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Title: Chronological Variation in Soil Density and Vegetative Cover of Compacted Skid Trails in Clearcuts of the Western Oregon Cascades

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Henry A. Froehlich

This study evaluated the recovery of compacted soils on logging skid trails in clearcuts of the western Cascade Mountains of Oregon. Soil types included clay, clay loam, silt loam, loam, sandy loam and loamy sands. Sites ranged in age from five to 38 years since harvest and 370 to 1100m in elevation. Soil bulk density, measured with a nuclear density probe, was used to characterize compacted soil conditions. A number of soil, vegetation and site variables were studied to determine possible cause and effect relationships with compaction recovery.

Study design consisted of nine sites with nine plots at each site. Plots were classed by level of use with three plots in each of the low, medium and high use level classes. At each plot, measurements of bulk density were taken at the skid trail center, skid trail

track and the less-disturbed area adjacent to the skid trail. Determination of vegetative cover was also made at these locations. Depths of measurement for bulk density were 5.1cm, 15.2cm and 30.5cm.

No statistical difference of bulk density values was detected between skid trail use-level classes. A similar result was found for the vegetative cover variables. Bulk density values on the skid trail center and skid trail track were statistically similar. However, density on the skid trail track (and center) were greater than those of the less-disturbed area ($\alpha = 0.05$). When the data were stratified by site age, the skid trail track still retained greater bulk densities than the less-disturbed area on the 38 year old site. No trends in bulk density changes were observed over time.

Interaction between herbaceous cover and overstory cover decreased the usefulness of these variables for correlation with recovery. However, shrubs indicated a reduction of percent cover on skid trails up to 21 years since harvest, but not after that time. This was the only variable measured which indicated possible skid trail recovery.

Regression analysis was performed using the bulk density difference between the skid trail track and less-disturbed area as the dependent variable and several soil, site and vegetative variables as independents. Multicolinearity among the independent variables was high and when coupled with the variable nature of the bulk density data, produced inconsistent results.

It was concluded that soil compaction can occur and persist on all soil types and that the recovery process is extremely complex. The large degree of variability inherent to the compaction process and recovery requires large sample sizes to detect statistically meaningful recovery trends.

Key words: Soil compaction recovery, forest harvesting, western Cascades, soil productivity, skid trails

CHRONOLOGICAL VARIATION IN SOIL DENSITY AND VEGETATIVE COVER OF COMPACTED SKID TRAILS IN CLEARCUTS OF THE WESTERN OREGON CASCADES

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Jon Vanderheyden

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Head of Department of Forest Engineering

Dean of Graduate School

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Typed by Linda S. Crooks for Jon Vanderheyden

COMMITTEE MEMBERS

Dr. H. A. Froehlich

Dr. R. L. Beschta

Dr. J. Vomocil

Dr. F. Obermiller

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHRONOLOGICAL VARIATION IN SOIL DENSITY AND VEGETATIVE COVER OF COMPACTED SKID TRAILS IN CLEARCUTS OF THE WESTERN OREGON CASCADES

I. INTRODUCTION

Problem Statement

The regeneration and harvest of timber from mountain watersheds has become a highly mechanized process. On slopes less than 40 percent ground based machines are often employed for yarding of logs and site pretreatment. The evolution of forest harvesting machinery has been one of increased power, speed and efficiency, as designs become more specific to the intended use. The potential impacts that this machinery may have on future site conditions has only been incorporated into design in recent years and at considerable cost. In general, the improved machine utility has been accompanied by size and weight increases which have increased the potential for adverse impacts to forest soils and their future productivity. Potential problems are most readily apparent on gentle, rolling terrain with less than 40 percent slopes where the economy and flexibility of tractor and similar skidder systems makes them the most desirable type of yarder for forest harvesting practices.

One of the most pronounced results of ground based logging is the extensive system of skid trails used to remove the felled and bucked timber. This system of trails generally covers from 20 to 40 percent of the harvest area. Soil beneath these trails is compacted to varying degrees, producing conditions which may potentially decrease productivity of the site and alter its hydrologic characteristics. The ramification of these impacts has not been well defined with respect to both the degree and duration of influence. It is of considerable interest to know how long the compacted conditions persist and what specific factors determine the rate of recovery.

Improved knowledge of recovery rates will further the understanding of soil behavior, aid the evaluation of compaction amelioration techniques and help to determine the influence of skid trails on timber harvest scheduling. The alteration of natural soil conditions potentially reduces the establishment and subsequent growth of the forest community, which can result in a reduction of the economic rate of return from the long term investment in growing stock. The most successful solutions to managerial problems concerned with natural resources are generally based on sound theoretical understanding of the processes involved and thorough evaluation of the economics related to the problems impacts and proposed methods of solution. Additional information concerning the duration of the compacted condition is essential to both the evaluation of the potential economic impact as well as the development of an efficient program for ameliorating the problem.

Study Objective

The objective of this study was to determine the rate of recovery of soils compacted during the harvest of timber by ground based yarding operations in the western Cascades mountains of Oregon. To help explain the variation in this process with different site conditions the following factors were also evaluated for their relationship to the recovery process:

(1) Re-establishment of vegetation on skid trails

(2) Soil type and characteristics

(3) Initial use level of the skid trail.

II. ATTRIBUTES AND BEHAVIOR OF FOREST SOILS PERTINENT TO THIS STUDY

The Concept of Soil

The term soil has a variety of definitions which creates a problem when interdisciplinary concerns are being addressed. The issue becomes acute in soil compaction studies and relationships between compaction and vegetative response because the mechanics of the compaction process borrow heavily from the engineering perspective while the effects on vegetation are more related to an agricultural viewpoint. Soil definitions reflect the use to which the soil is put. Engineering typically deals with structures, involving large capital expenses, which depend on dense, stable soil. If the soil in place is inadequate, it can often be excavated and replaced with a more desirable type. Agriculture utilizes large areas of soil and typically seeks to maintain natural surface conditions with some modification through tillage and nutrient additives. Less manipulative control is possible because economic and logistic constraints of agricultural practices are greater than in engineering. Reduced accessibility of the land and long term investments characteristic of forestry increase these constraints. Only minor adjustment of the soil is possible in meeting management objectives.

A single definition of soil is not likely to service all disciplines involved with this resource. The following introduction to soil properties pertinent to forestry as well as some of the related parameter definitions should serve as an adequate functional background for this report.

Summary of Soil Properties

Physical Nature of Soils

Soil is composed of three phases, solid, liquid and gas. The solids phase is composed of particulate mineral matter. The mean particle density (ρ_s), which varies with mineral composition, is given by Ms/Vs where Ms is the mass of the solids and Vs is the volume of the solids. These particles constitute a wide range of shapes and sizes which are often grouped into particle size classes. Three of the more predominant schemes used in the United States for classifying soils are shown in Figure 1. Textural classifications given in this report use the U.S.D.A. classification. Note that the only size division agreed upon by all three systems is the .002mm break for clays. The particle size distribution of a particular soil largely determines the stable packing tightness among grains and therefore affects the nature of the pore sizes and their distribution. This in turn influences the degree of physical contact among the fragments which has important ramifications on soil strength. Soil texture is a term often used in non-engineering disciplines and refers to the predominant size or size range of the particles of a particular soil (Hillel, 1971).

The void space between particles is characterized by the porosity which is defined as Vv/Vt, where Vv is the volume of the voids and Vt is the total volume (voids plus solids) or the void ratio (e)

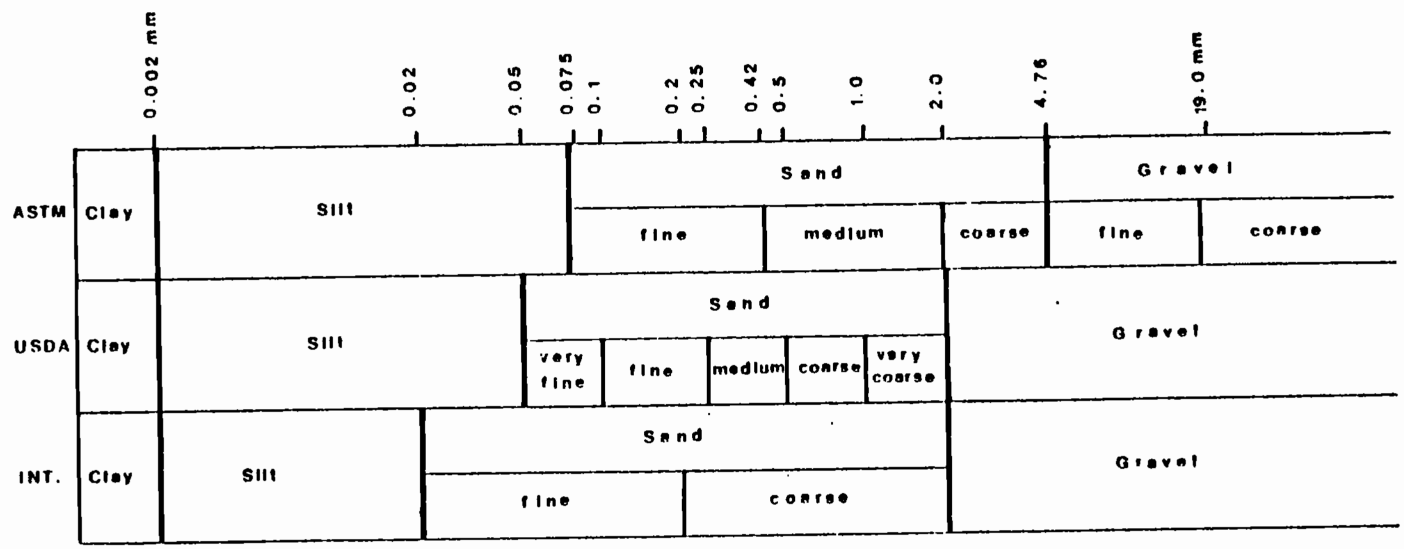

Figure 1. Classification of soil particle size classes according to particle diameter ranges for three systems used in the United States.

(e) which expresses the ratio between volume of the voids, Vv, and volume of the solids, Vs. The space occupied by the pores can be filled with water and/or gas in various proportions. The volumetric water content, θ, is the most basic relationship characterizing the relative amount of water in the soil and is defined as:

$$\theta = \frac{Vw}{Vs + Va + Vw} \qquad \text{Equation 1}$$

where Vs is as defined above, Va is the volume of air and Vw is the volume of water. When pores are filled with water the soil is said to be saturated. Because of the chemical interaction of the polar water molecule with the mineral particles, the soil is never completely dry under natural conditions. At intermediate values of pore saturation, air-water interfaces exist in the soil which can be functionally thought of as capillaries. The unbalanced molecular attraction of the water at this interface results in a force acting parallel to the surface of the water in all directions (Sowers and Sowers, 1970). The magnitude of this force is indirectly proportional to the square of the radius of the soil "capillary." This principle has tremendous importance for soil water relations and strength properties.

Storage of soil water can be broken down into detention storage, which is the water that will be drained by gravity within 48 hours and water retention which is the water remaining in storage pores after 48 hours of drainage. The amount of water in these two classes is determined by the pore size distribution. Retention storage is of importance to plants which require access to soil water over extended periods of time. Infiltration is defined as the actual rate of water movement through the soil surface into the soil profile while the infiltration capacity is the rate that water can enter the soil when it is in a saturated condition (Hillel, 1971).

Clay particles are especially important in affecting the characteristics of forest soils. Clay refers to a large group of minerals which may be amorphous or microcrystalline, of varying mineralogy and less than 0.002mm in size. The more common clays are layered aluminosilicates. They consist of two basic layer structures, one being in the form of a tetrahedron with a group of oxygen atoms surrounding a central cation (usually Si^{4+}) and the other in the form of an octahedron of oxygen atoms or hydroxyl groups surrounding a larger cation usually AL^{3+} or Mg^{2+} (Hillel, 1971). These layers are joined in ratios of 1:1, 2:1 or 2:1:1 by the sharing of oxygen atoms. Several of these basic repeating structures then link together to form a clay particle. When clay particles exist as separate entities in the soil solution the soil is said to be dispersed whereas when they form larger associations in solution they are said to be flocculated. Because of the large specific surface area of the clay size fraction, the amount present largely determines the physical and chemical behavior of the soil. For example, 90 percent of the surface area present in a soil consisting of 99 percent sand and one percent clay, is due to the clay (Li, 1956).

Substitutions of the central cation in a layer by a cation of differing charge (called isomorphic substitution) gives rise to unbalanced electrical charges in the clay structure which are normally negative. This leads to an attraction of cations from the soil solution to the vicinity of the clay surface. Taken together, the charged particle surface and the neutralizing cationic layer form the electrostatic double layer (Hillel, 1971). The dynamic nature of this layer and the reaction of charge fields with dipolar water molecules drastically alter the nature of soil properties from the more simplistic behavior of soils lacking significant proportions of clay. The prediction of soil behavior is further complicated by the fact that a wide variety of mineralogies are generally present in a given soil and quantification of the proportion of each is not readily obtained.

Soil engineers have used several rather subjective parameters to characterize clay soils for a number of years. The liquid limit is defined as the water content at which a trapezoidal groove of specific shape, cut in moist soil held in a specified cup, is closed after 25 taps on a hard rubber plate. The plastic limit is defined as the water content at which the soil begins to break apart and crumble when rolled by hand into threads 0.125 in. (.32 cm) in diameter (Sowers and Sowers, 1970). The difference between these two moisture contents is the plasticity index and can be thought of as the range of moisture contents in which a particular soil exhibits plastic properties. Warkentin (1961) interprets the liquid limit as that water content at which enough free water is present to allow clay particles to move with respect to one another relatively free from particle interaction forces. The variability of the values obtained for these parameters is dependent on consistency of the test procedure, the type of ions present in the soil solution as well as the particle size and composition of clay minerals (Brown, 1977).

The dry bulk density of soil (hereafter referred to as bulk density), BD, is the ratio of the mass of dried particles to the total volume of soil including pores (BD = Ms/Vt). Many of the strength relations of soil and properties of importance to vegetation are directly or indirectly related to this parameter. For instance, there is typically a high correlation between BD and porosity and a smaller though significant negative correlation between bulk density and infiltration (Free, Browning and Musgrave, 1940). Bulk density generally increases with an increase in depth from the soil surface; the magnitude of this increase depends on soil texture, climatic conditions at the surface and management history in the area.

The Importance of Soil Organic Matter and Biology

Microorganisms are critical to the soil system because of their role in the cycling of nutrients and the processing of the organic matter from plants using the soil as a growth medium. Organic matter is used by microbial populations as an energy source for their life processes (Kroth and Page, 1947). The organomineral byproducts of the microbial action chemically interact with the physical constituents of soil and can alter soil properties. An example of this is the directly proportional relationship between organic carbon content and the plastic limit in fine textured soils (Odell, Thornburn and McKenzie, 1960). Because of the low particle density of organic matter its presence in the soil also lowers the overall bulk density. Larger soil organisms such as insects and earthworms continually mix the surficial layers of the soil and keep it loose and friable. Such soils, typical of forest situations, have high infiltration rates, are readily penetrated by feeder roots and are able to support high air exchange rates critical to roots and microbes alike.

The biotic component also influences soil structure. Brewer defines soil structure as "the physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves" (Brewer, 1964 p. 132). Baver et al. (1972) call these compound particles aggregates when the primary particles are held together by a cementing agent. In soils with little clay to serve as cementing agent, organic molecules (apparently synthesized polysaccharides according to Baver et al., 1972) have been shown to substitute and fresh organic matter appears to be a more suitable source of these molecules (Kroth and Page, 1947). Quality organic matter also increases the stability of aggregates formed by earthworms (Swaby, 1950). The presence of aggregates in the soil simulates the physical effects of larger particles by forming pore sizes much larger than would be possible with the packing of constituents of a fine textured soil. Maintenance of such a condition is dependent on a healthy soil biota.

Mechanics of the Compaction Process

Soil compaction is defined as the packing together of soil particles by instantaneous forces exerted at the soil surface resulting in an increase in soil density through a reduction in pore space (Lull, 1959). The qualification of "instantaneous" is necessary because engineers usually separate this process from consolidation which is similar but allows enough time for the equilibration of the applied stress with the readjustment of soil particles and pore water.

The reaction of soil to the application of stress is intricate and complex. Most of the theory and analysis of physical soil behavior has been developed by engineers and the continued expansion of this study has gradually filtered into agriculture and forestry as these disciplines became aware of the unavoidable impacts of their management. Soil strength, defined as the ability of a particular soil in a particular condition to resist an applied force (Taylor, 1974) is essential to the prediction of soil reaction to external stresses. Stress, or the force per unit area, is generally thought of as effective stress because actual stress occurs at particle contact points and has a large value while the energy expenditure is somewhat less because of the small area involved. Effective stress, σ', is

$$\sigma' = Q'/A' \qquad \text{Equation 2}$$

where Q' is the total load and A' is the area to which the load is applied (Sowers and Sowers, 1970). These authors also show that since part of the area of application is pore space, the total stress, σ, is given by:

$$\sigma = \sigma' + U\ Av/At \qquad \text{Equation 3}$$

where σ and σ' are as given above, U is the pore pressure, Av is the area in voids and At is the total area. Because air is compressible and water is not, the U term is only present when pores are filled with water.

The shearing strength (τ) of soil has been developed from Colomb-Mohr yield theory and is given by:

$$\tau = \sigma\ \text{TAN}\ \phi + C \qquad \text{Equation 4}$$

where σ is the normal stress, ϕ is the internal angle of friction and C is the cohesion. This relationship is theoretical and its application is difficult because ϕ and C are not readily obtained. Additionally, development of the theory is based on ideal elastic, homogeneous, isotropic materials (Bekker, 1961), and these conditions are virtually never met in the field.

The compressive stress on a soil has a tendency to concentrate around the load axis (Soehne, 1958). This axial compression energy can be broken into three parts; (1) shear strain energy, (2) energy transmitted to sample surroundings and (3) volumetric strain energy (Chencellor, Vomocil and Aref, 1969).

The same authors found that most of the initial stress goes into volumetric strain but that greater than 50 percent of the total energy input goes into shear strain. The energy utilized to overcome frictional resistance is converted to heat (Li, 1956). Resistance to deformation of soil depends on mechanical strength which is a combination of cohesive strength and frictional strength (ASAE - SSSA, 1958). When the applied stress exceeds the shear resistance, failure occurs resulting in deformation of the soil. With sandy, cohesionless soils, particle deformation occurs with localized crushing at contact points along with the translation and rotation of grains and resultant alteration of the voids (Sowers and Sowers, 1970). Resistance in these soil types is determined by angle of contact and interlocking of grains. Cohesive soils, such as clays, are often saturated so that pressures are transmitted within them by pore pressure (Croney and Coleman, 1954). Deformation in these soils is dependent on rate of load application and water content and takes place by re-orientation and fracture of particles. Resistance is derived from interparticle friction, chemical interaction and capillary tension (Sowers and Sowers, 1970). The energy expended in the densification process is the compactive effort. As shear resistance is exceeded, the applied load starts to sink. The soil under the load is pushed downward and outward, thus mobilizing more strength until failure conditions are no longer met (Li, 1956).

The region of soil influenced by an applied load depends on the area and magnitude of stress, the initial soil bulk density and moisture content, and the soil texture (Soehne, 1958). The frequency and magnitude of vibration has also been mentioned (Froehlich, 1977) as a source of densification and is probably most important with cohesionless soils. Baver and others claim that about ten percent of compaction pressure of tires comes from horizontal stress (Baver, Gardner and Gardner, 1972). In a shear box study with sands and sandy loams, Raghavan and McKyes (1977) found increased compaction when normal loads are accompanied by shear. Chancellor (1976) reports that the lowest porosities also are produced by high shear deformation and high stress combined.

Pressures at the soil surface are mostly determined by the load per unit area whereas pressures deeper in the soil horizon are established by the total load supported (Chancellor, 1976). Cohron (1971) comments that external forces are applied to only a portion of the soil boundary and the resultant nonuniform stress distribution precludes detailed theoretical analysis. The author uses the following sinkage equation as an indicator of compaction with depth:

$$P_z = K \frac{(Z)^N}{b} \qquad \text{Equation 5}$$

where P_z is the soil resistance to penetration, K is the sinkage constant, Z is the depth below the surface, b is the smallest dimension of loaded area and N is the sinkage exponent which has a value of zero for cohesionless soils and one for purely cohesive soils. With increasing moisture content the flow of soil to the side at depth concentrates the applied forces at the axis of the load and increases the extent of impact deeper in the soil (Soehne, 1958). Thus for equation five to be accurate, moisture content would need to be included into the sinkage constant for a particular soil type.

The optimum moisture content for compaction is a function of pore size distribution and mineralogy and usually lies between field capacity and wilting percentage (Alexander, 1977). Soehne (1958) in working with a loamy clay soil found that to get an equivalent compaction at 24.1 percent moisture required only one ninth the pressure needed at 14.0 percent moisture and one fiftieth the pressure as at 3.4 percent moisture. Though compaction is strongly dependent on the moisture content there are other controlling factors. Organic matter content has been shown to protect the subsoil from surficially applied forces and lowers the amount of compaction that is obtainable (Free, Lamb and Carleton, 1947). Well graded soils with their extensive particle to particle contact offer more resistance to compactive effort (Harris, 1971) but are also compactable to higher densities. Gravel in soils decreases the compaction of fine grained soil constituents particularly when the proportional volume present is such that particle to particle contact occurs (Li, 1956).

