-12	1.20	17	1793	3
	0-12	1.17	5	1850	2	0-12	1.17	16	1532	0
	0-12	1.01	6	1252	6	0-13	1.14	23	1360	2
	0-13	1.00	25	1079	1	0-12	1.10	20	1962	1
	0-12	.96	46	1204	1	0-12	1.19	19	1471	1
	0-13	1.22	35	1198	2	0-12	1.25	18	1838	3
	0-13	1.25	33	1205	2	0-13	1.23	18	1705	1
	0-12	1.24	36	1638	1	0-12	1.18	17	1769	1
	0-13	.84	39	1371	4	0-13	1.02	19	1131	0
						0-13	1.04	15	1371	0
						0-12	1.18	26	1291	0
						0-13	1.27	26	2157	0
						0-12	1.09	33	1246	2
						0-12	1.26	22	1457	1
						0-12	1.00	17	1329	1
						0-13	1.36	19	2157	1
	14-25	1.13	13	1318	4	12-25	1.46	17	2282	0
	13-26	1.25	5	1841	1	12-22	1.30	16	1415	0
	13-26	1.21	7	1656	5	13-26	1.44	17	2057	1
	13-25	1.47	4	1462	1	14-23	1.36	22	1594	2
	14-26	1.06	7	1009	0	13-24	1.28	22	1540	1
	14-25	1.34	2	1699	1	13-25	1.49	16	1772	0
	13-25	1.53	2	1373	2	13-26	1.52	14	2211	1
	13-25	1.07	6	1642	6	13-24	1.35	17	1611	1
	14-25	1.23	6	1657	4	14-21	1.39	15	1021	3
	13-26	1.33	5	2110	1	14-23	1.15	20	1374	1
	13-27	1.23	4	1860	1	13-25	1.25	18	1749	4
	13-25	1.21	5	1079	4	13-21	1.41	17	1179	2
	14-23	1.28	29	1468	2	13-26	1.49	16	2073	1
	13-24	1.18	28	1224	3	12-22	1.32	17	1653	1
	14-24	1.28	26	1824	1	13-25	1.31	24	1896	0
A22	14-26	1.24	25	1531	4	13-24	1.34	27	1468	1
	14-25	1.00	25	1079	1	14-24	1.18	19	1435	2
	26-36	1.31	3	2043	5	25-37	1.53	16	2374	0
	27-38	1.57	11	2020	2	23-22	1.49	14	1615	0
	37-35	1.41	4	1720	4	26-36	1.57	12	2094	0
	26-34	1.43	5	1746	1	24-35	1.56	15	2152	1
	26-37	1.37	5	2157	0	24-34	1.58	15	1892	2
	26-34	1.32	5	1576	9	25-33	1.57	15	1442	3
	26-37	1.40	5	2109	3	26-34	1.47	17	1603	1
	26-35	1.38	7	1988	1	24-36	1.39	16	1341	1
	26-33	1.35	5	1600	7	22-35	1.49	17	2441	1
	27-33	1.50	4	1240	5					
	24-32	1.29	22	1278	0					
	25-37	1.59	19	2223	2					
	24-35	1.48	19	2075	5					
	26-36	1.21	25	1753	0					
	25-35	1.50	19	2050	1					
	25-37	1.55	21	2317	1					
	35-45	1.50	3	1871	5	32-41	1.60	16	1754	1
	34-43	1.60	5	1630	2	34-42	1.61	17	1845	1
A23	35-43	1.73	5	1546	3	33-41	1.65	14	1835	0
	33-44	1.48	4	2264	2	34-44	1.76	14	2304	4
	33-43	1.57	11	2020	2	33-41	1.69	13	1806	1
						31-43	1.60	19	2348	1
						35-44	1.58	19	1865	0

