The Effects of Compaction on Hydrologic Properties of Forest Soils in the Sierra Nevada

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Henry A. Froehlich

This study evaluated the effects of a crawler tractor, a rubber-tired skidder, and a torsion suspension vehicle on several soil and hydrologic properties in the western Sierra Nevada Mountains of California. Four sites, with soil textural classes ranging from a loam to a loamy sand and elevations between 680 and 2180 m, were studied at three moisture contents. Compaction was monitored with a double probe nuclear densiometer and an air permeameter after 1, 3, 6, 10, 15, and 20 round trips. Density measurements were made at five different depths. Infiltration capacities were determined with a small, portable rainfall simulator. Soil core samples were taken to observe porosity and conductivity levels before and after disturbance.

Compaction, or the change in bulk density, was significantly greater on the crawler tractor trails at all depths. When only the plots established in the outer positions of the trails were included, this distinction between vehicles could not be made. The crawler tractor generated more uniform compaction across its trails than either

the torsion suspension vehicle or the rubber-tired skidder. The greatest change in bulk density for all the vehicles took place in the surface five centimeters.

Infiltration capacities on the undisturbed sites were found to exceed predicted maximum precipitation rates. Mineral soil at the three higher elevation sites was very hydrophobic. This was thought to be due to the coating of soil particles with the metabolic products of fungal mycelia. The crawler tractor reduced infiltration capacities by 78 percent, while the torsion suspension vehicle and the rubber-tired skidder caused 67 percent decreases. Suspended sediment concentrations determined from runoff collected on the infiltration plots served as an erosion index for the skid trails. The crawler tractor trails had runoff with 40 percent higher sediment loads than that found on the trails of the other two skidders. Organic matter content was inversely correlated with the sediment levels.

Air permeability readings showed that the three vehicles produced very similar reductions in macroporosity in the surface 2.5 cm layer as the number of trips increased. Approximately 75 percent of the decrease in macropore space occurred by six trips. The air permeameter provided a relatively good index of compaction.

Porosity and conductivity levels determined from the soil core samples showed that machine differences did not exist in the track position. Macropore space was reduced 43 percent and the conductivity decreased 80 percent. Site differences were much more evident than vehicle differences.

Observations made after one over-wintering period showed that measureable recovery had not occurred.

Key words: soil compaction, ground based skidding, infiltration capacity, hydrophobicity, surface erodibility

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"Then it seemed to me that the Sierra should be called, not the Nevada or Snowy Range, but the Range of Light. And after ten years of wandering and wondering in the heart of it, rejoicing in its glorious floods of light, the white beams of the morning streaming through the passes, the noonday radiance on the crystal rocks, the flush of the alpenglow, and the irised spray of countless waterfalls, it still seems above all others the Range of Light."

John Muir

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INTRODUCTION

Problem Statement

Despite the increasing importance of cable logging systems, mobile ground based vehicles remain the primary method of transporting felled timber to landings on the majority of the forests in the United States. Fixed wheel, crawler tractors were the only type of vehicle available for this work until the 1960's. Highly mobile rubber-tired skidders then entered the market, to be followed by low ground pressure, torsion suspension vehicles in the 1970's. Currently, there are three types of skidders available for logging terrain with slopes up to 45 percent. The impact which these vehicles have on the soil resource is relatively unpredictable at the present. We cannot estimate the magnitude of the increase in bulk density, or the decrease in permeability and macroposity which a site will experience. The fact that these impacts are significant becomes apparent when it is realized that from 20 to 45 percent of a unit is commonly covered by skid trails after harvesting. Since the soil resource is the key to long range forest productivity, ways of quantifying potential harvesting impacts by these machine types need to be found before a site's potential has been unacceptably altered.

Compaction, or the compression and rearrangement of soil particles caused by dynamic pressure and vibration exerted by ground skidders, is the primary adverse result of this type of logging. Both total and macroscopic pore space are reduced by this process, while micropore space is increased. There are several reasons to be concerned about compaction. Of fundamental importance, and the focus of most previous studies, is that of reduced forest growth. A soil matrix which has large voids for rapid air and water permeability, as well as for penetration by fine roots, is required for maximum biomass production. When enough energy is applied to the upper part of the soil profile to drastically change the pore size distribution, the air capacity and water retention capabilities are also radically altered. The effects of compaction on root growth are complex. While it is accepted that root elongation is reduced considerably, it is still not known which of the factors association with compaction is the primary limiting factor. Undoubtedly there is an interaction between soil strength, water and nutrient availability, and aeration on fine root growth (Foil and Ralston 1967, Greacen and Sands 1979).

Changes in the hydrologic regime of forest soils by compaction are becoming increasingly important and are the area of emphasis for this study. The major effects of compaction are reduced infiltration capacity and increased surface runoff. Undisturbed forest soils nearly always have infiltration capacities which are able to handle the maximum precipitation rates for that area (Satterlund 1972). However, after disturbance by logging, the infiltration capacity may be lowered to the point where rainfall intensity will exceed it. The large macro-voids in the upper part of the profile, which rapidly transmit water downward, are converted into a restricting layer of dense, tightly packed soil. When overland flow is produced, rill and gully erosion on skid trails can quickly erode large quantities of valuable soil. If this is a widespread occurrence, site productivity can be lowered and water quality degraded.

Other hydrologic changes which result from compaction are less obvious and their importance is still being debated. It has been suggested that compacting a large percentage of a watershed can increase the size of peak flows from storm events (Harr, Fredriksen, and Rothacher 1979). Key factors affecting this would include the proximity of compacted areas to streams and the continuity of compacted areas so that overland flow could reach streams. Even if water flowing over severly compacted skid trails infiltrates back into undisturbed soil at frequent diversions, the hydrologic response time could be decreased. This has yet to be conclusively documented and more research in this area is needed.

Study Objective

The study described in this thesis was designed to evaluate changes in several soil physical and hydrological properties caused by skidding with the three machine types. Use of this knowledge will aid logging engineers, forest managers, and hydrologists in their assessment of alternative methods for harvesting logging units. This study was part of a larger study which had as its major objective the development of tools and techniques for preducting soil compaction from ground based logging vehicles. The data was also used to improve our understanding of the porosity, infiltration, and permeability aspects of soil compaction. The objectives of this portion of the project were to:

1) Determine which variables significantly affect infiltration on both undisturbed sites and compacted skid trails in the western Sierra Nevada.

2) Determine how bulk density at five depths in the soil profile and macropore space in the surface layer change as the number of trips with a given vehicle increases.

3) Determine the variables controlling surface erosion on the compacted skid trails.

4) Determine quantitatively how changing macropore space to micropore space by compaction influences hydraulic conductivity and drainage characteristics of the soils studied.

5) Determine if there were significant changes for infiltration capacities and surface macroporosity levels after one overwintering period.

All of the data in this thesis are used by permission of the Missoula Equipment Development Center and the study team members who organized this research project. Mr. Benjamin Lowman, of the Missoula Equipment Development Center, coordinated the funding and research direction with Oregon State University, the Tahoe National Forest, and the Region 5 Forest Service Office in San Francisco.

LITERATURE REVIEW

This summary of selected studies related to soil compaction and its effects on the hydrologic properties of soils is divided into two major areas. First, the compaction process is considered. This topic includes a brief review of the theory of soil compaction, a rather extensive look at compaction caused by logging vehicles, and a more general discussion of how compaction changes soil-water storage and movement. Second, several important hydrologic properties related to soil compaction are presented. Included are infiltration, surface erodibility, soil wettability, and air permeability. All four subjects are needed for the logical development of ideas and the comparison of results presented in this thesis.

The Compaction Process

Theory of Soil Compaction

Soil compaction can be defined as the increase in soil bulk density with a corresponding decrease in the void ratio (i.e., the volume of the voids divided by the volume of the solids). Several researchers have found that when a soil is compacted, it is the pore size distribution which is altered the most, rather than a large change in total porosity (Vomocil and Flocker 1961, Greacen and Sands 1979). Specifically, macroscopic pore space is reduced, while the proportion of micropores is increased. This occurs during compression when fine grains are forced into voids between coarse grains (Lull 1959).

The relative amount of compaction can be expressed in terms of porosity, bulk density, water infiltration, water transmission, or penetrometer resistance. Measurements of increases in dry bulk density are often thought to be the most direct way of quantifying compaction (Chancellor 1976). There are, however, more sensitive indicators. Vomocil and Flocker (1961) state that the change in the percent of macropore space and hydraulic conductivity are the most useful estimates of compaction. Since the most noticeable effect of compaction is often on infiltration, this parameter is sometimes chosen as the appropriate index (Vomocil et al. 1958, Doneen and Henderson 1953).

Different types of vehicles vary greatly in their potential for creating compaction problems. Factors which have been found to be important include vehicle weight, track width or tire inflation pressure, wheel slip, amount of vibration produced, vehicle speed, drawbar load, and the number of passes made (Vomocil et al. 1958, Chancellor 1976). Light vehicles which exert low ground pressure over a wide, flexible track are currently thought to minimize soil compaction and reduce surface disturbance (Froehlich 1978).

When considering the levels of compaction produced, certain soil properties have been found to be as important as vehicle characteristics. Soil mechanics studies indicate that there is an optimum moisture content for compaction and that above or below this content lower bulk densities will be obtained with the same energy input (Bowles 1979). Therefore, a soil's moisture content is often one of the most important factors affecting compaction (Weaver and Jamison 1950, Vomocil et al. 1958). Soil texture has also been shown to be of the utmost importance. Well graded soils which are high in silt sized particles have been found to be more prone to compaction than either pure sands or pure clays. This is because of the greater packing which can occur when a range of particle sizes are present (Lull 1959, Chancellor 1976). Vibration has been shown to be a very effective compacting tool for sands and gravels, while clays are compacted more efficiently with trampling action (Lull 1959). The organic matter content is another major factor affecting a soil's susceptability to compaction. Howard (1979) has recently found that the organic carbon content was the single most important variable for predicting the maximum densities of 14 soils. An increase in soil organic matter results in decreased compactability and requires a greater moisture content for maximum compaction (Lull 1959).

Additional soil factors which affect the amount of compaction resulting from vehicle travel include soil structure and initial soil density. Soils with unstable structure are subject to shear failures and extensive puddling when wet. This causes an extreme loss of macropore space (Chancellor 1976). Well aggregated soils initially have low bulk densities, but if the aggregates are weak and are easily crushed under stress, serious compaction can result. And for a given soil type, soils with low initial density will be more susceptible to compression than soils of higher density when equal stresses are applied (Lull 1959).

Logging Related Compaction Studies

Logging with ground based vehicles has been practiced since approximately 1945 (Steinbrenner and Gessel 1955). One of the first references in the literature describing harvesting effects on forest soil physical properties is by Hulisashvili (1945). He studied timber harvesting in the Transcancasus and eastern Georgia regions of the Soviet Union. Clearcutting reduced non-capillary pore space 51 percent in a pine-spruce-oak forest. This change resulted in a 3.5 fold decrease in permeability. In the United States, Munns (1947) was the first to state that logging vehicles could damage forest soils. Working in California, he found that infiltration rates were reduced 75 percent in skidder tracks. He also noted that 25 to 40 percent of a logging unit may be covered by skid roads. Shortly after this study, Garrison and Rummell (1951) did a large survey of tractor logged land in eastern Oregon and Washington. On these ponderosa pine forest lands they refined Munns' earlier disturbance estimate and concluded that 26 percent of the land was occupied by skid trails.

The first definitive study on forest soil compaction was done by Steinbrenner and Gessel (1955). They studied the effects of tractor logging on soils in southwestern Washington. On primary skid trails they found the permeability rate was decreased 92 percent, macroscopic pore space was reduced 53 percent, and bulk density was increased 35 percent in the surface 7.6 cm layer. In addition, Steinbrenner (1955) reported that under dry soil conditions four trips with a tractor reduced macropore space by 50 percent and the infiltration capacity by at least 80 percent. Under moist conditions, one trip with the tractor was found to produce the compaction caused by four trips when the soil was dry. Skid roads occupied 26 percent of the logging units.

In the 1960's it was recognized that these changes in skid trail soil properties were not simply short-term occurrences. Tackle (1962) used the infiltration capacity as an index to compaction in a western larch-Douglas-fir stand in western Montana. The first year after logging, the infiltration capacity of the tractor skid roads was only 4.1 percent of the undisturbed rate. Five years after logging, there was no apparent recovery. The possibility of high runoff rates and erosion were noted. In an eastern study, Perry (1964) examined infiltration in a 26-year-old North Carolina loblolly pine stand. He found it took 18 minutes for a given quantity of water to infiltrate areas compacted at least 26 years previously, while it took only 3.5 minutes for the same quantity to infiltrate the plantation soil. Recently compacted areas required 80 minutes to more than four hours. He concluded that at least 40 years would be needed for the reestablishment of normal percolation rates.

Moehring and Rawls (1970) expounded on Steinbrenner's (1955) findings that moisture content can be an important factor affecting compaction. Working in southeastern Arkansas, they found that when their loess soil was near field capacity, bulk density in the surface five cm layer of the tractor skid trails was increased 13 percent. Total pore space was reduced by 11 percent and macropore space was decreased by 49 percent. When this soil was near the permanent wilting point, none of these measured properties were significantly affected. Similarly, in South Carolina Hatchell, Ralston, and Foil (1970) found that compaction by tractors caused a larger decrease in macropore space on wet soils than on drier soils. Their wet weather logging resulted in puddling and did not greatly increase final bulk densities. Average results for primary skid trails in the surface five cm layer indicated that bulk density was increased 44 percent, infiltration capacity was decreased 89 percent, macropore space was reduced 48 percent, and capillary porosity was increased six percent. After four trips, 90 percent of the final bulk density was measured. Using tractors in the central Sierra Nevada Mountains of California, Miles (1978) reported that heavy surface compaction is reduced when logging is carried out during the dry season. He found a 47 percent increase in density in the surface 3.5 cm layer of the track regions of the primary skid trails during wet conditions, and a 38 percent increase during dry conditions.

In the last ten years, several studies have investigated the newer type of ground based vehicle--the rubber-tired skidder. Mace (1971) stated that the average bulk density increase in the surface five cm layer was 28 percent for tree length logging with these skidders in Minnesota. Infiltration rates decreased from 70 to nearly 100 percent on heavy and medium disturbance sites for both summer and winter operations. Very little recovery occurred after one over-wintering period. He concluded that once macropore structure is altered, which happens after only a few trips, increased compaction has little effect on decreasing infiltration rates. The fact that rubber-tired skidders exert a larger bearing pressure on the soil than crawler tractors and hence may present a more serious compaction problem caused Campbell, Willis and May (1973) to study this type of logging on Piedmont soils in Georgia. Twenty-three percent of their units were disturbed by skid trails. For the primary trails, bulk density was increased 16 percent in the surface 7.6 cm layer, macropore space was reduced 64 percent, and total porosity was decreased 16 percent. After ten trips, bulk density values no longer increased. There was no significant increase in bulk density in the skid trail centers.

In northern Mississippi, Dickerson (1976) reported that tree-length harvesting with rubber-tired skidders caused bulk density in the surface five cm layer to increase 20 percent in the wheel ruts. Bulk densities where only log disturbance had occurred were raised ten percent. Macropore space was reduced 68 percent, micropore space was increased seven percent, and permeability was decreased 90 percent in the wheel rutted areas. Bulk density measurements were made annually for five years to estimate recovery. Assuming a linear relationship, he concluded it will take 12 years for the density of the wheel rutted soils to return to the original levels. Similar trends were seen for the recovery of macropore space. Lenhard (1978) utilized a rubber-tired skidder on a volcanic ash influenced soil in Idaho to study compaction. He found that by four passes, soil shear strength was sufficient to prevent further large bulk density increases. Total pore space was decreased eight percent after four trips, but was reduced only one additional percent by 32 trips. There was a five percent reduction in macropore space by four trips; after 32 trips there was an 87 percent reduction. Therefore, he concluded that as the number of trips increased beyond the point where bulk density failed to increase significantly, there was a continued reduction in macropore space. Significant recovery of bulk density did not occur in one year's time.

Recent work in forest soil compaction has striven to find ways to lessen the negative impacts reported in the earlier literature, while at the same time allowing modern forest management techniques to be implemented. Froehlich (1976) studied compaction resulting from thinning a 35-year-old Douglas-fir stand in Oregon with a small crawler tractor. The clay loam soil was highly susceptible to compaction, and even though thinning was done before the rainy season, bulk densities increased 21 percent on the primary skid trails in the 0 to 15 cm zone. The newest ground skidder, the torsion suspension vehicle, was studied by Froehlich (1978) on three sites in Oregon. He found that most of the increase in bulk density was in the top ten cm of the skid trails. Bulk density values increased very little after the first few trips. The three sites showed drastic differences in their response to this skidder. Increases in bulk density in the surface five cm layer ranged from 3 to 72 percent after 20 trips. Only 12 to 15 percent of the area at each site was covered with visible skid trails.

While the logging studies cited above have dealt with changes in skid trail properties, they did not deal specifically with erosion on the trails. An early paper by Trimble and Weitzman (1953) found that the following factors were important when considering erosion on skid roads: grade of the road, length of the slope, intensity of use, duration of skidding, intensity and amount of rainfall, soil characteristics, and revegetation. Working in the Fernow Experimental Forest in West Virginia, they found it took 619 times longer for a given quantity of water to enter the B horizon exposed on a skid road when compared to the A horizon on an undisturbed forest soil. In a companion paper, Weitzman and Trimble (1952) devised a rating scheme for skid trail erosion potential on the medium textured silt loams found there. "Good" skid roads were not to exceed a 20 percent slope and "high order" skid roads were not to exceed a ten percent slope, except for short distances. For both classes, water-bars were to be installed after the logging operation. Evidence that skid trail erosion could be severe was seen at the Fernow Experimental Forest by Reinhart (1964). He found that the infiltration capacity had been decreased 94 percent in the track position of the skid trails. On steep skid trails without water-bars, the result was substantial overland flow and gully erosion. Dyrness (1965) reiterated the fact that both low slope gradient and water-bar installation reduce skid trail erosion greatly. Compaction by crawler tractors in the Oregon Cascades caused an 18 percent reduction in total pore space and a 48 percent increase in bulk density for the surface five cm layer. Skidding, however, was carried out on slopes of less than 20 percent and water-bars were established after logging was completed. Therefore, the resulting runoff velocity was reduced and sediment was transported for only short distances.

More recently, Dickerson (1975) studied skid trail erosion in northern Mississippi. Troughs were installed across the lower end of trails skidded straight up slopes ranging from 9 to 35 percent. Erosion was found to be sporatic; high sediment yields were not always produced by trails with high stormflow volumes. Regression analysis showed that no single independent variable or combination of variables allowed sediment production to be predicted. This was partly explained by the observation that sediment was often stored in minor depressions. Sediment loss averaged 15 kg per trail the first year and only two kg the second year; rapid establishment of herbaceous cover was thought to be the cause of the decrease in erosion. Finally, Johnson (1978) did a comprehensive study on infiltration and surface erodibility after harvesting in the Oregon Cascades. His investigation, done on sites logged six years previously, showed that tractor skid trails and windrowed areas had approximately 45 percent lower infiltration capacities and 70 percent higher surface erodibility estimates when compared to site averages. Definite evidence of recovery of compacted areas was measured. Skid trails which had been created only months prior to the study were compared with trails established six years earlier. Infiltration capacity increased 91 percent and the surface erodibility estimate decreased 84 percent. The substantial recovery was attributed to the shrinking and swelling soils present, freezing and thawing, and biological activity.

In summary, it can be seen that skid trail compaction and the response to it is highly variable. As was indicated previously, there are nearly an infinite combination of vehicle and soil characteristics which can cause different changes in bulk density, infiltration, and porosity. Therefore, predicting changes in these properties is not an easy task.

The Effect of Compaction on Soil-Water Relations

Agronomists have long been interested in how compaction affects the moisture contents of soils. Since total pore space is reduced after substantial compaction, the maximum amount of water retained at saturation is decreased. It also follows that when macroscopic pore space is converted to micropore space, less water can be held at low tensions and more water at higher tensions (Warkentin 1971). Hence, soil moisture characteristic curves tend to be flattened out after compaction (Hillel 1971). Gravitational water tends to drain too quickly from the large pore space in a soil to supply plants with moisture, so the reduction in macropore space results in more available water for their use. The benefits from increased water holding capacity are usually outweighed; however, by poor aeration, structure, and increased soil strength (Mirreh and Ketcheson 1973, Warkentin 1971).

Several researchers have attempted to relate bulk density and soil water content through carefully controlled laboratory experiments. Akram and Kemper (1979) studied four uncompacted soils with textures ranging from a loamy sand to a clay loam. Bulk densities of all the soils were highest when the soil was air dry, and lowest when the moisture content was from 50 to 100 percent of field capacity. The surface tension forces of water, which bound the soil particles together and allowed structure to form with sufficient strength to resist overburden forces, were used to explain this phenomenon. Beyond field capacity, the uncompacted bulk densities increased as the water content was raised. Archer and Smith (1972) compacted four soils with different textures and found that the water content, after equilibrating at 50 cm of water tension, increased linearly with bulk density over a wide range of densities. Eventually, with continued compaction, the reduction in total porosity becomes more important than the increase in micropore space. When this happens, the volumetric water content at field capacity is reduced. They report that a coarse textured droughty soil may have its available water holding capacity increased through compaction. Similarly, a very dense compacted soil can have a larger water capacity when the bulk density is decreased. Hill and Sumner (1967) found that severe compaction of sandy loams resulted in a decrease in moisture content at a constant matric suction, while moderate compaction caused an increased moisture content. Box and Taylor (1962) also showed that soil moisture characteristic curves are influenced by bulk density. They found that increasing bulk density 50 percent, at a constant moisture content, resulted in a greater matric potential which changed the slope and position of the curve.

Just as compaction changes water storage, it also affects water transmission. Permeability is directly related to a soil's pore size distribution (Hillel 1971). As early as 1938, Baver reported that permeability increases exponentially with a non-capillary porosity factor. Since then, several authors have found a strong correlation between macropore space and permeability (Bendixen et al. 1948, Meredith and Patrick 1961, Ranken 1974). Warkentin (1971) has found that when calculating water movement through compacted layers of soil with different densities, it is not possible to simply use the conductivity of the least permeable layer. The hydraulic gradient is not uniform through a layer with lower porosity. This results in a larger pressure drop through this layer and causes a larger flow of water through the profile than if a uniform gradient is assumed.

While saturated conductivities are always reduced by compaction, unsaturated conductivities are less affected and may even increase (Kemper et al. 1971). In order for a pore to transmit water it must remain filled. Compaction increases the number of micropores and they are often able to remain filled at medium suctions. Illustrating this with a clay loam, they found that increasing the bulk density by 36 percent resulted in at least doubling the conductivity at tensions above field capacity.

Discussion of Related Hydrologic Properties

The Infiltration Process

Infiltration is the process by which water enters and passes through the soil surface. Infiltration is generally measured as the maximum rate at which water enters the soil and is labeled the infiltration capacity. There are two basic forces which cause water to move into and through the pore space at the soil surface. As it does for all things, gravitational attraction pulls water downward, and in this case into the soil. When the depth of water increases above the soil pore, there is a positive hydrostatic pressure which is equal to the height of the column of water multiplied by the force of gravity. The other basic force involved is that of capillarity. This is the result of greater adhesive forces between the solid soil pore surfaces and water than the cohesive forces of the water molecules themselves (Hillel 1971). A column of water is pulled into a soil pore by this process. The force exerted is a function of the shape of the meniscus, or the curvature of the air-water interface (Satterlund 1972). Both the size of the pore and the amount of attraction between the water and the pore surfaces determine the shape of the meniscus. When soil particles are coated with substances which resist wetting, the meniscus will be convex rather than concave, and the capillary force will be negative.

Among the first to show that a soil's infiltration capacity significantly decreases with time was Horton (1940). He was able to successfully model this reduction with an algebraic equation. There are many reasons why infiltration rates change over the coarse of a storm event.

The principal cause is that the average suction gradient continually decreases as the infiltrating water penetrates deeper into the profile (Hillel 1971). The difference in the pressure head between the saturated soil surface and the dry soil below the wetting front is constantly dividing itself over a larger distance. While this was not thought to be of great importance to Horton, present day soil physicists are convinced of its significance. Horton believed that the infiltration capacity reduction was controlled by changes in the surface macro- and micro-structure from raindrop impact, the swelling of colloids, air entrapment, and the filling of pore space with fine silt and clay particles. Later researchers have indeed found that these factors are also important. For instance, McIntyre (1958) reported that the formation of surface crusts was due to the washing in of fine particles and compaction of the immediate surface layer (0.1 mm) by raindrop impact. This region was found to have extremely low permeability (5×10^{-6} cm/sec). And Dixon (1975) states that while surface connected macropores greatly aid infiltration, their contribution can be blocked by small air pressures.

The factors influencing a soil's final infiltration capacity are generally agreed upon now, after many years of research. Some of the more pertinent papers reviewed here show the wide range of factors which can control infiltration. One of the first comprehensive studies done was by Free, Browning and Musgrave in 1940. They examined 68 soils from across the United States and found that infiltration was best correlated with the indices of macropore space and the factors which determine the permanency of macropores. Non-capillary porosity, degree of aggregation, organic matter, amount of clay in the subsoil, suspension percentage, and the dispersion ratio were all found to be important. The correlations were not good (r^2 less than 0.26), indicating the large amount of variability in the soil types. Some of the early forestry literature (Lowdermilk 1930, Johnson 1940, Arend 1941) demonstrated the importance of forest litter for maintaining high infiltration rates. Without this protective cover, it was shown that silt and clay particles would seal surface pore space. Parker and Jenny (1945) found that infiltration in citrus groves was directly related to the quantity of organic matter that had been applied.