The interaction of compactive stresses with the variety of soil conditions makes study of related problems exceedingly difficult in the field. The lack of theoretical understanding except in the most simple of cases indicates that laboratory study is no less difficult.

III. SOIL IMPACTS FROM GROUND BASED LOGGING

Compaction During Logging Operations

Ground based vehicle logging had its advent in the Pacific Northwest sometime in the 1940's (Steinbrenner and Gessel, 1955) as the economics of railroad logging became less profitable. Initially most work of this type utilized the crawler tractor but early in the 1960's the development of the rubber tired skidder began to encroach into this domain (Cambell, Willis and May, 1973). Recently, vehicles with a combination of torsion-bar suspension and steel-track have come into use (Froehlich, 1978). Mass and ground pressure for the various vehicle types are given in Table 1. It should be kept in mind that the crawler tractor is still the most popular machine used for logging because of its multi-function utility and subsequent economic advantage.

The compactive effect a machine has on the soil depends on its total weight, ground pressure, vibration and soil conditions. Rigid wheels have a relatively small contact area and tend to sink into porous soils until enough contact area is mobilized to stop sinkage. Additional load on vehicles with pneumatic tires causes the tires to flatten and increases their contact area so that actual ground pressure remains proportional to the inflation pressure (Lull, 1959). Soehne (1958) notes that though surface pressures may be the same for various loads, compactive forces extend further into the soil profile with heavier loads. Actual compactive force is generally greater than the static contact pressures because of uneven ground

TABLE 1

WEIGHTS AND GROUND PRESSURES OF LOG YARDING VEHICLES

Type of Logging Vehicle	Approximate Unit Mass	Approximate Static Ground Pressure
Rubber-tired Skidder	10,000 - 18,000 lbs 4,500 - 8,200 kg	20 - 28 psi 138 - 193 kPa
Crawler Tractor	10,000 - 36,000 lbs 4,500 - 16,300 kg	6 - 13 psi 41 - 90 kPa
Torsion Suspension Steel-track	10,000 - 15,000 lbs 4,500 - 6,800 kg	7 - 9 psi 48 - 62 kPa

and draw load dynamics. Cohron (1971) notes that actual compaction is reduced by high speed passes because of the shorter duration of stress application. Reaves and Cooper (1960) found that stresses from a 16 psi (69.1 kpa) tractor tire are measurable as deep as 40 in. (101.6 cm) while a crawler tractor pulling a similar load produced noticeable stresses to only 25 in. (63.5 cm). The increase in compaction with horizontal shear has already been mentioned. Complete elimination of this horizontal component is not possible because of the nature of propulsion. Thrust is defined as the horizontal reaction produced by the ground when it is deformed by the load carrying and propelling components of a vehicle (Bekker, 1961). The same author gives the following equation for maximum soil thrust, Hm:

$$Hm = AC + W \tan \phi \qquad \text{Equation 6}$$

where A is the ground area in contact with track, C is the cohesion of the soil, W is the weight carried by the track and ϕ is the internal angle of friction of the soil. Traction derived from horizontal shear needs to be related to the various propelling strategies of the commonly used logging vehicles if relationships regarding vehicle impacts are to be of use.

The reduction of productivity at a site by logging depends on the nature of the disturbance and the area it covers. Table 2 displays many of the studies concerned with this aspect of logging impacts. In general, about 20 percent of a given clearcut area will be in compacted skid trails and landings when logged with ground based vehicles. There appears to be no trend in the disturbance

TABLE 2

AREA DISTURBED AS A RESULT OF GROUND BASED LOGGING ACTIVITIES

Year	Authors	Location	Disturbance Classification	Percent of Logged Area Disturbed
1940	A.L. Hormay	Northeast California	Subject to skidding	14
1947	E.N. Munns	California	Tractor trails and roads	25 - 40
1951	G.A. Garrison R.S. Rummell	Eastern Oregon and Washington	Deep disturbance	15
1955	E.C. Steinbrenner	Washington	Skid roads	26.1
1960	D.D. Woolridge	---	Ground surface disturbed	29.4
1965	C.T. Dyrness	Oregon Cascades	Skid roads	28
1967	J.A. Young D.W. Hedrick R.F. Keniston	Northeastern Oregon	Heavy soil disturbance	15
1970	G.E. Hatchell C.W. Ralston R.R. Foil	Coastal Plain of South Carolina and Virginia	Primary skid roads Secondary skid roads Log decks Total	17 22 2 41
1971a	A.C. Mace	Minnesota	Medium and heavy disturbance	19 - 30
1971	G.A. McDonald	North Carolina	Roads and landings	25
1973	R.G. Cambell J.R. Willis J.T. May	Georgia	Primary skid trails Secondary skid trails Turnarounds Log decks Total	4.5 15.0 2.3 1.2 23

levels with time despite the advances made in fitting machine design with intended use.

The extent of compaction depends on the type of equipment used, the terrain over which the logs are skidded, the frequency of travel on a given area, the type of soil and the soil moisture content (Lull, 1959). Froehlich (1976) adds volume of timber removed and operator skill and attitude to this list. Garrison and Rummell (1951) note that steep terrain (greater than 40 percent) increased the amount of deep disturbance caused by tractors by an average of 2.8 times. Because of the reduced maneuverability on such slopes there are generally fewer skid trails with more use and thus greater impact, partly due to increased amounts of excavation.

Resultant Changes in the Soil

Soil in the area of disturbance takes on properties different from that of the less-disturbed area. Movement of the soil grains during compaction depends on the structural arrangement of the particles and in finer soils, the degree of interparticle bonding (Harris, 1971). Grain movement can be rotational, translatory or simple reorientation (ASAE-SSSA, 1958). Besides the predominant affects of compaction, "soil displacement" or the churning, rutting and scalping of soil can occur (Moehring, 1970). In clays, free interstitial water and associated ions can be expelled from between structural layers (Rosenbaum, 1976). Harris (1971) notes that this removal of water can translate into a volume reduction if the water is free to drain.

Bulk density is the most often used indicator of compaction. Though grain displacement can change the pore size distribution and continuity, the overall effects are indicated by bulk density (ASAE-SSSA, 1958). Froehlich (1973) notes that increase in bulk density is almost directly related to loss of macropore space. Steinbrenner and Gessel (1955a) found this to be true on skid trails they studied, and also reported a 22 percent increase in bulk density over that of clearcut areas adjacent to the trail. A second paper by Steinbrenner and Gessel (1955b) reported a 35 percent increase in bulk density of skid trails. Moehring and Rawls (1970) found no change in bulk density values at the two inch depth when logging took place on dry soils but found a 13 percent increase on moist soils, a fact which re-emphasized the importance of soil conditions. In the southeastern U.S., Dickerson (1976) found a 20 percent increase in bulk density in the track portion of the trail and a ten percent increase in the trail center after seven trips with a skidder.

Frequency of travel over the soil appears to be unrelated to bulk density increases because the greater portion of increase comes in the first few passes. Steinbrenner (1955) noted little change in bulk density increases with greater distance from the landing. In Minnesota, Mace (1971a) also failed to relate bulk density to frequency of travel. Hatchell, Ralston and Foil (1970) reported that 2.5 trips resulted in densities within ten percent of the maximum attained. However, the same report stated bulk density on secondary skid trails increased from 0.75 g/cc to 0.92 g/cc, while the increase on primary skid trails was from 0.75 g/cc to 1.08 g/cc. The validity of comparing skid trail densities with areas adjacent to skid trail is supported by findings of Dyrness (1965). In comparing pre-logging bulk densities with post logging densities for the general clearcut and slightly disturbed classes no significant differences could be found.

The effects of machine passes on aggregates is to initially cause repositioning and loss of macropore space and subsequently, as pressures increase, plastic deformation (Day and Holmgren, 1952). Soil puddling occurs when soil structure is destroyed and orientation of clay particles is parallel (Moehring, 1970). This phenomena is most prevalent when logging takes place on very wet soils. With compaction on aggregated soils, bulk density increase may be minimal while permeability decreases are large and as such infiltration rate may be the most sensitive soil characteristic (Lull, 1959). Steinbrenner (1955) found this to be true when he studied infiltration rate, bulk density and macroporosity.

In summary, the densification of soil leads to greater particle to particle contact, reduced porosity and greater soil strength. The increase in relative proportion of solid to fluid phases results in higher heat conductivities and specific heat for the soil. The reduced pore volume decreases gas exchange rates, infiltration capacity and variation of the soil moisture regime. In addition, logging traffic removes the soil surface litter and organic matter. These conditions are likely to reduce soil biology populations in the impacted area.

Consequences For Vegetation

According to Dyrness (1973) disturbance history, nautral or man-caused, is as important as predisturbance stand composition in determining the plant community composition after disturbance. The soil conditions described above are partly responsible for such community changes. Alexander (1977) defines compaction hazard as the sensitivity of soils to compaction which will adversely affect vascular plant growth. Froehlich (1976) used similar logic in defining soil damage as any physical impact on soil which reduces the potential growth of residual trees or seedlings thinning units.

Soil alteration effects the plant through changes in the root environment. Though no studies could be found relating the effect of compaction on mycorrhizea, these symbiots are likely to be adversely affected because of their high concentrations just below the litter layer (McMinn, 1963). Plant reaction depends on the needs of the plant and the ability of the roots and soil to interact and meet these needs (Trouse, 1971). Nutrients are delivered to the plant as ions by mass flow, root contact with soil ions or diffusion, and the process is dependent on aerobic metabolism (Parish, 1971). That aeration is one of the primary concerns with compacted soils is not surprising. Hatchell (1970) cited reduced oxygen supply, high carbon dioxide and increased mechanical resistance as factors reducing root biomass. Zimmerman and Kardos (1961) noted reduced root weight with increasing bulk density.

Merideth and Patrick (1961) found a negative linear relationship between bulk density and subsoil root penetration by soil type and consequently hypothesized that there is no one critical bulk density which limits root penetration. The same authors note that a root can exert much more pressure radially than tangentially and thus primordia probably use macropores as entry points into new soil. Comparing seedlings of seven northwest tree species, Minore, Smith and Woollard (1969) showed that densities limiting to roots varied with soil texture. The species with the highest root biomass at all treatment levels was Red Alder (Alnus rubra Bong.). Compaction reduces the area of soil inhabited by roots and consequently decreases the available moisture and nutrients to the plant. The increased mechanical resistance and reduced soil aeration can also decrease seedling emergence by preventing root radicle penetration (Chancellor, 1976).

The physical resistance of compacted soil to roots may shift the energy relationships within the plant so that more energy is utilized by roots versus top growth (Gill, 1961). One direct impact on plant energy distribution is the increased soil water potential at a given water content due to smaller pores in compacted soil (Blake, Nelson and Allmaras, 1976). If a large enough water potential gradient cannot be produced by the plant to draw moisture from the soil, photosynthetic processes and respiration are stopped and the plant foregoes food production and growth which would have resulted from these energy sources. It appears that many of the variable results of compaction effects on agricultural yields have actually been because of the failure to consider the importance of water regime and water stress (Chancellor, 1976). Hatchell (1970) loosened compacted soil around loblolly pine seedlings and found no increase in growth when adequate soil moisture was supplied. Foil and Ralston (1967) found reduced seedling growth strongly associated with increases in bulk density. Froehlich (1973) reports loss in height growth of seedlings due to compaction ranging from 14 to 53 percent depending on soil type, degree of compaction and tree species. In a later paper, the same author showed that a 30 percent reduction in growth on 25 percent of a clearcut area would reduce yields on tractor lands by 7.5 percent (Froehlich, 1977). Moehring and Rawls (1970) found that traffic on one to two sides of trees did not influence growth but that traffic on three to four sides affected growth for all five years of their study. Youngberg (1959)[1] reported significantly reduced height growth of seedlings on skid trails and attributed results to higher clay content, higher bulk density and lower nitrogen content.

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[1]There is probably no other paper dealing with skid trail soil impacts more often misquoted than this one. The study looked at skid trails with severe top soil removal and exposure of C horizon material. The author states: "The disturbance caused by compaction alone was not considered in this study." Decreased nitrogen levels were cited as the major factor affecting seedling growth.

IV. RECOVERY OF SOIL FROM THE COMPACTED CONDITION

Processes Involved

Principal environmental factors affecting soils include: (1) Soil organisms, (2) precipitation, (3) temperature, (4) physio-chemical reactions, (5) topography, (6) water regime, and (7) time (Buol, Hole and McCracken, 1973). The resulting soil density is in dynamic equilibrium with these factors (Larson and Allmaras, 1971) and any perturbation which removes the soil from this balance will necessarily be "resisted" by the system. Thus a compacted soil will in time, "recover" or return to its equilibrium condition. The factors generally regarded as being the most influential in this process are: (1) frost heave, (2) shrinking and swelling, (3) root dynamics, and (4) soil biota.

Frost Heave

The freezing of the soil results in either frost formation or ice lensing. There are four basic types of soil frost: concrete, honey comb, stalagtite and granular (Bullard, 1954). Needle ice is an additional ground phenomenon that occurs when wet soils are above freezing and air temperatures are below. The process most influential in terms of compaction recovery is ice lensing.

Soil freezes when daily mean temperatures remain below zero degrees celsius for three of four sequential days (Sowers and Sowers, 1970). Depth of freezing depends on minimum temperature reached, length of cold spell, amount of heat present in the soil and rock, and the thermal properties of the soil (Taber, 1929). Freezing of water starts with the formation of small particles of the solid phase or nucleation. Martin (1959) notes that survival of a given ice crystal is dependent on energy dynamics, with stability being characterized by statistical probability. The likelihood of crystal formation becomes favorable at a point somewhat below freezing in soils unless foreign particles or nuclei are present in the water to serve as stabilizing points of crystallization. When water freezes there is a ten percent increase in volume over that of water and in saturated soil this means approximately a five percent increase in total soil volume, much less than observed with frost heave (Taber, 1930). However, when water freezes in the soil, tension is created in the soil water system such that water flows to the area of crystallization (Anderson, 1947). In small capillaries, water is under tension and has a depressed freezing point, enabling the capillaries to transport water to the larger pores where crystallization initiates (Sowers and Sowers, 1970). The crystallization process is accompanied by release of the heat of fusion and this heat is ultimately dissipated at the soil surface. Crystal growth occurs toward the soil surface following this dissipation of heat (Taber, 1929). The extent of crystal growth is a balance between the ability of the soil to supply water (function of pore size and available water source) and the rate of cooling. Capillary continuity to a source of water is a must for this process as the flow of water feeds ice formation, which releases heat and retards the rate of cooling. When supply is inadequate the temperature drops, causing an advance of the freezing front and an end to ice lense growth (Martin, 1959).

Not all soils are equally susceptible to frost heave. Coarse soils lack significant volumes of fine pores which remain unfrozen and allow water flow to the point of ice growth. In addition, Haley and Kaplar (1952) note that the presence of stones increases the thermal conductivity (thus rate of cooling) and reduces the volume of susceptible material. In fine soils a larger proportion of the soil water is physically held by chemical interaction with the soil particles and the finer pore size distribution limits the rate of water supply to the ice front resulting in a rapid temperature decrease. In light of this dependency on pore size, it should not be surprising that bulk density has been found to be highly correlated with frost heaving (Heidman and Thorud, 1975). Silts and fine sands are the soils generally most susceptible to the heaving process (Sowers and Sowers, 1970). Compaction makes coarse soils more susceptible to heave and all other soils less so (Larson and Allmaras, 1971).

On forest lands, additional factors which determine the occurrence of frozen soils are depth of snow, vegetative cover type and density, and surface organic matter quantities (Bullard, 1954). The insolating effects of these factors tend to reduce the likelihood of soil freezing in forest situations. Anderson (1947) noted that forest cover may delay the freezing of soil until after snow fall and hypothesized that frost heave may be an uncommon occurrence in the Sierra Nevada Mountains of California. Bullard (1954) concluded that soil freezing was insignificant in the Pacific Northwest based on similar reasoning accompanied with reconnaissance survey. In an economic evaluation of compaction, Gill (1971) noted that where annual frost penetration was less than 25 cm, adequate natural amelioration cannot be expected at adequate depths.

Shrinking and Swelling

Soil shrinking and swelling are commonly linked together as physical processes because their opposing nature has a similar impact on soil density. The mechanics of these processes are distinctly different and as such their occurrence is often dependent on dissimilar conditions and soil properties. However common causative factors are shared. The combined effects are most pronounced in climates where long and severe wet and dry seasons are experienced (Larson and Allmaras, 1971). In addition, the amount, type and orientation of clays has a major influence on the magnitude of both processes.

Shrinkage of the soil occurs when water is removed from the pores. The process can be separated into three stages; structural shrinkage, where the volume change is less than the water loss, normal shrinkage, where volume changes are equal and residual shrinkage where the pores begin to empty and soil volume changes are insignificant (Larson and Allmaras, 1971). As water is removed from the soil, sequentially smaller and smaller pores are drained. The first pores to drain are those between aggregates resulting in only minor soil volume changes. As more water is removed, the adhesive and cohesive forces of the menisci pull on the soil particles drawing them closer together (Brown, 1977). These forces are increased as the pore size decreases. Thus, fine grained soils generally have the largest potential for shrinkage provided that a large enough water potential deficit can be created to remove the water. Continuation of the process under such conditions leads to exceedence of shear failure conditions and development of cracks in the soil. The result is an overall decrease in bulk density. If conditions do not result in cracks, densification rather than loosening occurs. This latter phenomenon has been observed by Gill (1959).

The swelling process is confined to smectite clays. The interstices of these 2:1 structured phylosilicates have a large concentration of ions which equilibrate unbalanced changes in the octahedral layer and create an osmotic potential from the soil solution to the clay inter layer. The subsequent flow of water is the driving force of swell as the clay layers are forced apart by the increase in interlayer water. Ladd (1959) notes that compaction of clays forces particles closer together, potentially increasing their chemical attraction and reducing the swell potential. Cementing agents such as iron hydroxides, carbonates and organics can limit swelling by bonding clays to sand and silt grains (Larson and Allmaras, 1971). Seed, Woodward, and Lundgren (1962) observed that soil compacted at the same water content to a similar bulk density but using differing modes of compaction resulted different swelling potentials. The authors cited different clay micro structures as the cause. The paper concluded that soil structure, initial dry density, water content at time of compaction, method of compaction, water availability and solution chemistry were the most important factors leading to the realization of swell potential of a given soil. Though large volumes of 2:1 clays are required for heaving of the soil, smaller amounts are important in creating zones of weakness in soil which facilitate aggregate formation. Macropores resulting from this process signify the recovery of a compacted soil.

Root Activity and Organic Matter Decay

Gill (1961) defines growth pressure as the physical pressure which a plant exerts against the external medium. The ability of roots to do work is evidenced by the lifting of side walks and roadways which are bordered by live plants. Roots most likely gain entry to new soil areas by entering macropores and then, since they can exert much more pressure radially than tangentially, enlarge the new channel by radial expansion (Barley, 1968, Meredith and Patrick, 1961). McMinn (1963) notes that roots of trees in immature stands followed the surface of decaying roots of trees from the previous stand. When roots enter new soil the initial effect is to compact the soil in the immediate vicinity of the root (Barber, 1974). Roots also aid in structural development of the soil by creating weakness zones and increasing the heterogeneity of the soil (Larson and Allmaras, 1971).

Whether or not a root will penetrate a compacted soil depends on the plant species, soil strength and the soil oxygen content. In fine grained soils, oxygen supply is more likely to be the limiting factor especially when the soil is wet (Hopkins and Patrick, 1969). Douglas-fir [Pseudotsuga menziesii (mirb.) Franco] roots have been observed to parallel a fragipan layer while alder roots (Alnus spcs.) were able to penetrate through (McMinn, 1963). Whether this differential ability is related to the size of root primordia or the tangential extension force is apparently unknown. Larson and Allmaras (1971) note that roots of perennials are more likely to penetrate subsurface layers because they are present when soil is wet and has less strength. One of the more direct observations of the break up of compaction was an experiment by Zimmerman and Kardos (1961). They compacted soil cores by quarter inch layers in pots and then planted soybeans and sudgrass. Roots went down the sides of the pots then between the layers and broke up the surface zones of compacted soil.

Though shear is probably the major mode of soil loosening by roots, decay of pre-logging roots in the compacted zone is likely to also be of significance. Few studies of this aspect of recovery could be located in the literature. Weaver (1947) clipped back the tops of various grasses and found 20 percent of the root biomass still intact after three years. Turnover rates of roots appear to be highly variable but may be as much as half the total leaf fall for some conifers (Herman, 1977). The effect of root decay in lowering soil bulk densities is probably a long term process and represents just one of the many factors determining the equilibrium soil density level.

During yarding operations, organic debris on the soil surface is often churned and incorporated into the soil. The extent of this phenomenon is unknown but represents a reduction in bulk density by its presence and eventual decay. The amount of incorporation probably depends on type of machinery, soil type and condition, number of machine passes, level of organic debris loading and topography.

The Role of Micro and Macro Organisms

Soil microorganisms function in the recovery process primarily with their contribution to aggregation from which forest soils derive their porous though fragile nature. The importance of organic matter to this process and the role of microorganisms has already been discussed.