SITE ALT

	Control					Treatment				
	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)
	0-11	.54	13	706	36	0-12	.94	47	1088	9
	0-12	.76	16	931	11	0-11	.70	37	889	9
	0-11	.59	14	834	18	0-12	.74	60	982	3
	0-12	.67	13	935	14	0-11	.70	60	784	1
	0-11	.63	15	788	15	0-12	.80	51	997	32
A21 &	0-13	.76	12	1047	10	0-12	.84	52	898	6
A22	0-13	.80	11	1072	11	0-11	.74	50	838	11
	0-13	.73	11	927	21	0-11	.85	51	789	39
	0-11	.96	6	797	33	0-13	.94	41	1214	18
	0-12	.70	13	929	10	0-10	.88	39	618	30
	0-12	.70	13	937	11	0-11	.74	44	891	10
	0-12	.76	10	861	49	0-14	.88	45	1367	7
						0-11	.92	31	729	29
						0-12	.75	45	953	25
						0-12	.76	48	965	19
						0-12	.79	47	1109	15
						0-10	.63	44	704	29
						0-13	.88	46	1250	21
						0-11	.95	40	796	17
	11-22	.74	19	964	21	13-25	1.19	32	1139	23
	12-23	.74	12	1001	17	13-25	1.16	31	1209	25
	12-24	.75	13	1163	13	13-26	.86	54	1395	3
	12-24	.74	12	1028	20	12-22	.93	52	588	13
	12-24	.77	13	1080	9	13-26	.95	46	1198	14
	13-25	.78	10	1128	18					
	12-23	.73	12	756	27					
	13-24	.68	14	1036	19					
	12-21	.75	13	660	25					
	13-26	.89	10	1162	27					
	15-27	1.17	5	1130	35	15-25	.98	26	801	41
						14-25	1.02	41	879	49
						15-27	1.23	25	1113	32
						12-25	1.41	24	1160	22
IIA2						13-26	1.61	23	1320	43
						13-26	1.34	21	1095	36
						15-28	1.40	26	1270	23
						14-24	1.36	25	909	25
	25-35	1.03	5	852	34	26-38	1.20	22	1086	29
	27-38	1.20	4	934	40	27-40	1.24	23	1359	23
	28-39	1.17	7	1099	37	28-40	1.51	22	1364	24
	26-38	1.25	4	1123	38	25-38	1.38	20	1245	25
IIA2	28-40	1.25	5	1241	47	27-39	1.50	23	1159	43
	28-41	1.48	4	1572	51	28-39	1.31	20	1047	26
	26-37	1.27	4	1367	54	28-40	1.45	23	1198	39
	27-40	1.23	5	1454	39	25-34	1.24	24	653	44
	25-37	1.32	5	1204	65	30-42	1.47	17	1050	26
						26-37	1.38	17	1015	19

SITE AAR

	Control					Treatment				
	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)	Depth increment sampled (cm)	Bulk density (g/cm^3)	Soil moisture (% by wt)	Sample weight of <2 mm (g)	Coarse fragments (% by wt)
	0-12	.62	9	596	64	0-12	.56	62	639	59
	0-11	.48	10	413	71	0-13	.62	67	739	57
	0-13	.53	12	554	62	0-11	.55	53	477	71
	0-12	.52	12	495	68	0-14	.59	41	821	61
	0-13	.57	16	602	61	0-12	.55	55	578	64
	0-13	.65	8	605	64	0-13	.87	60	679	67
	0-13	.68	9	681	68	0-12	.75	56	571	67
	0-12	.63	34	490	66	0-14	.68	45	771	65
A21	0-12	.56	36	508	63	0-12	.69	48	610	67
	0-11	.57	39	400	65	0-12	.57	64	576	72
	0-12	.53	46	481	63	0-12	.63	58	548	64
	0-12	.59	42	468	66	0-13	.75	50	711	67
	0-12	.54	17	488	66					
	0-12	.56	28	463	61					
	0-12	.52	42	415	66					
	0-11	.51	41	376	70					
	0-11	.49	49	391	65					
	0-12	.46	29	424	69					
	15-27	.57	10	547	59	14-26	.66	59	540	69
	14-27	.56	12	615	63	15-28	.71	68	621	44
	15-28	.59	12	687	56	13-25	.73	37	560	64
	14-28	.65	13	789	55	16-29	.62	61	737	59
	16-27	.60	7	587	67	13-25	.68	55	520	64
	14-27	.71	9	614	68	15-27	.75	63	608	61
A22	15-28	.61	27	616	59	14-26	.69	49	604	64
	13-24	.61	28	439	66	15-27	.77	55	608	64
	14-26	.56	42	514	65	14-26	.63	49	533	71
	14-26	.58	34	566	65	13-25	.73	69	513	68
	14-25	.65	36	491	64	14-26	.68	57	512	66
	14-25	.60	19	482	64	15-25	.66	59	366	90
	15-25	.55	39	371	72					
	14-25	.56	37	455	70					
	16-27	.52	43	531	66					
	28-41	.62	11	605	66	27-39	.69	54	510	57
	28-42	.59	12	682	64	30-42	.63	76	564	74
	30-42	.61	12	553	63	26-38	.77	55	590	59
	29-41	.61	11	552	63	31-42	.76	59	568	62
	29-41	.64	6	652	69	27-40	.90	50	622	62
A22	29-42	.68	10	598	66	28-39	.72	55	463	67
	30-43	.72	13	650	71	28-40	.65	55	570	74
	26-38	.63	8	614	65	29-41	.82	46	565	63
	28-39	.67	12	534	68	28-41	.83	46	595	67
	27-39	.62	11	568	72	26-38	.66	53	550	61
	26-39	.70	13	598	66	28-40	.74	48	495	68
	27-39	.61	9	601	68	27-39	.70	52	502	65