More recent investigations include Dortignac and Love's (1961) work on the ponderosa pine ranges of Colorado. The two most important variables for infiltration were the weight of the dead organic material per plot and the percent of non-capillary pore space in the upper part of the surface horizon. In northern Utah, Meeuwig (1970a) found that he could explain 82 percent of the infiltration variability by including the variables plant and litter cover, bulk density, aggregation present, and initial moisture content in a multiple regression equation. For a loessal silt loam in Wisconsin, Knighton (1978) reported that bulk density, air-filled pore volume, organic carbon content, and litter cover were significantly related to infiltration.

In addition, Satterlund (1972) states that soil texture and structure are important characteristics influencing infiltration. Sandy soils generally have higher infiltration capacities than clay soils, but there are many exceptions to this rule. Well agregated clay loams can have very high capacities, and sandy soils are much more susceptible to hydrophobic problems. Finally, rounding out the list are soil frost and water temperature. Duley and Domingo (1943) showed that the temperature of infiltrating water is probably not a key factor. This is not, however, the case for frost, which can either effectively limit infiltration or even increase it depending on whether it is of the concrete or needle variety (Satterlund 1972).

Infiltration and Erosional Processes

When infiltration rates are reduced to the point where overland flow occurs, erosion will result in the absence of a protective litter layer. For the vast majority of cases in the forested environment, erosion only occurs after there has been disturbance, as was described with the logging compaction studies. It would be inappropriate to review all of the erosion literature here. Rather, a few illustrative studies will show the important factors involved. While this erosion research did not involve logging equipment, the principles that have been found apply to the current study.

When considering the potential erodibility of forest soils, the importance of the organic matter content and the percentage of bare soil is immediately evident. In central Idaho, Bethlahmy (1967) found that runoff and erosion were greater on southwest than on northeast exposures. This was explained by the fact that 28 percent of the southwest exposure was bare soil, while only 0.9 percent was bare on the northwest. Balci (1968) reported that eastern Washington forest soils were 45 percent more susceptible to erosion than western Washington soils. The parent material, percent slope, and simulated rainfall application rates were identical for both parts of the state. In the surface ten cm of the soil, the west side had over twice as much organic matter when compared to the east side; this was used to explain the differences in erodibility.

In an extensive review of forest soil erosion, Dyrness (1968) stressed the importance of water-stable aggregation in preventing particle transport. Soil parent material, organic matter content, climatic conditions, and soil chemical properties all affect the degree of aggregation which is developed. Wooldridge's(1964) research in central Washington supports Dyrness's claim. He found a decrease in mean aggregate size with increasing erodibility for granodiorite and basalt formed soils. Similar research by Andre and Anderson (1961) also found that the surface-aggregation ratio was significantly related to soil erodibility. Soil developed from acid igneous rock was approximately two and one half times as erodible as soil formed from basalt on their northern California plots.

Much of the wildland erosion research has been done on rangelands. Packer (1951) did one of the earlier range studies in southwestern Idaho. Simulated rainfall from an infiltrometer was applied to his wheatgrass and cheatgrass plots. The amount of runoff and erosion obtained were found to be best correlated with the total ground cover and the maximum size of bare soil openings. Since these sites had not been compacted by trampling, both total and non-capillary pore space showed no definite relation to runoff and erosion. A subalpine range in central Utah provided Meeuwig (1965) with the opportunity to evaluate the effect of grazing on infiltration and erosion. He reported that even moderate grazing can compact the soil to the point where decreased infiltration capacities and reduced soil stability can be significant in areas subjected to heavy summer thunderstorms. Soil erosion was found to be most highly correlated with the density of protective cover and secondarily with bulk density.

Later work by Meeuwig (1970a) further clarified the principles of rangeland erosion. Ungrazed sites in northern Utah subjected to simulated rainfall showed that plant and litter cover was the factor most highly correlated with eroded soil (r^2=0.76). Other significant variables included litter weight, slope gradient, and soil organic matter. An enlarged version of his previous research allowed Meeuwig (1970b) to study seven sites located throughout the intermountain region. On four of the sites, the percent of the soil surface protected by vegetation and litter were best correlated with eroded soil; for the other three, the most significant variable was the percent of the soil surface occupied by plants, litter, and stone. Clearly then, anything which protects the bare mineral soil from raindrop impact helps prevent erosion.

The impact which a falling raindrop has on the soil surface depends on the amount of kinetic energy it possesses. The kinetic energy of a single raindrop is proportional to the product of its mass and the square of its velocity (Ellison 1945). Thus, rainfall contains a tremendous amount of energy and can often break down good surface aggregate structure. The resulting single grained particles can then be easily transported. There are three distinct processes involved in the mechanics of soil erosion; they are detachment, transportation, and deposition. Raindrop impact energy is responsible to a large degree for the first two. This is certainly the case when referring to splash and sheet erosion (Ellison 1945).

There have been hundreds of studies on raindrop erosion; early papers simply described its occurrence, while more recent work has focused on prediction. Borst and Woodburn (1942) found that the elimination of raindrop impact with a straw mulch, rather than the reduction in overland flow velocity on the soil surface, was the key factor in reducing erosion on their plots in Ohio by 95 percent. Ekern (1950) reported that fine sand particles were the size class most easily transported by raindrop impact. Smaller particles underwent compaction and surface sealing; a resulting film of water at the surface then dissipated energy. Larger particles had too much mass to be easily transported. Smith and Wischmeier (1962) offer a comprehensive review of rainfall erosion, including a discussion of the soil and site factors affecting erosion, and a soil loss prediction model--the "universal rainfall erosion equation." Variables in the equation are rainfall, soil erodibility, slope, length of slope, crop management practice, and soil erosion control measures undertaken.

Soil Wettability

Within the last fifteen years, the topic of soil wettability has become of increasing interest to forest managers. Pioneering research by DeBano (1968) at the San Dimas Experimental Forest in southern California has led the way. It is now known that both naturally occurring and fire induced hydrophobic conditions are common in many parts of the world. Large areas of the Sierra Nevada Mountains are affected by these conditions (DeBano 1968, Meeuwig 1971). The causes of naturally induced non-wettable soil, the only type to be considered here, have been explored fairly extensively. The effects of ground based skidding on these types of soils, and the resulting changes in the hydrologic regime, have not been studied to any extent in the past.

One of the first modern theories of water repellancy was offered by Van't Woudt (1959). Working with a volcanic ash soil in New Zealand, he found hydrophobic conditions associated with both heath vegetation and coniferous zones, but not under grassland sites. He concluded that hydrophobic films coating the soil particles caused the repellancy. Further research by Bond and Harris (1964) showed that there are three major factors involved in naturally caused hydrophobicity. Studying soils in Australia, they reported that sandy soil types, vegatation cover, and fungal associations are interrelated in causing this soil condition. They found the repellance to be widespread, but always it was in conjunction with well developed plant cover, clay contents less than five percent, and widely varying total organic carbon contents. Examination of the water repellant horizons showed zones of great fungal mycelia growth. They determined that most of the mycelia belonged to the basidiomycete order. The sand's repellance was suspected to be related to the dominance of this type of fungi and its metabolic products, but this was not able to be proved since there were other hyphomycete fungi and bacteria present. They concluded that the sand grains, with their low surface area, had been coated with a thin organic film produced by these fungi.

DeBano _et al_. (1967) studied naturally induced repellancy at the

San Dimas Experimental Forest and came up with different results. They stated that the primary source of non-wettability was from organic substances coating soil particles produced by brush species. Microbial activity was not thought to be very important because of the hot, dry semi-arid climatic conditions found in southern California. Both fresh plant material and litter decomposition products were found to cause repellancy.

A study to determine if specific fungi isolated from water repellant soils could cause hydrophobicity in soils without plant material was undertaken by Savage, Martin, and Letey (1969). They found that two common soil fungi (*Aspergillus sydowi* and *Penicillium nigricans*) caused measurable repellancy in the sand. In a more elaborate description of this study, Savage (1968) stated how these two species of fungi were established in various sand-clay mixtures, in an attempt to make a more natural medium for growth. The *A. sydowi* culture with one percent clay was much more repellant than the pure sand culture. This was thought to be due to the increased orientation of certain polar organic molecules produced by the fungi with the charged surface of the clay. The overall conclusion was that microbial products play an important role in creating repellancy.

Summarizing present knowledge of the causes of natural water repellancy, it can be said that both plants and microorganisms produce organic substances which can create this condition. The most severely affected areas occur where the litter and upper soil layers are permeated with fungal mycelia (DeBano and Rice 1973). It is still not clear whether vegetative or microbial factors are the main cause of repellancy, but Savage (1975) states that he believes fungal growth is the principal contributor.

The hydrologic significance of naturally occurring water repellancy can be extreme. The most important consideration is that of reduced infiltration rates. Bond (1964) measured the effect of repellance on infiltration for several Australian soils. He found soils with the same texture and bulk density had infiltration rates varying from 1.3 cm/hr to 76 cm/hr. Soils with the low rates were coated with organic films which increased the contact angle of wetting. When alcohol, with a much lower surface tension, was used in the ring infiltrometers instead of water, normal infiltration patterns resulted. Bond clearly states why repellant soils resist infiltration:

> "The contact angles between the organic films on sand grains and water have been found to be high, frequently exceeding 90 degrees, in which cases the capillary tension acts in the reverse direction. Water is repelled and there must be sufficient hydrostatic head to overcome the repulsive force before water can be transmitted through the pores. Once the surfaces of the particles have become wet there is less resistance to wetting and hence to subsequent flow and the effect of the high contact angle is reduced."

Bond (1968) also observed seasonal variation in the intensity of water repellance. Late spring and summer had the lowest resistance, while autumn had the highest resistance to wetting.

Non-wettable conditions in the eastern Sierra Nevada were studied by Meeuwig (1971). He found extreme hydrophobicity below the soil surface which caused eight different types of wetting front patterns to be formed. The size, continuity, and location of the water repellant zone dictated the pattern observed. Repellancy was not a problem under scrub cover, since hydrophobic areas were broken up in several spots. Under pine litter, however, and especially at higher elevations, repellancy was severe. A continuous layer of hydrophobic soil tended to form, but usually roots or burrowing rodents broke it up enough to allow some of the water to enter the profile. While logging was not part of this study, Meeuwig accurately states that repellancy can further reduce infiltration when either low porosity due to compaction or surface sealing caused by raindrop impact on bare soil have occurred.

Air Permeability

As stated in the previous sections, the amount of macroscopic pore space in the upper part of a soil profile is a critical factor for infiltration. Equally important, macropores limit the amount of aeration available for plant root growth, and hence are vital for biomass production. The critical value of ten percent macropore space (60 cm of H_2O tension) for adequate aeration is often cited (Hatchell, Ralston, and Foil 1970). As early as the 1940's, researchers have used air permeability to index aeration potential, macroporosity, and soil structure. This measurement gives a sensitive indication of a soil's internal geometry for comparative studies, but is not a physical property of the soil influencing its mechanical behavior (ASAE-SSSA 1958).

The first devices made to measure air permeability in the field were large and difficult to use, but fairly precise. Evans and Kirkham (1949) described such an instrument for use on agricultural soils. It introduced air into the soil through an outlet which was sealed to the soil surface with paraffin, and permeability was calculated as the fall in pressure per unit time. Due to the extremely variable nature of their soils, they found a wide range of readings for different positions in the same plot, even when stones, cracks, and wormholes were not near the inlet tube. A simplified version of this instrument was introduced by Grover (1955). This device utilized a falling float to measure permeability. Tanner and Wengel (1957) modified this permeameter and reported that air permeability was a sensitive measure of soil compaction due to animal traffic.

The first truly portable air permeameter, and the one still in use today, was developed by Steinbrenner (1959). In order to make many readings rapidly, permeability was no longer measured as the fall in pressure per unit time, but rather simply indexed by backpressure readings. The soil tube is inserted in the soil and the resistance to the passage of air is recorded on the backpressure gauge. Steinbrenner was able to show that permeameter readings were significantly related to macroscopic pore space (r^2=0.77), as determined on soils drained to a tension of one third atmosphere. He stated that this device would be useful for infiltration studies and for detecting compaction.

While these measurements can be easily made, the question of how soil moisture content affects air permeability has often been raised. Obviously, as more of the pore space is occupied with water, there are less voids which will allow gas to move through them. Corey (1957) has shown that air permeability increases with decreasing soil water content. Aljibury and Evans (1965) used several soils with different textures and found that soil pores contributing the most to both air and water flow drain at tensions less than 100 cm of water. For soils which do not shrink or swell, they expect that air permeability at any moisture content between 100 cm and air dryness will be nearly constant. Recently, Howard (1979) found that the resistance to air permeability was significantly higher near the optimum moisture content for compaction than when the soils were drier. The optimum moisture content, as determined by the standard Proctor test, was near field capacity (one third atm.) for most of his soils. On the basis of these studies, it can be concluded that as long as a soil has been allowed to drain below field capacity, moisture contents should not interfere with permeability readings.

The usefulness of Steinbrenner's air permeameter for measuring soil compaction is still being debated. Various researchers have found quite different results with it. Shortly after Steinbrenner's initial success, Tueller (1962) used it to provide an index of site potential and range condition. He found a significant, but weak relationship between bulk density and permeameter readings (r^2=0.09). Significant negative correlations were found when permeameter readings were regressed against percent organic matter, total nitrogen percent, and cation exchange capacity. He concluded that overused, poor range conditions could be detected with this permeameter. The most positive study supporting air permeameter use also comes from the range literature. Gifford, Faust, and Coltharp (1977) evaluated several different instruments for measuring soil compaction on two study sites in Utah. They found that air permeameter readings were better correlated (r^2=0.74) with bulk density, as determined with soil cores, than were readings from a cone penetrometer, volumeasure, pocket penetrometer, or nuclear probe. However, readings with the probe were taken at a depth of ten cm, while all the other instruments measured the density of the surface five cm layer.

More recent studies have not been so optimistic about permeameter use. Johnson (1978) used the permeameter to monitor compaction caused by both ground based and cable logging on two sites in western Oregon. He took readings at several depths in soil pits to determine the most impermeable soil layer. Macropore space at 30 and 60 cm tensions were regressed against these readings, but only 21 to 28 percent of the variability was explained. High moisture contents were thought to have been a problem. Howard and Singer (1980) reported that air permeameter readings were not significantly correlated with bulk density (r^2=0.07) for 14 Cailifornia soils. The complexity of the relationship among total porosity, pore size distribution, density, and air permeability was used to explain the poor association. They were able to determine differences in permeability between obviously compacted areas and undisturbed areas, and the permeameter was thought to be useful as a relative measure of disturbance.

In conclusion, the usefulness of the air permeameter at the current time is questionable. Further field testing is needed before an accurate statement of its worth can be made. To that end, extensive testing was done with the permeameter on the four sites used in the present study.

THE STUDY AREA

Criteria for Site Selection

The four research sites used for this study are located within the Tahoe National Forest (U.S. Forest Service Region 5) on the western slopes of the Sierra Nevada Mountains of northern California (Figure 1). Sites were selected from areas with soil types representing at least 4000 ha and capable of sustaining commercial timber production of at least 6 m^3/ha/yr. Other requirements included a level aspect (less than 10 percent slope), lack of prior disturbance, and low probability for deep frost action. Once located, the research areas and surrounding forest vegetation were flagged to prevent further unauthorized encroachment. These areas will be protected by the Forest Service for at least ten years. A summary of the soil characteristics of the four sites is presented in Table 1 and a review of the site descriptions is found in Table 2. Appendix A contains complete soil descriptions for each site.

Summary of Sierra Nevada Geology

The Sierra Nevada Mountains have a complex history. Basically, this 580 km range was formed by injected salic lava which slowly cooled underground and formed a massive granitic batholith. Erosion exposed the granite, and in the Miocene and Pliocene epochs, faulting along the eastern flank caused the block to rise and tilt. This process has caused the Sierras to be characterized by a gradually descending western slope and an abrupt escarpment on the east. This relatively simple geologic history explains most of the formations making up the southern Sierras, but the northern Sierras, including the Tahoe National Forest,

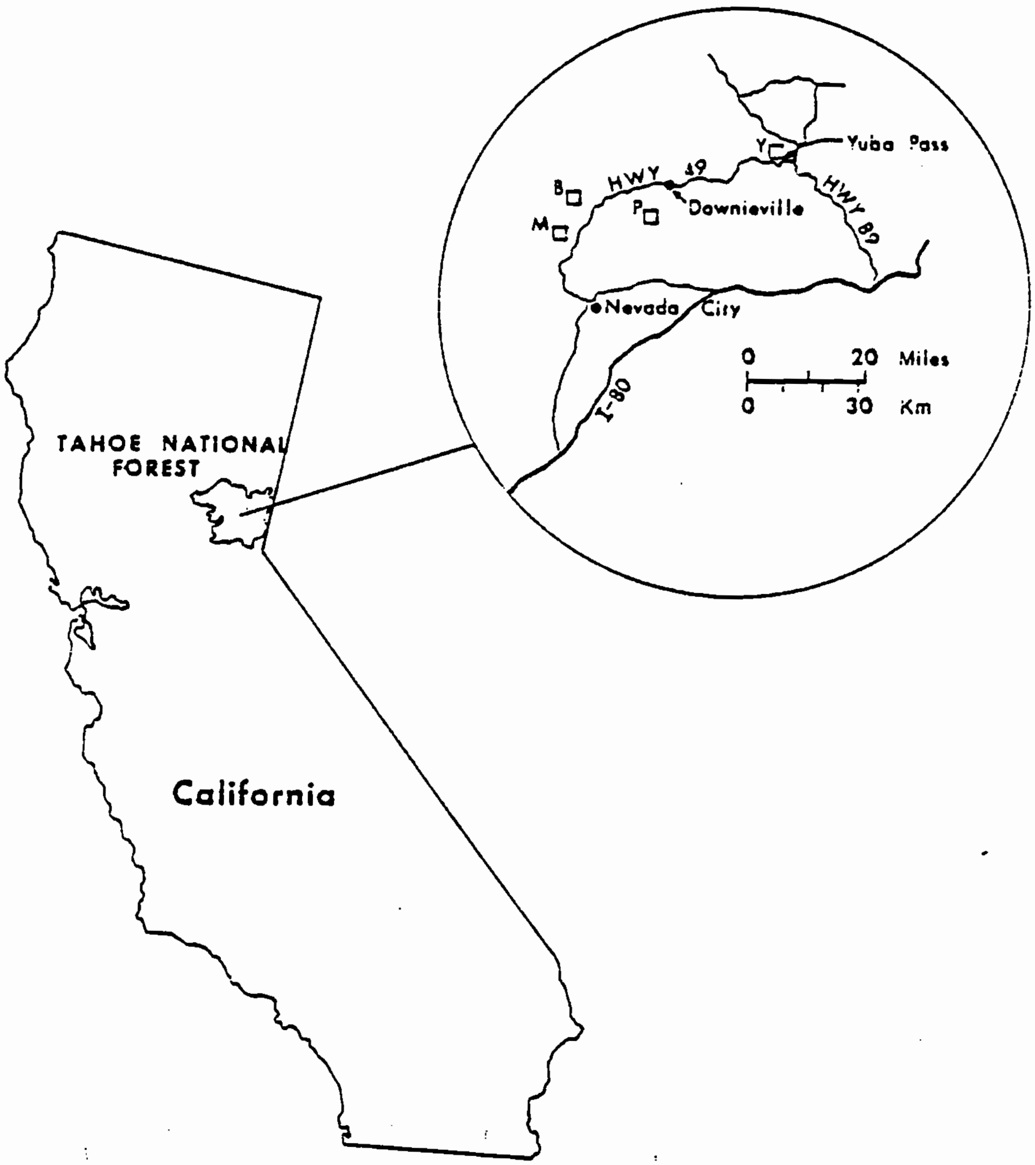

Figure 1. Locations of the four research sites in the Tahoe National Forest; Y = Yuba Pass, P = Pliocene Ridge, B = Bullards Bar, and M = Moonshine Road.

Table 1. Soil characteristics for the four research sites.[a]

	Yuba Pass		Pliocene Ridge		Bullards Bar		Moonshine Road	
Coarse Fragment (≥ 2 mm)	25%		44%		19%		3%	
Percent:	Total	Fines	Total	Fines	Total	Fines	Total	Fines
Sand	54	72	34	61	24	29	51	53
Silt	19	25	20	35	37	46	32	33
Clay	2	3	2	4	20	25	14	14
Plastic Limit	NP		NP		52.6		34.9	
Liquid Limit	—		—		58.2		38.6	
Activity Index	—		—		0.24		0.26	
Plasticity Index	—		—		5.6		3.7	
Soil Taxonomy								
USDA textural class	gravelly loamy sand		gravelly sandy loam		loam		sandy loam	
Unified soil classification	SM		SM		MH		ML	
Seventh Approximation	Dystric Xerochrept		Andic Xerumbrept		Xeric Haplohumult		Ultic Haploxeralf	
Organic Matter (percent)	1.6		3.9		5.4		3.7	
Average Dry Field Bulk Density (g/cm^3)	1.039		0.695		0.732		1.059	

[a]Soil samples taken from the surface 30 cm of the profile.

Table 2. Description of the four research sites.

	Yuba Pass	Pliocene Ridge	Bullards Bar	Moonshine Road
Elevation, m	2180	1510	975	680
Landform	Mountain slope	Flat-top ridge	Rounded mountain summit	Broad convex ridge
Aspect	W	W	S	S
Slope, %	10	5	7	3
Vegetation zone	Lodgepole Pine-Red Fir	Yellow Pine	Yellow Pine	Yellow Pine
Average Litter Depth (cm)	5.2	7.3	7.8	3.4
Soil Parent Material	Granodiorite	Andesitic Lahar	Schist (metasediment)	Siliceous Plutonic
Soil Series	Kriest	McCarthy	Sites	Musick

are more complicated. Prior to the injection of the molten lava, the area was covered with sedimentary marine beds which were metamorphosed and folded up into mountainous ridges and valleys. Most of this rock was weathered into a clay soil and eroded into the Sacramento Valley, thus exposing the granite below it. There are still remnents of this ancient rock, however, and where it exists are found soils of moderately high clay content. Furthermore, in the north, there were great floods of volcanic mud from craters and fissures which buried valleys on the west slope in the Tertiary Period (Storer and Usinger 1968). Much of this material still remains and has weathered into soils with unique properties. In the last million years, glaciation and continued faulting have influenced the Sierra landforms. Utilizing this background information, each of the four sites can be characterized.

Description of the Sites

Yuba Pass

This site is located at the crest of the Sierras at an elevation of 2180 m. Weathering of the granodiorite parent material has yielded a deep, relatively undeveloped soil profile. The soil type is a cohesionless loamy sand with 1.6 percent organic matter. Precipitation here, as throughout the Sierras, is predominantly in the winter months due to the Mediterranean climate of the region. Cyclonic storms formed in the Gulf of Alaska move down the coast and inland, depending on the location of the jet stream. Summer convectional thunderstorm activity in the northern Sierras is of little consequence. Here at Yuba, nearly all of the 180 cm of annual precipitation falls in the form of snow.

Snowpacks reach depths of at least two meters and last until the beginning of July.

This high elevation zone of the Sierras is called the Lodgepole Pine-Red Fir Belt and is sometimes referred to as the Canadian Zone. Cool summer temperatures and cold, harsh winters are to be expected here. A pure over-mature red fir (*Abies magnifica*) stand occupies our site location, but other species found in the area include Jeffrey pine (*Pinus jeffreyi*), lodgepole pine (*Pinus murrayana*), and quaking aspen (*Populus tremuloides*). Common brush species found here are chinquapin (*Castanopsis sempervirens*) and snow brush (*Ceanothus cordulatus*).

Pliocene Ridge

This flat ridge top site, at 1510 m in elevation, is located on one of the ancient volcanic mudflows. The andesitic material has weathered into a gravelly sandy loam with a moderate amount of amorphous clay. The shallow soil is cohesionless and has 3.9 percent organic matter. Annual precipitation is also heavy here, with at least half of the 180 cm falling as snow. This site is part of the Yellow Pine Belt, sometimes called the Transition Zone, and has all five mixed conifer species present: ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), sugar pine (*Pinus lambertianna*), and incense cedar (*Libocedrus decurrens*). California black oak (*Quercus kelloggii*) rounds out the overstory. Understory vegetation is made up of green manzanita (*Arctostaphylos patula*) and kit-kit-dizze (*Chamaebatia foliolosa*).

Bullards Bar

The relatively gently rolling topography of this site is part of the ancient folded marine beds which survived the erosion process. At 1040 m in elevation, the heavily weathered metamorphosed schist parent material has yielded a loam soil with 25 percent kaolinite clay. Plasticity and activity indices for this soil are low. After a careful search, this site was found to have the highest clay content in the Tahoe National Forest. At this low of elevation, most of the 165 cm of annual precipitation occurs as low intensity rainfall. A very productive mixed conifer stand occupies this site and is composed of all the species listed for Pliocene Ridge. In addition, tanoak (*Lithocarpus densiflorus*) is found in the overstory and shrub species in the understory include Sierra currant (*Ribes nevadense*), Sierra gooseberry (*Ribes Roezlii*), and thimbleberry (*Rubus parviflorus*).