Soil macrofauna includes rodents, insectavora, insects, myripods, arachnids, slugs and snails, wood lice, oligochaetes and nematodes (Larson and Allmaras, 1971). These animals mix the surface soil, incorporate and begin the processing of organics and create macropores through the soil which are used for tunnels and burrows. The effect of this activity is to reduce the soil bulk density. In comparing grazed versus nongrazed areas in the San Joaquin Valley of California, Ratliff and Westfall (1971) attributed lower bulk densities in the nongrazed area to gophers (*Thomomys bottae*, Wewa). In general, animal activity is not considered important to recovery of skid trails. The adverse environment present in the skid trail area is not likely to be inhabited by these mobile and selective life forms when adjacent areas of low soil strength and dense cover are available. However, the importance of animal activity probably increases after the recovery process has been initiated by other recovery processes.

Human Intervention

Management action to loosen compacted soils has taken the form of cultivation practices. Moehring (1970) reviewed possible alternatives available to foresters. Subsoiling and ripping are the most common practices involving the use of a crawler tractor equipped with a single to multi-toothed plow-like device which churns and breaks up the soil. Steinbrenner and Gessel (1955b) estimated the cost of this treatment at around 3.5 percent of the cost of tractor logging on a per acre basis. Results of subsoiling activity in New Zealand showed an increase in tree growth and survival after treatment but adverse affects persisted due to poor soil structure and clodiness (Berg, 1975). Roots were noted to follow fractures in the soil but lateral root spread was minimal. Baver, Gardner and Gardner (1972) claim these nonpenetrable clods are characteristics of subsoilers when used on compacted soils.

The practice of mechanical ripping of compacted soils is often cited as desirable because it accelerates recovery by natural processes. The extremes of moisture and temperature regimes are increased, aeration is improved, the physical forces of erosion are exposed to a greater percentage of the compacted soil and the strength of a massive soil condition is reduced. Slaking of clods resulting from entrapment of air by water entering pores becomes more feasible under these conditions. However, since the clods are individual entities their resistance fo swelling, shrinking and frost heave volume changes are reduced. If clods are not broken by this process their density is likely to increase. The expansive forces of ice are limited to ten percent because continuity of pores with a water source is broken. Finally it should be noted that the increase of erosive and slaking forces tends to lead to a puddled soil rather than an a-gregated one. As a result ripping may be counter-productive and short-lived (Greacen and Sands, 1979).

Previous Studies of Soil Compaction Recovery

Studies of the recovery of compacted soil conditions have used many different criteria for evaluation. Few field experiments have good controls because pre-treatment data is lacking and comparisons must be made between the treated area and an adjacent less disturbed area.

Garrison (1960) used desirable grazing species as an index of recovery and found that composition of such species was retarded about five years on seven year old skid trails. McDonald (1971) used percent cover of living and dead organic matter to evaluate recovery and found 55 percent cover after one year, 75 percent cover after two years and 95 percent cover after four years. Recovery of soil based on vegetative factors combines the interactions of predisturbance vegetation, soil type, elevation differences, moisture regime and severity of disturbance (Dyrness, 1973).

Several investigators have used hydrologic soil parameters for recovery evaluation. Tackle (1962) looked at infiltration capacities on broadcast burns, scarified areas and skid trails over a period of five years. He reported significant improvement of this parameter on all but the tractor skid roads. Johnson (1978) found no significant difference in infiltration capacities between skid trails and less disturbed soils in six year old clearcuts in the Oregon Cascades. Dickerson (1975) installed trenches to collect storm runoff on skid trails with seven trips by a loaded rubber-tired skidder. He reported sediment yields the second year were one tenth that of first year yields, despite similar storm patterns. The rapid recovery of these low use trails was attributed to revegetation. Use of hydrologic soil variables represent relatively direct methods of evaluating hydrologic recovery but are only an index of soil compaction abatement. Surface sealing, soil reaction, soil moisture status and soil texture interact with hydrologic soil variables and make them less discriminating to the evaluation of soil productivity recovery (Chancellor, 1976).

Garner and Tel Fair (1954) buried puddled and compacted soil cores in a forest, an old field and a garden and made observations regarding breakup of these cores. Within a year the field and garden cores showed signs of wireworm activity and development of cracks while the cores buried in the forest showed no signs of loosening after two years. Three years later some root penetration and

Ralston (1971) looked at the bulk densities on primary and secondary skid trails and log decks on sites which ranged from recent to 19 years old. A regression equation with a highly significant r^2 of .51 predicted a return to normal densities in 18 years. In a study of the effects of compaction in tree growth, Perry (1964) estimated recovery from compacted conditions in 40 years using a linear projection. Thorud and Frissell (1969 and 1976) mechanically compacted sandy loam and loamy sand soils in Minnesota and followed recovery of bulk density using a randomized block design. They found recovery to occur in between 4.5 and 8.5 years at the 0 to 6 in. (0 to 15.2 cm) depth but detected no change in bulk densities at the 6 to 9 in. (15.2 to 22.9 cm) depth. In Russia, Ivanov (1976) found that "automorphic soil" recovered from the compacted condition in five to seven years while "semi-hydromorphic" soils took 15 years. Depths at which these findings were derived was not reported by Greacen and Sands (1979) who reviewed the article.

Additional studies of the recovery process have been conducted in related disciplines. Evaluation of the persistance of plow layers and compacted subsoils in agriculture (van Duwerkerk, 1968; Blake, Nelson and Allmaras, 1976; Pollard and Webster, 1978) typically evaluate the problem while surface cultural activities are continued which diminishes the value of their results for application to the recovery process. All three of the above mentioned studies found no recovery. One exception to the continued cultivation is a study by Northup and Boyle (1975) which looked at abandoned agricultural fields earthworm activity was being initiated in the forest cores and a platy structure was developing (Talfair, Garner and Miars; 1957). Lack of microorganisms and insolation by the forest environment were cited as the cause of retarded recovery.

In Minnesota, Mace (1971a) found substantial recovery of soil based on bulk density for medium disturbance plots but little recovery of plots which had the "A" horizon removed. The most significant recovery of clay soils was noted to occur on plots with the greatest regrowth of vegetation. Miles (1978) found some recovery of surface bulk densities of skid trails but minimal recovery at depth in sandy loam soils. On sandy soils in Minnesota which were compacted during dry conditions, Mace (1971b) found complete recovery of soil density in just two years. Freeze-thaw processes were credited with this rapid return to friable conditions. In Northern Mississippi, Dickerson (1976) found that both disturbed and undisturbed sandy soils increased in bulk density from two years to five years after logging but that differences between the two treatments diminished after that period. The author extended a regression relationship to estimate recovery of the soil in about 12 years. Drissi (1975) looked at micro and macroporosity, total pore space and bulk density at cores extracted from logging roads up to 38 years old in an area that was once an agricultural field. The 0-5 cm depth recovered in approximately 18 years but the time span of the study was insufficient to establish recovery for the 10-15 cm depth. Quadratic projection estimated recovery of this depth at 50 to 60 years. Hatchell, Ralston and Foil (1970) and Hatchell and which had reverted to a prairie and a pine forest. They reported no difference in plow layer bulk densities after 30 years.

Recovery from soil compaction created by grazing is typically studied by fencing off an area from grazing activity and then comparing grazed and nongrazed units over time. Orr (1960) noted that the majority of recovery under such circumstances occurred in the first five years. Silt plus clay content was reported to have a direct correlation with bulk density recovery. A later study by Orr (1975) reported that it took two years for fenced and unfenced areas to develop statistical difference in bulk density. The study referred to earlier by Ratliff and Westfall (1971) reported a 0.35g/cc decrease in bulk density after 35 years of non-grazing. Lack of a control in rangeland soil compaction studies is a problem because grazed areas are continually "treated" thus precluding determination of absolute recovery values.

Estimates of recovery from compaction vary considerably because of differences in compactive effort applied to the soil, soil type, location of the study and the objective for which the study was initially designed. Most of the values reported for complete recovery from compaction are statistically invalid either because statistical evaluation was not performed or regression relationships were extended beyond the limits of the data base. That both quadratic and linear functions have been used in such extensions is evidence that the recovery process is not well understood.

This concludes the discussion of soil characteristics, processes and previous compaction recovery studies. The remaining sections of this report will describe the research project undertaken to meet the previously stated study objective.

V. THE STUDY AREA

Physical Aspects

This study was conducted in the Cascade Mountains of western Oregon between 122° - 122° 45' west longitude and 44° 20' - 44° 55' north latitude. Location of the nine study sites is given in Figure 2. This area encompasses two major physiographic provinces, the Western Cascades and the High Cascades (Baldwin, 1976). A general description of these provinces is given by Franklin and Dyrness (1973) and Baldwin (1976).

Climate

Climate of the area is maritime, a product of strong oceanic influence which tempers seasonal changes. During the winter, temperatures are comparatively mild for this latitude. Low pressure systems, generated by the Pacific Ocean, move inland and interact first with the coastal mountains and then the Cascades. Long duration, low intensity rainfall and continual low cloud cover produce 75-85 percent of the annual precipitation between October first and March 31 (Franklin and Dyrness, 1973). The bulk of precipitation and its form is largely determined by elevation, with amount increasing with altitude and form changing to snow. Detroit, Oregon at elevation 485m receives 193cm of annual precipitation with 156cm of snow while Government Camp, Oregon at 1280m receives 219cm annual precipitation of which 792cm is snow. A winter snowpack is maintained at elevations over about 1000m with a transition zone between that

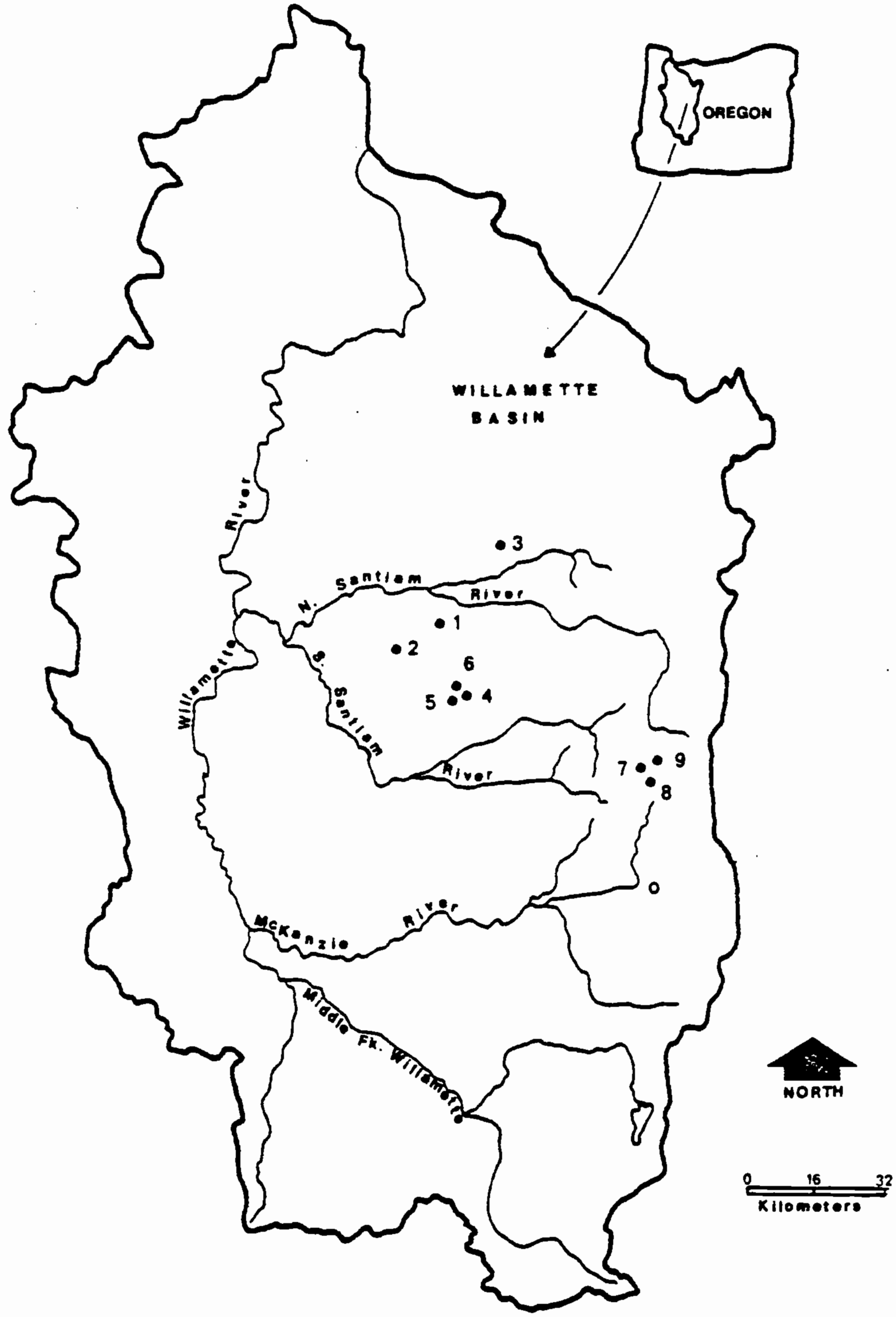

Figure 2. Map showing location of study sites in the Willamette basin.

elevation and 775m. Wintertime high pressures associated with clear skies, lower freezing levels to 100m or less but such occurrences are generally uncommon and of short duration. Summers are cool and dry with extended periods lacking in precipitation. Daytime temperatures commonly reach 25° to 35° C in July and August but coastal upwelling of ocean currents produce on-shore breezes which cool nighttime temperatures and reduce air mass instability.

Geology

Sites one through six are located along the western edge of the Western Cascades province which consists of old tertiary flows, tuffs, breccias and intrusive rock (Baldwin, 1976). Site three is more centrally located in the province and is positioned on an ancient slump bench near the crest of a high ridge. Soils in the province are generally deep and well developed with gentle slopes (Franklin and Dyrness, 1973). The surface soils tend to be coarser at higher elevations.

Sites seven through nine are located at the eastern edge of the province in a small valley between the Western and High Cascades. The High Cascades are typified by a geologically young age, high volcanic peaks and extensive basaltic lava flows (Baldwin, 1976). Much of the surrounding area, including these three study sites, is covered with volcanic pumice and ash with the resultant soils showing little profile development. Because of the location of this valley, cold air drains from surrounding mountains and alters the local climate to one similar to that of higher elevations as evidenced by the deep winter snow pack.

Vegetation

Sites one through six are in the *Tsuga heterophylla* zone[2] of the Oregon Cascades. The sub-climax *Pseudotsuga menziesii* (Mirb.) Franco is the dominant tree species in this zone between 150 to 1000m. The climax overstory generally consists of *Tsuga heterophylla* (Raf.) Sarg. and *Thuja plicata* Donn. Associate tree species include *Abies grandis* (Dougl.) Lindl., *Pinus monticola* Doug. ex D. Don and occasional *Pinus contorta* Dougl. ex Loud. Sites one, two, four, five and six appear to be in the *Tsuga heterophylla/Rhododendron macrophyllum/Gaultheria shallon* association. This association has sparse herb cover but dense shrub cover and is common in cool, mesic areas. Major shrub species include *Gaultheria shallon* Pursh, *Rhododendron macrophyllum* G. Don and *Berberis nervosa* Pursh. *Acer circinatum* Pursh is a common late serial successional community member. Site four approaches the *Tsuga heterophylla/Polistichum munitum* association with a large cover of *Polystichum minitum* (Kaulf.) Presl in the understory. However, *Libocedrus decurren* Torr. was also present in minute amounts.

Site three was in the *Tsuga heterophylla/Rhododendron macrophyllum/Berberis nervosa* association. The shrub layer commonly includes *Berberis nervosa* Pursh, *Acer circinatum* Pursh, *Vaccinum*

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[2] Field observations were correlated with the published plant community descriptions of Franklin and Dyrness (1973) throughout this section.

parvifolium Smith, *Rubus ursinus* Cham. and Schlecht. and *Rhododendron macrophyllum* G. Don. The dominant understory species include *Polystichum munitum* (Kaulf.) Presl and *Gaultheria shallon* Pursh. The late seral community frequently vegetates to *Berberis nervosa* Pursh and *Acer circinatum* Pursh.

Sites seven through nine were in the *Abies amabilis* zone. This zone is wetter and cooler than the *Tsuga heterophylla* zone, occurs between 1000 - 1500m elevation and has a significant winter snow pack. Moisture regime, dependent on soil type, explains community composition variation within this zone. The study sites were apparently in the *Abies amabilis*/*Xerophyllum tenax*/Lithosol plant association which is at the dry end of the community types. Tree species include *Pseudotsuga menziesii* (Mirb.) Franco, *Pinus monticola* (Dougl.) ex D. Don, *Pinus ponderosa* Dougl. ex Loud, *Abies grandis* (Dougl.) Lindl. and *Abies amabilis* (Dougl.) Forbes. Understory species include *Berberis nervosa* Pursh, *Xerophyllum tenax* (Pursh) Nutt. Shrub species typically consist of *Vaccinium membranaceum* Dougl. ex Hook, *Rhododendron macrophyllum* G. Don and *Pachistima myrsinites* (Pursh) Raf. The successional pattern since cutting disturbance in this area has led to extensive stands of *Ceanothus velutinus* Dougl. ex Hook.

VI. METHODS OF DATA ACQUISITION AND ANALYSIS

Study Design

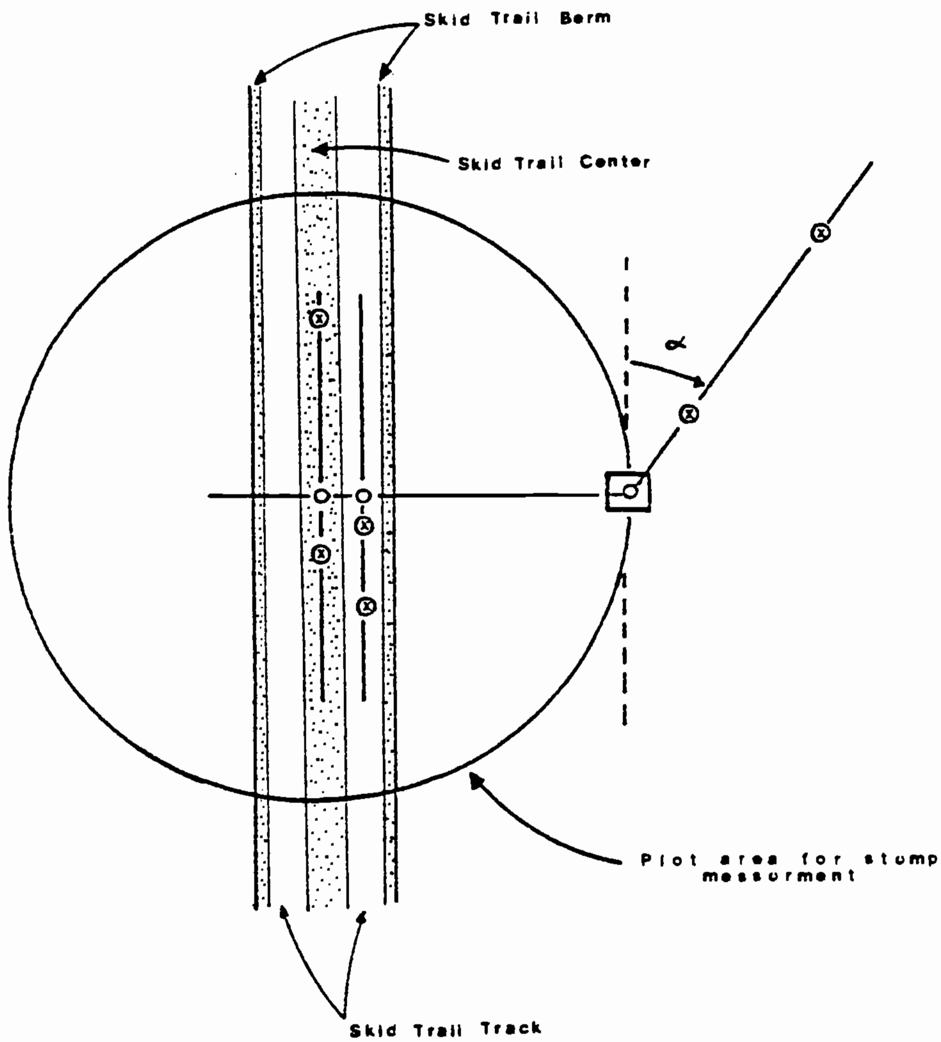
This study was restricted to clearcuts that were logged with ground-based yarding equipment in the Western Oregon Cascades. Initially 30 sites were to be selected for study but the decision to intensify on-site sampling forced a reduction to nine. In all 90 sites were field checked to determine their possible utility for this study. Sites were located on land managed by the Willametter National Forest, Willamette Industries, Inc. and the Salem district of the Bureau of Land Management. Ultimately three sites were located on the lands of each agency. Evaluation and selection of sites was based on the list and description of characteristics given in Table 3. Skid trail use categories were based on estimated number of trips over the plot area. Low use was considered as less than ten trips, moderate use, ten to 25 trips and heavy use, greater than 25 trips. To facilitate estimation of skid trail use level, skid roads were followed to a termination point to identify the area which they serviced. The skid trail use classes exceed that generally considered to differentiate between initial compaction levels. However the intent was to determine a relationship between use level and recovery, not initial compaction. It was hypothesized that clay orientation might continue to change even after maximum compaction is achieved. Three plots at each use level within each site were sampled giving a total of nine plots per site and 81 total plots. These plots served as the basic unit of field data collection.