APPENDIX V

INFILTRATION RATES

BEFORE AND AFTER MECHANIZED

SLASH PILING AT SITES AQT, MIX, AND LAC

Site AQT		Site MIX		Site LAC	
Infiltration rate		Infiltration rate		Infiltration rate	
Control	Treatment	Control	Treatment	Control	Treatment
(cm/hr)	(cm/hr)	(cm/hr)	(cm/hr)	(cm/hr)	(cm/hr)
10.0	3.6	32.4	1.2	8.4	2.4
18.0	0.0	3.6	2.4	12.0	0.0
6.0	6.0	2.4	20.4	7.2	2.4
14.4	2.4	4.8	0.0	30.0	0.0
14.4	1.2	0.0	1.2	1.8	0.0
25.2	9.6	9.6	6.0	6.0	0.0
13.2	1.2	12.0	1.2	8.4	0.0
7.2	1.2	6.0	1.2	3.6	8.4
20.4	6.0	18.0	.6	4.8	1.2
32.4	4.8	10.8	2.4	6.0	0.0
37.2	1.2	12.0	2.4	6.0	1.2
9.6	9.4	1.2	0.0	2.4	1.2
15.6	8.4	9.6	1.2	11.4	0.0
13.2	4.8	7.8	0.0	10.4	0.0
7.2	8.4	1.2	0.0	6.8	.8
7.2	1.2	14.4	0.0	8.8	.8
9.6	2.4	1.2	1.0	12.0	0.0
14.4	33.6	34.8	1.2	51.6	4.8
8.4	7.2	6.0	0.0	44.4	4.8
9.6	9.6	3.6	0.0	12.0	0.0
3.6	4.8	12.0	0.0	9.6	.8
6.0	10.8	12.0	0.0	12.0	1.2
13.2	2.4	6.0	1.2	30.0	0.0
18.0	6.0	4.8	0.0	4.8	0.0
18.0	1.2	1.2	0.0	6.0	0.0
12.0	2.4	3.6	0.0	16.8	.4
24.0	8.4	18.0	2.4	14.4	0.0
24.0	1.2	16.8	0.0	15.6	0.0
16.8	2.4	2.4	3.6	21.6	0.0
22.0	2.4	12.0	7.2	14.4	6.8
18.0	12.0	32.4	3.6	8.4	.4
14.4	1.2	9.6	0.0	27.6	5.2
31.2	3.6	2.4	0.0	34.8	10.0
13.2	4.8	21.6	0.0	4.8	0.0
3.6	31.2	12.0		38.4	0.0
		4.8		45.6	1.2
		6.0		21.6	0.0
		4.8		16.8	1.8
		24.0		4.8	8.4
		8.4		14.4	0.0
		7.8			
		27.6			
		12.0			
		16.8			