Moonshine Road

This low elevation site, at 680 m, is an example of the more common western slope formations where intrusive granitic parent material was exposed and weathered. A moderately deep sandy loam soil with low plasticity and activity indices has resulted. Annual precipitation averages 140 cm and occurs entirely as rain. While still included in the Yellow Pine Belt, the much warmer temperatures and lower rainfall have altered species composition at this site. Conifers still found at this elevation include ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and incense cedar (*Libocedrus decurrens*). Hardwood species present are madrone (*Arbutus menziesii*), California black oak (*Quercus kelloggii*), and tanoak (*Lithocarpus densiflorus*). The understory is made up nearly entirely of green manzanita (*Arctostaphylos patula*).

METHODS AND MATERIALS

Field Methods

Selection of the Sampling Periods

The four research sites in the Tahoe National Forest were studied during the summer and fall of 1979. Since soil moisture content has often been reported to be an important factor for compaction, three sampling periods were chosen to follow the natural drying process of the soil in this region. It was originally hoped that the first field sampling would occur when the soil moisture was above the optimum moisture content (OMC) for maximum compaction, as determined by a standard Proctor curve, the second would be near the OMC, and the last would be when soil moisture was below the OMC. Unfortunately, the northern Sierras experienced a dry spring in 1979 and moisture contents at all four sites were below the optimum moisture during the initial sampling period in late June to mid July.

In order to measure compaction under moister conditions, Pliocene and Moonshine had trails which were artificially wet-up during the second sampling period in August. Each trail had approximately 11,350 liters of water applied to it over 2.5 hours by six irrigation type sprinklers. The soil profiles were fairly evenly moistened throughout the upper 30 cm. The final sampling was carried out in late September to early October, when the soils were at their lowest moisture contents due to the long, dry summer associated with the Mediterranean climate. The Moonshine site, being the lowest in elevation, was so dry during the initial sampling that it was decided to irrigate those trails designated for the last sampling period with the sprinkler system in early August to get an intermediate moisture level. Even with these measures, Yuba and Pliocene were the only sites to be sampled at three distinctly different moisture contents. A summary of the moisture contents for each sampling period and site is given in Table 3.

Study Design

For each of the four sites, nine trails were laid out over an area of approximately 0.4 ha. Each trail was 30 m long and had a 15 m uniform subsection established within it. This stretch was usually unbroken but occasionally had to be split into two sections to avoid rotten organic material or large stumps. Ten randomly located plots were established for each subsection on each trail. Trails were 3.7 m wide and possible plot locations were at 0.5 m, 1.4 m, 2.3 m, and 3.2 m across the trail. Figure 2 illustrates the sampling scheme utilized at Bullards. When roots or rocks prevented a plot from being usable, a new plot was established by obtaining another set of coordinates from a random number table.

For each sampling period, three trails at each site were compacted. In groups of three, so as to allow the trails sampled in a given period to be adjacent to each other, a machine type was randomly assigned to a trail. The three vehicles used in this study were as follows: Caterpillar D6D crawler tractor (CT), John Deere 640 rubber-tired skidder (RTS), and FMC 210CA torsion suspension vehicle (TSV). Characteristics of these machines are given in Table 4. The sizes of these skidders

Table 3. Moisture contents for each trail.[a]

	Yuba Pass		Pliocene Ridge	
Trail	Vehicle	M.C.	Vehicle	M.C.
1	RTS	8.57	TSV	26.98
2	TSV	9.27	CT	26.98
3	CT	7.57	RTS	27.60
4	CT	12.58	TSV	40.57
5	RTS	13.48	RTS	37.42
6	TSV	12.61	CT	38.39
7	TSV	16.06	TSV	19.14
8	CT	17.44	CT	19.18
9	RTS	16.89	RTS	19.23

	Bullards Bar		Moonshine Road	
Trail	Vehicle	M.C.	Vehicle	M.C.
1	RTS	26.50	CT	21.43
2	TSV	26.70	TSV	14.90
3	CT	24.75	RTS	19.72
4	CT	21.46	RTS	11.48
5	TSV	23.60	CT	11.63
6	RTS	19.25	TSV	12.62
7	CT	21.16	CT	12.19
8	RTS	20.72	TSV	12.22
9	TSV	19.66	RTS	12.21

[a]The moisture contents for each trail were found by averaging the values at each of the ten plots in the surface 30 cm.

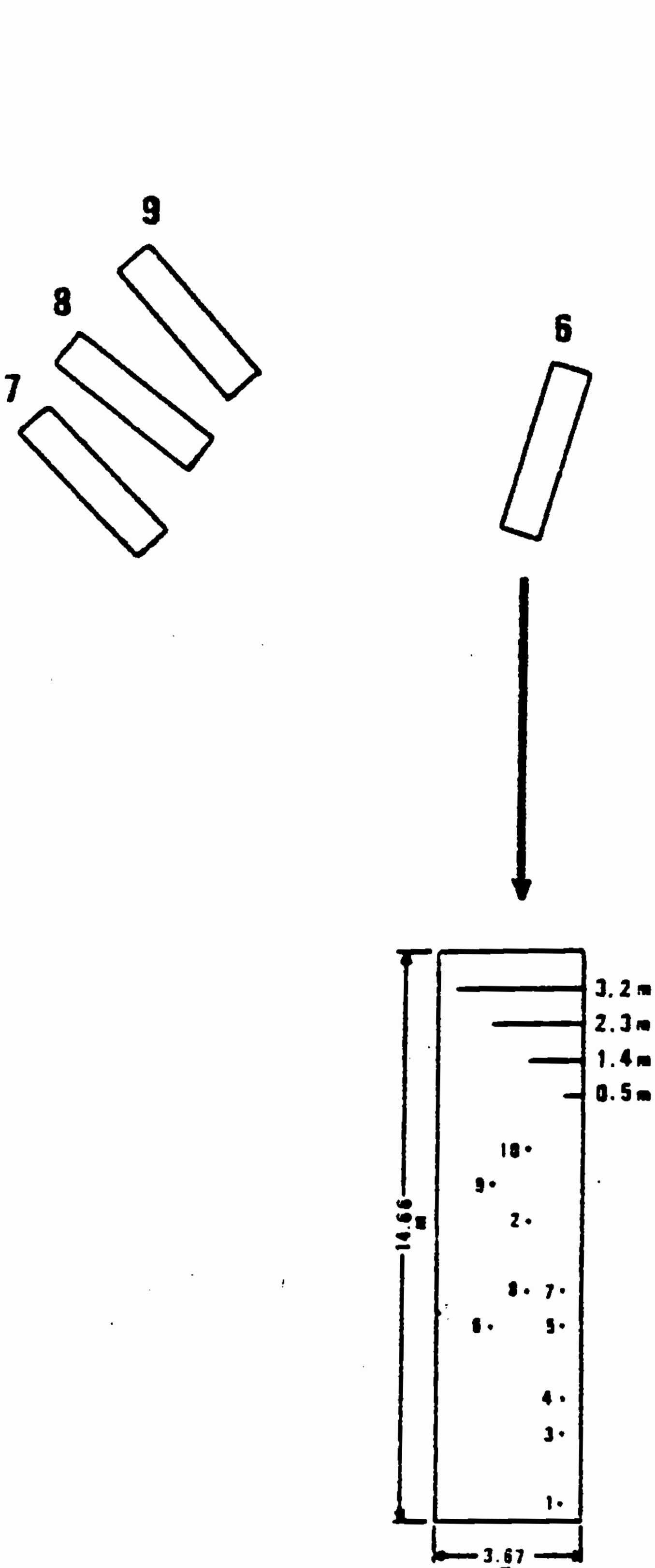

Figure 2. Skid trail layout and an example of plot locations used at Bullards Bar.

Table 4. Characteristics of the three logging vehicles.

	Caterpillar D6D	John Deere 640	FMC 210CA
Machine Type	Crawler Tractor	Rubber-Tired Skidder	Torsion Suspension Vehicle
Operating Weight (no load), kg	17840	9080	13380
Ground Contact Area, cm^2	27355	13523	32077
Static Empty Ground Pressure, kg/cm^2	0.625	0.876 (front) 0.412 (rear)	0.400
kPa	64.0	85.9 (front) 40.4 (rear)	40.9
psi	9.3	12.5 (front) 5.9 (rear)	5.9
Design log payload, kg	7270	3640	7270
Mean Turn Weight Used, kg	6426	3471	6426

were chosen for their wide use in current logging operations in the northern Sierras.

The vehicles were driven down the trails in a manner which would simulate true skid trail use. The equipment operator was instructed to move down the trails in several positions, so as to avoid a single track position. As a result, all of the plot locations were disturbed by the vehicles' tracks or wheels to some extent. Therefore, the sampling scheme devised with the ten random plots did not allow a comparison of track and center positions to be made. Rather, the four positions indicated the uniformity of trail compaction.

In order to prevent biasing the compaction process on heavily vegetated trails, virtually all large trees, poles, saplings, and brush were removed by hand with chain saws. Stumps from the larger trees were trimmed nearly flush to the ground. Organic debris was piled between the trails; large logs were winched off the trails and used to make up the turns pulled by the skidders. The loads for the three vehicles varied. The crawler tractor and the torsion suspension vehicle, being larger and built for bigger payloads, skidded turns of about 6400 kg. The rubber-tired skidder, in contrast, is built for speed and lighter turns, so it dragged loads averaging 3500 kg.

Bulk Density Measurements

Two Campbell Pacific Nuclear double probe densiometers were used to monitor changes in bulk density after skidding. These prototype models allowed the density of different layers in the soil profile to be measured quickly and accurately. Initial bulk density measurements were made at each of the ten plots in a trail prior to disturbance. These readings were made at depths of 5, 10, 15, 20, and 30 cm below the mineral soil surface. At least two 30-second readings with the probe were recorded at each depth. This entire process was repeated after 1, 3, 6, 10, 15, and 20 round trips by a skidder. A round trip was defined as a pass by a vehicle with a turn of logs, and then back without a turn.

Holes for the densiometers' source and detector probes were made by driving steel rods, held in place by a heavy steel template, into the soil with small sledge hammers. After the readings had been made at a given plot, bright colored flagging was inserted into each hole and the plot was recovered with litter. This procedure usually enabled the same holes to be remeasured after subsequent trips. When the flagging was completely ripped out by a skidder, the plot was relocated by measuring the appropriate coordinates from fixed reference points. Both before disturbance and after 20 trips, soil moisture samples were taken at 0 to 15 cm and 15 to 30 cm depths near each of the ten plots on each trail. These were obtained with a small diameter soil tube corer which was pushed into the soil. The samples were placed in labeled plastic bags and later analyzed in the laboratory.

Air Permeability Measurements

A portable air permeameter, very similar to Steinbrenner's (1959) original model, was used to index changes in macropore space on the skid trails (Figure 3). The tanks were filled with nitrogen gas to approximately 6200 kPa. Nitrogen was used instead of air because it was more easily obtained. Before making readings with the permeameter, the

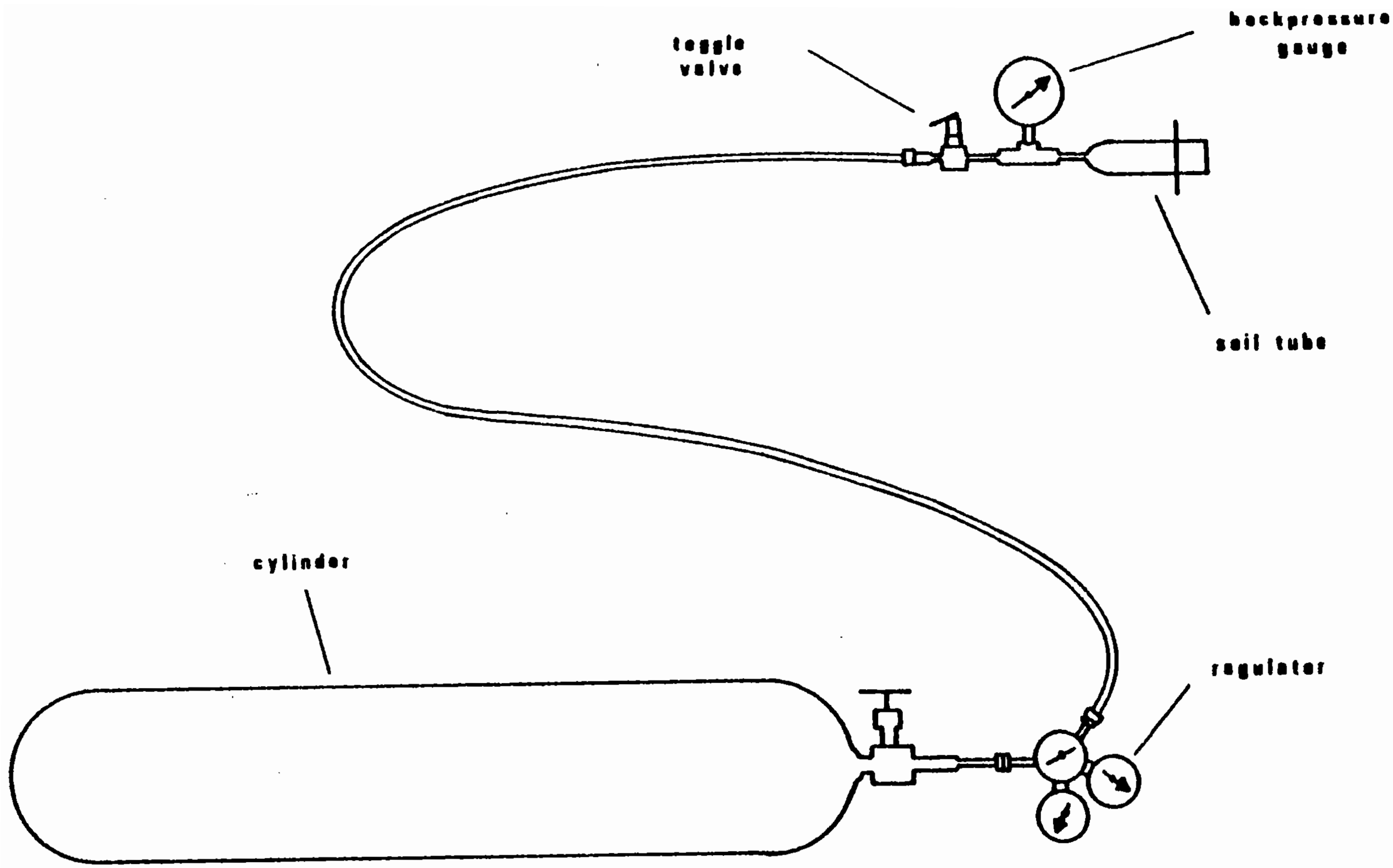

Figure 3. Air permeameter.

maximum backpressure was adjusted to 103.4 kPa (15 psi). This was done by placing the palm of the hand over the soil tube outlet to completely seal it, opening the toggle valve, and adjusting the regulator valve. After a few readings had been made, this process had to be repeated to compensate for pressure changes in the cylinder. To make measurements with this device, the soil tube is pressed firmly into the soil until the flange on the tube is in contact with the soil. With one hand holding the soil tube above the flange, the toggle valve is opened and gas is allowed to flow into the soil. The system quickly stabilizes and a reading is made on the backpressure gauge; the toggle valve is then closed.

Air permeability measurements were taken at the ten plots established on each trail. They were made initially with no disturbance and after 1, 3, 6, 10, 15, and 20 round trips. Pliocene and Yuba had a large amount of gravel in their surface horizons, and it was very difficult to get a tight seal around the gas orifice. Often, several attempts at inserting the soil tube were needed before an acceptable seal was obtained. Generally, only one reading per plot was made, but if it seemed unreasonable, a second was taken and the mean was used. Readings on the undisturbed trails were made after the litter had been completely scraped away with a trowel. The trails after disturbance were characterized by a mixture of loose, powdery mineral soil and organic matter in the surface layer. This material was also scraped away so that the soil tube could be placed in firm soil.

Infiltration and Erodibility Measurements

A small, portable rainfall simulator was chosen to measure changes in the infiltration capacity caused by skidding (Figure 4). This instrument was originally conceived by Chow and Harbaugh (1965) for laboratory tests. It was modified by Meeuwig (1971) for field work, and further refinements were made at Oregon State University by Froehlich and Hess (1976). To operate the infiltrometer, a 18.9 liter (5 gal) water tank is first suspended on a stand 1.5 m above the ground. Rubber tubing is used to connect the tank to the infiltrometer. A calibrated flow gauge on the tank indicates the precipitation rate; adjustments are made by opening or closing the small valve inserted in the tubing. Rainfall is simulated by having water drip through 522 evenly spaced needles embedded in a Plexiglas base. Water is uniformly applied to an area of 3120 cm^2. A steel trough is installed directly below the lower edge of the infiltrometer on the downhill side to collect runoff. The difference between the rate of application and the rate of runoff is called the infiltration capacity.

During the first sampling period, water was applied to the undisturbed trails, or on plots immediately adjacent to the trails if disturbance had started, at a rate of 7.6 cm/hr. It was felt that this rate represented the highest possible intensity which could be expected in this part of the Sierra Nevadas. A rainstorm with a 30 minute intensity exceeding 6.4 cm/hr can be anticipated to occur there only once every 100 years (U.S. Weather Bureau 1961). Since the infiltration capacity was always found to exceed this rainfall intensity, during the third sampling period, when the soils were at their driest and

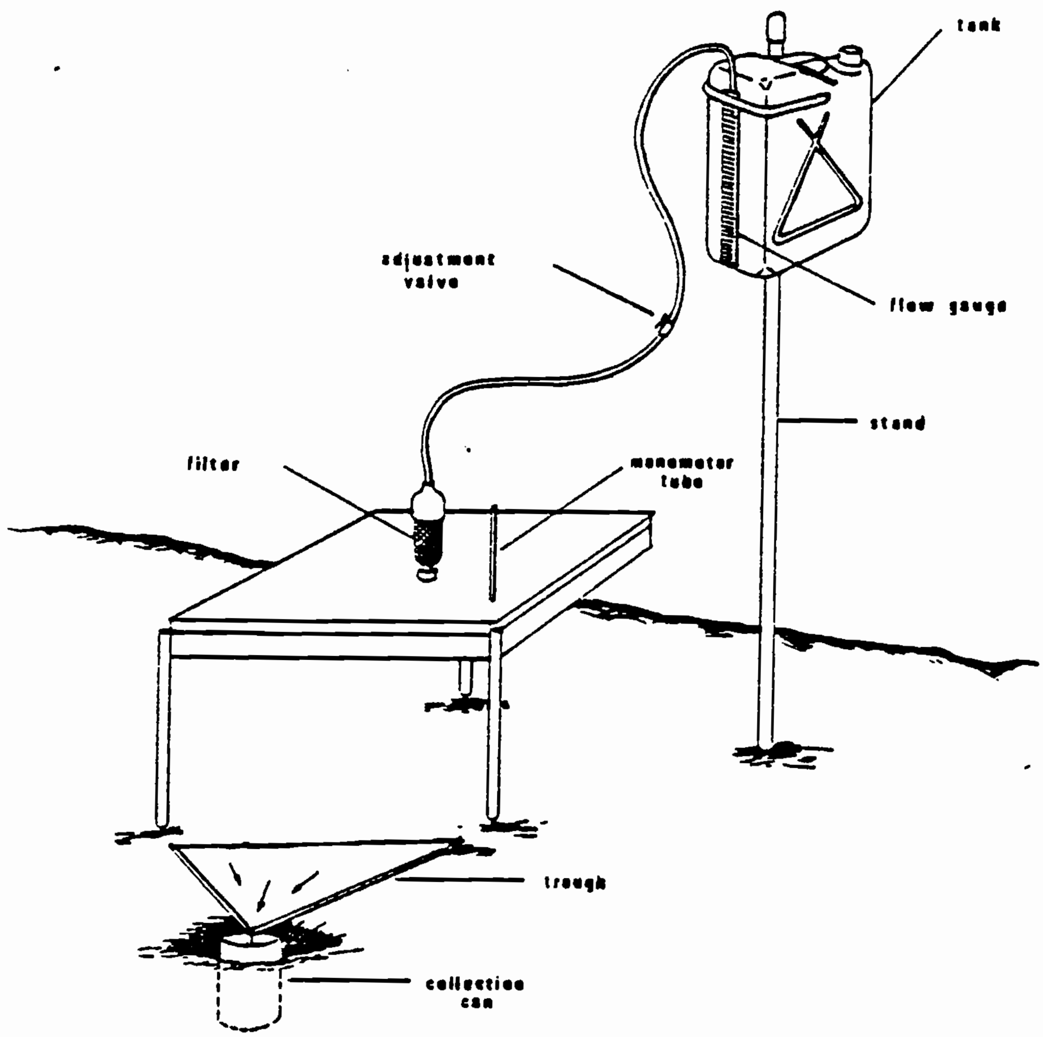

Figure 4. Schematic of the infiltrometer used in this study.

hydrophobic effects were most pronounced, simulated rainfall was applied at a rate of 17.8 cm/hr. An estimate of the maximum rate at which water could pass through the soil surface was needed to evaluate the reductions produced by the various skidders. These measurements established a starting reference point from which to assess changes produced by logging disturbance. For both these pre-disturbance tests, one plot was established for each of the trails under study for that sampling period.

After 20 trips had been completed by a skidder on one of the trails, three post-disturbance infiltration measurements were made. Plot locations which appeared representative for the trail as a whole were chosen in the left and right track positions and in the center of the trail. Since the trails were intentionally located on sites with very little slope, use of this infiltrometer was restricted to the parts of the trails with the steepest gradient. This allowed runoff to be easily collected by the trough. In order to reduce the chance of sampling plots which did not typify the trails, they were never located immediately adjacent to one another across a given trail. The surface of the plots were smoothed to remove large ruts which would channel runoff water. Water was applied at a rate of 7.6 cm/hr on all post disturbance plots.

The plots were first pre-wet with 7.6 liters of water at a rate of 7.6 cm/hr to assure relatively uniform conditions between treatments. This water was then allowed to drain into the profile for 15 minutes prior to the actual infiltration test. During this time, a small pit was dug just below the end of the runoff trough. A large metal can was placed in the pit, under the lip of the trough, to collect runoff. When the infiltration test was started, the time was recorded. Runoff was then measured and recorded at the end of three minute intervals though-out the duration of the test. This was accomplished by switching metal cans at the correct time and measuring the runoff in a 500 ml graduated cylinder. Water was applied to the plot until the infiltration rate had stabilized; this generally required 20 to 30 min. When stabilization had occurred, runoff water and sediment from a three minute sample were poured from the graduated cylinder into a clean turbidity bottle and packed for later analysis in the laboratory. These samples provided a crude erosion index for the various trails (Johnson 1978).

After the infiltration test had been completed, a sample of the organic matter and mineral soil mix in the surface five cm of the plot was placed in a labeled plastic bag. When time permitted, the lower third of the plot was dug away to expose the wetting front which had developed. Descriptions and sketches were made to reveal where the restricting layer for water movement was located.

Soil Sampling Techniques

An impact type bulk density sampler, similar to the standard Uhland soil core sampler, was used to obtain relatively undisturbed soil samples for porosity and conductivity measurements. The samples were taken in brass rings which were six cm in length and 5.36 cm in diameter. Spacers were put at both ends of this ring in the steel cutting cylinder to prevent sample damage. The corer was driven into the soil with a special hammer which slid up and down a section of galvanized pipe attached to the steel cylinder. This sampler has proven to be useful in several experiments on forest soils (Ranken 1974, Yee 1975, Johnson 1978).

After the steel cylinder had been driven into the soil, a shovel was used to carefully dig around its sides and below its bottom cutting edge. Then a trowel was pushed under the bottom of the cylinder to allow the sample to be removed with as little disturbance as possible. This was particularly important for the non-cohesive soils found at Yuba and Pliocene. If after inspection, the core appeared to be free of large rocks, roots, and chunks of rotten organic matter, and was removed intact, the packaging process began. First the core was forced out of the cylinder and the spacer rings were carefully removed. Excess soil was scraped away with a knife blade and small roots were trimmed with a knife or scissors. When the soil surfaces were flush with the edge of the ring, the core was wrapped in a double layer of cheesecloth on one end and a sheet of plastic on the other. These were held in place with rubber bands. The core was then placed in a plastic bag which was tied to prevent moisture loss. Finally, the core was put in a soil can to protect it during transport.

Even with this level of field care, the sampling procedure used may have caused unexpected problems. The soil cores were taken, for the most part, in soils which were so dry that shattering of the structure probably occurred to some extent.[1] Just how serious of a concern this was is not known.

Samples taken prior to compaction were obtained either directly in a skid trail, or immediately adjacent to the trail if a skidder had

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[1]Personal communication with Mr. David McNabb, Watershed Specialist, Forestry Intensified Research (FIR), Oregon State Univ. Extention.

started its runs. These pre-disturbance cores were taken in two positions in the soil profile. The litter layer was carefully scraped away and surface cores were obtained where the A_1 horizon began. To sample the most dense, and hence the most restrictive layer for water movement into the near surface part of the profile, cores were also taken at a depth of 30 cm below the start of the A_1 horizon. One surface and one subsurface core was obtained for each of the trails in this study.[2]

After 20 trips on each trail, post-disturbance cores were taken from two positions in the soil profile. The surface powdery mixture of organic material and mineral soil was removed so that surface cores were acquired in firm soil. Subsurface cores were taken in the layer 6 to 12 cm below the surface of the firm, compacted soil. It was hypothesized that this was the zone of maximum compaction and the greatest restricting barrier to water movement. Both surface and subsurface post-disturbance cores were always taken in positions which represented maximum compactive effort by tracks or wheels. Also, as with the pre-disturbance cores, one surface and one subsurface core was obtained for each of the 36 trails.