TABLE 3

CRITERIA FOR SELECTION OF STUDY SITES

Characteristic	Description and Basis for Evaluation
Type of silviculture	Only clearcuts were used. Timber volume removed and level of use a given skid trail sustained were more easily evaluated under such conditions.
Ease of skid trail location	It was essential to be able to locate skid trails. Air photos were used to locate landings. Skid trails were followed from these to establish the area which each trail serviced. This estimation of skid trail use levels.
Site access	Sites had to be accessible to allow equipment to be carried in with reasonable time and ease, but inaccessible enough so that recreational traffic did not complicate impact history.
Age	Wanted study to span as large a time period as possible, as previous studies had estimated up to 60 years for recovery. However, the use of tractors for logging has a history of about 40 years to this set the upper age limit.
Skid trail excavation	Study was intended to evaluate recovery from the compacted condition and not excavation. It was essential that excavated skid trails be omitted. This was probably the most frequent reason used for initial site and plot exclusion.
Stoniness	Excessive volumes of stone increase variability of the initial compaction. In addition, analysis of soil bulk density by nuclear densiometry is greatly complicated by excessive stone volumes. Sites over approximately 30 percent stone content were omitted.

A schematic of the plot data collection is given in Figure 3. (Techniques used for the collection of data are described in later sections.) A point was chosen on the skid trail such that the plot center could be located five paces in either direction. The position five paces toward the landing was assigned the value of zero and the position five paces distal to the landing was assigned a value of ten. A random number between zero and ten was then chosen to locate the plot center. Bulk density values were measured at three points along a line perpendicular to the skid trail. One location was at the plot center, another in an arbitrary direction from plot center on the skid trail track and a third at a point 7.5 meters from the plot center in the area adjacent to the skid trail. This distal position served as the less-disturbed sample location for bulk density measurements. A soil sample of approximately $0.02m^3$ was obtained within two meters of this point for laboratory soil analysis. Litter depth was determined at the location of soil sample collection. When the less-disturbed area showed evidence of disturbance, the plot location line was extended. Vegetation transects ten meters in length were centered over the skid trail center and track sample points, running parallel to the track orientation. The third vegetation transect was started at the less-disturbed sample point and oriented along a randomly selected azimuth between 0° and 180° from an imaginary plane parallel to the skid trail. Estimates of herbaceous vegetation cover were obtained at two random positions of each transect. The random number selected for this was between zero and 100 and corresponded to a decimeter



- o Location of bulk density and canopy densiometer readings.
- □ Location of soil sample.
- —— Ten meter vegetation transects.
- ⊗ Random locations for herbaceous cover estimates.
- ∝ Random angle for undisturbed vegetation transect, 0 - 180°.

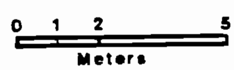


Figure 3. Plan view of data collection scheme at each plot.

value along the transects. Diameter and distance from plot center of all stumps within 7.5 meters of the plot center was also obtained.

Field Measurement Techniques

Descriptive Data of the Plot

Descriptive data were obtained to characterize each plot. These plots included presence of erosion, rutting depths, possible differences in soil type between skid trail and less-disturbed area and anomalies in regard to bulk density samples such as buried logs and high rock content. Slope of the skid trail was recorded to the nearest degree as measured with a clinometer. Aspect of the general area of the plot was determined with a compass and recorded as an azimuth between zero and 360°. Elevation was determined by plotting the approximate unit boundaries on 15 minute U.S. Geologic Survey maps with 12.2m contours. One elevation was used for all plots at a given site.

A root factor (RF) was used as an index of roots present in the skid trail at the time of compaction. This factor was derived by computing the basal area of the stump and dividing it by the distance between the stump and plot center. An RF was determined for all stumps within 7.5 meters of the plot center and their sum was equal to the RF for the plot. The index of pre-logging root density was deemed important because roots increase the bearing capacity of soils (Greacen and Sands, 1979) and also may aid recovery when they decay in a compacted soil mass.

Measurement of Vegetation

The role of vegetation in soil compaction recovery is dependent on root activity in the compacted soil zone. However sampling of root systems is exceedingly time consuming and the variability of their distribution requires large sample sizes to obtain meaningful data. Drissi (1975) collected root data in his work on compaction recovery but the results were too variable to be of use. Rather than forego the vegetative aspect of recovery it was decided to use percent plant cover as an index of root activity. Percent plant cover is the proportion of the ground surface covered by a vertical projection of the above ground plant parts (Hutchings and Pase, 1962). Foresters commonly estimate the radial extent of roots by the spread of the overstory crown. Smith (1964) concluded that root extent could be estimated by crown spread for management purposes but cautioned that variability was high. Data from McMinn (1963) for Douglas-fir seems to support this hypothesis for both dominant and suppressed trees past 25 years of age. Applicability of this relationship to shrubby and herbaceous vegetation is not well documented. However, the extension was made to simplify sampling and analysis, with full awareness that the relationship probably would not hold for grasses or reclining type life forms.

Since the objective of vegetation sampling was only to aid explanation of variability in the recovery process, plant classification information was not collected in an arduous manner. As such the vegetative portion of this study was "nonfloristic" (Brown, 1954) with quantification based on life forms rather than species.

Plants that were readily identifiable were classified to genus and species but the data are not presented. Collection of data was based on the botanical life forms described in Table 4.

Three stage sampling was used to collect the vegetative data. This was necessary because of the diverse conditions encountered in clearcuts spanning a time range of recent to 40 years since harvest. The line intercept method was used to measure shrubs and tree seedlings less than approximately 2.5 meters. A ten meter cloth tape, delineated in decimeters, was suspended between two, 1.25cm by 2m steel poles using vise-grips with modified clamps to hold the ends. A plumb-bob was traversed the length of the tape, recording the intersection distance of woody shrubs and seedlings in an imaginary plane above and below the tape. Percent cover was calculated by dividing the intersection distance by transect length and multiplying by 100.

If a plant extended above 2.5m, none of that plant's cover intersecting the tape was recorded. This omission was necessary to avoid duplicate sampling of plant cover as recorded with the canopy densiometer. The densiometer consists of a 7.5cm polished dome with a cross-like array of 26 squares engraved on its surface. The densiometer is held at breast height and the number of quarter squares covered with the reflection of vegetation are summed and multiplied by 0.96 to give the percent cover. The sampled area consists of a projection above the instrument extending over an angle of approximately 40° from the vertical. Readings with this device were taken at the center of each line transect and the measurement recorded was an average of two readings from opposite directions. Tall

TABLE 4

DESCRIPTION OF BOTANICAL LIFE FORMS USED IN THE COLLECTION OF PLANT DATA

Botanical Life Form	Description
1. Tree	A woody perennial plant having a single mainstem with generally few or no branches on its lower part and crowned with a head of branches and foliage (Gove, 1961, p. 2435)
2. Shrub	A woody plant with branches at or near the base, without a well defined or linear stem and generally less than three meters in height (Brown, 1954)
3. Herb	A seed producing annual, biennial or herbaceous perennial that does not develop persistent woody tissue but dies down at the end of a growing season (Websters) (Gove, 1961, p. 1058)
(a) Grass	Green herbage consisting predominantly of narrow-leaved monocotyledonous plants (Websters) (Gove, 1961, p. 990)
(b) Forb	A herb other than a grass; a broad leaved herb (Websters) (Gove, 1961, p. 886)

vegetation outside of the root influence zone is included in this sample. As such this data is as important to interpretation of understory vegetation samples as it is to the characterization of the extent of roots. In particular, densiometer data aids analysis of understory vegetation with consideration for the negative relationship between tree crown cover and herbage cover (Young, Hedrich and Keniston, 1967).

Herbaceous vegetation was characterized by the use of a ten-point sample frame. The frame used for this sampling is described by Sharrow and Tober (1979). With point sampling, the sample area is reduced to a dimensionless point and cover is estimated based on frequency of contacts or "hits" (Pieper 1973). A pin sharpened to a fine point is lowered through notches in the sample frame and contact by the point with herbaceous vegetation is included as a hit. Percent cover is determined by dividing the number of hits by the total number of points and multiplying by 100. Only the first hit in layered communities was recorded. The frame worked well in most cases with the exception of those areas having dense, tall stands of fireweed (*Epilobium angustifolum* L.) or bracken fern [*Pteridium aquilinum* (L.) Kuhn]. In these instances the majority of plant cover was above the sample frame and only the lower stems were in the sample. Fortunately this problem was encountered on only four or five plots.

Measurement of Soil Compaction

Any of the previously discussed variables indicative of soil compaction would have been usable for the evaluation of the study objective. Dry bulk density was chosen for two reasons. First, this variable is accurately and quickly measured with minimum disturbance to the sampled soil by the employment of nuclear densiometry. Numerous samples can be obtained, improving estimates of the mean. Secondly, previous studies of the recovery of compacted soils used this parameter as their evaluating criteria and its use here facilitates comparison of results. Additionally, bulk density is a basic component of the theoretical evaluation of the soil compaction process.

Bulk densities were measured at three locations in each plot. The skid trail track and skid trail center represented two hypothetical levels of impact, one beneath the actual vehicle weight and the other subjected to the partial weight of the log payload. This hypothesis assumes the vehicle remains in a consistent path within the skid trail with each pass. These locations were then compared with the bulk density of soil in the less-disturbed area adjacent to the skid trail. This area is not strictly undisturbed soil because it is potentially subject to impact during the falling and bucking operations and no visible evidence of this activity remains to determine if such a disturbance has occurred. However, the undisturbed-like character of this locale is supported by the data of Dyrness (1965) mentioned earlier.

To determine the variation of recovery with depth beneath the surface, readings were taken at 5.1cm, 15.2cm and 30.5cm. To calculate the dry bulk density it was necessary to obtain moisture content of the soil. Two soil samples, one for the soil surface to 17.8cm depth and the other for 18.0cm to 31.0cm depth were collected from the soil between the probe access holes and returned to the lab for moisture determination. These sampling depths were adjusted for recent precipitation and visible water gradients to assure that moisture samples were representative of the soil moisture conditions.

The Cambell Pacific Nuclear Corp., nuclear moisture/density gauge, model B (R) Mark II Portaprobe was used to obtain the bulk density data. This instrument is a two probe unit, with one probe housing a cesium 137 radiation source and the other a monochromatic detector. Gamma radiation of a specific wave length is emitted by the source and the amount received by the detector is dependent on the density and length of the sampled media. The two probes are mounted to the porta probe unit so that distance between probes remains constant. This method of density determination follows the laws of basic radiation physics with the attenuation of radiation governed by:

$$Ix = \frac{Io\ e^{-\lambda\mu x}}{x^2} \qquad \text{Equation 7}$$

where Io = radiation intensity at the source (millicuries)
Ix = radiation intensity at distance, x (millicuries)
e = base of natural logarithms
$\lambda\mu$ = linear attenuation coefficient (cm^{-1})
and x = distance from source (cm).

Since wavelength and energy are related, deflection of radiation (dependent on the density of the medium which is proportional to the linear attenuation coefficient) alters both of these characteristics. However, equation 7 is only valid for monochromatic radiation and as such the detector must be sensitive to only the wavelength emitted by the source (vanBavel, Underwood and Ragar, 1957). The soil density value determines the linear attenuation coefficient and controls the relationship in equation 7.

Field operation of the probe requires some site preparation. The soil is first scraped clear of surface organic matter and leveled using the edge of the hold access guide plate. The guide plate and a hammer (similar to a fence-post driver attached to a pin) were used to locate and drive the portaprobe access holes. The portaprobe was then aligned over the access holes and the probes were lowered into the soil to specified depths. Half minute readings were taken until two consecutive values agreed within five percent. These two readings were then averaged. At the beginning and end of each day a standard count was obtained. This involves obtaining ten, half minute counts while the probe rests over a control source located in the carrying case. By adding and subtracting the square root of the average of these ten counts to and from the average, a range of values is obtained which can be used to evaluate the electronics of the probe. Since the radiation source is a random energy emitter, generally six to eight of the standard counts will fall within this range if the unit is functioning properly.

The standard count average is also used to compute the bulk density. Bulk density values are determined using a calibration curve and the ratio method. At ratio of observed count for the soil over the average of the standard counts is determined at several known bulk densities and soil depths when constructing a calibration curve for each depth. The wet bulk density of the soil is obtained by determining the ratio for an unknown soil and comparing it to the calibration curve for each depth. The percent soil moisture (weight basis) is multiplied by the unit mass of water to give an equivalent bulk density of soil water. This value is subtracted from the wet bulk density to give the dry bulk density. These calculations were done on a Hewlett-Packard 9830 computing system.

The portaprobe functioned well under most conditions encountered in the field. The possible exception was very compacted stony soils where access was difficult. Moving the probe to a new adjacent location was required in some instances. Since the sampled volume of soil was removed for moisture samples it was possible to make note of rock content and buried organic debris that were included in the bulk density reading.

Lab Analysis of Soils

Soil Pretreatment

The bulk soil sample from the less-disturbed area of each plot was brought back to the lab in sealed plastic bags. The soil was emptied into 30cm by 60cm plastic bins and placed under a ventilation hood to air dry at approximately 20°C until a stable weight was obtained, generally requiring three to four days. Pieces of organic matter larger than 1.0mm diameter and 2.5cm in length were removed from the samples. Atterburg limits, particle size distribution and organic matter content were determined for each of the 81 soil samples.

Atterburg Tests

The Atterburg tests are used to characterize the plastic nature of the soil. This information is important to determination of soil reaction to surface stress and is also related to shrink-swell potential. Only the liquid and plastic limits were determined for soils in this study. In addition, the difference between these two values was calculated to obtain the plasticity index. The liquid limit is defined as:

> "...that water content at which a pat of soil placed in a brass cup, cut with a standard groove, and then dropped from a height of 1cm will undergo a groove closure of 12.7mm when dropped 25 times." (Bowles, 1970, pg. 16).

The actual water content at 25 blows was found indirectly from a graph of soil moisture content versus the log of blows required for groove closure. Points for the graph were found by performing the test procedure as outlined by Bowles (1970) at three moisture contents bounding the liquid limit value.

The plastic limit is defined as that water content of the soil at which a thread just crumbles when it is rolled down to a diameter of 3mm. The procedure, again outlined by Bowles (1970) involves rolling soil into 3mm ribbons at various moisture contents until a moisture value is reached where this size ribbon begins to fall apart. This requires some practice at obtaining uniformity in the process to get reproducible results. An average of three tests were used for this value.

Soil for the above tests was acquired by passing the air dried soil through a sample splitter until approximately $250cm^3$ was obtained. The sample was then ground with a mortar and rubber-tipped pestal and sieved through a number 40 sieve (0.425mm openings) until 100 - 150 grams of sieved soil was collected. Distilled water was used for all the Atterburg limit determinations.

Hydrometer Analysis

Hydrometer analysis of soil was developed in 1927 (Bouyoucous, 1962). This technique is employed to determine the distribution of particle sizes less than 2mm in size and uses the relationship between velocity of fall of a particle in a fluid and particle size developed by Stokes. Stokes law is:

$$U = \frac{d^2 g}{18} (\rho s \rho f) \qquad \text{Equation 8}$$

where U = settling velocity
d = particle diameter
g = acceleration due to gravity
ν = fluid viscosity
ρs = density of the solids
and ρf = density of the fluid.

This law assumes the falling particles are spherical and fall independent of one another in a fluid at known temperature. Fluid turbulence created by large particles must be avoided as this increases the forces resisting particle fall. Also, the particles must be large enough to be unaffected by Brownian motion. These latter two constraints limit the size analysis to particles between 0.0002mm and 2.0mm in diameter. Resistance to fall is determined by the fluid viscosity and as such this analysis is very temperature dependent requiring close control of this variable.

There is considerable debate regarding methods of sample pretreatment and dispersion of aggregates despite the length of time the method has been in use. It is generally regarded that any technique which increases the percent of clay size particles is reducing aggregation and is therefore yielding a closer approximation of the true particle distribution. That aggregates survive the various treatments they are subjected to says that these units may be functioning in the soil as larger particles particularly in terms of physical behavior. This fact puts hydrometer analysis results into a relative perspective. Harsh chemical treatments used to reduce aggregation may increase our knowledge of the particle size distribution (essential for consistent classification of soils) but decreases our characterization of the in situ soil. Clay mineral studies have reported destruction of clays with some sample pretreatments. As early as 1938, Drosdoff and Miles (1938) found disintegration of unhydrated micas with hydrogen peroxide pretreatments. The significance of this type of process balanced with the failure to obtain aggregate breakdown has been the principle source of debate concerning pretreatment methodologies. A fine degree of particle size resolution was not needed to meet the objectives of this study and as such no chemical pretreatment of organics was applied. Given the limited resources available to this study this decision represented a considerable savings of time.

The hydrometer procedure used was basically that developed by Bouyoucous (1962) with several modifications. Soil was sieved through a number five sieve (4.0mm) and oven dried at 105° for 24 hrs. From this soil, 50g was obtained to run the hydrometer analysis. The sample was placed in a 20cm porcelain evaporating dish and covered with 100ml of four percent sodium metaphosphate (Lab grade, $NaPO_3$) and left to disperse for 12 to 18 hours. After soaking, the mixture was stirred and poured into a settling cylinder. Distilled water was added until the cylinder was one quarter full and then the contents were mixed with an air-jet at 68.9 kpa for five minutes. The cylinder was then filled with distilled water. Five minutes were allowed for the temperature to equilibrate before starting the test. The cylinder was stoppered and inverted for exactly one minute and then set on the lab bench while simultaneously starting the time of fall. Two to three drops of amyl alcohol were used to reduce the floating froth and allow reading the hydrometer at the fluid surface. Readings were taken at 40 seconds and two hours, the settling times for silt and clay size particles (U.S.D.A. classification) respectively. These times are based on a fluid temperature of 19.4°C and corrections for deviations from this temperature were applied.

The reader will note a discrepancy between the sizes allowed by Stokes equation (less than 2.0mm) and the sizes used in the above procedure (up to 4.0mm). This error was unfortunately made throughout the analysis and was discovered only when rechecking the procedures at the end. There was insufficient time to redo the analysis, so correction of the results had to be attempted. The approach used was to rerun the analysis for representatives of the major soil types and establish a predictive relationship which could be used to convert the results to more realistic values. In general the duplicate analysis results were within four to five percent of the original values. Complete discussion of the correction methods is contained in Appendix A.

Mechanical Sieve Analysis

Mechanical sieve analysis of the soil was done to aid in classification and grouping of the soils for later analysis. Results of the sieving were plotted in the usual manner with the log of grain diameter on the abscissa and percent finer on the ordinate. All material larger than 5.0cm was removed from the soil before sieving because analysis of this large material would not be statistically representative. The sieve nest used consisted of nine sieves and a pan. In order of decreasing opening size, (in mm) the sieves used were: 19.0, 9.51, 4.75, 4.00, 2.00, 0.85, 0.42, 0.150, 0.0075.

A 200 to 300g sample of oven dried soil obtained with a sample splitter was placed into a 20cm porcelain evaporating dish. Approximately 200ml of four percent sodium metaphosphate ($NaPO_3$) was added to the dish and the soil was soaked for a minimum of 12 hours. The presence of weak rock particles and very stable aggregates precluded the use of pulverization techniques to reduce soil aggregates. After soaking, the soil slurry was transferred to a number 200 sieve (0.075mm) and the mixture was gently stirred by hand while tap water was run over the soil until the water flowing through the sieve was clear. The material retained on the sieve was oven dried at 105°C for 24 hours and then reweighed. Material finer than number 200 sieve was calculated by subtracting the dry residue weight from the original sample weight. The residue was sieved with the nested sieves described above, for five minutes to obtain the particle size distribution.

Organic Matter Content

Soil organic matter was obtained because the amount of initial compaction is greatly influenced by this parameter. Soils with high organic matter contents compact less and therefore require less recovery. The sample splitter was used to obtain two samples of approximately 25g from the soil of each plot. These samples were placed into tared, 2.5cm porcelain dishes and then oven dried at 105°C for 24 hours. The weight of the oven-dry soil plus tare was obtained to within ± 0.01g. The samples were ashed 18 at a time in a furnace at 500°C for six hours. The soil was removed from the furnace and cooled in a desiccator before recording the final weights. Percent organic matter was expressed on a weight of mineral soil basis.

Statistical Analysis

The statistical variables used in the analysis are described in Table 5. Relationships among variables were first investigated by plotting scattergrams of variable pairs. The existence and nature of relationships between variables can be readily seen with this technique. The skid trail track, skid trail center and the less-disturbed areas at each plot were used as treatments throughout the analysis. Skid trail use categories represented level of treatment.

Paired t-tests were conducted between treatments for herbaceous, shrub and tree cover. Treatment comparisons were also made by depth for the bulk density data. These tests were first made with all the data combined and then repeated for various stratifications. The data groupings used were: (1) low, medium and high skid trail use; (2) 5, 8, 10, 21, 23, 31, and 38 year site age classes; and (3) clay, loamy, sandy loam and loamy sand soil groups. Loamy soils included loams, silt loams and clay loams.

Analysis of the effect of treatment level on skid trail bulk density and vegetative cover of herbs, shrubs and trees was conducted using analysis of variance techniques. Experimental design was simple randomized block, with site as blocks and skid trail use level as treatments.