APPENDIX VI

SLASH WEIGHTS BEFORE AND AFTER SLASH PILING AT THE FIVE STUDY SITES

SITE AQT
Slash Weight Before Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	3.58	6.12	3.82	.00	13.52
2	6.56	8.56	25.14	.00	40.26
3	8.95	18.35	7.73	15.71	50.74
4	3.88	4.89	7.17	12.64	28.58
5	1.19	4.89	3.17	.00	9.25
6	5.97	14.68	26.91	17.88	65.44
7	10.44	18.35	15.46	4.47	48.72
8	7.46	9.79	68.26	13.69	99.20
9	9.55	8.56	3.35	2.86	24.32
10	3.88	3.67	72.54	10.06	90.15
11	10.74	4.89	50.19	.00	65.82
12	2.69	1.22	6.98	.00	10.89
13	8.95	22.02	84.55	.00	115.52
14	4.48	19.57	21.60	.00	45.65
15	5.37	19.57	42.18	.00	67.12
16	3.58	11.01	38.55	.00	53.14
17	6.56	18.35	45.91	.00	70.82
18	8.35	12.23	29.89	.00	50.47
19	5.37	14.68	51.40	.00	71.45
20	6.86	17.13	23.56	.00	47.55
21	8.06	12.23	40.04	.00	60.33
22	2.35	.00	4.01	.00	6.36
23	1.76	2.40	3.82	27.94	35.92
24	4.99	8.39	29.70	27.94	71.02
25	4.11	3.60	41.16	31.36	80.23
26	2.64	3.60	8.29	.00	14.53
27	4.40	.00	16.76	13.69	34.85
28	6.75	7.19	36.13	.00	50.07
29	5.57	4.80	43.30	.00	53.67
30	7.04	7.19	38.83	.00	53.06
31	4.99	4.80	28.03	.00	37.82
32	9.09	9.59	26.44	.00	45.12
33	5.57	10.79	44.32	.00	60.68
34	1.47	2.40	29.70	.63	34.20
35	5.87	8.39	62.76	.00	77.02
36	7.92	13.19	33.24	30.17	84.52
37	5.28	22.78	43.11	2.23	73.40
38	.88	.00	33.43	.00	34.31
39	6.16	5.99	10.15	.00	22.30
40	2.93	8.39	19.93	.00	31.25
41	6.75	7.19	30.45	5.66	50.05
42	12.61	15.52	34.45	18.23	80.81

SITE AQT
Slash Weight After Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	5.67	3.67	1.71	.00	11.05
2	3.81	5.50	1.17	.32	10.80
3	1.64	9.18	1.40	.00	12.22
4	4.48	2.45	.59	.00	7.52
5	3.13	3.05	2.37	.00	8.55
6	1.49	1.61	1.52	.00	3.62
7	1.19	1.84	1.19	.00	4.22
8	1.03	4.20	2.28	1.19	8.70
9	2.20	1.80	1.49	1.43	6.92
10	2.79	4.80	1.49	.00	9.08
11	2.35	0.60	1.91	.56	5.42
12	4.69	3.60	1.17	.00	9.46
13	2.05	4.20	2.10	1.71	10.06
14	2.29	4.80	2.84	.00	9.93
15	1.03	1.80	.75	2.82	6.40
16	1.76	4.80	1.12	.00	7.68
17	2.64	4.20	2.42	.00	9.26
18	2.05	1.80	2.28	.00	6.13
19	3.23	3.00	.75	.56	7.54
20	2.49	1.20	1.58	.00	5.27
21	2.13	3.03	6.24	.00	11.40
22	1.06	1.81	1.16	.31	4.34
23	2.89	2.42	2.33	.00	7.64
24	1.06	1.21	4.93	.00	7.20
25	2.43	4.84	1.16	.56	8.99
26	2.58	3.03	2.89	5.58	14.08
27	1.22	1.81	1.16	.31	4.50
28	6.23	2.42	5.77	.31	14.73
29	1.22	3.03	1.58	1.43	7.26
30	2.89	2.42	.42	1.99	7.72
31	2.43	2.42	5.35	.31	10.51
32	1.22	1.81	5.03	1.43	9.49
33	1.82	4.23	1.58	1.12	8.75
34	1.22	3.63	6.14	.00	10.99
35	3.50	4.84	.74	.00	9.08
36	1.22	3.03	1.58	.56	6.39
37	2.43	4.23	4.14	.00	10.80
38	1.67	3.03	17.41	.00	22.11
39	2.58	2.42	9.12	.00	14.12
40	1.37	7.26	2.42	1.12	12.17