Soil Disturbance

For each of the 36 trails, a representative cross section was established by driving nails into trees on either side and stretching a cloth measuring tape horizontally between them. Prior to disturbance, the distance from at least eight points on this tape to the start of the

[2] Due to exceptionally rocky conditions at Pliocene and large roots at Bullards, there were missing samples at the 30 cm depth.

A_1 horizon was recorded. After 20 trips, the tape was restrung and the distance from it to the start of the loose mineral soil was recorded for the same points, as well as for important high and low points. The amount of displacement was found by calculating the difference in initial and post-disturbance end areas.[3]

Sampling Done After one Over-Wintering Period

The four sites were revisited for one week in late June, 1980 to study possible recovery from compaction, erosion problems, and revegetation. Air permeability measurements were made at each of the original ten plots on every trail.[4] Standard infiltration tests, as were described earlier for post-disturbance plots, were done on four trails at Moonshine, three trails at Bullards, and one trail at Pliocene. The three plots per trail were located in approximately the same positions used during the previous summer. Descriptive and photographic records were made of revegetation by grasses and forbs. Trails were carefully examined for rilling and gullying as signs of surface erosion from winter storms and spring snowmelt. Also at this time, new soil core samples were taken at Bullards and Pliocene to replace those taken the previous summer which had unreasonable conductivities due to high organic matter content.

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[3] Mr. David Lysne and Ms. Mary King did this field and computational work.

[4] One trail at Yuba was covered with snow and was not remeasured.

Laboratory Analysis

Oven Dry Soil Weight

Soil moisture samples collected during the initial sampling period were dried in a microwave oven. Approximately 30 grams of soil were placed in glass petri dishes and dried for at least ten minutes. Samples from the second and third test periods were dried in a conventional 105°C oven for 24 hours prior to weighing.[5]

Turbidity and Suspended Sediment Concentration

Turbidity measurements were made with a Hach Model 2100A Turbidimeter. The day prior to analysis, the turbidity bottles were shaken and stirred to resuspend colloidal particles. Immediately prior to pouring 25 ml samples, the sediment in the bottles was gently resuspended by stirring to avoid air bubble introduction. These samples were diluted with distilled water until readings between 0 and 100 ntu (nephelometric turbidity units) could be made. Multiplying by the number of dilutions allowed these readings to be converted back to the true sample turbidities (APHA 1976).

Suspended sediment concentrations were determined with a Millipore filter system and glass filter papers. The turbidity bottles were again shaken and 100 ml were immediately poured into a graduated cylinder. A vacuum pump pulled this water through the funnel, leaving the sediment on the glass filter. Distilled water was used to wash sediment from the bottom of the graduated cylinder and the edges of the funnel onto the

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[5] Mr. J. Azevedo did this work.

filter. The filter papers were then dried in a 105°C oven for one hour, cooled in a desiccator, and weighed. After subtracting the tare for the filter, the weight of the sediment was known. This number was then converted to milligrams per liter.

Organic Matter Content

The samples taken in the surface five cm of the infiltration plots were frozen upon arrival at the laboratory to prevent biological growth or decay. When all the field work was completed, the samples were thawed, dried in a 105°C oven, and stored in plastic bags. In groups of six, they were divided in a soil splitter until two samples of approximately 100 grams were left. After redrying these samples in a 105°C oven for 24 hours and getting an oven dry initial weight, they were placed in porcelain dishes of known weight. These dishes were then put in a muffle furnace and burned for nine hours at 550°C. In order to get complete combustion, the samples were removed from the furnace after five hours and carefully stirred. After weighing the remaining soil and ash mix, the organic matter content could be calculated. The two samples were averaged for each plot. The organic matter content of the mineral soil was determined by both the muffle furnace method and by the Walkley-Black organic carbon technique.[6]

Soil Classification

Initial sieving of large soil samples in the laboratory indicated the percentage of rock greater than 6.4 mm in diameter at each site.

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[6] The Walkley-Black values were provided by the Pacific Northwest Forest and Range Experiment Station, Corvallis, Oregon.

Mineral soil from the surface 30 cm of the profiles which passed a 6.4 mm sieve in the field was used for the other procedures described. To determine the standard USDA textural classes for these soils, a hydrometer test (ASTM D422-63) was performed on the fraction smaller than two mm. Air dry 50 gram duplicate samples were treated with concentrated hydrogen peroxide to remove the organic matter. After drying and getting a corrected weight, a five percent solution of sodium pyrophosphate was added to the samples. Several days were then allowed for aggregate dispersion. Next, the samples were placed in a malt mixer and agitated for 15 minutes. Dilution with distilled water followed until the volume of soil and water reached 1000 ml. Hydrometer readings were taken at 1, 2, 4, 8, 15, 30, 60, and 120 minutes in a standard cylinder (Bowles 1970).

For the fraction greater than 0.074 mm, a nested set of sieves were used to determine the particle size distribution. In order of decreasing opening size, the sieve sizes were: 4.76, 2.00, 0.841, 0.420, 0.250, 0.105, and 0.074 mm. Prior to sieving, samples of approximately 200 grams were treated with a five percent sodium pyrophosphate solution for 12 hours. Wet sieving was then done to wash out particles smaller than 0.074 mm. The remaining material was dried in a 105°C oven for 24 hours, weighed, and placed in the seven sieve nest (ASTM D422-63). The samples were not pulverized because of the soft, crumbly rock present in the soil from both Bullards and Pliocene.

To describe the plasticity of the four soils, Atterberg limit tests were performed.[7] The liquid limit is arbitrarily defined as "...the

[7] These tests were done by Mr. D. Lysne.

water content at which 25 blows of the liquid limit machine closes a standard groove cut in the soil pat for a distance of 12.7 mm" (Bowles 1979). This test (ASTM D-423) was done on five samples for each site and the results averaged. Similarly, the plastic limit test (ASTM D-424), which requires the water content at which a ribbon of soil crumbles when rolled to a diameter of three mm, was performed on five samples for each site and the mean reported. The results of these tests allowed the soils to be placed in the Unified Classification System used in soils engineering.

Soil Proctor Curve Analysis

Standard Proctor curves (ASTM D-698) were produced for each of the soils.[8] An automated Proctor machine (Soil Test, Inc.) was used for this research. After compacting each of the three layers of soil with 25 blows and weighing, the compressed cylinder was forced out of the mold. Soil samples from several locations in this block were placed in petri dishes and dried for 24 hours at 105°C. Dry bulk densities were then calculated. Soils with at least 12 different moisture levels were compacted for each of the four sites. This allowed very accurate curves to be drawn and revealed the optimum moisture content for maximum compaction with this energy input.

Hydraulic Conductivity

When the field work was completed, the soil cores were stored in a 4°C cold room to prevent bacterial and algal growth which could clog

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[8] These tests were done by Mr. J. Azevedo

pores and reduce conductivity (Klute 1965). Before unpackaging the cores, they were allowed to equilibrate to room temperature for at least 12 hours. Then the cores were removed from the soil cans and plastic bags, examined, and prepared for saturation. The cores were saturated in deaired water in a large steel tray for at least 16 hours. Water was deaired by placing 60 cm of mercury suction on 18.9 liters for 30 minutes. A magnetic stirrer was used to create sites for bubble formation and resulted in efficient gas removal. This method was found to be superior to boiling water to remove dissolved oxygen.

A constant head permeameter was used to determine saturated hydraulic conductivity (Figure 5). Cores, with double layers of cheesecloth placed over both ends, were individually removed from the saturation tray, placed in a deep basin filled with water, and inserted into the permeameter. The inlet end of this device is located below where the core is positioned, and the outlet end is above the core. This ensures that water moves through all the soil pores. In an attempt to simulate natural conditions, water was forced through the core as it would flow through the soil profile; the top end of the core was therefore placed at the bottom of the permeameter. By putting the core in the permeameter under water and clamping it tightly in place, nearly all air was kept out of the system.

The permeameter was removed from the basin and set next to the ringstand holding the constant head reservoir. The hydraulic head was determined by measuring the distance between the top of the reservoir and the top of the outlet pipe. The lowest head which resulted in a moderate amount of flow from the permeameter was utilized. Undisturbed

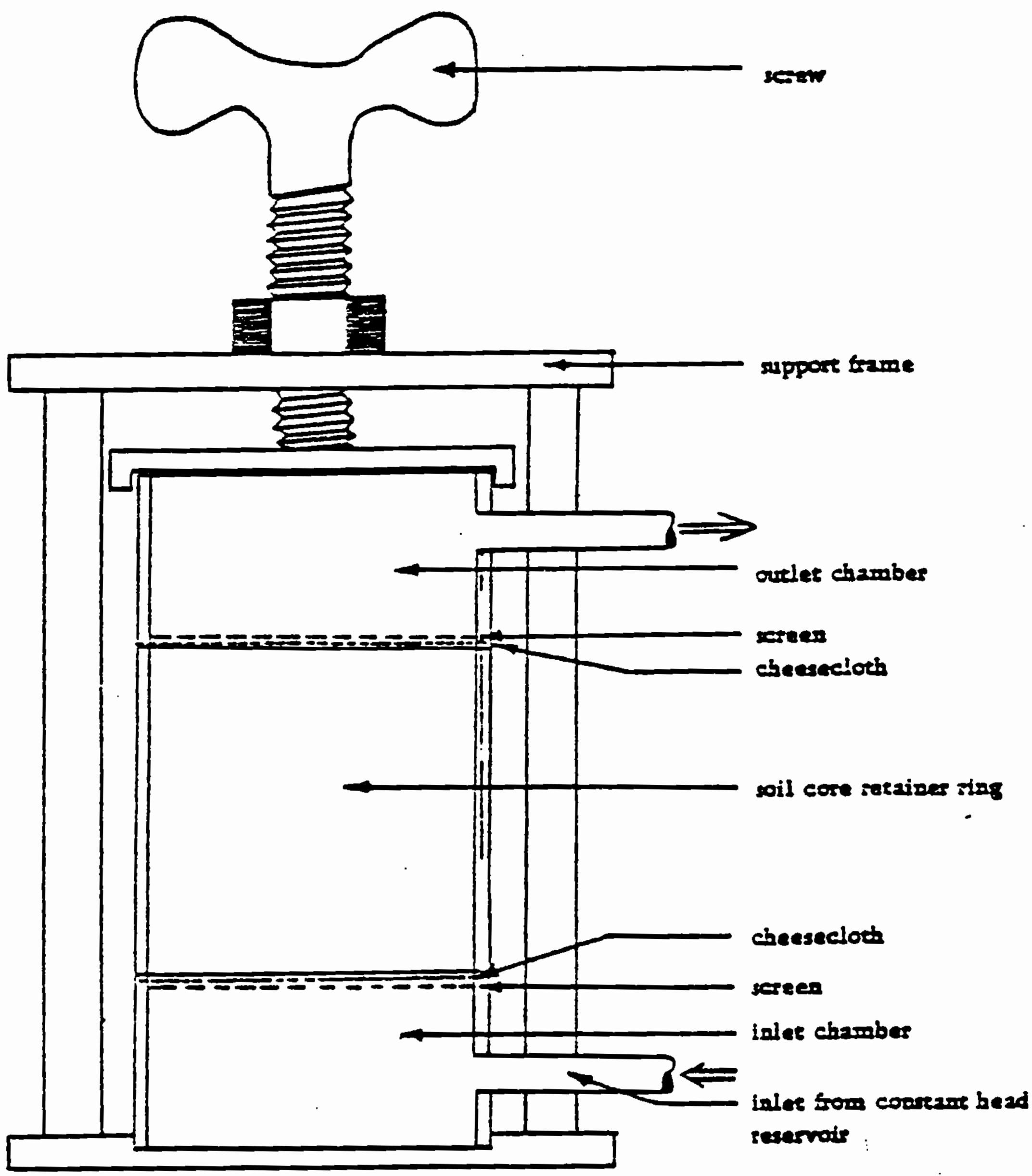


Figure 5. Constant head permeameter frame with soil core retainer ring in place (after Ranken 1974).

samples required heads of as little as six cm, while extremely compacted cores demanded heads of up to 77 cm. The reservoir was set at what was estimated to be a reasonable head for the core being studied and the clamp blocking the flow from the reservoir to the permeameter was removed. If the flow was excessive or nonexistent, the reservoir height was adjusted.

When a reasonable amount of flow was being collected and sufficient time for equilibration had passed, the first test was begun. A stopwatch recorded the length of time water was allowed to flow into a beaker. Times ranged from 30 to 180 seconds, depending on the quantity of water collected. The temperature of the water which passed through the core was measured as well. A second test was run and its results were compared with those of the first test. If there was considerable disagreement, a third test was done to accurately establish the conductivity. With the completion of the tests, the core was removed from the permeameter and put back in the saturation tray.

Moisture-Tension Relationships

After the saturated conductivities of a group of cores had been determined, total porosity measurements were made. Ranken's (1974) C-clamp method was used. This device simply consists of a large C-clamp with brass plates welded on each end (Figure 6). A saturated core was placed in the deep basin used previously for the permeameter, and the clamp was tightened over the core under water. Both the clamp and the brass retaining ring were carefully towel dried before weighing. After weighing, the cores were placed on prepared tension tables.

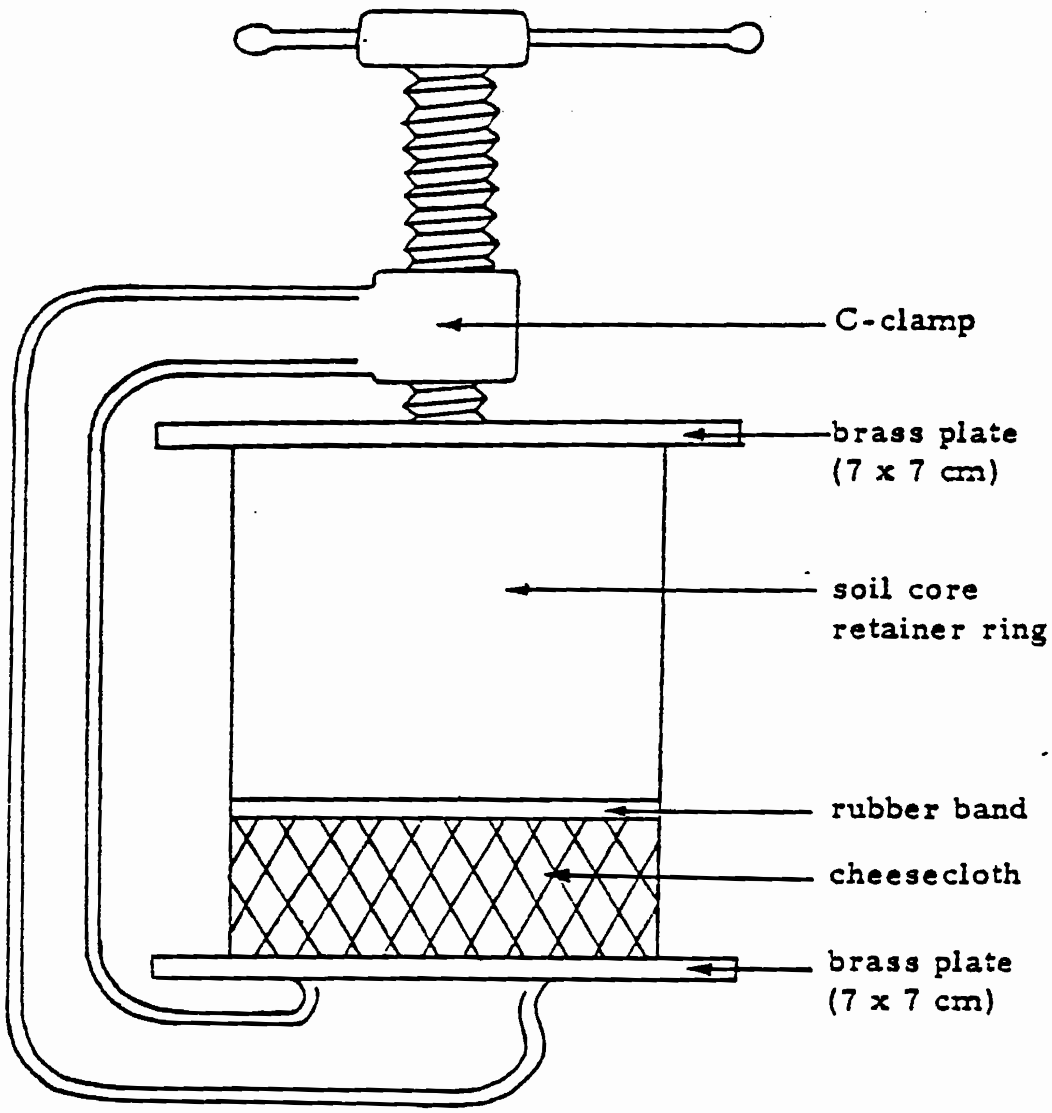


Figure 6. C-clamp apparatus (after Ranken 1974).

Tension tables provide a simple method for determining drainage characteristics of soil cores at low suctions (Leamer and Shaw 1941, Vomocil 1965). Based on the hanging water column concept, tensions of up to 100 cm of water are possible. Calculations of the mean pore radius drained at a given tension can be easily made with the capillary rise equation. Macropore space can be computed by subtracting the moisture content of a sample subjected to 60 cm of tension from the moisture content when the core is completely saturated (Appendix B).

The tension tables used in this study consisted of a Plexiglas box with a hinged cover and a 6.4 mm drainage pipe embedded in the bottom. Tygon tubing connected the outlet on the table to glass tubing inserted in a cork, which in turn was placed in a 500 ml Erlenmeyer flask (Figure 7). The tension applied was found by measuring the vertical distance between the outlet on the flask and the midpoint of the soil cores. In order to achieve a uniform distribution of suction, a nylon screen was placed over the Plexiglas bottom. A 36 X 51 cm sheet of clean, thick blotter paper was positioned over the screen to hold the column of water up. The pores in the blotter paper are small enough to prevent the menisci from being broken, and yet still allow rapid water movement through the system (Leamer and Shaw 1941).

The tension tables were set up in the following manner. First, the Erlenmeyer flask was positioned on a ring stand so that the appropriate tension would be applied. Deaired water was then slowly poured over the blotter paper to a depth of approximately one cm, with the tygon tubing clamped. The blotter paper was smoothed and pressed firmly against the screen with a hard rubber roller to remove air bubbles. The clamp was

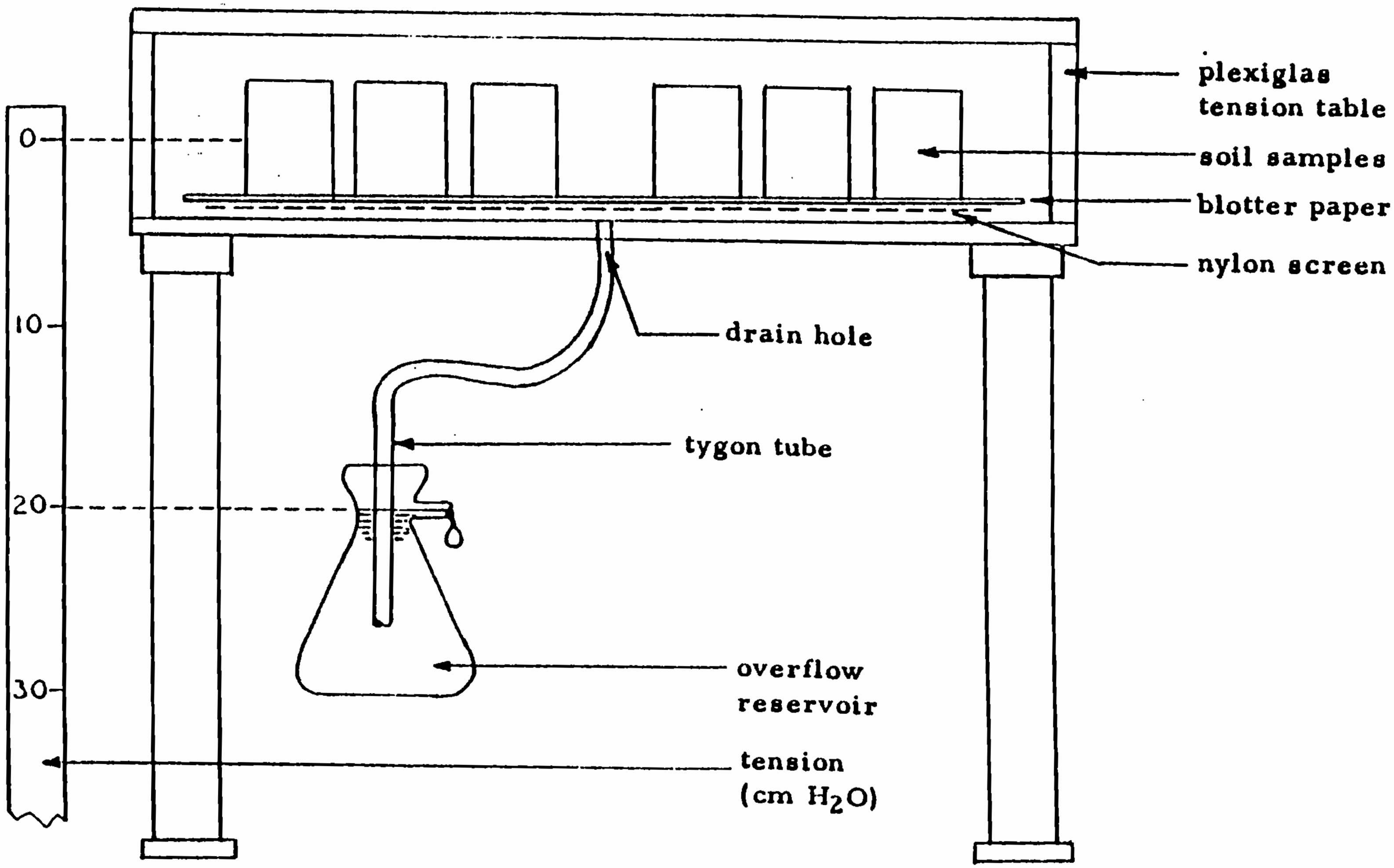


Figure 7. Tension table (after Ranken 1974).

opened and water was allowed to flow through the tubing, into the already full flask, and through the outlet to a beaker on the floor. When water stopped dripping from the flask's outlet and the column held, the table was ready to have cores placed on it.

The soil cores were subjected to suctions of 10, 20, 30, 50, and 80 cm of water. Groups of 18 to 21 cores were brought through the progression together. Cores were left on the tables to equilibrate for 48 hours at the lower three tensions and 72 hours for the higher tensions. Masking tape was used to seal the Plexiglas lid to minimize evaporation from the cores. When equilibration was reached at the ten cm tension, the tygon tubing was clamped, the masking tape removed, and the cores placed on damp towels. Individually, the exterior portion of a core was dried and its weight recorded. After this had been done for an entire group, they were placed on a previously prepared table set at 20 cm. This process was followed for the succeedingly higher tensions. Since silt and clay particles from the cores clog pores in the paper and reduce water transmission, clean blotters were used after each run.

When the last core in a group was weighed after equilibrating at 80 cm, the oven dry weight of the soil in the cores was determined. The soil from the brass ring was carefully removed and placed in a soil can of known weight. Soil was also removed from the cheesecloth and put in the can. The soil was then dried for 48 hours in a 105°C oven. Lids were placed over the cans, and they were allowed to cool prior to weighing. Tare weights for the brass ring, rubber bands, and cheesecloth were obtained after drying for one hour. Sample calculations for total porosity and moisture contents at the various tensions are found in Appendix B. Drainage curves were drawn and studied for each core. It was from these curves that the 60 cm moisture contents used in calculating macroporosity were obtained.

Complete soil-moisture characteristic curves commonly extend to 15 bars of suction. This allows the available water capacity of a soil for plant use to be determined. Soil texture, and not structure, controls the amount of water which can be held at higher tensions (Hillel 1971). Therefore, disturbed samples of mineral soil from all four sites were subjected to suctions of 1/3, 1, 3, 5, 10, and 15 bars.[9] A pressure plate apparatus was used for the lower two tensions, while a pressure membrane setup was used for the higher tensions.

Statistical Analysis

This study utilized a split plot design. The four sites sampled at three different moisture levels constituted the major treatment. Randomly assigning the three machines to the three subplots at each site made up the minor treatment. The experimental design can thus be illustrated as follows:

Source		d.f.
Site		3
Moisture		2
Site X Moisture (Error A)		6
Machine		2
Moisture X Machine		4
Site X Machine Site X Moisture X Machine	(Error B)	18
Total		35

[9] This work was done by the Oregon State University Soil Testing Laboratory.

If the analysis of variance revealed significant (alpha = 0.10) machine differences and the moisture X machine interaction term was not significant, Duncan's Multiple Range Test was used to compare vehicle types. Similarly, if the analysis of variance indicated that significant site differences existed, Duncan's test was used to compare sites. It must be realized that the analysis of variance performed was only an approximate test, since there were no replications of the major treatments.