Regression analysis was performed using difference in bulk density between the skid trail and less-disturbed area at 5.1, 15.2 and 30.5cm soil depths as the dependent variables. This analysis was done using: (1) the raw data, (2) data averaged by combining the three similar use level plots in each site, (3) stratification by use

TABLE 5

DESCRIPTION OF VARIABLES USED IN THE STATISTICAL ANALYSIS

Variable No.	Variable Name	Variable Description	Intended Use	Units
1	USE	Use level of skid trail	Determine use level affect	No. of trips
2	AGE	Age of clearcut	Base recovery by age	Years
3	BD2T	Bulk density @ 2.5cm in skid trail track	Unit of recovery	g/cm^3
4	BD6T	B.D. at 15.2cm in skid trail track	" "	" "
5	BD12T	B.D. at 30.5cm " " " "	" "	" "
6	BD2C	B.D. at 2.5cm in skid trail center	" "	" "
7	BD6C	" 15.2cm " " " "	" "	" "
8	BD12C	" 30.5cm " " " "	" "	" "
9	BD2U	" 2.5cm in less disturbed area	" "	" "
10	BD6U	" 15.2cm " " " "	" "	" "
11	BD12U	" 30.5cm " " " "	" "	" "
12	SAND	Percentage of sand in soil	Characterization of soil	%
13	SILT	" silt "	" "	"
14	CLAY	" clay "	" "	"
15	ACTIND	Activity index of soil	Index of swelling potential	No units
16	ORGMAT	Organic matter content of soil	Relationship to recovery	%
17	HERBT	Cover by herbs on the track	" "	"
18	SHRUBT	" shrubs "	" "	"
19	TREET	" trees "	" "	"
20	HERBC	" herbs on the center	" "	"
21	SHRUBC	" shrubs "	" "	"
22	TREEC	" trees "	" "	"
23	HERBU	" herbs in the less disturbed	" "	"
24	SHRUBU	" shrubs "	" "	"
25	TREEU	" trees "	" "	"

TABLE 5, continued

Variable No.	Variable Name	Variable Description	Intended Use	Units
26	ELEV	Average elevation of site	Index of freeze-thaw process	Meters
27	SLOPE	Slope of skid trail at plot	Level of initial impact	%
28	ASPECT	Aspect as an azimuth	Climate of site/plot	Degrees
29	RF	Root factor of prelogged area	Recovery and initial impact	$(\text{Meters})^2/\text{m}$
30	SOILTYP	Soil group of plot	Stratification of analysis	Clay; loamy; s. loam; l. sand
31	T2U2	Var. 3 minus Var. 9	Dependent recovery variable	g/cm^3
32	T6U6	Var. 4 minus Var. 10	" " "	"
33	T12U12	Var. 5 minus Var. 11	" " "	"
34	C2U2	Var. 6 minus Var. 9	" " "	"
35	C6U6	Var. 7 minus Var. 10	" " "	"
36	C12U12	Var. 8 minus Var. 11	" " "	"
37	PLAIND	Plasticity index	Characterization of soil	%
38	MC6	Moisture content at 15.2cm less dist.	Characterize soil conditions	"
39	LIQLIM	Liquid limit	Characterization of soil	"
40	SICLAY	Silt plus clay content	Recovery variable	"

level and (4) stratification by soil group. The regression analysis was employed to determine at what point the bulk density differences returned to zero with age. In addition, by investigating the variables which best correlated with recovery it was intended to differentiate among those recovery processes which were responsible for any bulk density changes which occurred. Only results important to the understanding of these objectives are reported.

VII. RESULTS AND DISCUSSION

Descriptive Data For Sampling Locations

Data describing the location and characteristics of each site are summarized in Table 6. Average elevation for the nine plots was 820 m with a maximum of 1100 m and minimum of 370 m. This elevation range covers climatic conditions from little or no snow to that of a continual winter snowpack. Whether or not significant soil freezing occurs in the areas of snowpack accumulation was not determined. Site ages ranged from five to 38 years with a mean of 21 years. In selecting sites, the attempt was to have a progression of ages on three general classes of soil, i.e. sandy, loamy and clayey. In general this objective was met.

The root factor, used as an index of prelogging root volumes in the impact area, had a relatively high variability. Given the diversity of site location and soils, this result was expected. This variable can also be used to estimate timber volumes for each site, as the method of procurement was essentially a fixed plot timber cruise. The mean value of the root factor was 0.31 m^2/m with a maximum of 0.85 m^2/m, a minimum of 0.0 m^2/m and standard deviation of 0.21 m^2/m. The plot by plot data values of this variable, the basal area estimates using this same data, along with aspects and slopes are given in Appendix B. The maximum slope of skid trail for this study was 26 percent with a mean of four percent.

TABLE 6

DESCRIPTION AND LOCATION OF STUDY SITES

Site	Legal Description	Managing Agency	Year Logged	Age	Clearcut Area (Hectares)	Average Skid Trail Slope (%)	Elevation (M)	Likely Plant Community Association[1/]
1	T10S, R2E, Sec 5	U.S.D.I. B.L.M.	1948	31	18	13	610	Tsuga heterophylla/ Rhododendron macro-phyllum/Gaultheria shallon
2	T10S, R1E, Sec 29	U.S.D.I. B.L.M.	1971	8	16	1	370	" " "
3	T8S, R3E, Sec 13	U.S.D.I. B.L.M.	1974	5	28	1	1040	Tsuga heterophylla/ Rhododendron macro-phyllum/Berberis nervosa
4	T11S, R2E, Sec 26	Willamette Industries	1941	38	32	7	760	Tsuga heterophylla/ Rhododendron macro-phyllum/Gaultheria shallon
5	T11S, R2E, Sec 34	Willamette Industries	1956	23	18	6	670	" " "
6	T11S, R2E, Sec 24	Willamette Industries	1958	21	17	4	760	" " "
7	T13S, R7E, Sec 19	U.S.D.A. For. Serv.	1948	31	26	2	1070	Abies amabilis/ Xerophyllum tenax/ Lithosol
8	T13S, R7E, Sec 31	U.S.D.A. For. Serv.	1956	23	20	5	1000	" " "

TABLE 6, Continued

Site	Legal Description	Managing Agency	Year Logged	Age	Clearcut Area (Hectares)	Average Skid Trail Slope (%)	Elevation (M)	Likely Plant Community Association[1]
9	T12S, R7E, Sec 31	U.S.D.A. For. Serv.	1969	10	8	2	1100	Abies amabilis/ Xerophyllum tenax/ Lithosol

1/ Plant community associations based on prototype descriptions of Franklin and Dyrness (1973).

Soil Analysis

Analysis of soils was performed for each plot because the location of plots within sites were quite dispersed. With the exception of site four, soils were surprisingly uniform within each site. Table 7 summarizes the data by site for the mechanical analysis (hydrometer), Atterburg tests and organic matter contents. Description of soil types listed in this table are given in Appendix C.

Organic matter contents were high, as is characteristic of forest soils. The percent organic matter was based on samples sieved through a number ten sieve (2.0 mm opening). Note the reduced organic matter contents of the more infertile soils derived from pumice ash at sites even, eight and nine. The reduced organic contents coupled with the wide temperature regime of these soil types (Cochran et al. 1967) probably limits soil microbe populations, thus restricting compaction recovery processes which would be dependent on microbial processes.

One third of the soils in this study were plastic as defined by the uniform soil classification system. Only these soils have potential for amelioration of compaction by swelling. The realization of this potential depends on the amount and mineralogy of the various clay types. A technique which was used to characterize clay types is displayed in Figure 4. Different clays have contrasting clay content versus plasticity index curves. By comparing this relationship from soils of unknown clay types with those of known clays an indication of mineral composition can be obtained.

TABLE 7

SUMMARY RESULTS OF MECHANICAL ANALYSIS, ATTERBURG TESTS AND ORGANIC MATTER DETERMINATIONS BY SITE

Site	Average Particle Size Distribution Sand %	Silt %	Clay %	Range of Plasticity Index %	U.S.D.A. Soil Texture	Unified Soil Symbol	Soil Classification[1/]	Organic Matter Content (%)
1	30	36	34	9.3-18.7	Clay loam	MH	McCully	16
2	21	32	47	8.2-27.6	Clay	MH	Jory-Nekia	22
3	56	33	11	NP*	Sandy loam	SM	Whetstone	34
4	38	33	29	NP-14.7	Clay loam	MH	Hembre-Kinney	22
5	50	29	21	NP-11.5	Loam	SM	Hembre-Klickitat	25
6	62	29	9	NP	Sandy loam	SM	Hembre-Kinney	22
7	73	24	3	NP	Loamy sand	SM	SRI Unit 66	8
8	72	26	2	NP	Loamy sand	SM	SRI Unit 66	9
9	61	37	2	NP	Sandy loam	SM	SRI Unit 67	15

*NP indicates soil was non-plastic.

1/ Soils series given for sites one through six were taken from mapping reported by Thomas, B. R., J. A. Pomerening and G. H. Simonson (1969). SRI units were taken from the Willamette Nat. For. Soil Resource Inventory by H. A. LeGard and L. C. Meyer (1973).

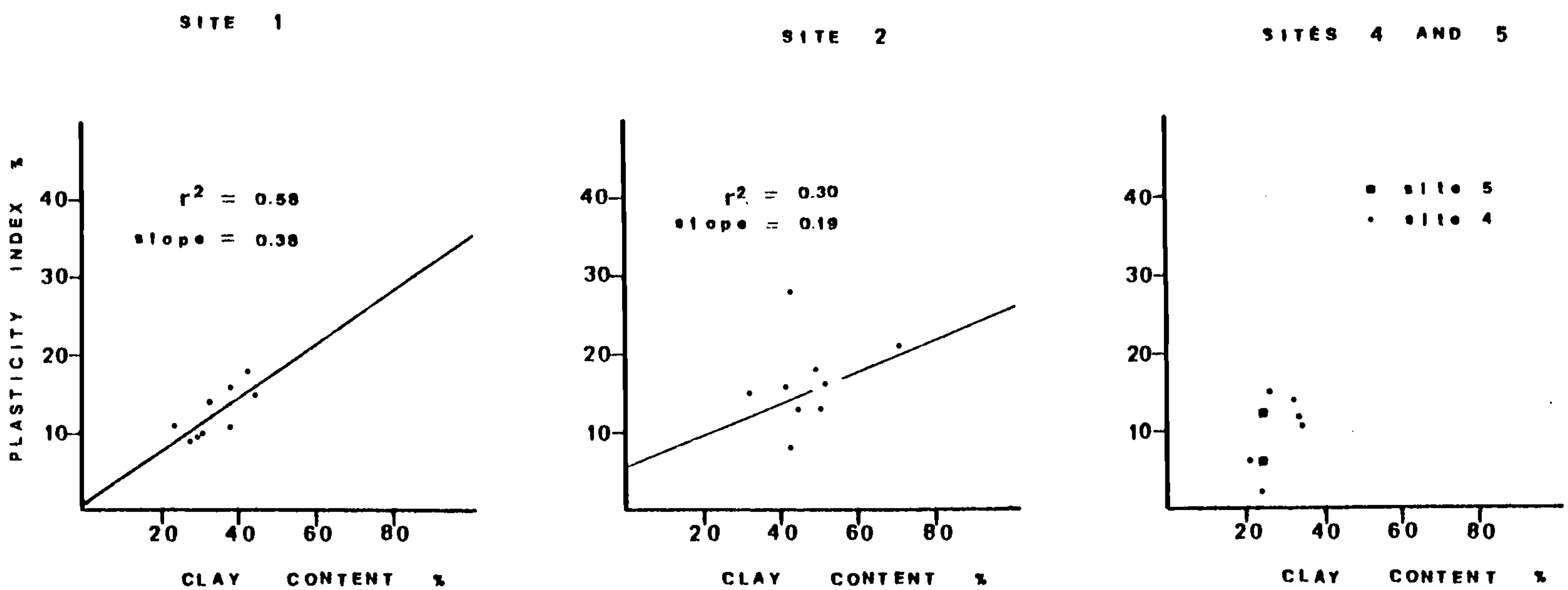


Figure 4. Clay content versus plasticity index for plots in sites one, two, four and five. Site four had three non-plastic plots and site five had seven non-plastic plots. No regression relationship was fitted for these latter two sites.

The steeper the slope of the plot, the greater is the likelihood of 2:1 type swelling minerals. Data from sites one and two appear to be kaolinitic in mineral composition (Seed, Woodward and Lundgren, 1962). The data for sites four and five were too scattered to define a statistical relationship and probably represent mixed mineralogies.

Bulk Density Measurements

Bulk density measurements were the primary criteria for evaluation of the study objective. In sum, over 1500 readings were made with the portaprobe, which yielded 729 bulk density values distributed over three depths, at three locations per plot and 81 total plots. All values were expressed in g/cm^3.

Portaprobe Operation

The portaprobe readout gives radiation counts divided by ten. For standardization, summation of ten counts gives the actual radiation count average. If the probe is functioning properly, the standard counts will follow a normal distribution with 67 percent of the values within one standard deviation of the mean. The square root of the actual average count is the normal standard deviation (Campbell Pacific Nuclear Corp., 1977). This value divided by ten is then added and subtracted from the readout standard count average and gives the normal deviation range. Standard counts were taken at the beginning and end of each day, except on short days where only one standardization series was obtained. The means of these standard counts along with their respective normal deviations are shown in Figure 5. While exceedence of normal deviations is statistically expected, consistently below normal deviation is regarded as an indicator of an improperly functioning gauge. This is because once a given count is obtained, the chances of getting that value again are statistically improbable. This casts some doubt on probe function on August 24th and 25th (sites two and five) but in general a random relationship appears to occur throughout the study.

What is disconcerting is the consistent reduction in the standard count average during the day. Afternoon averages were frequently lower than the morning readings. This necessitated using the morning standardization count for the ratio of early morning readings, an average of morning and afternoon standard counts for the ratio used in late morning and early afternoon readings, and the afternoon average for the ratio of late afternoon readings. Reduction of standardization averages could be a product of procedure. In the morning the probe was taken from its storage box and standard counts were obtained without the source probe ever being lowered from its interior shield. The afternoon standard count was taken shortly after the final soil reading of the day. Whether or not a buildup of radiation occurs which would affect the morning standard counts is not known, but such an occurrence is one possible explanation of the anomalous behavior.

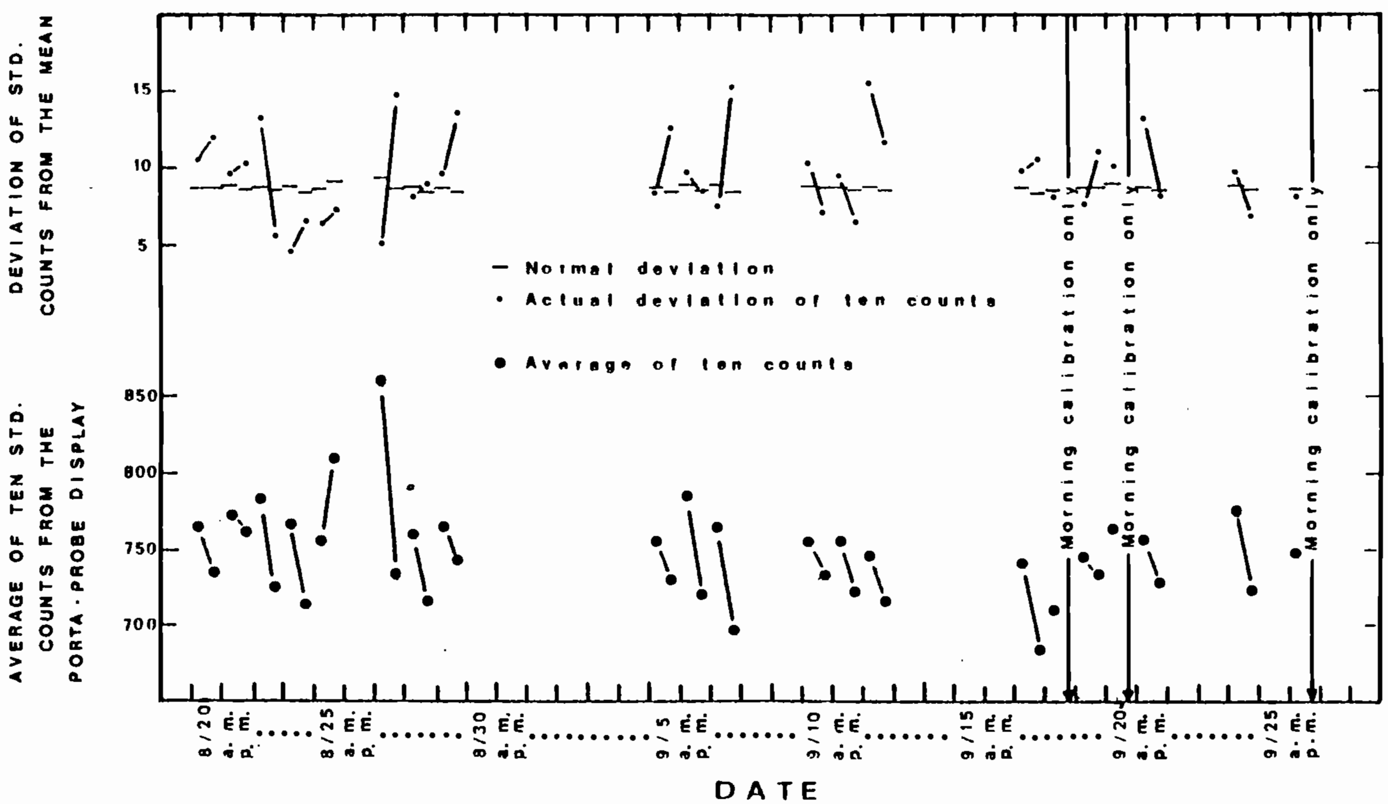


Figure 5. Morning and afternoon average standard counts for the nuclear soil density probe with normal deviation from mean and actual deviation from the mean by date.

Absolute Bulk Density Values

Bulk density values measured on skid trails in this study were lower than generally reported in the literature (Steinbrenner and Gessel 1955a; Mace 1970; Dickerson 1975; Hatchell, Ralston and Foil 1970). The maximum value of 1.26 g/cm^3 was nearly two deviations above the mean and minimum values were up to four deviations from the mean bulk density at 30.5 cm depth.

The average 15.1 cm depth, less-disturbed bulk density was 0.77 g/cm^3. Table 8 gives the average bulk density values by depth for the three treatments. The values reported in this table combine all the data irrespective of soil type or treatment level. Comparison between treatments reveals significant differences ($\alpha = 0.05$) between the skid trail track and less-disturbed areas. No differences were found between skid trail track and center. Dickerson (1976) found a 20 percent increase at the skid trail track with only a ten percent increase at the center, but no statistical tests of these findings were presented. Field observations of the trails indicate physical dissimilarities but bulk density, as measured in this study, did not characterize this difference.

Bulk Density Differences Between Treatments

Influence of skid trail use level. Analysis of variance was used to evaluate the effect of skid trail use level on the difference between treatment bulk density values. A randomized block design was used for this test with study sites as blocks. Bulk densities of corresponding depths between treatments were subtracted to create the

TABLE 8

STANDARD DEVIATIONS AND AVERAGES OF BULK DENSITIES BY DEPTH WITHIN TREATMENT WITH COMPARISONS BETWEEN TREATMENTS

Treatment	Depth (cm)	Average Bulk Density (g/cm^3)	Standard Deviation (g/cm^3)	Comparison Between Treatments[1/]	
				Skid Trail Track	Less-Disturbed
Skid Trail Track	5.1	0.79	0.22		**
	15.2	0.88	0.20		**
	30.5	0.92	0.19		**
Skid Trail Center	5.1	0.76	0.19	NS	**
	15.2	0.85	0.20	NS	**
	30.5	0.91	0.23	NS	*
Less-Disturbed Area	5.1	0.67	0.20	**	
	15.2	0.77	0.19	**	
	30.5	0.85	0.21	**	

[1/] NS denotes no statistical difference at $\alpha = 0.05$ level.
* denotes statistical difference at $\alpha = 0.05$ level.
** denotes statistical difference at $\alpha = 0.01$ level.
Sample size, m = 81.

test variables. Figure 6 summarizes the findings for the comparison between skid trail track and the skid trail center. No significant difference between treatments were found based on skid trail use level. This result agrees with previous studies of use level by Steinbrenner (1955) and Mace (1970). Compaction levels near maximum values are generally obtained with about ten passes over the soil by logging equipment. The hypothesis that skid trails on steep slopes become more compacted because there are fewer trails receiving more use (Garrison and Rummell 1951) is not supported by these results. Bulk density increases under these conditions are likely a result of increased horizontal shear and/or increased excavation and exposure of subsoils. Based on the results of the above tests, skid trail use level was omitted from subsequent analysis.

Influence of soil type. Soils were separated into the clay, loamy, sandy loam and loamy sand soil groups described earlier. Clay soils were represented by 12 plots, loamy soils 21 plots, sandy loam soils 38 plots and loamy sand soils by 10 plots. Results of the comparison between skid trail track and less disturbed area are presented in Figure 7. No statistical difference ($\alpha = 0.05$) was detected for bulk density differences between soil types. It should be emphasized that these comparisons lump the data of the various site ages, irrespective of the compaction recovery which may have occurred since logging. If approximately equal levels of compactive effort were applied to all sites, results in Figure 7 would reflect the compactibility of the different soils as well as the effect of recovery processes.