SITE MIX
Slash Weight Before Slash Piling

Transect	Slash Diameter Classes .25–1" (tons/acre)	1–3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	Total slash weight (tons/acre)
1	8.19	8.47	16.76	.00	33.42
2	11.41	2.12	14.43	.00	27.96
3	1.46	1.06	9.12	.00	11.64
4	4.09	8.47	13.69	.00	26.25
5	11.11	1.06	12.85	.00	25.02
6	4.09	2.12	97.68	.00	103.89
7	9.36	7.41	43.34	33.80	93.91
8	9.65	5.29	52.24	.99	67.18
9	5.85	4.23	66.02	.00	76.10
10	8.77	4.23	66.11	.00	79.11
11	1.17	3.17	10.61	.00	14.95
12	2.63	3.17	54.47	.00	60.27
13	6.73	7.41	24.21	.00	38.35
14	7.02	6.35	27.19	.00	40.56
15	2.05	3.17	12.20	.00	17.42
16	5.32	3.17	39.48	.00	47.97
17	11.24	10.58	29.89	.00	51.71
18	9.18	10.58	17.97	.00	37.73
19	.29	3.17	10.71	.00	14.17
20	8.77	19.05	50.66	75.98	154.46
21	3.84	2.12	23.47	.00	29.43
22	.29	1.06	35.94	.00	37.29
23	.88	5.29	6.98	3.42	16.57
24	2.66	2.12	51.31	.00	56.09
25	2.05	3.17	43.30	.00	48.52
26	3.51	2.12	18.90	.00	24.53
27	2.05	1.06	33.06	.00	36.17
28	2.05	5.29	18.06	.00	25.40
29	3.22	3.17	20.67	.00	27.06
30	4.09	2.12	61.83	.00	68.04
31	3.51	4.23	24.96	.00	32.70
32	7.90	7.41	5.31	.00	20.62
33	.58	.00	3.17	.00	3.75
34	4.97	7.41	100.75	10.06	123.19
25	.00	2.12	11.83	.00	13.95
36	2.34	11.64	18.34	.00	32.32
37	1.75	4.23	196.30	.00	202.28
38	1.75	2.12	13.97	.00	17.84
39	2.63	5.29	50.75	4.56	63.23
40	2.05	12.70	22.72	.00	37.47
41	.00	2.12	44.04	.00	46.16
42	.58	1.06	10.80	.00	12.44
43	1.75	1.06	47.40	.00	50.21
44	.88	.00	6.89	.00	7.77
45	3.80	.00	37.15	.00	40.95
46	3.80	2.12	26.54	6.35	38.81
47	1.17	5.29	34.92	.00	41.38
48	1.17	1.06	63.41	5.59	71.23
49	4.97	3.17	25.61	3.42	37.17
50	2.05	6.35	25.98	.00	34.38

SITE MIX
Slash Weight After Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	.59	1.06	1.49	.00	3.14
2	.15	1.59	1.58	1.26	4.58
3	.44	2.12	1.16	.00	3.72
4	.88	.53	10.48	.00	11.89
5	2.78	1.59	4.00	.00	8.37
6	3.66	2.12	3.40	2.23	11.41
7	3.66	1.59	11.97	.00	17.22
8	2.63	3.70	7.78	.00	14.11
9	5.85	5.29	11.73	.00	22.87
10	5.12	5.29	9.03	2.83	22.27
11	.59	1.59	3.40	.00	5.58
12	1.90	1.59	18.81	.00	22.30
13	1.02	1.59	4.66	.00	7.27
14	1.32	2.12	.00	.00	3.44
15	2.05	1.59	6.61	.00	10.25
16	4.39	.53	9.50	.00	14.42
17	2.93	.00	5.82	.00	8.75
18	4.97	.53	1.91	.00	7.41
19	3.66	.53	6.29	.00	10.48
20	2.93	2.65	5.35	.00	10.93
21	1.90	1.06	4.00	.00	6.96
22	2.78	2.65	6.29	.00	11.72
23	1.32	.00	5.87	.00	7.19
24	1.90	2.12	2.51	.00	6.53
25	1.90	1.59	16.25	.00	19.74
26	4.39	1.06	1.91	.00	7.36
27	3.66	2.65	3.86	.00	10.17
28	2.93	1.06	.00	.00	3.99
29	5.12	3.70	7.87	.00	16.69
30	2.93	3.18	6.43	.00	12.54
31	1.02	1.59	4.19	.00	6.80
32	.73	.00	.74	.00	1.47
37	1.32	3.18	.00	.00	4.50
34	1.46	3.70	6.66	.00	11.82
35	1.02	3.70	1.16	.00	5.88
36	5.85	1.59	9.41	.00	16.85
37	3.66	3.70	15.60	.00	22.96
38	2.19	9.53	2.33	.00	14.05
39	1.46	1.06	.00	.00	2.52
40	2.93	2.12	.84	.00	5.89
41	1.02	2.12	3.91	.00	7.05
42	1.32	.00	3.82	.00	5.14
43	.44	1.06	1.91	.00	3.41
44	1.90	1.59	5.68	2.83	12.00
45	1.76	2.12	3.77	.00	7.65
46	2.05	.53	1.16	.00	3.74
47	1.32	2.65	5.73	.00	9.70
48	.59	.53	1.16	.00	2.28
49	.88	.53	10.29	.00	11.70
50	.59	1.06	23.98	.00	25.63