Due to the highly variable nature of forest soils, significance in this thesis refers to an alpha level of ten percent. If higher significance was found, differences in means were reported at that alpha level. Unpaired t-tests were used to compare the track and center position values for a measured property of a given vehicle. Paired t-tests were used to compare conductivities and porosity levels before and after treatment for a given vehicle, as well as to determine if the sites had undergone recovery after one over-wintering period.

RESULTS AND DISCUSSION

Bulk Density Measurements

Changes in the Surface Layer

Analysis of the nuclear probe bulk density values revealed that the greatest change took place in the surface five cm layer (Figure 8). It was in this part of the soil profile that the energy applied, both from dynamic pressure and vibration, caused the largest reduction in the void ratio. Plotting absolute bulk density values against depth showed that the trails from all the vehicles ended up with similar densities at the five cm depth. The change in bulk density, however, was found to be significantly different by vehicle type, since the crawler tractor trails were initially less dense than those for the other two vehicles (Table 5). The crawler tractor compacted the surface five cm approximately 35 percent more than either the torsion suspension vehicle or the rubber-tired skidder (sign. at alpha = 0.05).

When considering only the outer two plot positions (i.e., those located at 0.5 and 3.2 m across the trail), the change in bulk density at the five cm depth was nearly the same for each of the three machines. Apparently, the soils at that depth received sufficient energy after 20 trips to negate any differences in ground pressure between vehicles. Inner plot positions for the trails, in contrast showed differences between machines. Crawler tractor trails had significantly higher densities for the inner plots when compared to the torsion suspension vehicle and rubber-tired skidder trails. In fact, densities for the inner plots

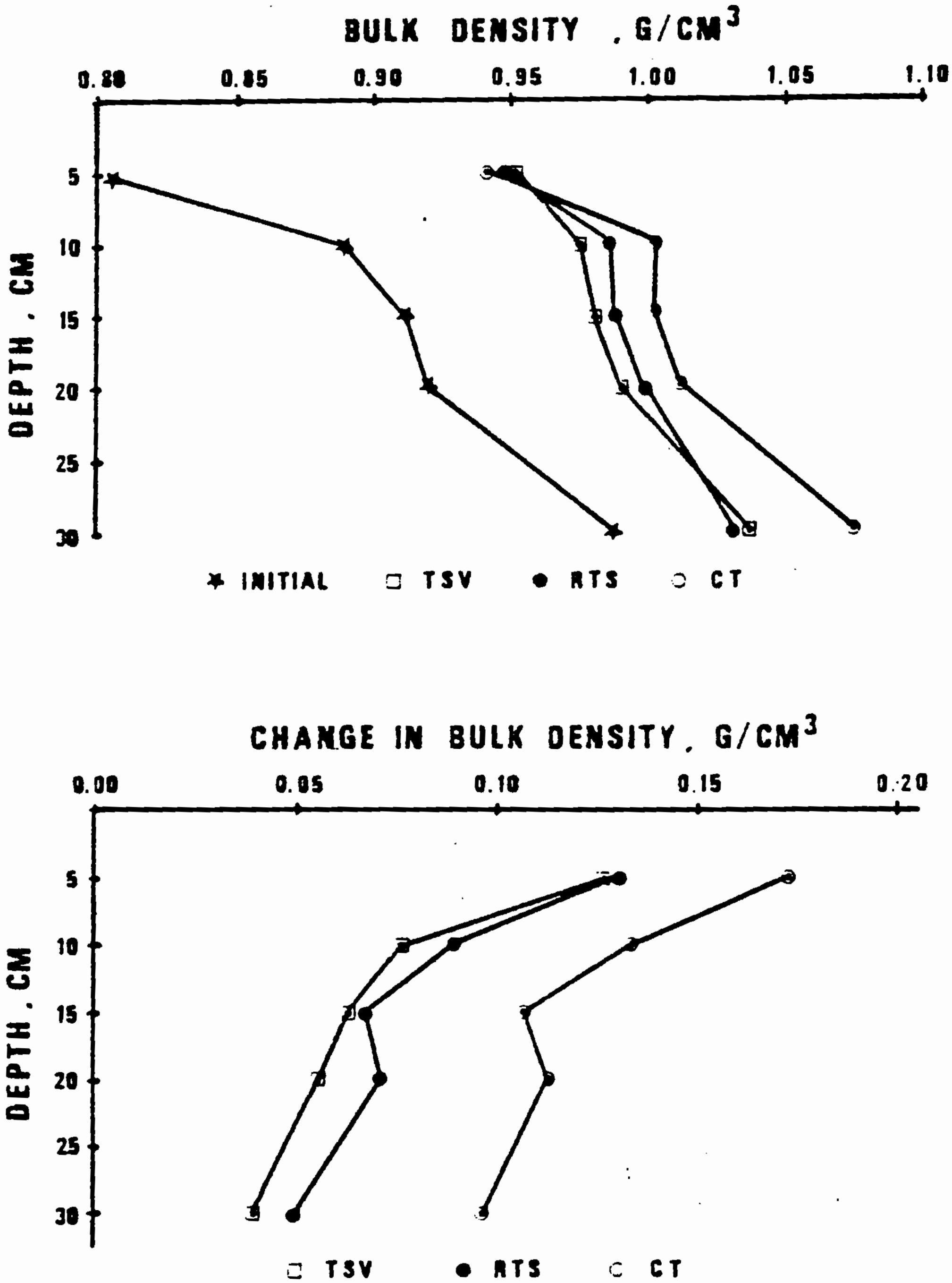


Figure 8. Mean absolute bulk density values and change in bulk density for all four sites plotted against depth.

Table 5. Change in bulk density in the surface five centimeters (g/cm^3).

Trail Means[a]

	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[b]
CT	0.256	0.119	0.178	0.139	0.173	b
TSV	0.191	0.060	0.130	0.129	0.127	a
RTS	0.162	0.120	0.135	0.105	0.130	a
	0.203	0.100	0.148	0.124		

Outer Positions

	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[c]
CT	0.222	0.099	0.172	0.131	0.173	a
TSV	0.202	0.081	0.173	0.170	0.165	a
RTS	0.185	0.145	0.169	0.119	0.151	a
	0.203	0.108	0.171	0.140		

Outer vs. Inner Positions[d]

	CT	TSV	RTS
Outer	0.173	0.165	0.151
Inner	0.173[NS]	0.091*	0.107[NS]

[a]Trail includes all four plot locations.

[b]Means with the same letter are not significantly different at alpha = 0.05.

[c]Means with the same letter are not significantly different at alpha = 0.10.

[d]NS denotes no statistical difference at alpha = 0.10.
* denotes statistical difference at alpha = 0.10.

of the crawler tractor trails were nearly identical to those for the outer positions, indicating uniform compaction across the trail. The torsion suspension vehicle and the rubber-tired skidder, on the other hand, showed lower compaction for the inner plots than for the outer plot positions. This difference was only significant for the torsion suspension vehicle.

Part of the variation between machine impacts on the trail inner plots could have resulted from differential disturbance and excavation caused by the turn of logs being pulled. The torsion suspension vehicle's turn was hoisted higher off the ground than the crawler tractor's; the rubber-tired skidder's turn was only approximately one half as large as that pulled by the other two vehicles. Probably even more important were the machine dimensions themselves. The rubber-tired skidder and the torsion suspension vehicle are wider than the crawler tractor. To physically stay within the trail boundaries established and yet alter the track position, a wider vehicle leaves more of the center of the trail undisturbed by track or wheel pressure (Figure 9). Therefore, the chance of a machine tracking on the two inner plots was marginally greater with the crawler tractor than with the other vehicles.

The progression of compaction with increasing numbers of trips is shown for the surface layer in Figure 10. This graph indicates the magnitude of the initial densities for each of the vehicle's trails. After 20 trips, the trails for all three machines had mean densities at the five cm depth of approximately 0.95 g/cm^3. The soils apparently rapidly increased in strength with compaction and successive trips with the

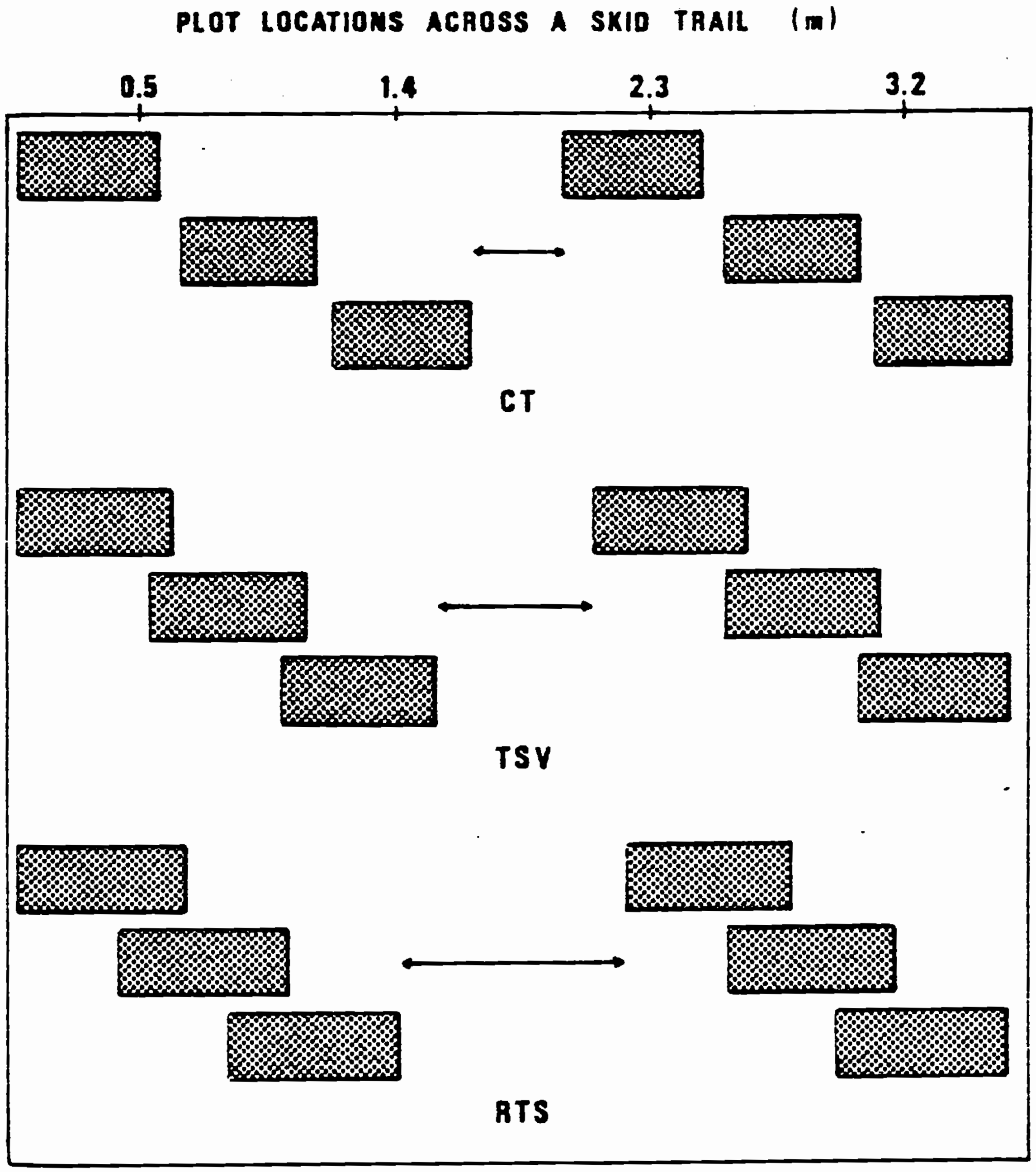


Figure 9. Hypothetical stretch of a skid trail showing representative track (blocks) and center (arrows) areas for the three vehicles.

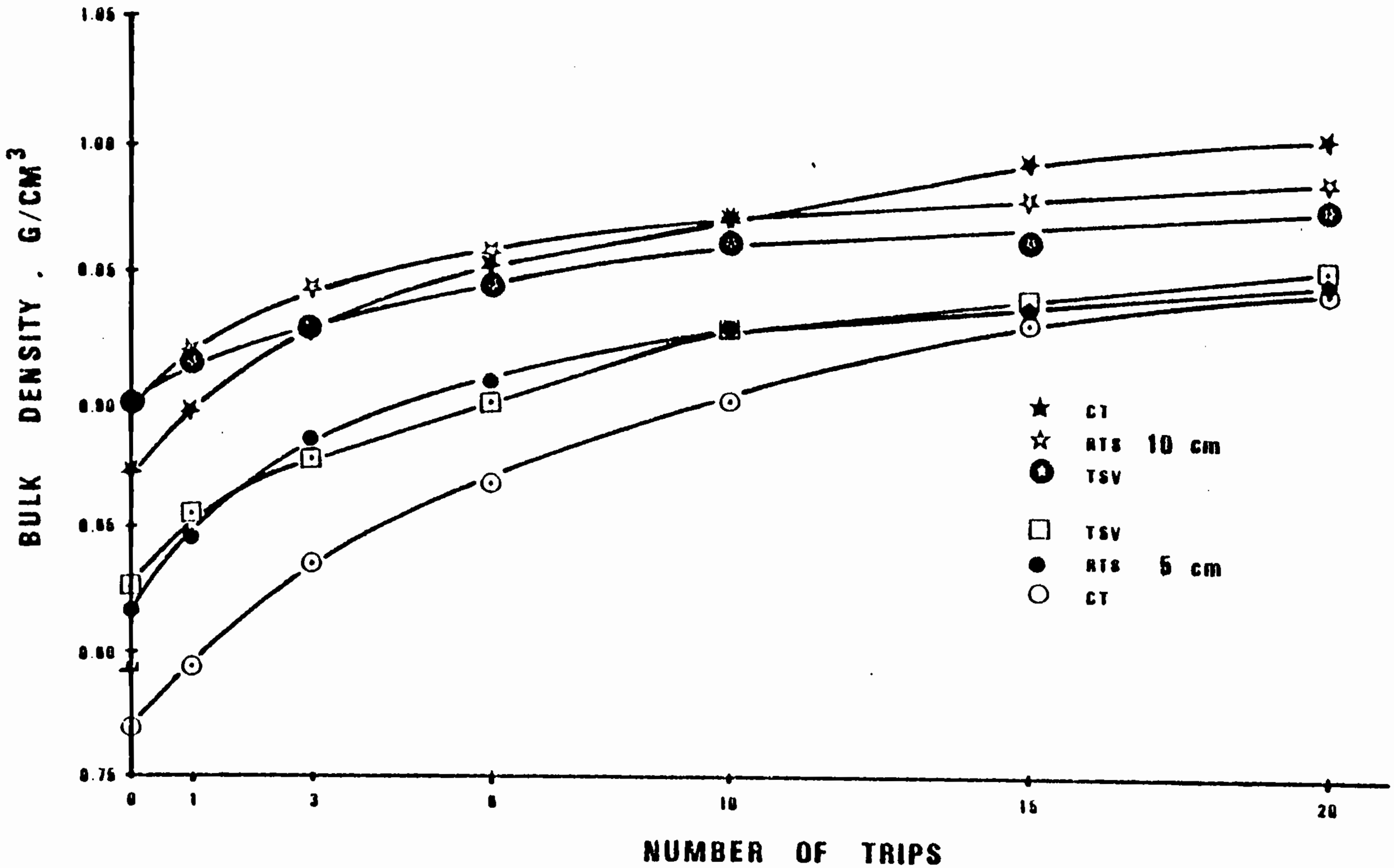


Figure 10. Mean bulk density values for all four sites plotted against number of trips (five and ten centimeter depths).

machines produced progressively smaller increases in soil density.

Changes at Ten Centimeters in Depth and Greater

Differences in the amount of compaction produced by the three machines were more distinct at the ten cm depth. When considering trail means, the crawler tractor caused a 74 percent larger increase in density when compared to the torsion suspension vehicle, and 51 percent more compaction than the rubber-tired skidder (Table 6). It appears that it is at this depth that the effects of vehicle differences in ground pressure and vibration readily show up. Analysis of variance revealed that there were no statistical differences in the compaction levels produced by the vehicles when only the outer two plot positions were included. Similarly, no significant differences could be found between the outer and inner positions for any of the vehicles. As was seen with the five cm depth values, however, the crawler tractor produced much more uniform compaction over the trail than either of the other machines.

When plotting density values for the trail means against the number of trips at the ten cm depth, a new pattern emerges (Figure 10). The crawler tractor trails, even though starting with the lowest density values, now ends up after 20 trips with the highest values. Although the absolute bulk densities with 20 passes are not significantly different, the change in bulk density between zero and 20 trips certainly did differ.

At the 15 cm depth and greater, changes in density closely followed the pattern described for the ten cm zone (Figure 8). The crawler

Table 6. Change in bulk density at a depth of ten centimeters (g/cm^3).

Trail Means[a]

	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[b]
CT	0.152	0.114	0.131	0.137	0.134	b
TSV	0.120	0.071	0.064	0.054	0.077	a
RTS	0.128	0.108	0.085	0.037	0.089	a
	0.133	0.098	0.093	0.076		

Outer Positions

	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[c]
CT	0.139	0.116	0.136	0.134	0.134	a
TSV	0.133	0.090	0.085	0.067	0.095	a
RTS	0.150	0.144	0.112	0.031	0.109	a
	0.141	0.117	0.111	0.077		

Outer vs. Inner Positions[d]

	CT	TSV	RTS
Outer	0.134	0.095	0.109
Inner	0.133[NS]	0.057[NS]	0.067[NS]

[a] Trail includes all four plot locations.

[b] Means with the same letter are not significantly different at alpha = 0.01.

[c] Means with the same letter are not significantly different at alpha = 0.10.

[d] NS denotes no statistical difference at alpha = 0.10.

tractor trails had a 66 percent larger increase in density than the torsion suspension vehicle and rubber-tired skidder trails at 15 cm and a 102 percent larger increase at 30 cm. At the latter depth, however, vehicle differences were again less distinct (sign. at alpha = 0.05). The fact that compaction occurred even at 30 cm is important and indicates how much of the soil profile has its pore size distribution altered by this process. Nevertheless, since the largest change in density occurred in the surface ten cm, values from this zone received the most attention for this part of the study. Restricting layers for water and air movement which could change the hydrologic regime of these soils were located in this ten cm zone.

Differences in Compaction by Site

Due to the high variability encountered in calculating the change in bulk density, no significant differences in levels of compaction were found when comparing the four sites. Mean changes at each site, however, illustrate how susceptible the various soils were to compaction (Table 5). Yuba, with its low organic matter and lack of aggregate structure, experienced the largest increases in bulk density. For the surface five cm layer, Pliocene had the least compaction; it is possible that this was due to a thick litter layer and the anamolous compaction properties of soils with moderately high amorphous clay contents (Wada 1977). Extremely low initial bulk densities at Bullards allowed it to undergo moderate compaction in spite of its high organic matter content, thick litter layer, and stable aggregate structure. Conversely, high initial densities permitted only moderate compaction at Moonshine even though its aggregate structure was very weak and organic matter content was not high.

Comparison Between Nuclear Probe and Soil Core Values

The fact that the soil core samples taken for porosity measurements could also be used for soil bulk density measurements allowed a simple comparison between core and nuclear probe density values to be made (Table 7). Vibrations caused by the hammering procedure used in taking the cores, as well as friction along the internal surface of the retaining ring, undoubtedly resulted in artifically high estimates for some of the cores. Also, cores with large rocks and roots were rejected when sampling, while the probe was able to measure a more representative soil layer. Carefully done calibration curves for gauge readings versus bulk density allowed the probe measurements to be accurately converted into wet bulk densities.[10] Additionally, the sample size for the probe was much larger than that for the cores. Therefore, in my opinion, the probe values are the best estimates of the true field densities.

Air Permeability Measurements

Indexing the Compaction Process

Readings with the air permeameter showed that a large percentage of the reduction in macropore space in the surface 2.5 cm of the soil profiles occurred after only a few trips (Figure 11). It is readily apparent that all three vehicles applied sufficient energy to convert macropore space to micropore space in a uniform manner in this zone.

[10] This calibration work was done by Mr. J. Azevedo.

Table 7. Comparison of bulk density measurements using soil cores and the nuclear probe (g/cm^3).[a]

		UNDISTURBED		
		Core		Probe
Yuba				
	0 - 6 cm	1.094	5 cm	0.932
	30-36 cm	1.192	30 cm	1.130
Pliocene				
	0 - 6 cm	0.674	5 cm	0.653
	30-36 cm	0.757	30 cm	0.773
Bullards				
	0 - 6 cm	0.692	5 cm	0.655
	30-36 cm	0.952	30 cm	0.905
Moonshine				
	0 - 6 cm	1.039	5 cm	0.975
	30-36 cm	1.138	30 cm	1.143
		COMPACTED		
		Core		Probe
Yuba				
	0 - 6 cm	1.117	5 cm	1.135
	6 -12 cm	1.172	10 cm	1.190
Pliocene				
	0 - 6 cm	0.775	5 cm	0.752
	6 -12 cm	0.795	10 cm	0.784
Bullards				
	0 - 6 cm	0.831	5 cm	0.802
	6 -12 cm	0.867	10 cm	0.828
Moonshine				
	0 - 6 cm	1.287	5 cm	1.099
	6 -12 cm	1.237	10 cm	1.153

[a]Each value listed for the core method is the mean of 9 samples; Each value listed for the probe method is the mean of 90 samples.

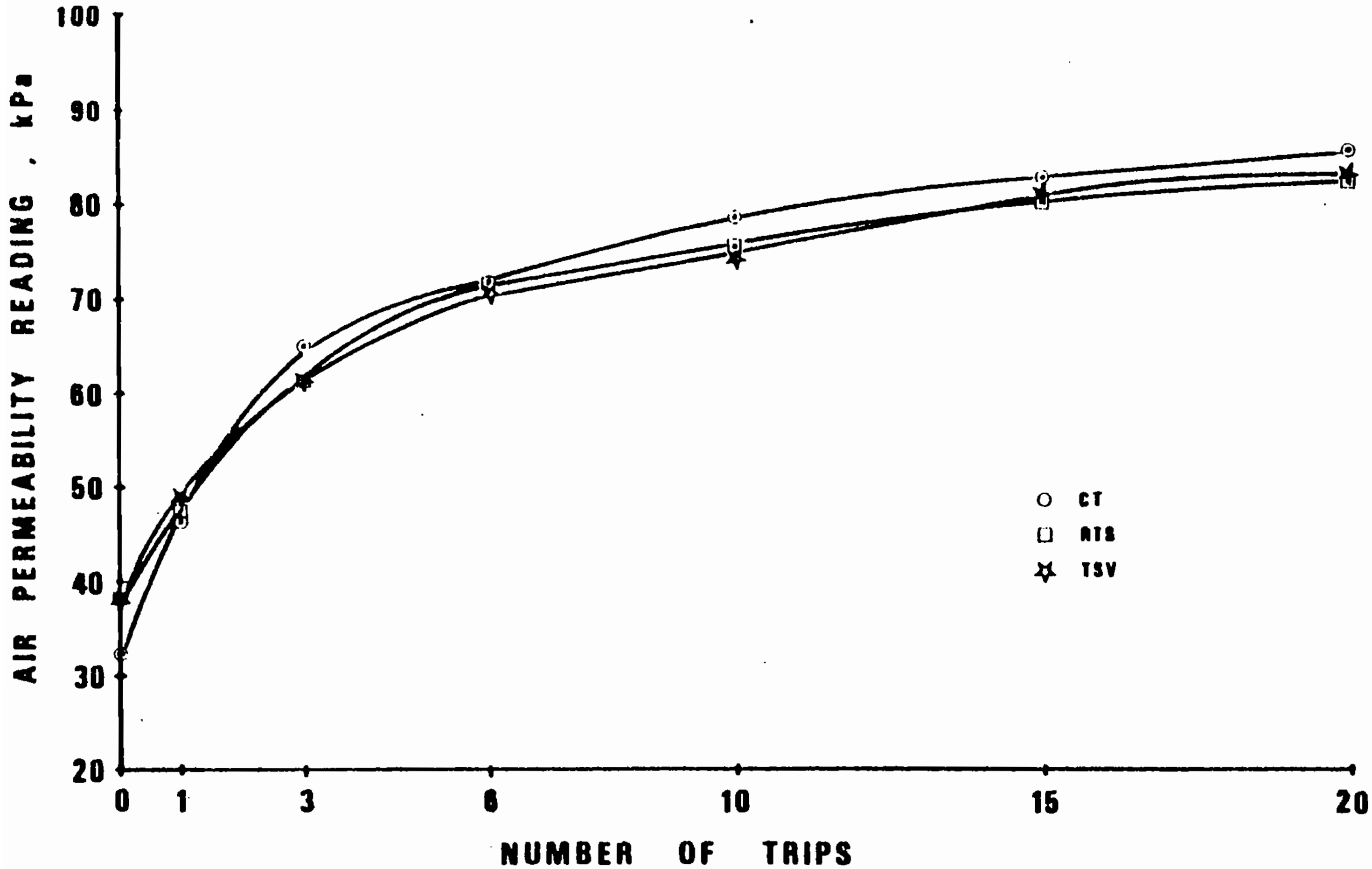


Figure 11. Mean air permeability readings plotted against number of trips.

By six trips, 74 percent of the reduction in macropore space had occurred. After 20 trips, the mean backpressure readings for all the vehicles were slightly over 82.7 kPa (12 psi). Initial readings in the undisturbed state averaged 36.1 kPa (5.2 psi).