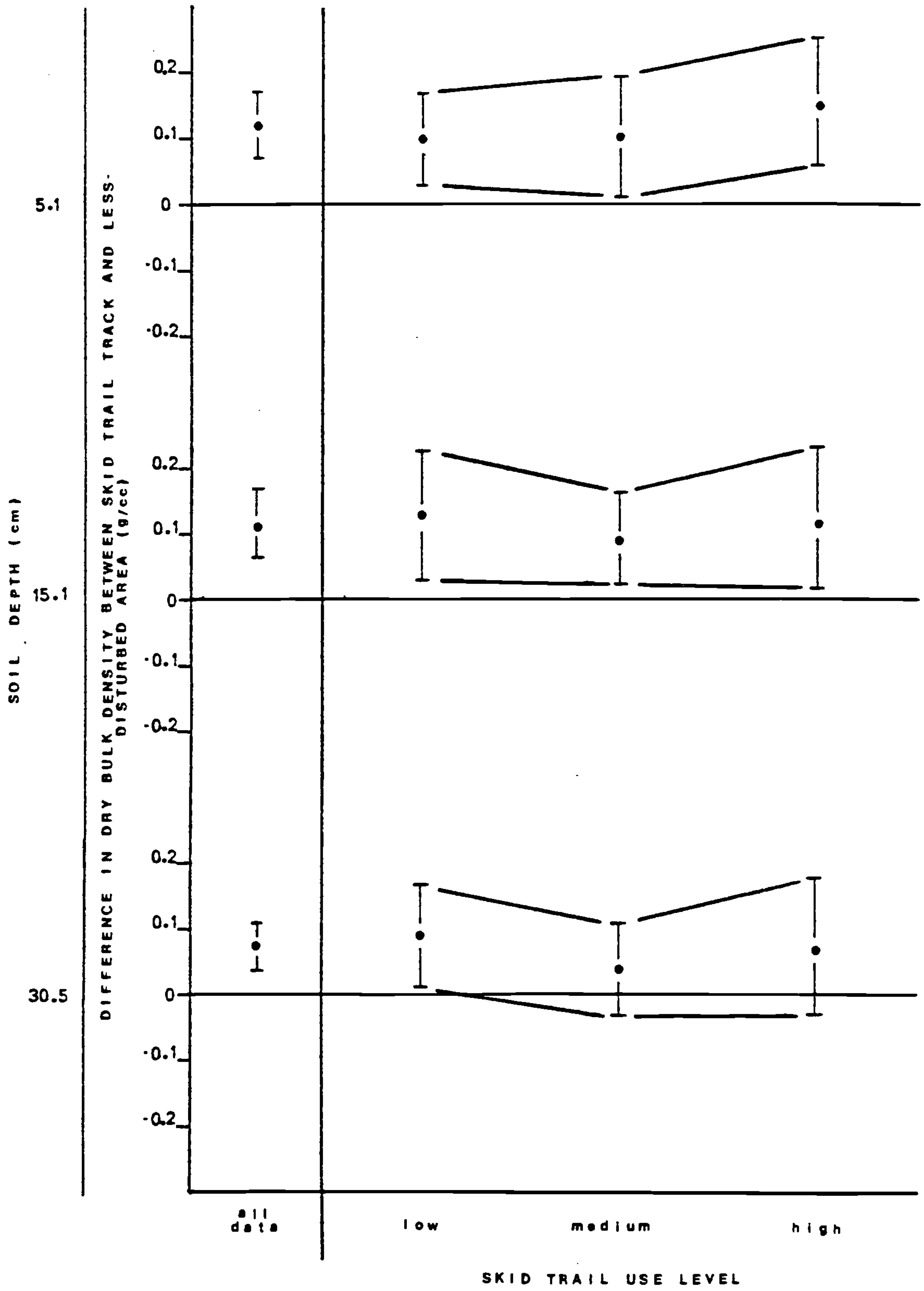


Figure 6. Influence of skid trail use level on dry bulk density difference between skid trail track and less-disturbed area. Lines delineate 95% confidence limits.

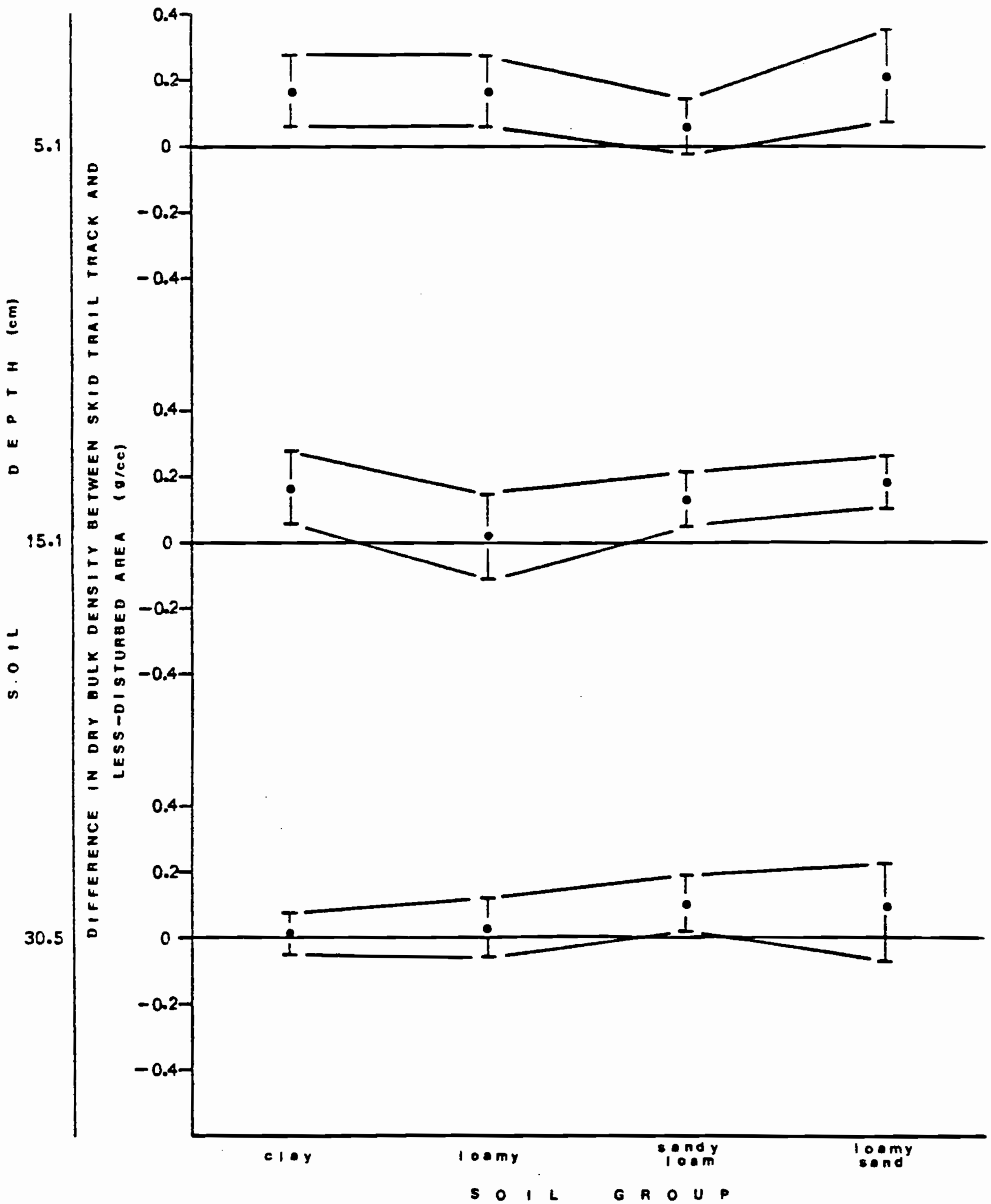


Figure 7. Bulk density differences between the skid trail track and less-disturbed area compared by soil type. Lines delineate 95% confidence limits.

Statistically significant ($\alpha = 0.05$) differences between treatments were observed at 5.1 cm depth for all but the sandy loam soils. The exact opposite result was found at the 30.5 cm depth. At the 15.1 cm depth, treatments yielded statistically different bulk densities for clay, sandy loam and loamy sand soils.

Several questions are raised by these results but few are answered. Lack of difference between treatments could indicate either recovery from compaction or insignificant initial compaction. Initial impact would be minimal if the surface soil was displaced rather than compacted, an occurrence which is quite possible with cohesionless soils. The vertical extent of compaction is generally in excess of 25 cm. However, in soils with high clay contents, much of the compactive energy is absorbed nearer the soil surface which raises the question of whether the 30.5 cm depth was ever compacted. If we assume that recovery processes are most active near the soil surface and these depths are still compacted, it follows that uncompacted soils below the surface never were densified. This appears to be the case with the clay and loamy soils. One intent of Figure 7 is to show the background variability between treatments which is attributable to soil type. Since soil group cannot be separated from site age, Figure 8 also helps to break down the sources of variability. Note the skew towards older ages for the loamy and loamy sand soils and the more even distributions of the clay and sandy loam soils.

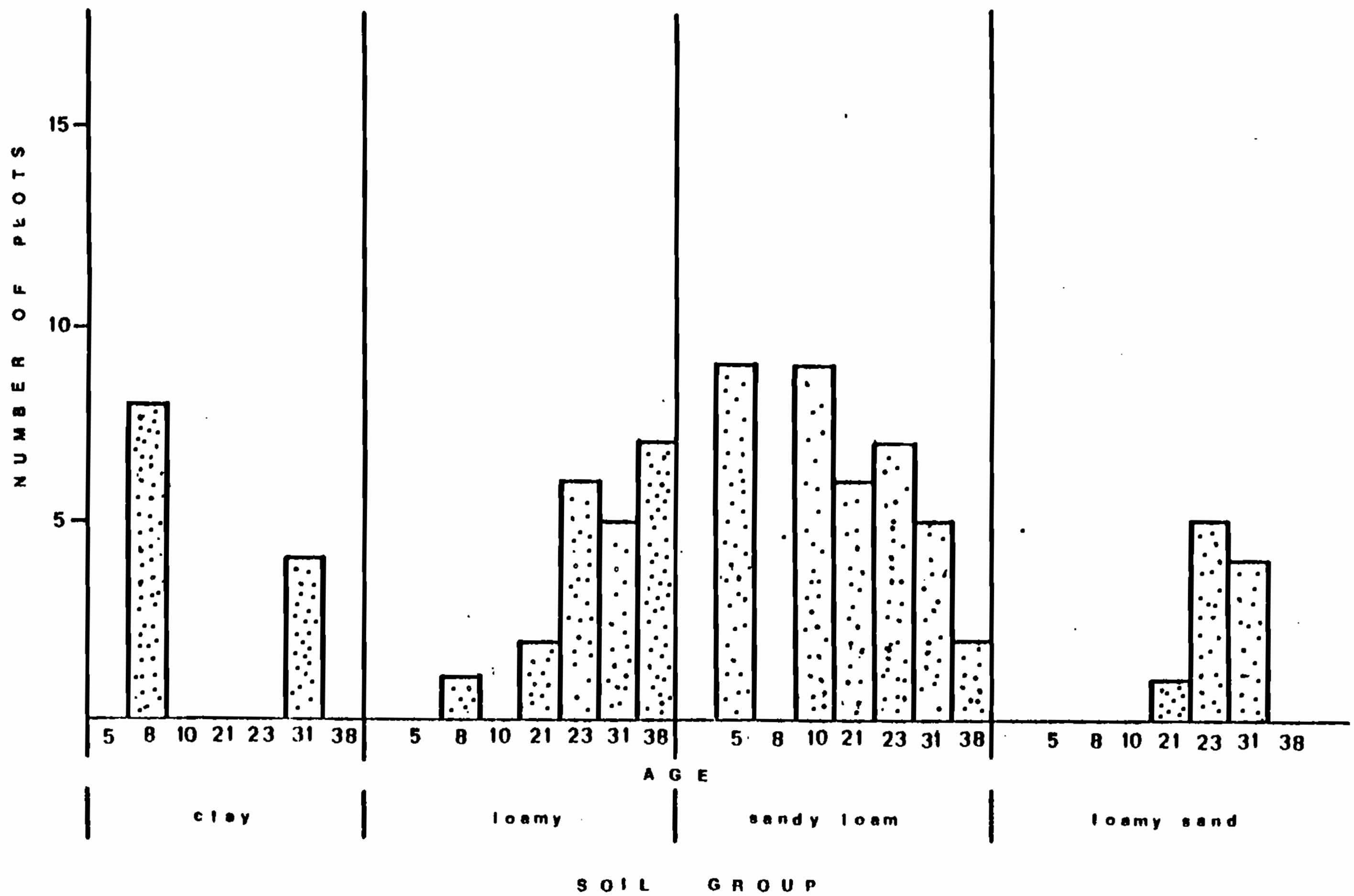


Figure 8. Number of plots in each age class by soil group.

Bulk density differences through time. Figures 7 and 8 deserve further comment concerning their implications to compaction recovery. Plots less than ten years since harvest made up two-thirds of the clay soils group. The 5.1 and 15.1 cm soil depths on the skid trails of these plots retain bulk densities significantly higher than comparable depths in the less disturbed area. However, it appears that the 30.5 cm depth was not affected by logging traffic. Shrinking and swelling processes would be expected to be most active in these soils but the apparent lack of smectite clays indicates that this was not a major form of amelioration. Interpretation of the results for the loamy soils group is more difficult. The assumption of no impact at 30.5 cm depth might be applied again, but its use at the 15.1 cm depth is not a logically sound extension. Puddling of surface soils, contributing to high bulk densities at the 5.1 cm depth in combination with recovery at the 15.1 cm depth is a possible but hypothetical explanation of results. The majority of plots in the loamy soils group exceed 30 years since harvest. This fact, coupled with the physical characteristics of these soils (moderate but significant amounts of clay, even particle size distribution), makes them the most likely to recover, yet the surface bulk density readings indicate a compacted condition.

The sandy loam soils group had 38 plots with a very even age distribution. The results of recovery would likely be balanced by the effects of initial compaction. The surface soils of the skid trails were statistically similar to the less-disturbed soils but compaction was indicated at 15.1 and 30.5 cm depths. Given the non-cohesive nature of these soils, it is likely that the surface soil was subject more to movement and churning than to compaction and as a result may not have been densified. The subsoil, even with the mixture of site ages, has significantly higher ($\alpha = 0.05$) bulk densities.

All plots on loamy sand soils exceed 20 years since harvest. Compaction remains at the surface and 15.1 cm depths but track bulk densities are not significantly higher at 30.5 cm. This result is similar to that of the clay soils and runs contrary to popular viewpoints. Compaction problems are generally thought to be most critical on high clay soils because of their compactibility. Results here indicate that compaction can occur and persist on loamy sand soils as well.

Figure 9 gives the difference of bulk density between skid trail track and less disturbed area over time. Mean values are plotted with their 95 percent confidence limits at each site age. Ages 31 and 23 years represent data from 18 plots while all other ages are from nine plots.

It was hypothesized that significantly different values would occur on younger sites and that differences would diminish with time. This hypothesis was apparently incorrect. When all the data are combined, highly significant differences ($\alpha = 0.01$) between treatments result (ref. Table 8), but variability obscures any obvious interpretations when the data are stratified by age. The large variability at 21 years is probably due to the variation of soil type and gravel content at this site. The only age having

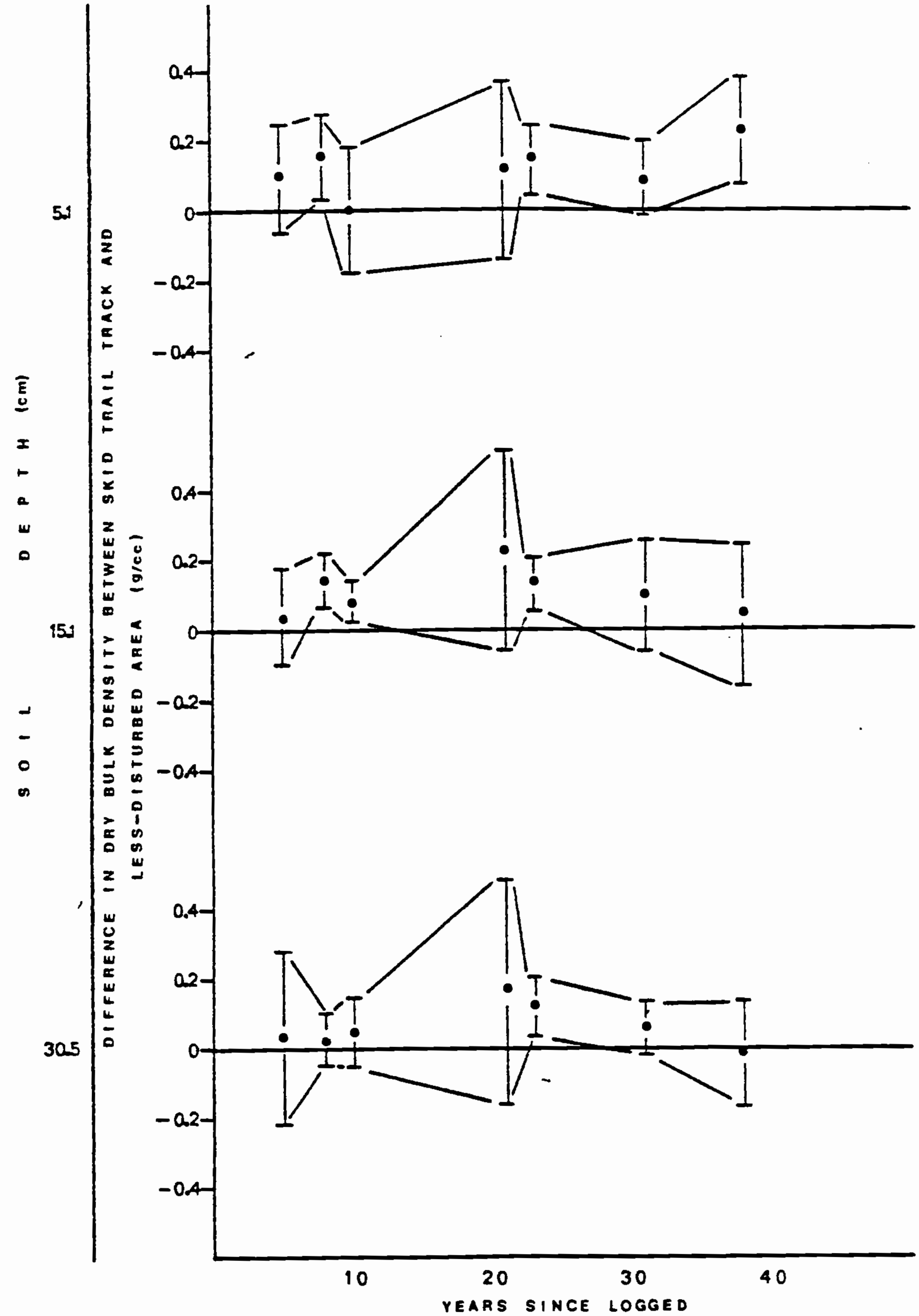


Figure 9. Variation of bulk density differences between track and less-disturbed area through time. Lines delineate 95% confidence limits.

significantly higher bulk densities at each depth was the 23 year old class. This fact, in conjunction with the combined data results, suggests that increased sample size would show a statistical difference between treatments at more age-depth combinations than observed in Figure 9.

In summary, skid trail bulk densities are higher than soils in the less-disturbed area next to the skid trail. Trends of bulk density change through time were not observed. These results appear to conflict with those of published results reviewed earlier but many of these reports lacked detailed statistical analysis which casts doubt on the recovery ages they reported.

Vegetative Cover Measurements and Recovery

Percent Cover Through Time

Vegetation on skid trails aids in the amelioration of the compacted condition by the growth of roots. However, as the soil recovers, more vegetation is likely to find suitable habitat on this area. Separation of cause and effect is extremely difficult because the cause initiating the effect is indeterminant.