SITE LAC
Slash Weight Before Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25–1" (tons/acre)	1–3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	1.46	5.63	46.84	.00	53.93
2	1.46	4.23	14.62	1.11	21.42
3	1.31	14.08	20.02	.00	35.41
4	.59	1.41	48.98	.42	51.40
5	2.63	11.26	35.57	.00	49.46
6	1.46	16.90	4.84	16.90	40.10
7	.88	4.23	20.77	.00	25.88
8	.88	8.45	53.92	.00	63.25
9	.29	9.86	49.17	.00	59.32
10	2.93	9.86	28.77	1.26	42.82
11	3.80	16.90	8.66	.00	29.36
12	.88	11.26	161.00	.35	173.49
13	3.51	7.04	38.46	.28	49.29
14	2.05	4.23	13.97	.21	20.46
15	4.98	18.31	19.83	.00	43.12
16	2.63	5.63	24.02	.00	32.28
17	2.34	11.26	10.34	7.61	31.55
18	1.76	7.04	28.31	49.73	86.84
19	6.14	8.45	6.98	.00	21.57
20	4.39	2.82	14.15	.00	21.36
21	4.68	5.63	27.75	.00	38.06
22	8.78	28.17	29.33	9.50	75.78
23	1.76	2.82	74.68	.00	79.26
24	.88	8.45	13.32	.35	23.00
25	5.85	16.90	138.00	.00	160.75
26	5.27	14.08	55.78	.70	75.83
27	4.39	8.45	20.02	.00	32.86
28	2.93	9.86	41.85	.42	55.06
29	5.85	16.90	57.00	.00	79.75
30	2.34	11.27	27.75	.00	41.36
31	2.34	5.63	17.79	.00	25.76
32	5.56	12.68	11.45	1.26	30.95
33	1.17	1.41	43.86	.00	46.44
34	.29	.00	9.50	.00	9.79
35	2.05	2.82	22.07	.00	26.94
36	3.51	2.82	15.37	.00	21.70
37	2.05	5.63	31.38	.28	39.34
38	.88	.00	21.98	.00	22.86
39	3.21	9.86	27.28	.00	40.35
40	4.39	11.27	3.82	1.47	20.95
41	4.10	4.23	16.58	.00	24.91
42	9.36	9.86	24.58	.00	43.80
43	4.97	5.63	20.67	.00	31.27
44	2.93	11.27	15.55	.00	29.75
45	2.34	11.27	13.41	.00	27.02
46	4.68	4.23	37.15	.00	46.06
47	3.22	9.86	22.26	.00	35.34
48	4.39	11.27	17.41	.00	33.07
49	3.51	2.82	15.18	.00	21.51
50	2.05	1.41	5.49	.00	8.95

SITE LAC
Slash Weight After Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	.59	.00	3.59	1.50	5.68
2	2.05	1.41	2.42	.31	6.19
3	.73	2.11	4.10	.00	6.94
4	.59	1.41	4.14	.00	6.14
5	1.32	.70	1.16	.87	4.05
6	1.02	.70	3.26	.00	4.98
7	1.76	2.82	4.66	.31	9.55
8	1.02	1.41	5.17	.00	7.60
9	.73	4.23	5.59	.00	10.55
10	1.61	1.41	2.10	.00	5.12
11	2.19	5.63	6.75	.00	14.57
12	4.39	1.41	2.75	.00	8.55
13	2.34	7.04	13.97	.56	23.91
14	1.76	2.82	6.98	.00	11.56
15	3.66	2.82	2.75	.00	9.23
16	2.05	1.41	2.33	.00	5.79
17	1.46	4.93	3.17	.00	9.56
18	1.76	3.52	10.24	.00	15.52
19	3.66	2.82	9.36	2.30	18.14
20	3.07	2.82	2.42	.00	8.31
21	2.05	2.82	4.00	.00	8.87
22	2.05	3.52	3.07	.00	8.64
23	.44	.00	3.12	.31	3.87
24	1.90	3.52	1.91	.00	7.33
25	.88	.70	4.94	.00	6.52
26	.88	2.82	5.17	.00	8.87
27	2.05	3.52	.74	.31	6.62
28	1.02	1.41	3.91	.56	6.90
29	1.46	4.23	4.66	.00	10.35
30	1.76	2.11	2.75	.00	6.62
31	3.36	.70	2.65	.00	6.71
32	1.76	9.15	7.68	.00	18.59
33	2.34	4.23	6.70	.00	13.27
34	1.46	4.93	5.59	.00	11.98
35	.59	3.52	3.72	.00	7.83
36	1.46	1.41	6.05	.00	8.92
37	.73	.00	1.58	.00	2.31
38	.88	5.63	5.91	.00	12.42
39	.44	1.41	2.84	1.26	5.95
40	.88	2.11	1.16	.00	4.15