The relationship between air permeability readings and bulk density values for the surface five cm zone was investigated. The curves drawn in both Figures 10 and 11 illustrate that compaction, indexed either by bulk density or backpressure readings, occurs to a large extent by the first few trips and then levels off. Therefore, a strong correlation between these two variables would be expected. In fact, regression of air permeability readings against surface bulk density values with simple linear models yielded r^2 values of: Yuba = 0.349, Pliocene = 0.255, Bullards = 0.345, and Moonshine = 0.255. All the relationships were highly significant. These relatively low coefficients of determination can be explained by the high variability of forest soil composition and the large effects this can have on air permeability. That the correlations must be site or soil specific is illustrated by the fact that when values for all the sites were pooled, the added variability decreased the r^2 to 0.192.

When mean bulk density values for a given number of trips were plotted against the mean air permeability for the same trip numbers, extremely good linear relationships were seen for each site (Figure 12). Over 94 percent of the variability was accounted for with these models. The slopes on the least squares fit lines were nearly identical for Pliocene, Bullards, and Moonshine. Yuba's slope was only found to be half as great. Possible explanations for this difference include the

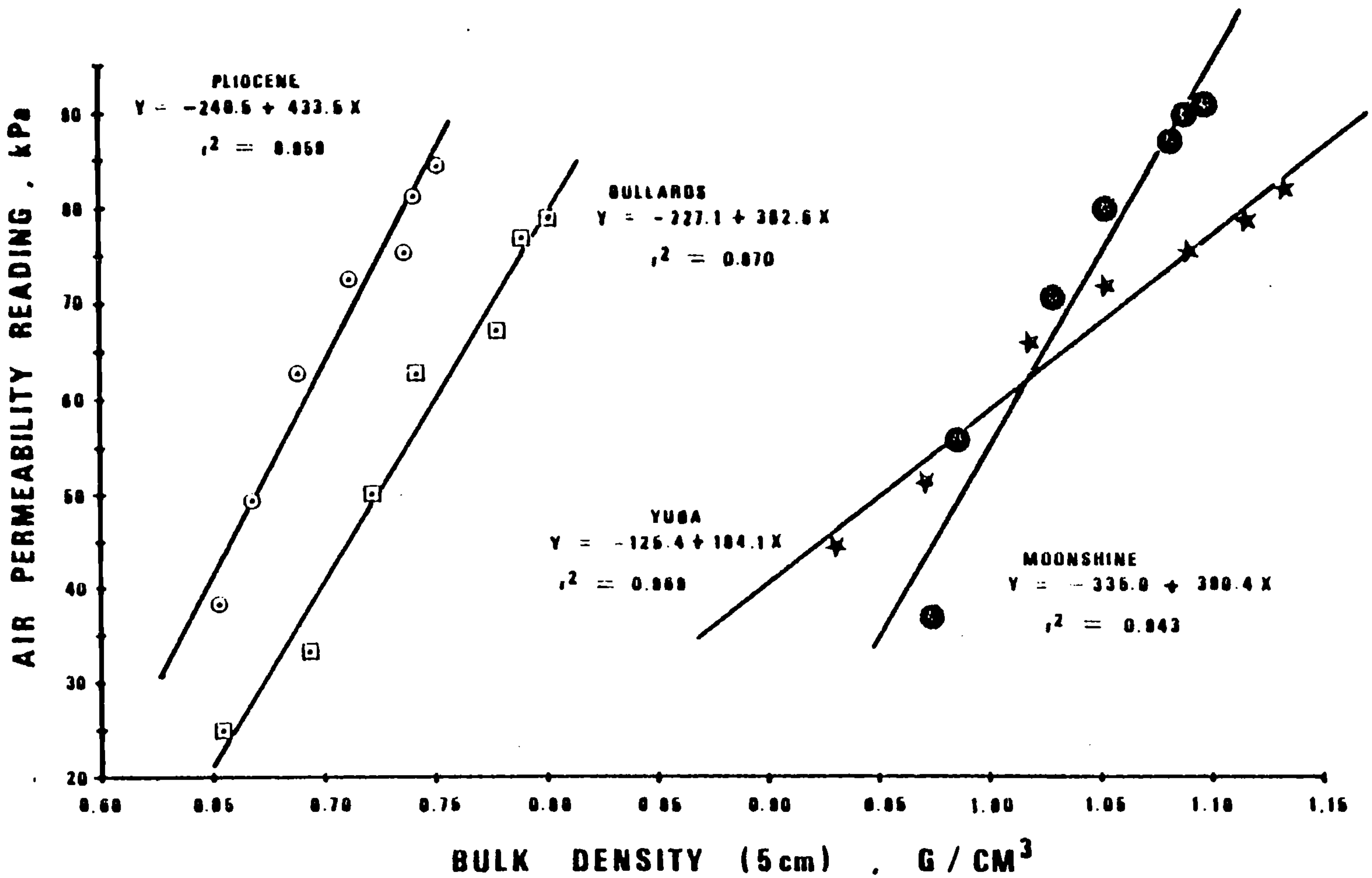


Figure 12. Mean air permeability readings plotted against mean bulk density values by site.

very low organic matter content and the very high percentage of sand found at this site.

On the basis of these results, the air permeameter can be considered to provide a relatively good index for changes in bulk density when the mean of at least ten points in a 15 m strip is utilized. Individual point variation will always be high due to the nature of forest soils and their formation. The portability and ease of use of the air permeameter make it a valuable tool for this type of observation.

Effect of Moisture Content on Readings

The moisture content of the soils were not found to influence air permeability readings unless they were above field capacity. Two tailed t-tests were run for initial permeameter readings at both the wettest and the driest moisture contents for Yuba and Pliocene (16-8%, 40-19%, respectively). These sites were chosen for this analysis because of their wide ranging moisture contents. While the means were significantly different in both cases, the highest means corresponded to the dry condition. Initial bulk density, therefore, must have been much more important for permeability than moisture content. The only site to be sampled when its moisture content was at or above field capacity was Yuba in June, 1980. The moisture content averaged 23 percent, with locations near melting snow patches going to 33 percent. One third bar field capacity on small disturbed samples is 24 percent. Undisturbed readings showed that this moisture content raised the mean value from 44.8 kPa (6.5 psi), measured in the summer and fall of 1979, to 58.6 kPa

(8.5 psi). This difference was highly significant and very evident in the field.

Relation Between Air Permeability and Macropore Space

Only a moderately strong correlation was found between air permeability readings and macroporosity, as determined from the soil cores (Figure 13). The amount of macropore space found in a surface core was paired with the mean of the ten permeability readings taken for a trail. This was done for both undisturbed trails and those exposed to 20 passes by the machines. There are several reasons why only 44 percent of the variability was explained by a simple linear model. First, the cores were taken from the surface six cm, while the soil tube on the air permeameter extends into the soil only 2.5 cm. Macropore space decreases rapidly with depth due to lower organic matter incorporation and less soil fauna activity. Second, for a true comparison, soil cores must be sampled from spots immediately next to permeability plots and paired with the mean of several readings from only that plot. Finally, site heterogeneity was very high. The correlation was found to be much higher for the sites which had low initial bulk density and high macroporosity; r^2 values were 0.742 for Bullards and 0.672 for Pliocene, while only 0.359 for Yuba and 0.284 for Moonshine.

Due to these problems, Steinbrenner's (1959) original relationship relating these variables is considered more accurate than the equation generated in this study. His linear equation:

$$Y = 42.1 - 0.34\,X \qquad r^2 = 0.77$$

where: Y = percent macropore space (one-third bar)
X = air permeameter reading (kPa)

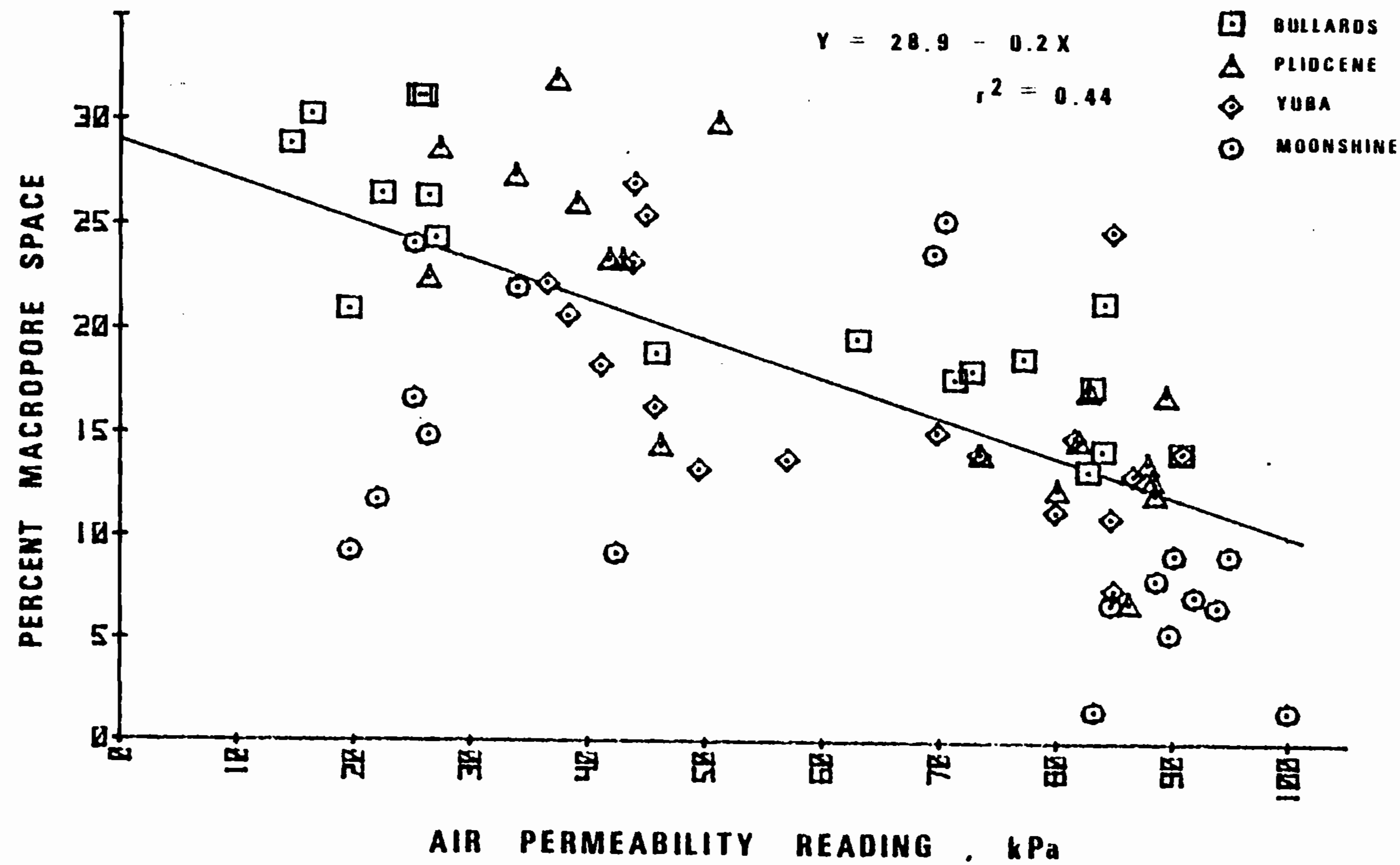


Figure 13. Mean air permeability readings plotted against macropore space (macropore space was determined with 60 cm of water tension).

was derived from samples which were not plagued by the problems mentioned above. This equation was generated from measurements on glaciated and residual soils found in western Washington. It is not anticipated that soil differences would preclude the use of this equation on our sites.

Infiltration Measurements

The infiltration capacities measured for this study must be considered to be only indices of the true rates observed during a storm event. As is the case for nearly all infiltrometers, simplifying assumptions have been made with the instrument used in this study which prevent it from simulating natural conditions. Meeuwig (1971) states that this infiltrometer overestimates infiltration capacities on bare mineral soil due to artifically low raindrop impact. This results in less surface puddling than would naturally occur. Raindrops of the size produced by the needles (2.9 mm) require a fall distance of 7.2 m to attain 95 percent of terminal velocity (Dohrenwend 1977). The fall distance from this infiltrometer is only 0.5 m. Another major disadvantage is that the simulated raindrops always strike the soil surface at the exact same location, thus creating miniature craters. Natural rainfall, of course, hits the soil surface in a random manner. Errors can also be introduced by lateral movement of water, since this infiltrometer operates without a plot frame.

In spite of these problems, this type of rainfall simulating infiltrometer has many advantages over other methods. Its ease of use and portability make it a reasonable alternative to the more sophisticated

Rocky Mountain Infiltrometer in steep, forested terrain. Also, a rainfall simulator at least starts to address the raindrop impact issue. Ring infiltrometers, commonly used in the past, provide a much cruder estimate of infiltration. In addition to ponding water and creating a positive hydrostatic head, they disrupt the soil near the boundary of the ring and cause unnatural channels for flow. In conclusion, the portable rainfall simulator used provides a better estimate of infiltration than some other methods, but still must be considered an index of the true rate.

Infiltration on Undisturbed Soils

The infiltration capacity measured on the undisturbed trails for the four sites was always found to exceed 7.6 cm/hr when the soils were slightly moist during the early part of the summer. This was to be expected, since forest soils often have exceedingly high infiltration capacities. In the fall, when the soils had dried considerably, the infiltration capacities determined were: Yuba: 6.4 cm/hr, Pliocene: 14.5 cm/hr, Bullards: 12.9 cm/hr, and Moonshine: 16.1 cm/hr. The difference between sites is due primarily to hydrophobic conditions experienced by the three higher elevation sites.

Field and laboratory observations indicated that soils from Yuba, Pliocene, and Bullards were extremely non-wettable. Water droplets remained "balled up" on the surface of the mineral soil from these sites for over 15 minutes. Mineral soil from Yuba did not wet-up by capillary action. The cause of this hydrophobic condition on these sites seems evident. The undisturbed litter layers, whether they were fir, pine, or a conifer mixture, were all heavily inoculated with fungal mycelia. The hyphae were spread throughout the decomposing litter and into the A_1 horizon. Apparently, metabolic products from fungal decomposition of the litter layer are adsorbed onto the mineral soil particle surfaces when they are washed into the soil profile by rain or melting snow (Bond and Harris 1964). Being basically insoluble, they remain on the particles and resist water penetration. The more extreme hydrophobic conditions are thought to be associated with litter from true fir species (i.e., Abies magnifica and Abies concolor). The soil at Moonshine exhibited no hydrophobic traits. This was to be expected as there was little fungal mycelia, no true fir litter, and a hot, dry environment which favored rapid litter decomposition.

In the undisturbed state, the non-wettable condition was usually of little consequence. Large patches of litter allowed almost no water passage and substantial sections of mineral soil in the A_1 horizon remained dry during simulated rainfall. There were inevitably a few large macro-voids which allowed sufficient water movement into the deeper part of the profile within the small infiltrometer plot (Figure 14). These voids probably result from the activity of the soil fauna or are produced by root development and decay (Aubertin 1971).

The most severe hydrophobic problems occurred at Yuba. Pure stands of red fir in the western Sierra have been previously found to cause extremely non-wettable soils (DeBano 1968). Yuba's mineral soil became almost totally hydrophobic by the end of the summer when it had dried to approximately 11 percent moisture content in the surface 15 cm. The much lower infiltration capacity found here was primarily the result of

Figure 14. Infiltration on undisturbed plots; upper photo shows hydrophobic soil at Yuba, lower photo shows hydrophobic soil with macro-voids to allow water transmission at Pliocene.

three interrelating factors. First, 72 percent of the soil was in the sand size class. The low surface area of the soil particles was easily covered with adsorbed hydrophobic compounds. Second, the red fir litter and fungal mycelia supplied these compounds very readily. Finally, the climate and soil fauna present are apparently incapable of establishing an aggregate structure with macro-voids.

Water infiltrated well in the soil at Bullards, even in a dry condition, due to its excellent aggregate structure. The fact that the soil at Bullards exhibited hydrophobic conditions with 25 percent clay may seem puzzling, since primarily sandy soils have been reported in the literature to experience this. Perhaps the discrepancy can be explained by the stability of the aggregates found here. It seems conceivable that the exterior portions of these non-expanding kaolinitic clay aggregates could adsorb enough hydrophobic compounds to become nonwettable.

Infiltration Capacities After Compaction

Post-disturbance measurements showed that the crawler tractor caused a 78 percent reduction in infiltration capacity after 20 trips, while the torsion suspension vehicle and the rubber-tired skidder produced a 67 percent decrease (Table 8). The final infiltration rate on the crawler tractor trails was significantly lower than that found on the trails made by the other vehicles. When only infiltration tests which were run in the track positions were included, analysis of variance revealed there was no significant difference between vehicles. Clearly then, it was the center of the trails which were differentially

Table 8. Final infiltration capacities, post-disturbance (cm/hr).

Trail Means[a]

	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[b]
CT	3.04	2.68	3.30	2.08	2.78	b
TSV	4.29	3.39	5.35	3.29	4.08	a
RTS	2.93	5.50	4.62	3.29	4.09	a
	3.42	3.86	4.42	2.89		

Track Position

	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[c]
CT	3.85	2.19	3.17	1.77	2.75	a
TSV	3.37	3.15	4.31	2.07	3.23	a
RTS	3.18	4.65	3.51	2.80	3.54	a
	3.47	3.33	3.66	2.21		

Track vs. Center Position[d]

	CT	TSV	RTS
Track	2.75	3.23	3.54
Center	2.83[NS]	5.79**	5.18*

[a] Trail includes both track and center positions.

[b] Means with the same letter are not significantly different at alpha = 0.01.

[c] Means with the same letter are not significantly different at alpha = 0.10.

[d] NS denotes no statistical difference at alpha = 0.10.
* denotes statistical difference at alpha = 0.10.
** denotes statistical difference at alpha = 0.01.

disturbed by the machines. There was no significant difference in infiltration between the center of the crawler tractor trails and the track position, while there was a significant difference for the other two vehicles. These results compare favorably with the bulk density data presented previously.

Cross-section measurements of the amount of soil displacement by the three machines showed that the crawler tractor removed 2435 cm^2, the torsion suspension vehicle removed 1288 cm^2, and the rubber-tired skidder removed 1592 cm^2 (Lysne 1981). The crawler tractor, therefore, caused more surface disturbance and exposed more mineral soil than the other vehicles. When dealing with mineral soil that is hydrophobic, excavation and disruption of macropore channels produces lower infiltration capacities (Figure 15). Photographs taken after skidding also showed that the crawler tractor trails were more evenly disturbed than those for the other vehicles.

Significant differences in infiltration capacity existed between sites after compaction (Table 8). The soil at Bullards allowed water to penetrate its skid trail surfaces most readily, due to the ability of its aggregates to sustain stress without undergoing deformation during compression. The soil at Moonshine, in contrast, had its weak aggregates crushed into a very compact, impermeable layer. Because of this, infiltration capacities were lowest at this site. Soils at Pliocene and Yuba had intermediate levels of infiltration. Hydrophobic conditions prevented these sandy soils from having higher rates expected of their textural class.

The numerous wetting fronts exposed on the infiltration plots

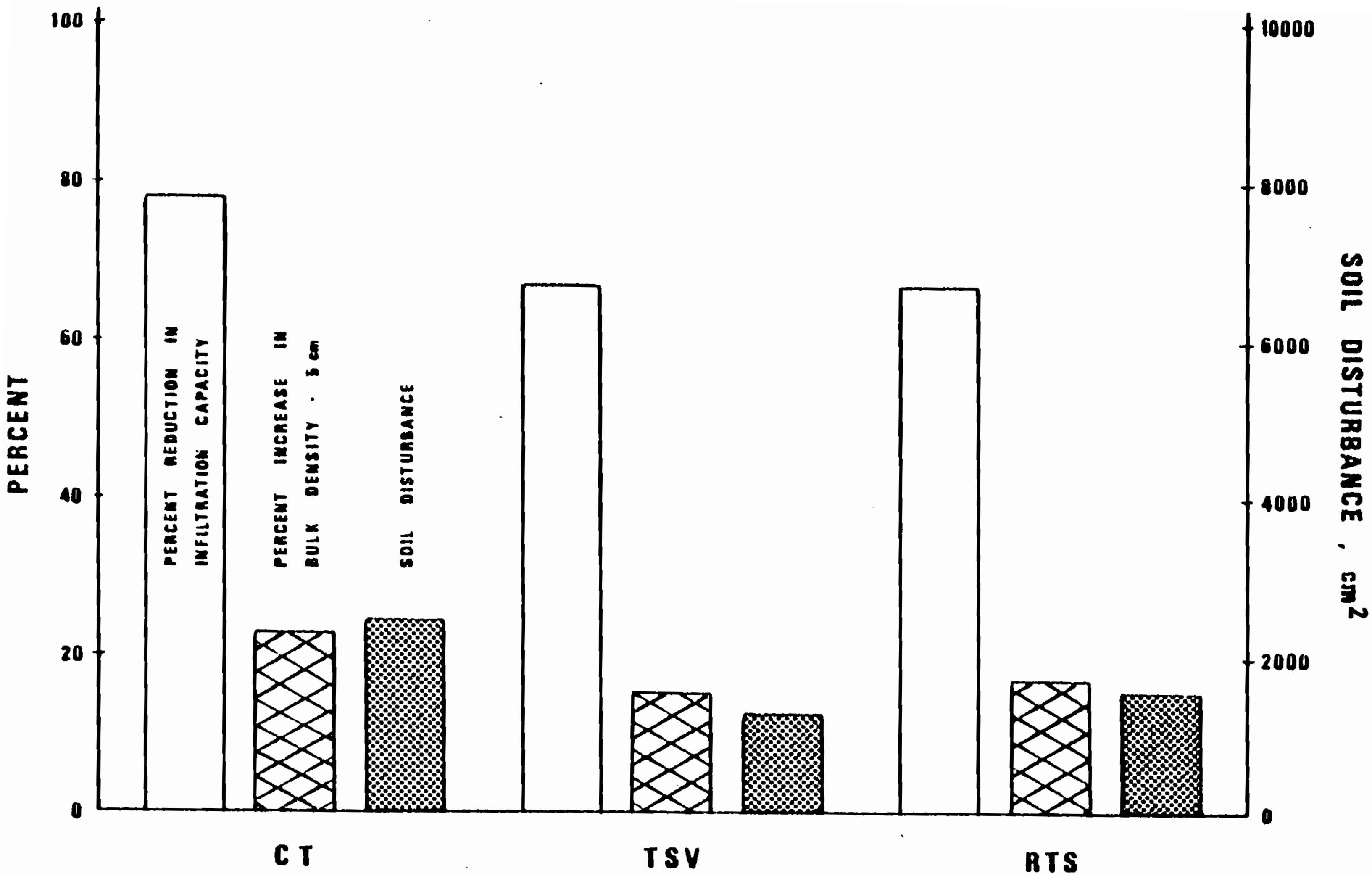
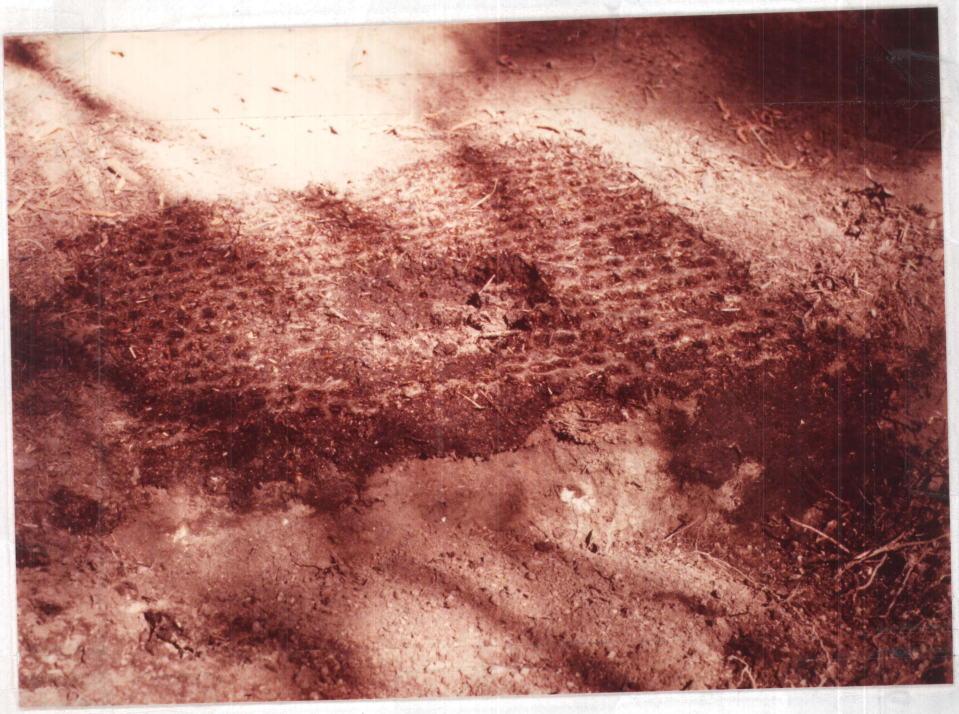


Figure 15. Corresponding reductions in infiltration capacity, increase in bulk density, and amount of soil disturbance for each vehicle type.

revealed the location of the restricting layer for water movement into the soil profile (Figure 16). In the track position, wetting fronts generally penetrated approximately ten cm through the powdery, pulverized soil-organic matter mix and stopped shortly after encountering the firm compacted layer. The soil-organic matter mix acted like a large sponge which, after soaking up all of the water it could hold, was finally forced to allow overland flow. Variations of this pattern were seen at Yuba. In spots where nearly pure mineral soil was exposed at the surface, the ultra hydrophobic soil simply did not allow water to infiltrate. Extreme cases were seen in which water had penetrated only 0.3 cm; corresponding infiltration capacities were less than 0.5 cm/hr. Very irregular wetting fronts were seen at all of the hydrophobic sites. Areas with a higher percentage of pulverized organics allowed the infiltrating water to penetrate much more readily than areas with nearly pure mineral soil. In addition, wetting fronts were observed to move much deeper into the profile in the less disturbed center areas, particularly for the torsion suspension vehicle and rubber-tired skidder trails.