The change in percent vegetative cover values with time for the skid trail track and center are given in Figure 10. Overstory, as given in this figure, is all vegetation measured with the canopy densiometer and includes cover outside the skid trail. The values for overstory at five years since harvest reflect the influence of timber at the edge of the clearcut site. The overstory data is

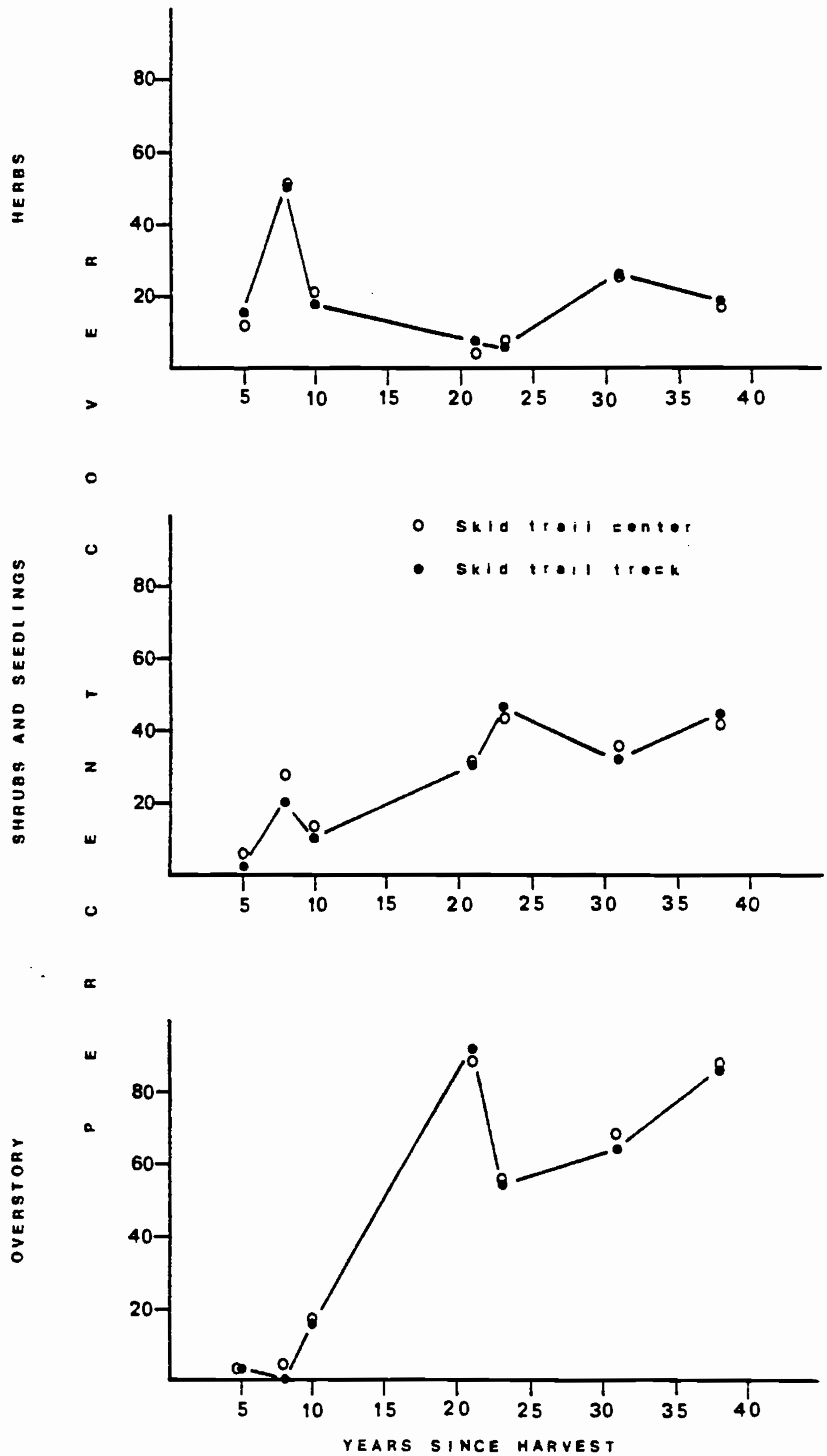


Figure 10. Percent cover changes with time for herbs, shrubs and seedlings and overstory on skid trail track and center.

given here to enable more meaningful interpretation of the herbaceous cover which is indirectly related to canopy cover. This relationship holds very well for all sites although the actual values are not consistently proportional. The cover by shrubs increases fairly steadily from four percent at five years after harvest to 44 percent at 38 years. The different vegetation associations and site locations coupled with lack of plant classification information precludes analysis of species composition. Most likely this characteristic would change with the alteration of the shade providing understory but such analysis was outside the scope of this study.

Percent Cover Differences Between Treatments

The plotted points in Figure 10 for the skid trail track and center reveal little difference between these two treatments. Paired t-tests at the 0.05 level support this observation. Comparisons between the skid trail track and less-disturbed areas, however, indicate dissimilar treatment responses. Comparison between treatments is made within each soil group in Figure 11 regardless of plot age (reference Figure 8 for plot age distribution for each soil group). Skid trail shrub cover was suppressed on sandy loam and loamy sand soils ($\alpha = 0.05$ level) despite the large representation of plots older than 20 years in these soil groups. Sandy loam soils were significantly compacted at 5.1 cm and 15.1 cm soil depths. However, the clay soils group was compacted at these same depths and no shrub cover depression was noted, making generalizations tenuous. The significantly different ($\alpha = 0.05$ level) canopy cover on the clay soils is difficult to interpret for reasons mentioned

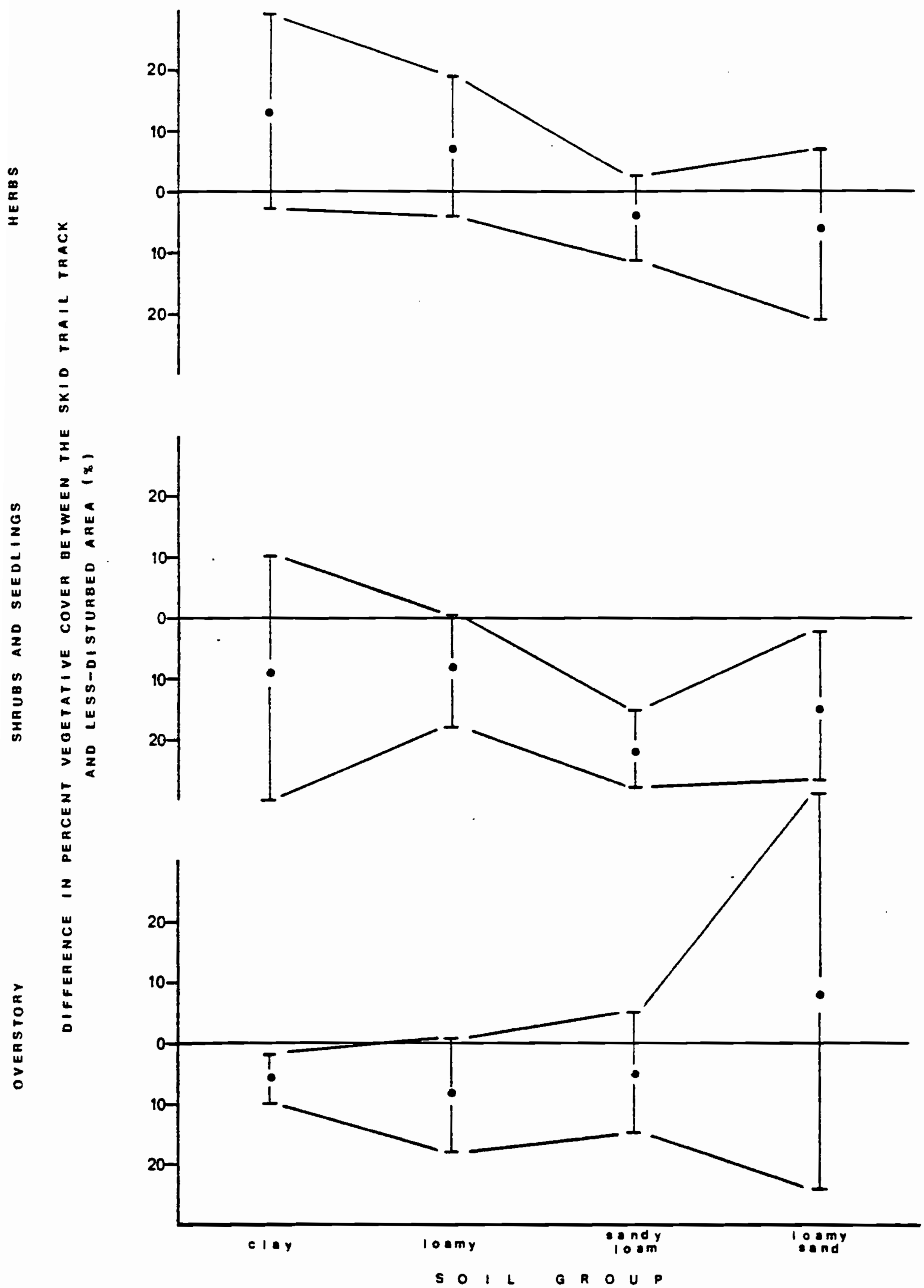


Figure 11. Vegetative cover differences between skid trail and less-disturbed area for each soils group. Lines delineate 95% confidence limits.

previously but does indicate a retarding of crown closure over the skid trail on these soils.

Figure 12 shows the change in vegetative cover differences between treatments through time. Because the overstory data represents vegetation outside the treatment area, these results are not presented. Herbaceous cover was not significantly different for the skid trail track versus the less-disturbed area at any age since harvest ($\alpha = 0.05$). However, shrub cover was significantly lower on the skid trail track for the first 21 years following yarding but not at any point subsequent to that time. The different measurement methods used for identifying life forms does influence the results, but bias is largely removed by confining treatment comparisons to within life form comparisons. The similarity of the standard deviations for each vegetative group indicates similar levels of precision and further adds to the validity of the above comparison. Correlation between shrub cover and bulk density through time is difficult to establish because of the high variability of the bulk density data.

Results of Regression Analysis

Regression analysis was used to determine the relationship between bulk density changes and a variety of independent variables. These variables are listed in Table 9. Multicolinearity between the independent variables was a continual problem. Correlation coefficients describing the degree of association between variables are given in Appendix D. The effects of interaction become apparent during stepwise regression analysis through the change of t-values

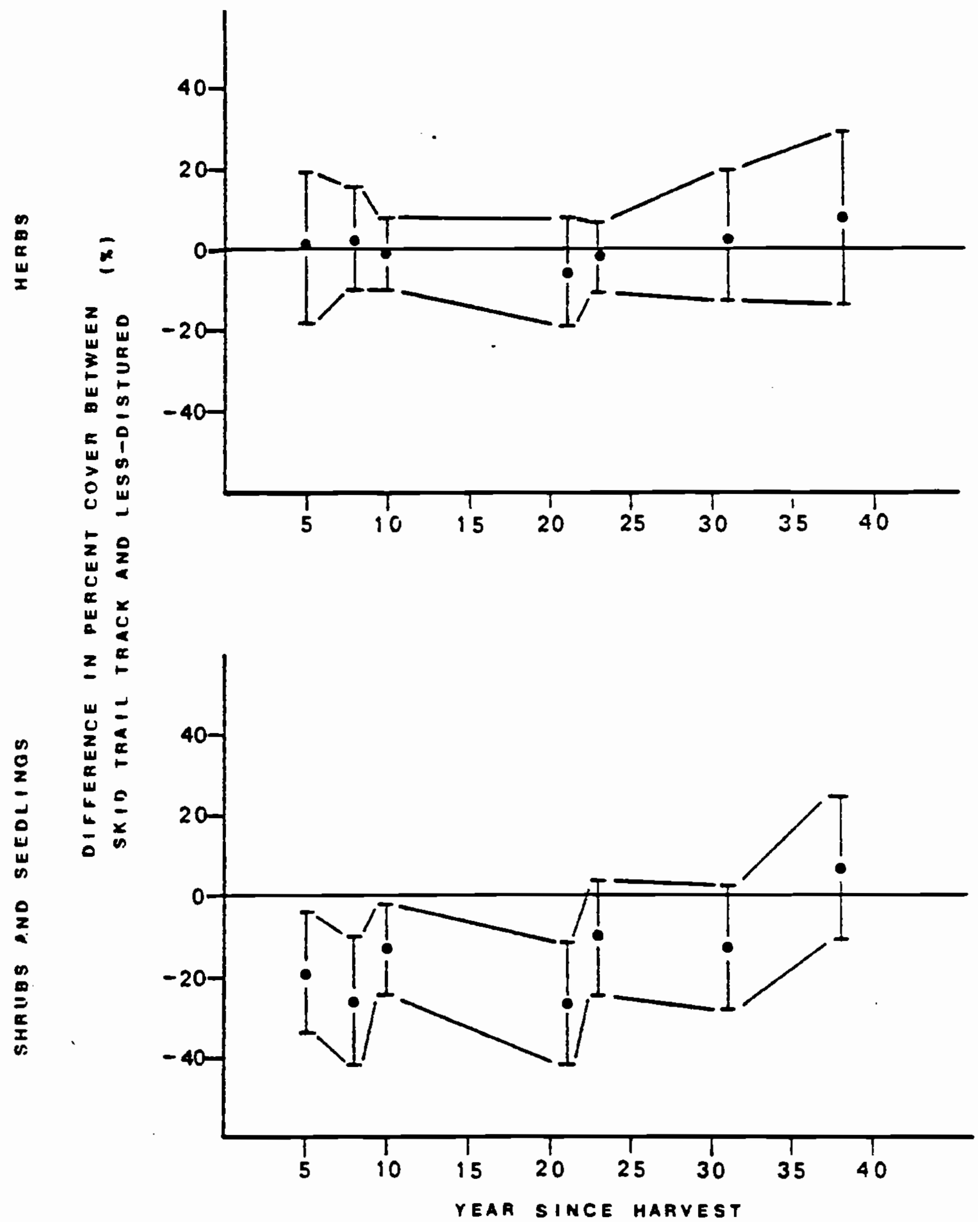


Figure 12. Change in vegetative cover differences between the skid trail track and less-disturbed area through time. Lines delineate 95% confidence limits.

TABLE 9

INDEPENDENT VARIABLES USED IN REGRESSION ANALYSIS

	Independent Variable	Units
X_1	Age	Years
X_2	Activity Index	% Moisture
X_3	Organic Matter Content	%
X_4	Herb Cover (Track)	%
X_5	Shrub and Seedling Cover (Track)	%
X_6	Overstory Cover	%
X_{13}	Elevation	Meters
X_{14}	Root Factor	M^2/M
X_{15}	Silt + Clay Content	%
X_{16}	Herb + Shrub Cover	%
	Interaction Variables	
X_{18}	a. $X_{14} * X_{15}$	
X_{19}	b. $X_1 * X_3$	

for the regression coefficients in the model when new variables are added. The abundance of insignificant regression coefficients in significant regression relationships is also a product of high multicolinearity. If significant correlation is present between such variables, an interaction term is added to the list of possible variables. If two highly correlated variables appear in a relationship but have significant regression coefficients, the interaction effects can generally be ignored providing that individual regression coefficients are not analyzed. Many of the interactions in this study could have been avoided with more careful thought during the study design. Interactions between soil parameters and vegetation variables were expected. The effects of soil clay content on tree productivity is reflected in the interaction between clay content and the root factor. Elevation interacted with soil type because coarser soils derived from volcanic ejecta tended to occur at higher elevations. This soil distribution, in addition to the climate changes associated with elevational increases, led to interactive effects between elevation and vegetation variables. It can be seen that interactions complicate the interpretations of regression relationships and reduce the value of this analytical tool.

The dependent variable was the difference between track bulk density and less disturbed bulk density at the three soil depths. A set of three equations (one for each depth) were developed for each division of the different stratifications which included the raw data, skid trail use level, data averaged by use levels within site, and soil groups. The regressions using the raw nonstratified data are omitted because significant relationships were not obtained. The analysis of variance results between skid trail use level and bulk density indicated that use level was not a useful variable. The regression equations for the averaged data and the soil group stratifications are given in Table 10.

For the averaged data, the coefficients of determination (r^2) increase with depth, which is probably a result of decreased variability of bulk density lower in the soil profile. The variable nature of the soil organic matter distribution in the upper soil horizons probably is related to this phenomenon. For example, the age-organic matter interaction term is the only highly significant regression coefficient at the 5.1 cm depth. Organic matter content is also a significant variable at the 15.1 cm depth. The reason for the age-organic matter interaction is not immediately apparent. As a site ages, the organic matter might be expected to decrease because of decreased input sources resulting from tree removal. However, the effects of organic matter on skid trail bulk density are also important at the time of initial compaction. High organic content would tend to lessen the amount of compaction obtained with a given compactive effort and the effects of site age would not yet be important. The dual effect of organic matter content on bulk density values is difficult to separate but an overall influence does exist.

At 30.5 cm depth, 71 percent of the variation in bulk density differences was explained by the regression equation using elevation and silt plus clay content as the only highly significant variables.

TABLE 10

REGRESSION EQUATIONS FOR DESCRIPTION OF CHANGES IN BULK DENSITY DIFFERENCES BETWEEN SKID TRAIL TRACK AND LESS DISTURBED AREA[a/]

Independent Variables	Averaged Data			Clay Soils			Loamy Soils			Sandy Loam Soils			Loamy Sand Soils		
	DEPTH														
	5.1	15.1	30.5	5.1	15.1	30.5	5.1	15.1	30.5	5.1	15.1	30.5	5.1	15.1	30.5
Intercept	+ .073 NS	+ .56 **	+ .81 **	·	- .36 *	- 1.0 *	- .70 *	+ .20 *	+ .55 *	·	·	·	+ .29 **	+ 1.7 **	- .13 **
Age	·	- .0017 NS	·	·	·	+ 10 NS	·	·	·	·	·	·	+ .025 *	+ .013 NS	+ .034 *
Activity Index	+ .004 NS	- .52 *	·	·	·	·	·	- .74 *	- .70 *	·	·	·	·	·	·
Organic Matter	·	- .0067 *	·	·	·	+ .0073 NS	·	·	- .14 NS	·	·	·	- .043 **	- .026 *	·
Herb Cover	·	·	·	·	+ .0084 **	·	·	·	·	·	·	·	·	·	+ .027 **
Shrub and Seedling Cover	·	·	- .0012 *	·	+ .003 NS	·	·	·	- .0024 *	·	·	·	·	·	+ .016 **
Overstory Cover	·	·	·	·	·	- .027 NS	- .003 NS	·	·	·	·	·	·	·	- .0043 **
Elevation	·	- .00005 NS	- .0001 **	·	·	·	+ .0005 **	·	·	·	·	·	- .0009 **	- .0005 **	·
Root Factor	·	·	·	·	·	+ .54 *	·	·	+ .18 NS	·	·	·	·	·	- .34 **
Silt Plus Clay Content	·	·	- .0078 **	·	·	·	·	·	·	·	·	·	·	·	·
Age * Organic Matter	- .0003 **	·	·	·	·	·	·	·	·	·	·	·	·	·	·
Silt + Clay * Root Factor	- .011 *	·	·	·	·	·	·	·	·	·	·	·	·	·	·
r^2	.31 *	.36 *	.71 **	NS	.63 *	.71 *	.36 *	.26 *	.69 **	NS	NS	NS	.90 **	.73 *	.96 **
Residual d.f.	23	22	23		9		18	19	16				6	6	5
Regression d.f.	3	4	3		2		2	1	4				3	3	4

*Significant at the $\alpha = 0.05$ level.

**Significant at the $\alpha = 0.01$ level.

NS Not significant.

a/ Regression equations read down. An example for the averaged data at 5.1 cm depth is: Bulk density difference = 0.073 + 0.004 Activity Index + 0.0003 Age * OM - 0.011 Silt + Clay * Root Factor.

Both of these variables were indirectly related to recovery which makes interpretation unclear because they were also indirectly correlated to one another. Increase of shrub and seedling cover also was associated with reduction of bulk density differences at this depth.

The data was separated by soil group for further regression investigations to determine how the different soils might relate to bulk density changes. Since silt plus clay content was a criteria for stratification, it was omitted from the list of possible variables. The soil group with the largest data base (sandy loam soils) had no significant regression relationships describing the bulk density differences between treatments. This lack of relationship also occurred with the surface layer of the clay soils group. The clay soils regressions lacked the influence of elevation and activity index. Uniformity of these variables within the data probably explains this occurrence. The only significant variables for any of the relations in this group were herb cover at the 15.1 cm depth and root factor at the 30.5 cm depth. Herb cover interaction with the overstory cover and site age has been discussed and is important here because herb cover increases with treatment bulk density differences. Recently compacted sites have little overstory, receive a lot of sunlight and have high herb cover values.

For the loamy soils group the only highly significant variable was elevation at the 5.1 cm depth. This was contrary to what was hypothesized because bulk density differences increased with elevation, where frost action forces would tend to increase.

Activity index was indirectly related to bulk density at the 15.1 and 30.5 cm depths (α = 0.05). The effects of this variable, used to characterize shrink/swell forces, were not important in any of the other soils. The importance here could indicate increased resistance to compaction occurring on dry soils or recovery as a result of shrinking and swelling processes.

Loamy sand soils had the highest coefficients of determination, mostly a result of the relatively large number of regression variables compared to the sample size. At the 5.1 and 15.1 cm depths, elevation and organic matter content were indirectly related to bulk density differences. At 30.5 cm depth, it was the vegetation variables that were most important but these were directly related, again a contrary result. The root factor was significant at this depth also but the increase in pre-logging root density was indirectly correlated with skid trail bulk density differences. In all three equations, age was directly related to difference in treatment bulk densities. Thus as age of site increased, the difference between skid trail bulk density and less disturbed area increased. This phenomena has been observed before (Gill, 1959) in laboratory tests but not, so far as the literature search revealed, in field studies. It is doubtful that reduced pore sizes and increased shrinking potential could explain these results especially over such an extended time period. It is possible that exposure of the soil to harsher climatic conditions by removal of the overstory may reduce bulk densities in the less-disturbed area but this is also an unlikely occurrence.

The large number of independent variables and high correlation among them led to contrasting relationships using regression analysis. No obvious generalizations concerning factors of recovery can be made. Although this result detracts from achieving the objective of this study, it does provide some insight into past and future research concerning soil compaction recovery. By selection of a minimum number of independent variables, interaction effects may not be exposed and simplified relationships established by such studies may not necessarily explain actual occurrences. For example, if this study would have investigated only frost heave using the assumption of increased occurrence with elevation, a conclusion might have been reached that this process was responsible for bulk density reductions on skid trails. Soil type and vegetation interactions with elevation would have been ignored and the erroneous conclusion would have been accepted and supported by statistical tests. Though the interactive effects are undesirable from a statistical standpoint, they provide useful information particularly in new research areas involving complex natural processes.