SITE ALT
Slash Weight Before Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	4.10	7.56	33.15	.28	45.09
2	7.02	7.56	41.44	7.40	63.42
3	11.99	10.80	63.97	.00	86.77
4	4.68	8.64	64.63	.00	77.95
5	14.63	11.88	17.88	.00	44.39
6	5.85	5.40	36.22	.00	47.47
7	3.51	7.56	21.42	.00	32.49
8	8.19	11.88	13.13	.00	33.20
9	25.45	22.68	40.41	.77	89.31
10	4.10	3.24	6.15	.00	13.49
11	4.39	8.64	9.13	.00	22.16
12	6.50	13.09	67.91	.00	87.50
13	5.61	9.82	15.95	14.67	46.05
14	5.27	4.32	32.78	.00	42.37
15	4.43	4.36	49.57	.00	58.36
16	5.32	3.27	33.67	.00	42.26
17	4.77	7.71	51.86	.64	64.98
18	5.97	6.61	44.93	.00	57.51
19	2.09	4.41	8.83	.29	15.62
20	6.86	6.61	60.79	.00	74.26
21	4.43	6.54	51.35	.00	62.32
22	6.27	7.71	13.58	23.51	51.07
23	5.67	6.61	30.11	.00	42.39
24	7.76	13.22	47.11	.00	68.09
25	5.97	5.51	59.08	.00	70.56
26	5.37	4.41	17.00	27.56	54.34
27	10.44	11.02	45.69	.00	67.15
28	.00	2.18	32.35	.00	34.53
29	8.06	12.52	59.17	.00	79.75
30	4.48	6.61	33.72	.00	44.81
31	6.86	4.41	33.81	.64	45.72
32	2.69	12.11	29.64	.86	45.30
33	3.58	3.31	58.41	.00	65.30
34	2.98	3.31	33.72	.00	40.01
35	13.72	9.91	116.64	.00	140.27
36	6.56	7.71	41.41	.00	55.68
37	3.62	11.12	20.24	.00	34.98
38	7.46	6.61	36.57	.00	50.64
39	5.17	26.96	53.85	.00	85.98
40	3.28	6.61	44.55	.57	55.01

SITE ALT
Slash Weight After Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	2.19	2.70	3.86	.21	8.96
2	.88	3.24	5.45	.00	9.57
3	1.32	3.24	31.29	.24	36.09
4	.88	2.16	4.61	.11	7.76
5	3.80	2.16	14.67	.00	20.63
6	.29	2.70	2.75	.11	5.85
7	3.36	4.86	11.22	.14	19.58
8	5.12	4.32	12.66	.84	22.94
9	.73	1.62	8.52	.35	11.22
10	.29	1.08	10.15	.00	11.52
11	.73	.00	6.98	.00	7.71
12	1.92	2.18	3.95	.00	8.05
13	1.63	2.18	9.41	.14	13.36
14	1.46	1.62	6.19	.42	9.69
15	3.25	2.73	9.97	.14	16.09
16	1.92	2.18	7.24	.00	11.34
17	3.28	1.10	15.01	.00	19.39
18	1.94	.00	5.89	.00	7.83
19	1.49	1.10	8.60	.53	11.72
20	3.73	4.96	7.31	.11	16.11
21	1.77	1.09	.42	.00	3.28
22	2.69	1.65	15.77	.29	20.40
23	1.19	2.20	3.13	.14	6.66
24	2.24	3.31	3.09	.00	8.64
25	.90	.55	1.28	.00	2.73
26	1.94	4.96	8.26	.14	15.30
27	.75	1.65	0.00	1.14	3.54
28	3.10	4.36	6.91	.00	14.37
29	1.04	.00	2.90	.00	3.94
30	2.39	2.75	4.65	.39	10.18
21	1.19	3.31	7.17	1.53	13.20
32	3.13	5.51	7.22	.00	15.86
33	2.69	0.00	4.94	.00	7.63