Assuming that the overestimation of the infiltration capacities measured on the skid trails have not caused large relative errors, the hydrologic significance of the reductions can be addressed. The highest intensity storm for this region which can be expected on an annual basis with a 30 min duration is 2.0 cm/hr. A storm with a return interval of two years is expected to produce precipitation at a rate of 2.5 cm/hr for 30 min. The estimated five year-30 min intensity is 3.6 cm/hr, and the ten year-30 min intensity is 4.1 cm/hr (U.S. Weather Bureau 1961).



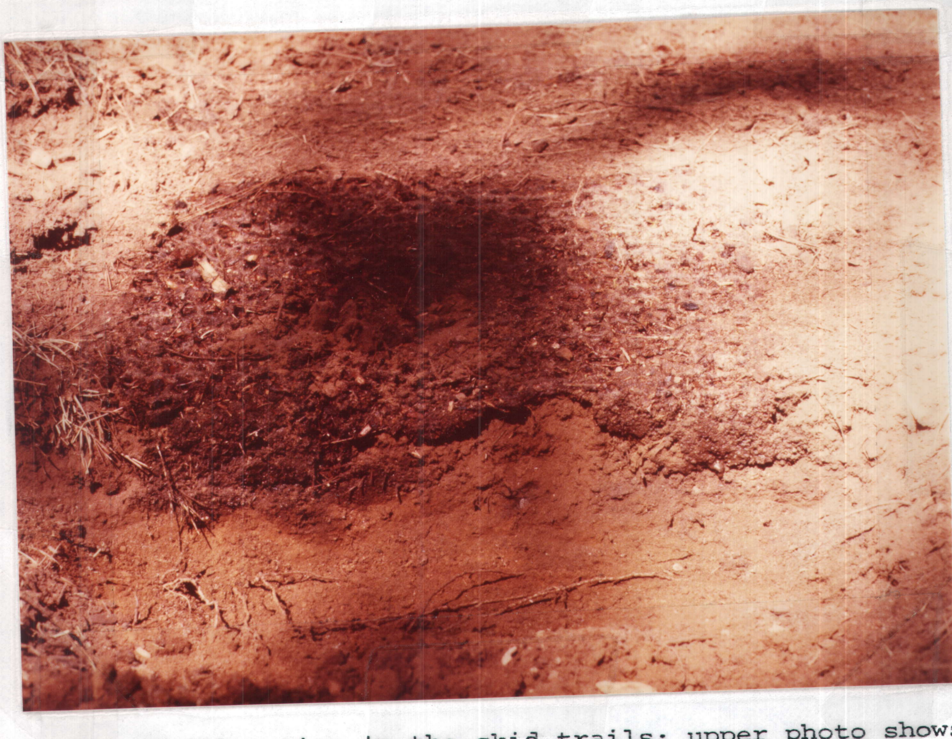


Figure 16. Infiltration in the skid trails; upper photo shows restricted infiltration at Pliocene in the track position and deep penetration towards the TSV trail center, lower photo shows irregular wetting front resulting from hydrophobic mineral soil at Bullards.

This means that the infiltration capacity of the crawler tractor trails, on the average, will be exceeded approximately once every three years. The infiltration capacities of the torsion suspension vehicle and rubber-tired skidder trails will be exceeded once every ten years. This data does not apply to Yuba Pass, where the vast majority of the precipitation falls as snow. Revegetation, litter fall, and other factors will tend to increase the infiltration capacity of these trails over time.

Factors Affecting Infiltration on the Skid Trails

To determine the significant variables affecting infiltration on the skid trails, a stepwise multiple regression procedure was utilized. Variables included in the analysis were: total porosity in the surface six cm, macroporosity in the surface six cm, macroporosity in the six to 12 cm layer, saturated hydraulic conductivity in the surface six cm, saturated hydraulic conductivity in the six to 12 cm layer, bulk density at five cm, bulk density at ten cm, change in bulk density at five cm, change in bulk density at ten cm, organic matter content in the surface five cm above the compacted mineral soil, organic matter content of the mineral soil, slope, moisture content, sand, silt, and clay percentages. The equations generated from this analysis indicated that a model of the infiltration process on these soils could not be produced from the data set. The manner in which the variables were included in the equations seemed to convey little physical meaning. This result seems plausible, since there was no way to quantify the highly variable hydrophobic conditions experienced at three of the sites.

The best single variable correlated with infiltration was the organic matter content in the surface five cm above the compacted mineral soil, with an r of 0.585. This variable was exceedingly important at Yuba, where for track and center plots, it explained 66 percent of the variability in the infiltration capacity. This illustrates how important organic matter was in breaking the virtual seal of the hydrophobic mineral soil. The other significant variables affecting infiltration were macropore space in the six to 12 cm zone (r = 0.456), and saturated hydraulic conductivity in the six to 12 cm zone (r = 0.302). There was no clear relationship between moisture content and infiltration capacity. Undoubtedly, there was a complex interaction between hydrophobicity, moisture content, and macropore space on the resulting infiltration.

Surface Erosion Measurements

Suspended Sediment Concentrations

Analysis of the water samples taken from the infiltration plots revealed that the sediment concentrations were extremely variable and the sample population was highly skewed. Therefore, before statistical tests were done, a square root transformation was performed on the data set. This resulted in a normal distribution of the concentrations. Runoff from the crawler tractor trails was found to contain approximately 40 percent more sediment than runoff from the torsion suspension vehicle and rubber-tired skidder trails (sign. at alpha = 0.01). When only the track position data was studied, there was no statistical difference between the means for any of the machines (Table 9). As has been seen previously, it was the center of the trail which differed markedly in sediment production. The track and center positions produced nearly identical concentrations on the crawler tractor trails, but were significantly different on the torsion suspension vehicle and rubber-tired skidder trails. This again indicates greater disturbance by the crawler tractor over the entire trail. Significant site differences were not found.

The sediment concentrations reported are to be considered an index to erosion potential at best. They provide only a crude estimate of the erosion which would naturally take place. Arend and Horton (1943) state that the use of high, constant rain intensities in infiltration studies causes the production of wave trains or surging runoff, with the resulting erosion being in excess of that obtained on the same area with natural storms. For the majority of the plots established in the current study, a system of dams would develop which would effectively hold back sediment. Then, suddenly, these would break at irregular intervals, yielding momentarily high sediment loads. No estimates of sediment yields, such as kg/ha of skid trail, were made due to the artifical nature of the tests.

Turbidity

Turbidity readings were not found to be of great value in indexing erosion potential from the skid trails. Higher turbidity readings were obtained at the sites with significant silt and clay fractions, even though sediment concentrations were not larger (Table 10). Thus, the

Table 9. Post-disturbance suspended sediment concentrations (mg/l).[a]

	Trail Means[b]					
	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[c]
Undist	43	44	50	93	58	
CT	1702[f]	1192	1526	1748	1538	b
	(684)	(287)	(1051)	(725)	(730)	
TSV	1421	1004	921	1214	1147	a
	(803)	(704)	(1407)	(901)	(933)	
RTS	1371	851	1119	850	1051	a
	(780)	(632)	(1389)	(961)	(957)	

	Track Position					
	Yuba	Pliocene	Bullards	Moonshine	Mean	Sign[d]
CT	1732	1180	1406	1919	1552	a
	(655)	(213)	(969)	(858)	(746)	
TSV	1652	1332	1060	1483	1382	a
	(779)	(637)	(1487)	(826)	(826)	
RTS	1538	993	1422	1085	1260	a
	(827)	(674)	(1503)	(1119)	(1032)	

	Track vs. Center Position[e]		
	CT	TSV	RTS
Track	1552	1382	1260
	(746)	(948)	(1032)
	NS	**	*
Center	1509	512	551
	(728)	(548)	(491)

[a] All comparisons were done after the values had undergone a square root transformation to normalize the population.

[b] Trail includes both track and center positions.

[c] Means with the same letter are not significantly different at alpha = 0.01.

[d] Means with the same letter are not significantly different at alpha = 0.10.

[e] NS denotes no statistical difference at alpha = 0.10.
* denotes statistical difference at alpha = 0.10.
** denotes statistical difference at alpha = 0.01.

[f] All values in parentheses are standard deviations.

Table 10. Post-disturbance turbidities, trail means (ntu); suspended sediment concentration-turbidity relationships.

	Yuba	Pliocene	Bullards	Moonshine	Mean
CT	171 (85)[a]	174 (96)	283 (179)	503 (221)	286 (205)
TSV	146 (101)	117 (60)	224 (295)	345 (256)	209 (211)
RTS	112 (51)	106 (51)	193 (224)	237 (246)	163 (172)

Yuba: $Y = 7.02X + 482.06$ $r^2 = 0.64$

Pliocene: $Y = 5.13X + 337.67$ $r^2 = 0.48$

Bullards: $Y = 5.29X - 37.13$ $r^2 = 0.92$

Moonshine: $Y = 3.50X + 3.00$ $r^2 = 0.97$

where: Y = suspended sediment concentration (mg/l)

X = turbidity (ntu)

[a]Values in parentheses are standard deviations.

erosion indices were biased by colloidal particles. Therefore, these values did not undergo transformation and statistical analysis was not performed on them. Correlations between turbidity and suspended sediment on a site basis were generally good.

Factors Affecting Surface Erodibility

The organic matter content in the surface five cm above the compacted mineral soil was clearly the most significant variable influencing suspended sediment concentrations. It explained 30 percent of the variability in the track positions ($r = -0.544$). A summary of the surface organic matter content is presented in Table 11. The torsion suspension vehicle trails were found have 35 percent more organic matter at the surface than the crawler tractor trails; the rubber-tired skidder trails had an even larger 48 percent advantage. Although these differences, as for those in the track positions, were significant, a moisture-machine interaction was found. Therefore, an alpha level could not be assigned to the various means. Also contrary to previous results, there was no statistical difference between the means for the track and center positions of the torsion suspension vehicle and rubber-tired skidder trails.

Earlier research has often found a strong correlation between erosion and percent bare ground, depth of litter, weight of dry litter, percent herbaceous cover, and slope (Meeuwig 1970a, Packer 1951). When the soil is not covered with protective litter or vegetation, the situation is much different. Balci (1968) states that soil organic matter content usually has the strongest correlation with erosion hazard

Table 11. Organic matter content in the surface five centimeters above the compacted mineral soil (percent).[a]

Trail Means[b]

	Yuba	Pliocene	Bullards	Moonshine	Mean
CT	18.8	26.8	35.4	16.8	24.5
TSV	25.2	31.6	51.4	22.1	32.6
RTS	20.5	47.0	52.9	24.7	36.3

Track Position

	Yuba	Pliocene	Bullards	Moonshine	Mean
CT	23.0	27.5	36.0	15.7	25.6
TSV	21.6	32.5	49.1	18.3	30.4
RTS	21.8	48.1	51.1	29.0	37.5

Track vs. Center Position[c]

	CT	TSV	RTS
Track	25.6	30.4	37.5
	NS	NS	NS
Center	22.2	37.0	33.9

[a]Significance was not assigned to the Trail Means and Track Position means because of a moisture-machine interaction.

[b]Trail includes both track and center positions.

[c]NS denotes no statistical difference at alpha = 0.10.

indices in such instances. Since after 20 trips, the trails in this study were covered with a layer of loose mineral soil and finely ground organic matter, it is not surprising that the organic matter content was the best indicator of erosion. Other individual variables with significant correlations were slope ($r = 0.441$) and the change in bulk density at 10 cm ($r = 0.312$). Stepwise multiple regression run on the suspended sediment concentrations with the variable list given in the infiltration section did not yield physically meaningful equations.

Saturated Hydraulic Conductivity Measurements

Comparison by Vehicle Type, Position, and Site

Analysis of variance showed that the mean surface conductivities in the track positions of the trails after 20 passes could not be statistically distinguished by machine type (Table 12). This indicates that with 20 trips by any of the skidders, enough energy is dispersed into the surface six cm to make vehicle differences indeterminate. The mean reduction in conductivity was 80 percent in this surface zone.

The hypothesis that the restricting layer for water movement in the surface part of the undisturbed soil profile could best be approximated by conductivities determined at the depth of 30 cm appears to have been correct. A highly significant difference of 54 percent in conductivity was seen from the surface six cm to the 30 cm depth of undisturbed soil. After compaction by the skidders, the restricting layer for water transmission was moved upwards to the surface six cm zone. Analysis showed that the conductivity means after skidding in this layer were lower than

Table 12. Saturated hydraulic conductivity, track position (cm/sec).

BY MACHINE TYPE[a]

	UNDISTURBED		COMPACTED	
	0 - 6 cm	30-36 cm	0 - 6 cm	6-12 cm
CT	0.0127	0.0069	0.0030	0.0040
TSV	0.0185	0.0083	0.0020	0.0038
RTS	0.0143	0.0056	0.0035	0.0051

BY SITE[b]

	UNDISTURBED		COMPACTED	
	0 - 6 cm	30-36 cm	0 - 6 cm	6-12 cm
YUBA	0.0104	0.0071	0.0045	0.0040
PLIOCENE	0.0193	0.0081*	0.0027	0.0052
BULLARDS	0.0213	0.0094*	0.0036	0.0067
MOONSHINE	0.0096	0.0044	0.0005	0.0013

[a]Each value represents the mean of twelve samples.

[b]Each value represents the mean of nine samples, except where distinguished with *. These values are the mean of six samples.

those in the six to 12 cm layer. Conductivities in the surface six cm layer after compaction were approximately 60 percent lower than those in the 30 to 36 cm layer of the undisturbed profiles. The reduction in conductivity between these two restricting layers was statistically significant.

The conductivities of the surface six cm layer after compaction were significantly different when evaluated by site. At Yuba the very low content of silt and clay particles prevented the pores between the sand grains from being packed efficiently; its cores, therefore, had the highest conductivities. Soils at Pliocene and Bullards, both with high initial macroporosity levels, sustained larger drops in conductivity. Pliocene's high sand content and Bullards' extremely stable aggregates kept their levels above those found for Moonshine cores. This low elevation site apparently had the appropriate combination of sand, silt, and clay; low organic matter content; and weak aggregate stability to allow massive compaction. The blockage of interconnecting pore space for water transmission was nearly complete for these cores.

Relation Between Conductivity and Macropore Space

As was stated in the literature review, hydraulic conductivity is strongly correlated with the percentage of non-capillary pore space in a soil sample. The relationship found by regression analysis for both surface and subsurface cores is presented in Figure 17. The following equation was the best fitting model:

$$Y = 0.000221\, e^{0.175\, X} \qquad r^2 = 0.800$$

where: Y = saturated hydraulic conductivity (cm/sec)
X = percent macropore space (60 cm of H_2O tension)

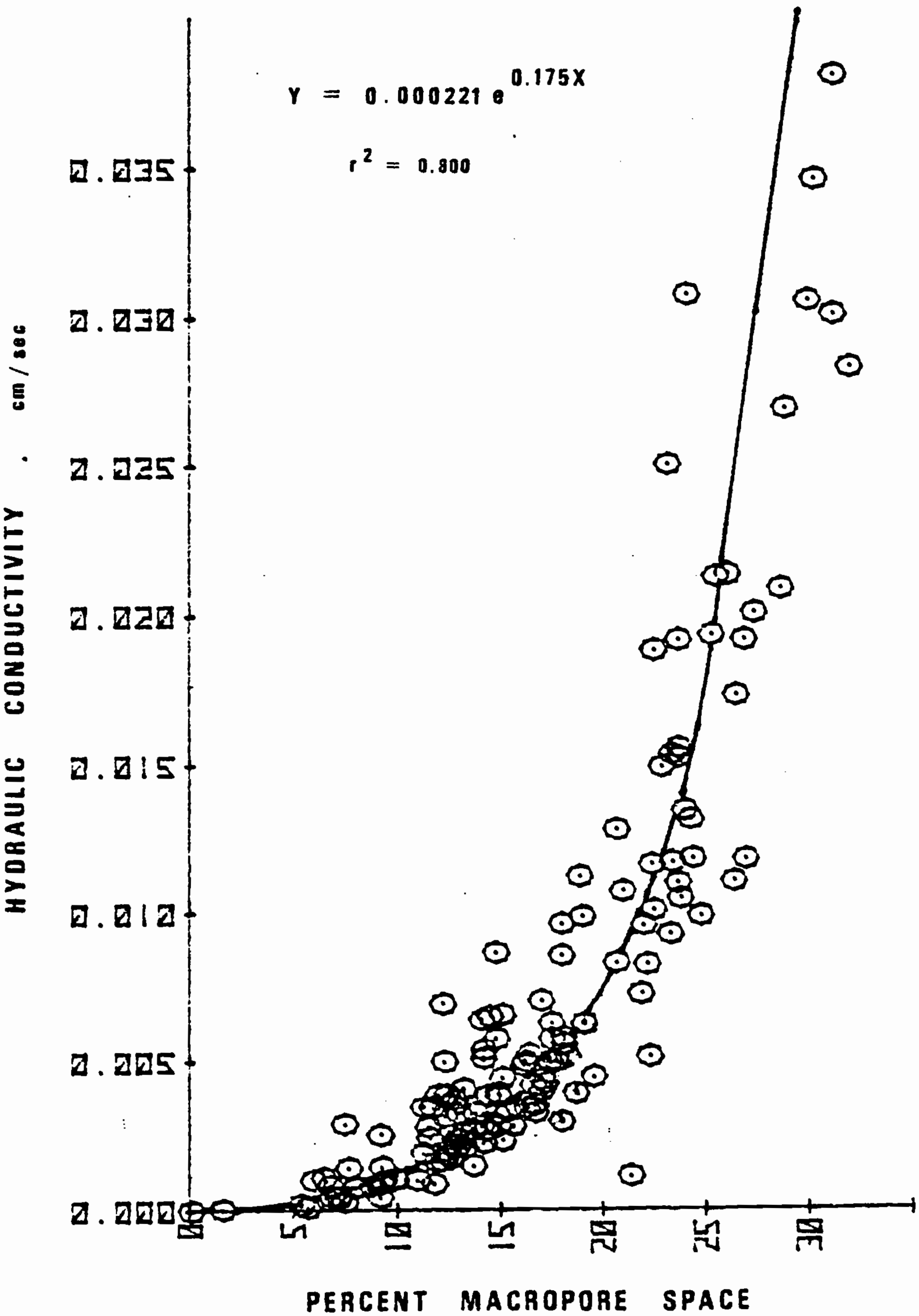


Figure 17. Saturated hydraulic conductivity plotted against percent macropore space (macropore space was determined with 60 cm of water tension).

This relationship shows that for 20 percent macropore space, a level typically met in undisturbed surface soils, conductivity will be 0.007 cm/sec. At ten percent macropore space, the point where aeration becomes a serious problem, conductivity is only 0.001 cm/sec. Therefore, that 50 percent decrease in macroporosity results in an 86 percent drop in conductivity.

Soil Porosity Measurements

Comparisons by Vehicle Type, Position, and Site

Macroscopic pore space decreased 43 percent in the surface six cm of the track positions of the skid trails, but significant differences between vehicles could not be determined. Similarly, the mean absolute macropore space percentages after compaction in the surface layer could not be distinguished by machine (Table 13). As was seen with the conductivity measurements, all three machines transmitted enough energy to the soil to produce statistically uniform porosity levels with the sample size and methods used. Total pore space decreased only four percent in the surface six cm layer after compaction; micropore space increased 22 percent in this zone.

Analysis showed that there was no significant difference in the amount of macropore space after compaction in the surface six cm layer when compared to that in the six to 12 cm zone. In the undisturbed state, a 23 percent reduction in non-capillary porosity was found when testing levels in the surface six cm against those in the 30 to 36 cm layer. The largest decreases were seen at the sites which had low

Table 13. Soil porosity measurements in the track position (percent).[a]

	Yuba	Pliocene	Bullards	Moonshine	Mean
			UNDISTURBED		
0 - 6 cm					
Macro	20.0	25.3	26.5	17.4	22.3
Micro	31.6	34.7	35.2	35.5	34.3
Total	51.6	60.0	61.7	52.9	56.6
30-36 cm					
Macro	17.0	17.1*	19.7*	15.7	17.2
Micro	35.7	48.3*	38.8*	35.9	38.9
Total	52.7	65.4*	58.5*	51.6	56.1
			COMPACTED		
0 - 6 cm					
Macro	14.0	13.5	17.2	6.2	12.7
Micro	39.2	42.3	44.4	40.7	41.7
Total	53.2	55.8	61.6	46.9	54.4
6 -12 cm					
Macro	13.9	14.1	18.0	9.5	13.9
Micro	38.3	46.4	43.3	39.3	41.8
Total	52.2	60.5	61.3	48.8	55.7

[a]Each value represents the mean of nine samples, except where distinguished with *. These values are the mean of six samples.

initial bulk densities and high initial surface macroporosities; Pliocene experienced a 31.8 percent decrease and Bullards dropped 25.8 percent. Yuba and Moonshine, in contrast, had 14.7 and 11.3 percent reductions, respectively. In the natural, uncompacted soil profile, this change in the proportion of large pore space with depth is due mainly to less organic matter incorporation and poorer structure. It can also be due to a number of profile development mechanisms, such as eluviation of clay particles into the upper part of the B horizon.

Due to the high variability encountered in surface macroporosity levels, analysis of variance showed that there was no significant differences in the amount of reduction seen at the four sites (Table 13). Mean decreases observed were: Yuba - 30 percent, Pliocene - 47 percent, Bullards - 35 percent, and Moonshine - 64 percent. Moonshine's weakly aggregated soil had enough silt and clay to allow extremely tight packing. Indeed, it was only at this site that a significant reduction in total porosity was found; a decrease of 11.3 percent was recorded. A mean of just 6.2 percent macropore space was found in the surface six cm after compaction here. This level was statistically significantly lower than that observed at the other sites. Moonshine was the only site found to be below the critical level of ten percent macropore space needed for the aeration of plant roots.

Pore Size Distribution

To further clarify the porosity characteristics in the surface six cm layer of the four sites, a pore size distribution diagram is presented in Figure 18. For the soil at Yuba, the large proportion of pores

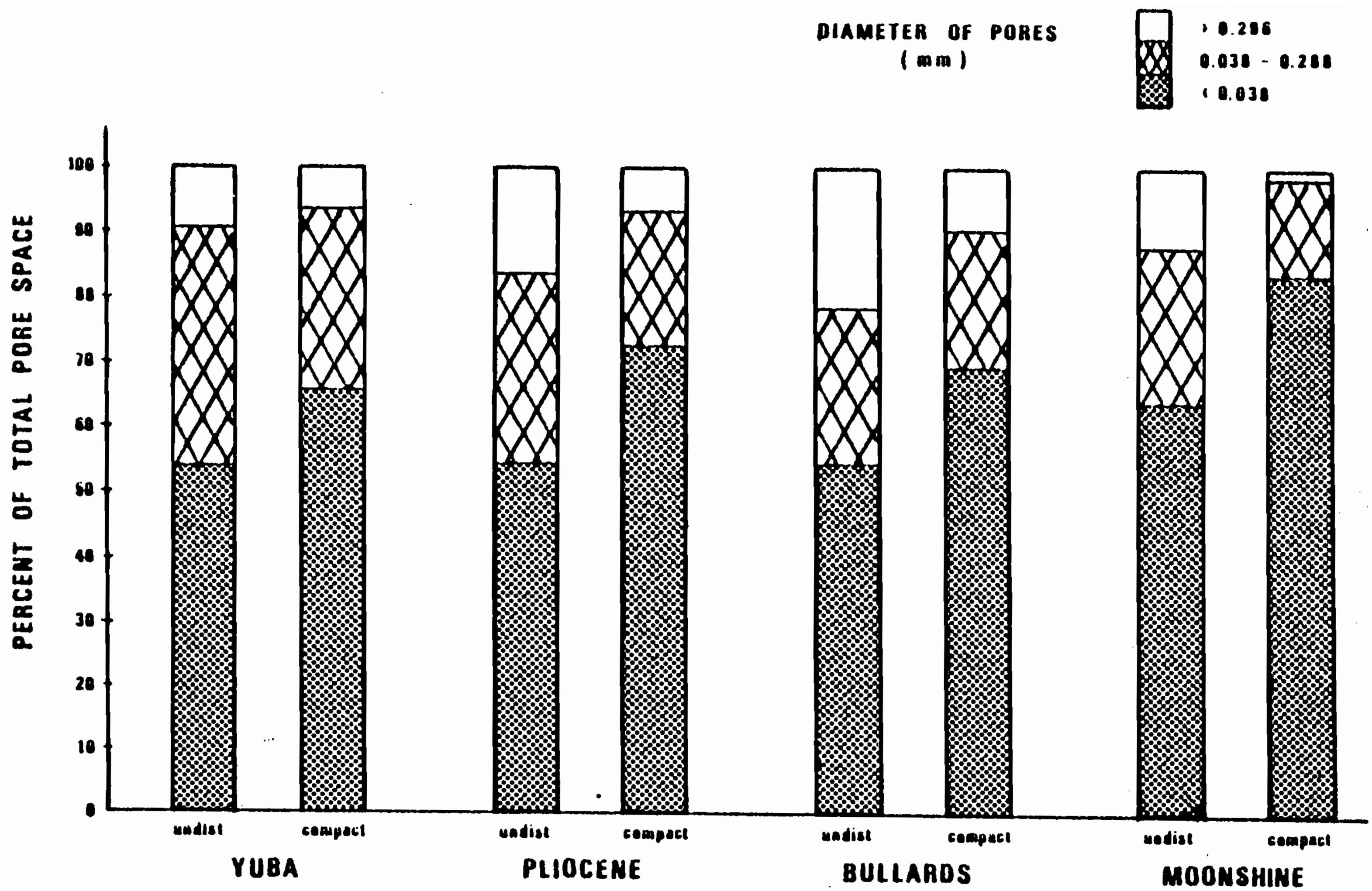


Figure 18. Pore size distribution before and after compaction.

in the 0.038 to 0.296 mm range is evident for the undisturbed surface layer. Lacking aggregate structure, there were few very large pores present. The high percentage of medium and fine sand grains allowed only a modest 29 percent decrease in the largest pore class after compaction. This site contrasts greatly with the other three.