VIII. CONCLUSIONS AND FUTURE RESEARCH NEEDS

Conclusions

Skid trails formed during ground-based yarding operations yielded increased soil bulk densities on all soils studied in this project. Soil types included clay, clay loam, silt loam, loam, sand loam and loamy sands. No bulk density change trends were observed when the data was stratified by site age and evaluated in a chronosequence.

Compaction extends over the width of the skid trail with the skid trail center and track being indistinguishable as measured by bulk density. Vertical extent of the compaction condition was evidenced as deep as 30.5 cm but this was not a consistent result. No physical plot conditions could be correlated with compaction depth and this factor is probably related to soil conditions at time of initial compaction.

The interaction of herbaceous vegetation with the overstory canopy limits the usefulness of both of these variables for correlation with compaction recovery. However, percent shrub and seedling cover exhibited recovery trends and represents a possible indicator of compaction recovery using vegetation. Shrub cover on skid trails was not significantly different from that of the less disturbed area after 21 years from harvest. Correlation between the shrub recovery and bulk density data was not possible because of the bulk density variability. No consistent associations between bulk density or vegetative parameters with soil type were apparent.

Regression relationships between bulk density treatment differences and site characteristics varied in an inconsistent manner both within and among soil types. The explanation of variability about the dependent regression variable was reduced by the high degree of multicolinearity among the independent variables. This interaction exemplifies the complexity of the compaction recovery process and indicates that simple relationships between recovery and recovery processes are unlikely to be found. As such, those relationships that are established initially will likely be empirical descriptions without illustrating cause and effect.

The portaprobe functioned well as a field unit but the inconsistency of standard counts during the day was an anomaly of unknown origin. It appears that this problem added further variation to an already extremely variable soil characteristic. Variation of bulk density results from soil variability interacting with dynamic compactive efforts and incorporated organic matter. This necessitates keeping measurement variation sources to a minimum. The decision to obtain more complete plot information for the evaluation of skid trail use level and vegetative parameters was at the cost of bulk density samples which may have reduced the effects of measurement errors.

Suggestions for Further Study

The attempt to identify dominant recovery processes was not successful. Further studies of this problem should avoid mixing the evaluation of recovery rate and recovery processes because the large variability inherent in soil density demands extremely large sample sizes if randomized sampling is employed. Attempts to correlate recovery with vegetation should consider the time demands that will be required for measurement and adequate sample size. Such efforts should concentrate on shrubby vegetation. Laboratory work with compacted cores and vegetative growth, freezing and thawing, wetting and drying and mixes of these processes is needed to establish documentation of the recovery processes which are presently assumed to operate.

Observations in the field indicate that excavation of soil on skid trails may be as serious a problem as compaction on hummocky terrain and slopes in excess of 25 percent. Though ground skidding on steep slopes is becoming less popular, the problem still exists on hummocky terrain. Evaluation of the extent of this problem should be undertaken.

Past studies of compaction should be considered for remeasurement to see how much recovery might have been achieved. Care should be exercised to obtain adequate sample sizes and measurements should be made with the same device as used during the initial study. The need to publish the results, regardless of results, is emphasized.

Finally, comparison needs to be made between the various bulk density measurement techniques. The absolute value cannot, of course, ever be determined, but comparisons between methods would greatly facilitate interpretation of results reported in the literature. Such a study should include samples of varying densities on several soil types and soil conditions. Possible methods to evaluate should include several nuclear devices, the common core method and the sand cone process.

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APPENDICES

APPENDIX A

CALCULATIONS FOR THE CORRECTION OF HYDROMETER ANALYSIS

The inclusion of particles larger than 200mm in the samples for hydrometer analysis reduces the validity of this analysis but does not preclude its use. Errors introduced by this inclusion include; (1) creation of turbulence by the rapid rate of fall of such large particles which increases particle interaction and the forces resisting particle fall and (2) the percentage of size class constituents is based on particles which are not normally in the sample. The effect of the first error is to increase the number of particles in suspension at any given time and therefore increases the percentage of silt and clay while the influence of the second error is to reduce the percentages of these constituents.

The first approach for correction was to use the results of the mechanical sieve analysis to estimate the proportions of the hydrometer samples that were between 2.0mm and 4.0mm. This amount was proportionately subtracted from the sample weight and percentage of the size fractions were recalculated based on the sample weight remaining. Comparison of these corrections with the hydrometer replications showed poor agreement and in fact the replications were closer to the originals than they were to the corrected values.

The final correction procedure used was one developed using regression analysis. The equations and their supportive data are given in Table A . One equation was developed for sand size particles and one for the clays based on the data presented in the

TABLE A

CORRECTION OF HYDROMETER ANALYSIS

Site No.	Plot No.	Percent of Sample Between 2.0-4.0 mm	I Original Analysis (with larger than 2.0 mm)			II Analysis With No Material Larger Than 2.0 mm			III Results of Predictive Equation		
			Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
1	3	5.9	16.8	33.4	49.8	21.1	34.7	44.2	24	29	47
2	2	2.7	3.2	27.2	69.6	15.1	25.7	59.2	12	23	65
2	8	3.3	8.3	33.4	58.3	14.9	29.7	55.4	17	28	55
3	5	13.1	49.4	32.4	18.2	57.1	35.1	7.8	52	30	18
6	9	2.2	56.1	27.2	16.7	55.5	27.3	17.2	58	25	17
9	6	7.2	60.2	35.2	4.6	59.9	35.7	4.4	61	33	6

NOTE: Predictive regression equations were derived from the original data and the data resulting from redoing the analysis without the particle sizes larger than 2.0 mm. Equations were developed for sand and clay size particles only with the silt fraction obtained by difference. The two equations used are given below and the results of their use are displayed above in Column III.

Percent clay = .91 (Org. percent clay) + 1.68 (r^2 = .98)

Percent sand = .86 (Org. percent sand) + 9.47 (r^2 = .98) table. The results of these two equations were added and the sum was subtracted from 100 to obtain the percent silt. Corrections were applied to only those soils having more than three percent of the total sieved weight in the 2.0 to 4.0mm size fraction.

APPENDIX B

SKID TRAIL SLOPE, ASPECT, ESTIMATED BASAL AREA AND ROOT FACTORS BY PLOT

Site	Variable	Units	Plot 1	2	3	4	5	6	7	8	9	Average Basal Area* Per Hectare
1	Slope	%	0	25	10	14	8	8	18	19	16	$55.8\ \frac{m^2}{hec}$
	Aspect	x°	180	200	140	160	170	255	180	170	170	
	Basal Area	m^2	1.95	1.16	0.20	1.92	0	0.11	1.07	0.48	1.98	
	Root Factor	m^2/m	0.57	0.20	0.04	0.41	0	0.02	0.14	0.14	0.49	
2			0	0	0	0	3	3	0	4	0	$29.0\ \frac{m^2}{hec}$
			-	207	-	-	315	315	-	225	-	
			1.58	0.60	0	0	0.17	0.81	0.15	0.83	0.47	
			0.25	0.11	0	0	0.02	0.11	0.03	0.15	0.06	
3			10	0	0	0	0	0	0	0	0	$75.9\ \frac{m^2}{hec}$
			90	-	-	-	338	-	-	202	-	
			0	1.42	1.56	3.11	2.22	2.23	2.61	2.30	2.34	
			0	0.19	0.52	0.57	0.62	0.51	0.44	0.32	0.41	
4			0	0	24	0	0	26	0	14	0	$94.1\ \frac{m^2}{hec}$
			238	240	270	260	-	285	305	270	180	
			1.39	1.87	1.90	1.52	2.01	3.06	1.92	1.05	1.13	
			0.32	0.39	0.40	0.36	0.49	1.04	0.50	0.17	0.23	
5			6	0	0	0	0	9	12	15	9	$102.4\ \frac{m^2}{hec}$
			255	270	40	270	270	55	60	60	320	
			1.90	0.34	3.28	1.70	3.41	0.20	2.27	0.73	2.45	
			0.31	0.14	0.70	0.40	1.32	0.03	0.41	0.13	0.44	

APPENDIX B, Continued

Site	Variable	Units	Plot 1	2	3	4	5	6	7	8	9	Average Basal Area* Per Hectare
6	Slope	%	8	0	4	0	9	0	12	5	0	$166.6 \frac{m^2}{hec}$
	Aspect	x°	70	-	200	100	100	110	80	110	-	
	Basal Area	m^2	3.72	2.14	2.79	5.13	2.62	4.73	3.33	2.58	2.03	
	Root Factor	m^2/m	0.61	0.60	0.57	0.85	0.44	1.27	0.84	0.43	0.37	
7			0	0	0	0	8	0	0	0	6	$97 \frac{m^2}{hec}$
			-	-	-	-	-	-	-	-	45	
			0.89	1.44	2.15	1.46	2.95	0.19	2.85	2.56	0.94	
			0.12	0.24	0.38	0.25	0.72	0.03	0.47	0.42	0.21	
8			0	0	0	6	8	6	12	8	6	$87.0 \frac{m^2}{hec}$
			100	100	-	40	110	28	110	105	100	
			1.58	1.72	1.26	0.37	2.90	1.15	1.14	1.84	1.50	
			0.39	0.54	0.23	0.06	0.52	0.26	0.43	0.27	0.36	
9			7	0	0	0	11	0	0	0	0	$77.3 \frac{m^2}{hec}$
			225	210	210	210	225	-	-	-	-	
			2.73	1.12	2.05	110	112	0.87	1.17	2.35	0.88	
			0.61	0.22	0.36	0.21	0.29	0.23	0.31	0.40	0.18	

*Average basal area per hectare based on average stump basal area and .0177 hectare plot size for stump measurements.

APPENDIX C

DESCRIPTION OF SOIL SERIES

AND

SRI UNITS

Soil Series:	Hembre (tentative series)[3]
Classification:	Fine-loamy, mixed, mesic Typic Haplumbrepts — unified = SM
Parent Material:	Colluvium
Bedrock:	Basic igneous extrusive rocks
Topography:	Sharp ridges, numerous sharp finger ridges and draws which are perpendicular to the stream valleys and steep·side slopes. The landscape is stable.
Features:	Deep, well drained soils on moderate to very steep mountainous slopes.
Profile Description:	Hembre loam
0-30 cm:	Dark brown loam, friable, strongly acid. 25 to 36 cm thick.
30-112 cm:	Reddish brown clay loam, friable, very strongly acid. 81 to 107 cm thick.
112 cm + :	Basalt bedrock

Typical Properties:

(1)	Shrink-swell	Low
(2)	Erosion hazard	Low
(3)	Compaction hazard	Low-Med.
(4)	Maximum density	1.18 g/cm^3
	@ Moisture content	37%
(5)	Liquid limit	NP
(6)	Plastic limit	NP

[3]Description taken from Thomas *et al*. 1969.

Soil Series:	Jory[4]
Classification:	(USDA) Clayey, mixed, mesic Xeric Haplohumults (Unified symbol) ML-MH
Parent Material:	Colluvium
Bedrock:	Basic igneous rocks
Topography:	Broad ridge tops, rounded ridge noses and long sideslopes with a moderately dense dissection pattern. Sloping to steep foothills.
Features:	Very deep, well drained soils. Annual precipitation from 100 to 150 cm. Dry summer period.
Profile Description:	Jory silty clay
0-48 cm:	Dark reddish brown silty clay, friable, medium acid. 41 to 66 cm thick.
48-250 cm + :	Dark reddish brown clay, very firm, strongly acid.

Typical Properties:

(1)	Shrink-swell	Medium
(2)	Erosion hazard	Moderate
(3)	Compaction hazard	High
(4)	Maximum density	1.42 g/cm^3
	@ Moisture content	30%
(5)	Liquid limit	45%
(6)	Plastic index	13%

[4]Description taken from Thomas *et al*., 1969.

Soil Series:	Kinney[5]
Classification:	(1) USDA - fine-loamy, mixed, mesic Andic Haplumbrepts (2) Unified Symbol - SM
Parent Material:	Colluvium
Bedrock:	(Not given)
Topography:	Gently sloping to steep sideslopes generally lacking deep dissection, with broad, rounded ridge tops and broad finger ridge noses.
Features:	Deep, well drained soils, annual precipitation ranging from 150 to 230 cm.
Profile Description:	Kinney cobbly loam
0-25 cm:	Very dark brown cobbly loam, friable, strongly acid. 20 to 50 cm thick.
25-135 cm:	Dark brown cobbly clay loam, friable, very strongly acid. 68 to 102 cm thick.
135 cm + :	Weathered bedrock.

Typical Properties:

(1) Shrink-swell	Low
(2) Erosion hazard	Medium
(3) Compaction hazard	Low-medium
(4) Maximum density	1.06 g/cm^3
@ Moisture content	44%
(5) Liquid limit	63%
(6) Plastic limit	3%

[5]Description taken from Thomas et al., 1969.

Soil Series:	Klickitat[6]
Classification:	(1) USDA - loamy - skeletal, mixed, mesic Typic Haplumbrepts (2) Unified symbol - SM
Parent Material:	Colluvium
Bedrock:	(Not given)
Topography:	Sharp ridge tops and ridge noses and on steep or very steep sideslopes adjacent to drainages. Dissection pattern is moderately sparse.
Features:	Moderately deep, well drained soils occasionally shallow to bedrock and/or high in stone content. Annual precipitation from 200 to 305 cm.
Profile Description:	Klickitat gravelly clay loam
0-38 cm:	Dark reddish brown very gravelly clay loam, friable, strongly acid. 28 to 56 cm thick.
74-119 cm:	Dark brown very gravelly loam, very friable, very strongly acid, 70% coarse fragments. 38 to 51 cm thick.

Typical Properties:

(1)	Shrink-swell	Low
(2)	Erosion hazard	Low
(3)	Compaction hazard	Low
(4)	Maximum density @ Moisture content	(No data)
(5)	Liquid limit	
(6)	Plastic index	

[6] Description taken from Thomas *et al.*, 1969.

Soil Series:	McCully[7]
Classification:	(USDA) Fine, mixed, mesic Typic Haplumbrepts (Unified symbol) - ML
Parent Material:	Colluvium
Bedrock:	Basic igneous rocks*
Topography:	Rolling hills to moderately steep slopes. Sparse dissection pattern with drainages possessing deep and very steep sideslopes.
Features:	Deep, well drained soils. Annual precipitation ranges from 150-203 cm.
Profile Description:	McCully clay
0-30 cm:	Dark reddish brown clay, friable, strongly acid. 25 to 36 cm thick.
30-147 cm:	Reddish brown clay, firm, very strongly acid. 96 to 129 cm thick.
147-274 cm + :	Variegated dark yellowish brown, dark brown and very dark gray brown gravelly loam, very strongly acid.

Typical Properties:

(1)	Shrink-swell	Medium
(2)	Erosion hazard	High to very high
(3)	Compaction hazard	High
(4)	Maximum density	1.09 g/cm^3
	@ Moisture content for 0-18 cm depth	14%
(5)	Liquid limit	65
(6)	Plastic index	NP

[7]Description taken from Thomas et al., 1969.

Soil Series:	Nekia[8]
Classification:	(USDA) Clayey, mixed, mesic Xeric Haplohumults (Unified symbol) - ML
Parent Material:	Colluvium
Bedrock:	Basic igneous rock
Topography:	Gently sloping, long, broad ridges and finger ridge noses. On steeper slopes the ridge noses are rounded and drainages are very steep. Sparse dissection pattern.
Features:	Moderately deep, well drained soils. Has dry summer months and is occasionally shallow to bedrock. Annual precipitation from 102 to 152 cm.
Typical Profile Description:	Nekia clay
0-46 cm:	Dark reddish brown clay, friable, strongly acid. 30 - 46 cm thick.
46-91 cm:	Dark reddish brown clay, firm, strongly acid. 43 - 64 cm thick.
91-114 cm:	Yellowish red very stony clay, firm, strongly acid.

Typical Properties:

(1)	Shrink-swell	Medium
(2)	Erosion hazard	Medium
(3)	Compaction hazard	High
(4)	Maximum density	1.42 g/cm^3
	@ Moisture content for 0-15 cm depth	29%
(5)	Liquid limit	40%
(6)	Plasticity index	12%

[8] Description taken from Thomas *et al*., 1969.

Soil Series:	Whetstone[9]
Classification:	(USDA) Coarse-loamy, mixed, ortstein Typic cryorthod (Unified symbol) - GM
Parent Material:	Colluvium
Bedrock:	
Topography:	Moderately steep to very steep but even side-slopes.
Features:	Moderately deep soils. Cold climate. Annual precipitation from 178 to 229 cm.
Typical Profile Description:	Whetstone stony loam
2-13 cm:	Dark reddish brown loam, firm, weakly cemented, extremely acid. 8 to 15 cm thick.
13-48 cm:	Dark brown stony loam, friable, very strongly acid. 30 to 41 cm thick.
48-122 cm + :	Dark yellowish brown stony loam, friable, very strongly acid.

Typical Properties:

(1)	Shrink-swell	Low
(2)	Erosion hazard	Medium
(3)	Compaction hazard	Low
(4)	Maximum density @ Moisture content	(No data)
(5)	Liquid limit	NP
(6)	Plasticity index	NP

[9]Description taken from Thomas *et al.*, 1969.

Land Type:	Unit 66 SRI[10]
Classification:	(1) est. USDA - loamy-skeletal Entic Cryandepts (2) Unified symbol - SM
Parent Material:	Glacial till and volcanic ejecta
Bedrock:	Basalts and Andesites
Topography:	Smooth to somewhat uneven glaciated lava flows gentle hills. Slopes less than 40 percent.
Features:	Deep to very deep, well drained but may have perched water table over compacted subsoil. Annual precipitation from 175-205 cm.

Profile Description:

0-18 cm:	Dark brown, fine sandy loam, very friable, slightly acid.
18-51 cm:	Dark yellowish brown, sandy loam, friable, slightly acid.
51-91 cm:	Dark yellowish brown, gravelly sandy loam, slightly firm, acidic.
91-305 cm + :	Very dark gray, gravelly sandy loam, very firm and moderately compacted, slightly acid.

Typical Properties:

(1)	Shrink-swell	Low
(2)	Erosion hazard--Moderate to severe @ surface	
(3)	Compaction hazard	Low
(4)	Maximum density @ Moisture content	
(5)	Liquid limit	NP
(6)	Plastic index	NP

[10]Description taken from Legard and Meyer, 1973.

Land Type:	SRI Unit 67[11]
Classification:	(1) USDA; loamy skeletal Entic Cryandepts (2) Unified symbol; GW - GM
Parent Material:	Glacial till and volcanic ejecta
Bedrock:	Basalt and Andesites
Topography:	Smooth to uneven glaciated lava flows. Slopes typically less than 40%.
Features:	Moderately deep to deep, well drained to locally poorly drained. Perched water table over compacted subsoil. Annual precipitation from 175-205 cm.
Profile Description:	
0-13 cm:	Dark brown fine sandy loam, very friable.
13-56 cm:	Dark brown loam, friable, slightly acid.
56-81 cm:	Dark brown, very fine sandy loam, friable, slightly acid.
81-117 cm:	Very dark gray, gravelly sandy loam, very firm and moderately compacted.

Typical Properties:

(1)	Shrink-swell	Low
(2)	Erosion hazard--Moderate to severe @ surface	
(3)	Compaction hazard	Low
(4)	Maximum density @ Moisture content	
(5)	Liquid limit	NP
(6)	Plasticity index	NP

[11]Description taken from Legard and Meyer, 1973.

CORRELATION COEFFICIENTS BETWEEN THE INDEPENDENT VARIABLES

	Age	Activity Index	Organic Matter	Herb	Shrub	Tree	Herb	Shrub	Tree	Herb	Shrub	Tree	Eleva-tion	RF	Silt + Clay	Herb + Shrub Track	Silt + Clay * RF	Age * Organic Matter
					Track			Center			Less Disturbed							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	---																	
2	.19	---																
3	-.44*	.04	---															
4	-.18	.75**	.06	---														
5	.56**	.36	-.04	0	---													
6	.79**	.17	-.11	.20	.68**	---												
7	-.17	.72**	.04	.91**	.14	-.18	---											
8	.55**	.39*	-.10	.06	.93**	.63**	.23	---										
9	.80**	.19	-.12	-.19	.68**	.99**	-.17	.65**	---									
10	-.29	.43*	.02	.46*	-.30	-.31	.37	-.24	-.27	---								
11	.32	.22	-.20	.07	.63**	.52*	.05	.64**	.55**	-.10	---							
12	.82**	.19	-.16	-.20	.78**	.92**	-.15	.71**	.91**	-.46*	.50**	---						
13	-.05	-.77**	-.19	.64**	.49**	-.23	-.64**	-.53**	-.24	-.39*	-.48*	-.29	---					
14	.08	-.58**	.16	-.57**	0	.27	-.57**	-.02	.24	-.55**	-.03	.27	.44*	---				
15	-.07	.87**	.30	.81**	.32	.06	.78**	.34	.06	.41*	.21	.06	-.86**	-.56**	---			
16	.33	.75**	.01	.62**	.79**	.41*	.68**	.77**	.42*	.05	.54**	.48*	-.78**	-.35	.75**	---		
17	.16	-.11	.45*	-.19	.30	.49**	-.21	.24	.46*	-.45*	.09	.46*	.02	.79**	-.01	.12	---	
18	.72**	.30	.20	-.08	.70**	.82**	-.07	.64**	.83**	-.28	.29	.82**	-.34	.17	.26	.50**	.53**	---

*Significant at α = 0.05 with 25 d.f.

**Significant at α = 0.01 with 25 d.f.