SITE AAR
Slash Weight Before Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	5.56	6.85	21.05	.00	33.46
2	6.14	10.96	40.79	.00	57.89
3	6.14	10.96	65.65	6.29	89.04
4	3.51	12.33	31.48	.00	47.32
5	2.34	1.37	25.89	.00	29.60
6	2.63	4.11	36.41	.00	43.15
7	3.31	14.11	23.98	.00	41.40
8	6.03	18.34	68.39	.00	92.76
9	4.82	5.64	20.24	39.56	70.26
10	9.04	11.29	31.27	52.08	103.68
11	4.52	8.47	57.14	24.31	94.44
12	8.13	14.11	20.24	.38	42.86
13	1.51	7.06	36.74	67.40	112.71
14	8.13	8.46	50.16	.00	66.75
15	3.62	11.29	11.80	.00	26.71
16	6.63	9.88	31.46	.00	47.97
17	4.52	14.11	124.11	.00	142.74
18	7.53	12.70	18.32	.00	38.55
19	8.74	8.47	70.31	.00	87.52
20	4.82	11.29	47.29	.00	63.40
21	2.13	9.97	27.99	17.55	57.64
22	15.21	7.12	52.88	.00	75.21
23	4.56	.00	22.18	.00	26.74
24	7.00	9.97	25.00	.00	41.97
25	2.43	5.70	8.62	.00	16.75
26	6.39	14.25	23.44	23.53	67.61
27	7.00	4.27	54.52	.00	65.79
28	3.96	8.55	87.45	.00	99.96
29	3.35	2.85	71.47	.00	77.67
30	1.22	7.12	48.81	12.28	69.43
31	2.74	2.85	60.53	.00	66.12
32	3.35	8.55	5.52	10.46	27.88
33	4.87	1.43	59.95	.00	66.25
34	9.73	17.10	133.16	.00	159.99
35	1.22	.00	.00	.00	1.22
36	8.82	4.27	21.02	73.87	107.98
37	2.13	2.85	135.68	9.68	150.34
38	6.69	9.97	24.99	4.65	46.30
39	6.39	2.85	40.29	17.72	67.25
40	4.87	4.27	14.14	.00	23.28
41	7.91	4.27	51.91	.00	64.09

SITE AAR
Slash Weight After Slash Piling

Transect	Slash Diameter Classes				Total slash weight (tons/acre)
	.25-1" (tons/acre)	1-3" (tons/acre)	3+" Sound slash (tons/acre)	3+" Rotten slash (tons/acre)	
1	2.19	4.11	9.87	.00	16.17
2	1.76	1.37	9.08	2.23	14.44
3	2.34	3.43	4.00	.56	10.33
4	2.78	.69	4.42	.00	7.89
5	2.78	3.43	7.40	.00	13.61
6	1.32	.69	3.49	.00	5.50
7	.60	.00	6.38	.00	6.98
8	1.66	5.64	8.54	.00	15.84
9	1.51	2.12	20.33	5.18	29.14
10	1.81	1.41	6.28	.00	9.50
11	1.66	4.23	6.76	.00	12.65
12	.30	.71	5.95	.00	6.96
13	.90	6.35	9.02	.00	16.27
14	2.56	4.94	7.43	.00	14.93
15	.30	.71	6.47	.56	8.04
16	.90	2.12	5.95	.00	8.97
17	3.77	4.23	1.63	.00	9.63
18	1.05	.00	8.73	.00	9.78
19	.90	7.06	21.29	.00	29.25
20	1.51	.71	4.65	.00	6.87
21	1.98	2.14	4.50	.00	8.62
22	1.37	2.85	8.04	.00	12.26
23	1.06	.00	1.65	.00	2.71
24	.91	2.85	4.60	.00	8.36
25	1.52	1.42	7.41	.00	10.35
26	1.22	2.14	4.07	.00	7.43
27	1.67	2.14	9.73	1.78	15.32
28	2.59	3.56	7.94	.00	14.09
29	2.74	4.99	2.08	.00	9.81
30	1.37	.71	5.04	.00	7.12
31	1.67	4.99	5.37	5.23	17.26
32	1.22	4.27	8.43	.00	13.92
33	0.61	.00	5.52	.00	6.13

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