Soil at Pliocene, with more organic matter incorporated in its A horizon than that at Yuba, had almost twice as much pore space in the greater than 0.296 mm class. After 20 trips with the skidders, a 58 percent decrease was observed for the largest pore class in the surface six cm. The situation was very similar for the soil at Bullards. Of all the sites, the greatest amount of pore space in the sizes which rapidly conduct water were found in this soil's surface layer. This was attributed to the stable aggregates present. Post compaction reduction in the largest pore class was 57 percent. Finally, for the soil at Moonshine, a distressing picture of serious environmental damage is seen. Compaction has produced an effective barrier for water movement, gas flow, and in all likelihood, fine tree roots. An 88 percent reduction in the hydrologically significant largest pore class occurred.

Soil Drainage Characteristics

Soil moisture characteristic curves visually illustrate the drainage patterns which result from the pore size distributions just discussed. These curves plot suction against moisture content; increasing tension is associated with decreasing soil wetness. The volume of water remaining at equilibrium in a soil sample at any given suction is a function of the pore size distribution. The curves drawn for the three vehicles from cores taken in the surface six cm are presented in Figure 19. The loss of large, rapidly draining macropores by compaction produces an obvious flattening of the initial drainage curve. Assuming that 80 cm of tension can be considered a reasonable estimate of field capacity for these sandy soils, approximately eight percent more moisture is available for plant use after compaction in this zone.

Nearly identical curves were drawn for the cores taken at the six to 12 cm depth (Figure 20). These further portray the fairly uniform levels of compaction produced by the three vehicles throughout the surface 12 cm of the track positions. Also drawn on this figure is the curve for drainage from the undisturbed 30 to 36 cm zone. The close relationship of this curve to the post-disturbance curves again illustrates how macropore space is naturally reduced with depth.

Drawing post-disturbance moisture characteristic curves by site, instead of vehicle, represents the varying effects compaction can have on soil drainage (Figure 21). Extremely even drainage is seen for the soil at Yuba due to the uniform pore size distribution encountered at these very low tensions. The greater percentage of pores in the larger size classes for soil at Bullards and Pliocene produce curves which show decreasing drainage at higher tensions. Finally, the exceptionally flat curve seen for Moonshine soil is the sign of a heavily compacted soil with very little non-capillary pore space.

To illustrate how soils from the four sites drain through the dry summer months, soil moisture characteristic curves with suctions up to 15 bars were drawn from analysis of disturbed soil (Figure 22). The curve for Pliocene shows that the intragranular porosity found in the

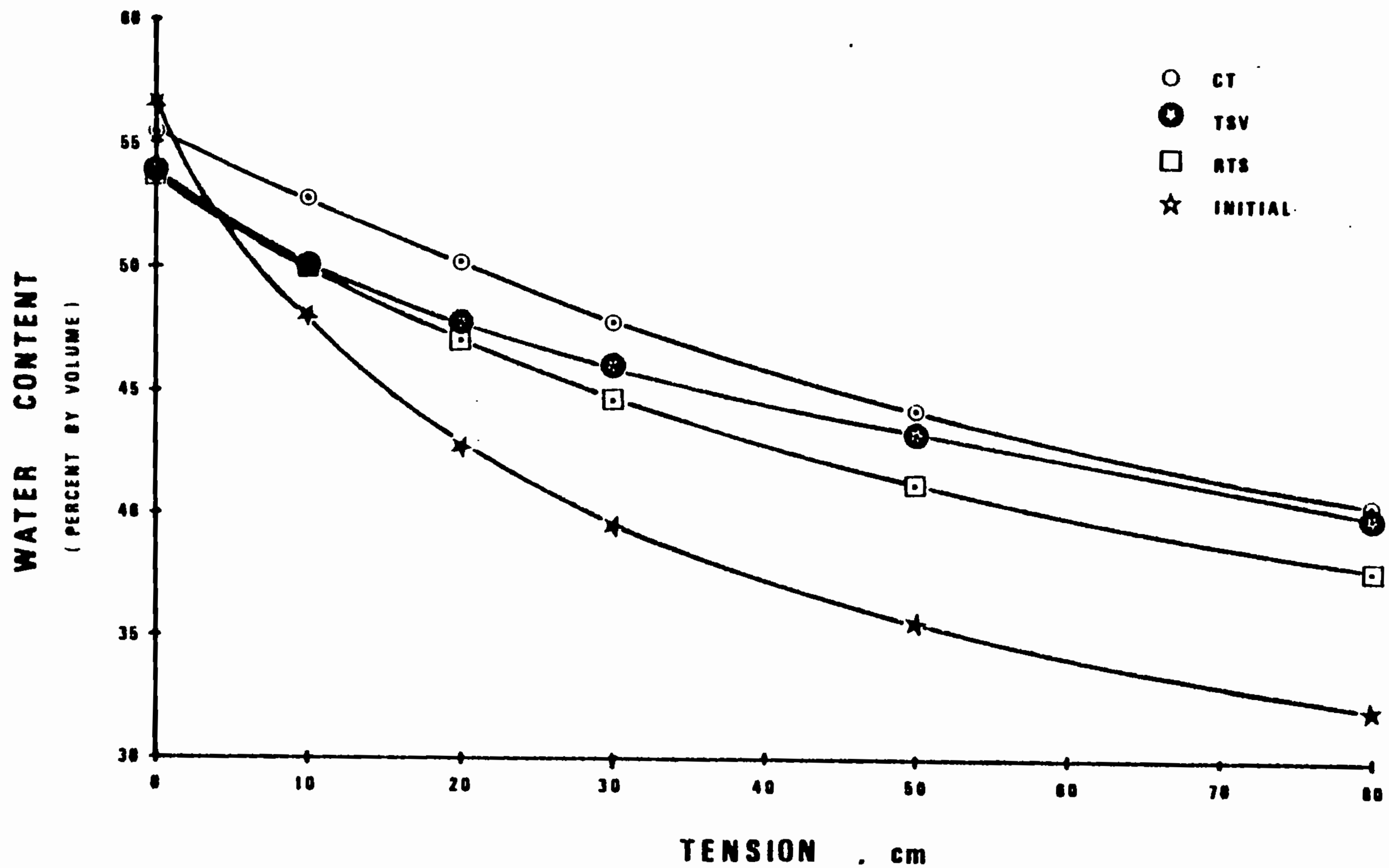


Figure 19. Soil moisture characteristic curves for the surface six centimeter layer.

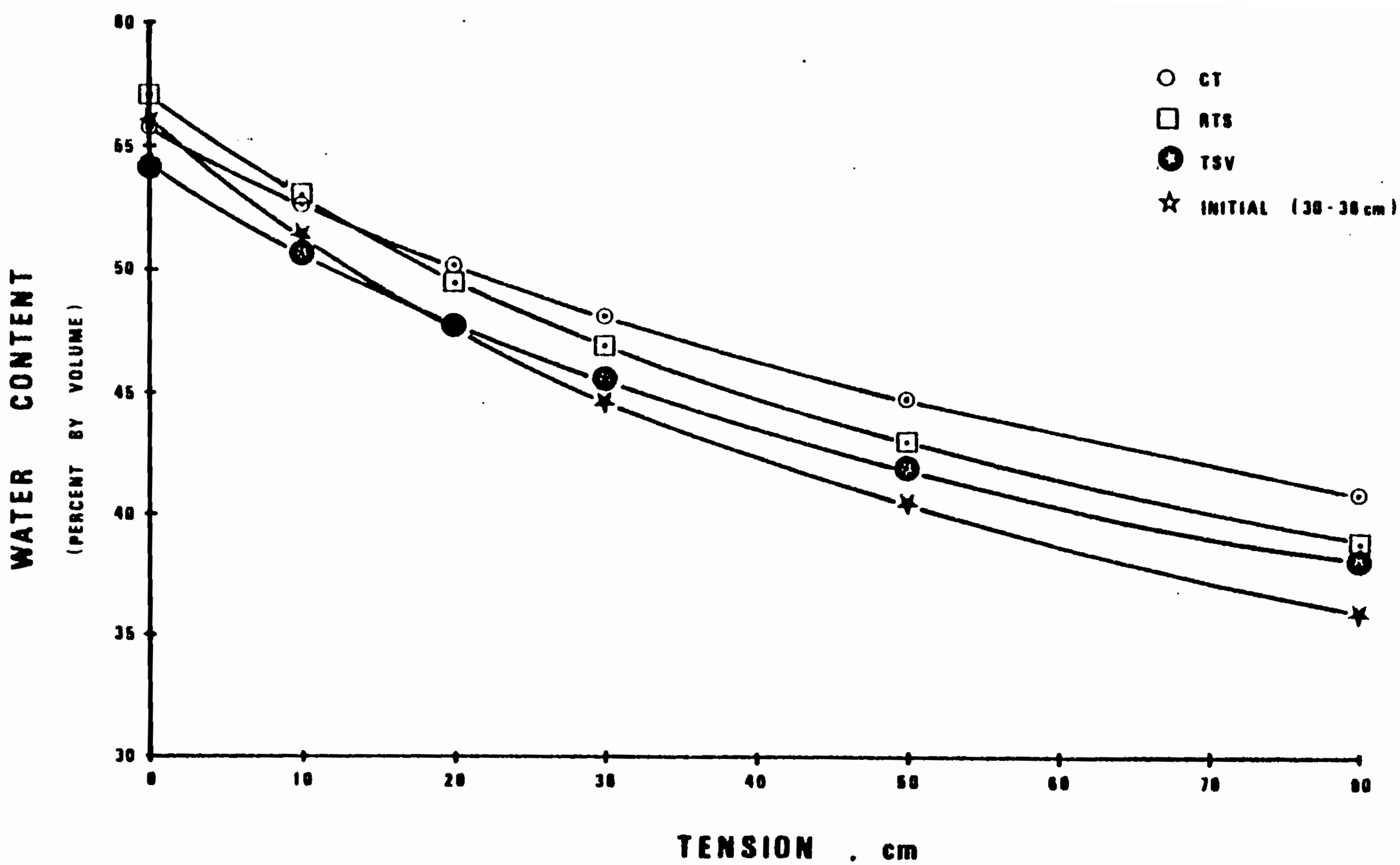


Figure 20. Soil moisture characteristic curves for the subsurface zones.

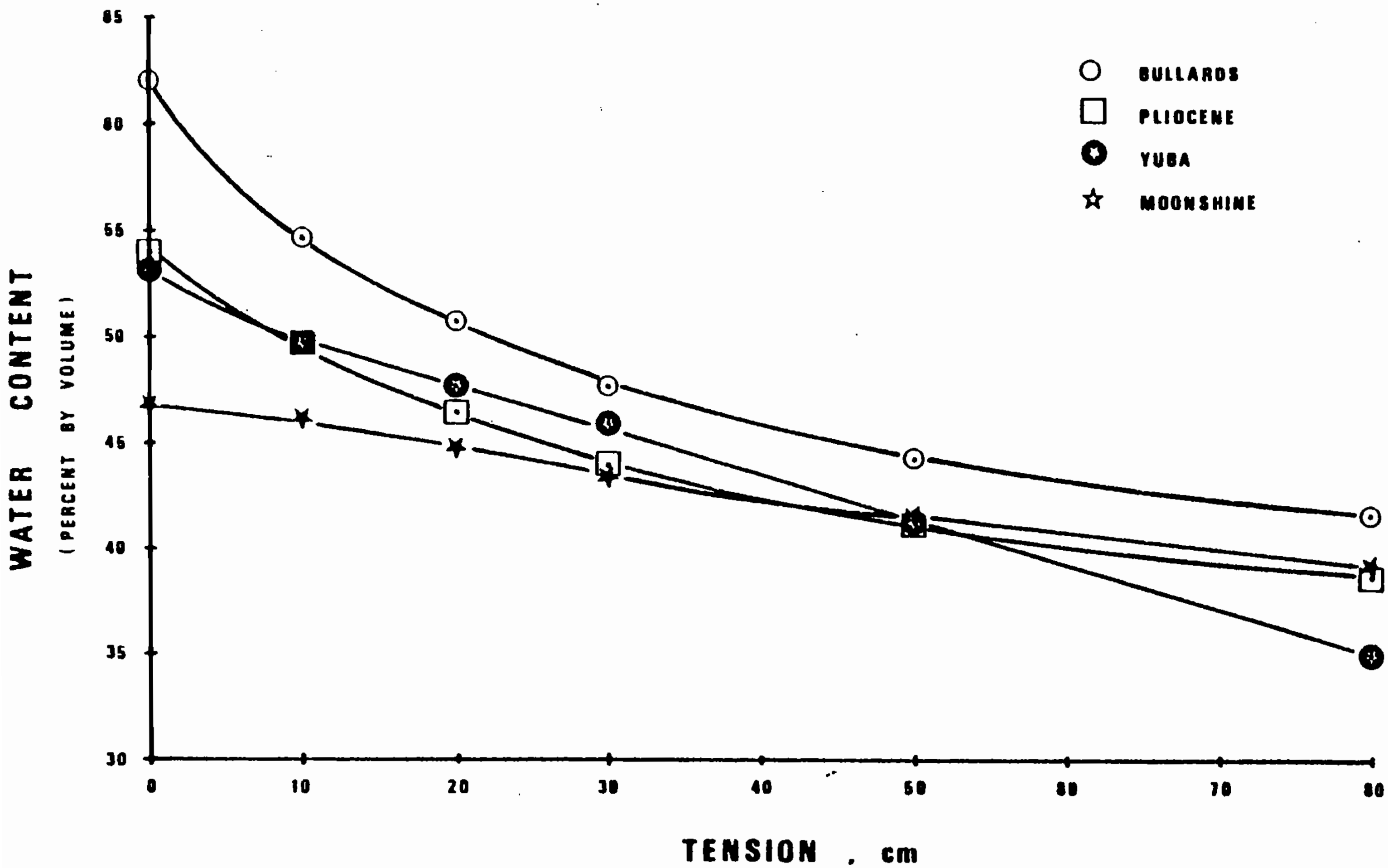


Figure 21. Soil moisture characteristic curves for each site after compaction.

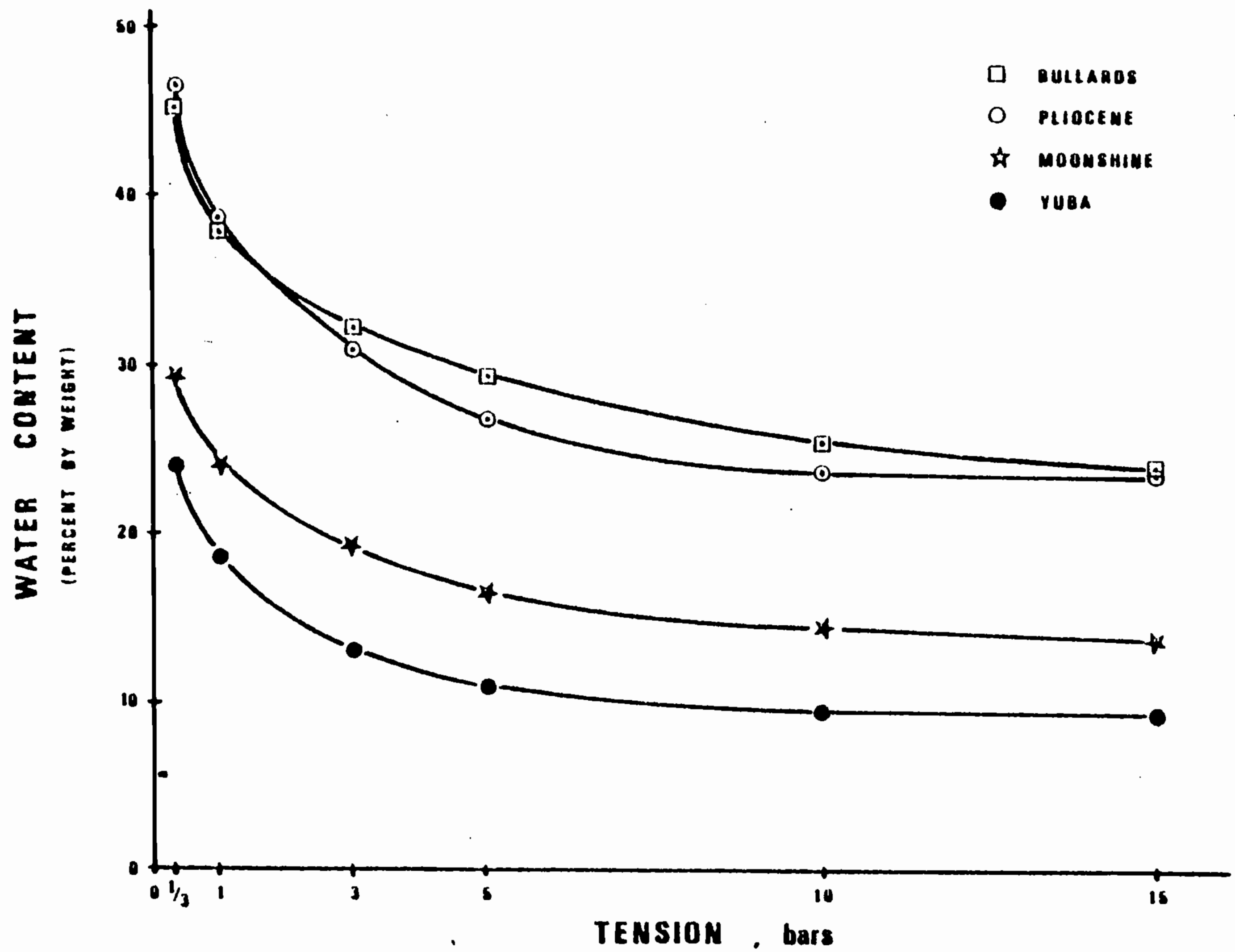


Figure 22. Soil moisture characteristic curves for disturbed soils at higher tensions.

soil particles here, as well as the amorphous clay content, caused the water holding capacity to be well above what would be expected for a sandy loam with 61 percent sand. At 15 bars suction, a moisture content of 24 percent was found. In contrast, Yuba's 72 percent sand allowed the soil to drain to a low nine percent moisture content. Soil at Bullards and Moonshine drained to 24 and 14 percent, respectively. Measurements of field soil moisture contents revealed that by early fall, the mineral soil was slightly drier than 15 bar levels at all four sites. Therefore, at least for the fall of 1979, conifers on these sites were under stressed moisture conditions.

Investigation After One Over-Wintering Period

The four sites were revisited in June, 1980 to look for signs of possible recovery of the compacted skid trails. It became quickly apparent, however, that one over-wintering period in the Sierra Nevada Mountains is not long enough to remedy the compaction produced by 20 loaded skidder trips. Ameliorating mechanisms such as frost heave, root invasion, organic matter decay, and soil fauna activity often require more than a decade before significant reductions in bulk density occur. Even after that length of time, recovery of primary skid trails may not be apparent, as has been recently discovered by Froehlich (1979) in eastern Oregon and Vanderheyden (1980) in the Oregon Cascades. In the western Sierras, with an absence of 2:1 expanding clay minerals for shrink-swell recovery, and the probable low occurrence of frost heave (Anderson 1947), it seems reasonable to assume that recovery will be very slow.

The results of the remeasurement of the ten random plots on all of the skid trails with the air permeameter showed that significant recovery had not taken place in the surface 2.5 cm (Table 14). For the majority of the trails, there was no significant difference in the means measured in 1979 and 1980. For the ten trails where there was a significant difference, six of the means decreased and four increased. This surface zone of the compacted soil profiles would logically be the first zone to show recovery, had it occurred.

The remeasurement of selected infiltrometer plots at Pliocene, Bullards, and Moonshine further emphasized the lack of recovery. For the 24 plots remeasured, the mean infiltration capacity was 2.64 cm/hr. The mean for these plots the previous summer was 3.52 cm/hr. Bullards' 1979 mean for the remeasured plots was 4.67 cm/hr; in 1980 it decreased to 2.10 cm/hr. Similarly, Pliocene's 1979 mean on the remeasured plots was 3.11 cm/hr; in 1980 it was only 1.58 cm/hr. Moonshine's 1979 mean infiltration capacity for the 12 plots studied was 2.75 cm/hr, while the 1980 mean was determined to be 3.31 cm/hr. These sample sizes were too small for statistical analysis.

It is hypothesized that the washing of silt and clay particles into the remaining surface macropore space of soil at Bullards and Pliocene accounted for the large decreases in infiltration capacity recorded. The loose, powdery mineral soil-organic matter mix which covered all of the trails immediately after skidding was converted into a firm, somewhat consolidated layer sitting above the compacted mineral soil. It is likely that raindrop impact on the unprotected trails washed a portion of these fine particles into the surface part of the profile. At

Table 14. Air permeability readings after one over-wintering period (kPa).

Site	Trail	1979 Mean	1980 Mean	Sign[a]
Yuba	1	86.7	snow	-
	2	84.7	88.6	-
	3	90.9	82.7	**
	4	81.6	87.4	-
	5	84.9	91.4	*
	6	80.0	79.8	-
	7	84.9	80.9	-
	8	73.4	80.5	-
	9	69.8	76.8	-
Pliocene	1	82.0	71.4	*
	2	73.6	83.2	*
	3	80.1	81.2	-
	4	87.9	83.5	-
	5	82.8	77.2	-
	6	89.5	93.2	-
	7	88.5	86.4	-
	8	88.3	91.1	-
	9	86.3	80.3	-
Bullards	1	63.1	58.4	-
	2	72.8	59.0	*
	3	71.4	73.8	-
	4	84.1	89.5	-
	5	84.2	75.8	-
	6	82.8	82.9	-
	7	90.8	89.9	-
	8	83.2	88.5	*
	9	77.3	68.7	-
Moonshine	1	100.0	92.6	**
	2	89.9	94.3	-
	3	93.9	91.3	-
	4	88.7	92.3	-
	5	94.9	89.2	*
	6	83.3	92.3	*
	7	91.9	90.4	-
	8	84.7	83.6	-
	9	90.2	80.7	*

[a]* denotes statistical difference at alpha = 0.10.
** denotes statistical difference at alpha = 0.01.
- denotes no statistical difference at alpha = 0.10.

Bullards and Pliocene, this process can be envisioned to be important, since a fairly large percentage of macropore space was left after compaction. This, however, was not the case at Moonshine, where almost all of the large pore space was lost to the compaction process (Table 13). Similar observations have been reported in the literature. Gifford (1972) measured infiltration capacities on a plowed big sagebrush site in southern Idaho and found the biggest decrease in the fall of the second year, even though the percent cover had nearly doubled. Johnson and Beschta (1980) state that their infiltration plots in western Oregon had sufficient soil exposure to allow silt and clay particles to seal surface macropore space.

The interference from hydrophobic surface conditions was much less noticeable at Bullards and Pliocene in 1980. This was due to the moist state the soils were in following a wet spring. Hydrophobic conditions will not limit water entry into the soil profile until the soil particles have sufficiently dried. Although no runoff samples were bottled for laboratory analysis, it was obvious that suspended sediment concentrations were much lower than those collected the previous summer. A rough estimate of this reduction would be an order of magnitude difference.

There was evidence of washing and sorting of gravels on the skid trails, particularly at Pliocene, but serious rilling and gully formation did not occur. This was primarily due to the fact that the trails were located on slopes of three to ten percent. Had they been placed on slopes approaching 30 percent, there is little doubt that more serious erosion problems would have occurred. At all of the sites except Yuba, which experienced primarily snowfall, soil pedestaling was very evident. Where chunks of wood or small stones protected the loose, powdery soil from raindrop impact, the pedestals often sat six cm above the base level.

Perhaps the runoff on the skid trails took place when the soils were still hydrophobic during the first fall storms. Under these conditions, the final infiltration capacity would not have been reached. Alternately, the infiltrometer estimates of the infiltration capacities were much too high and the trails' rates were exceeded by the natural rainfall intensities. It is not likely that the storms during the winter of 1979-80 had maximum intensities of the three to ten year recurrence interval level in the northern Sierras.

The trails at all sites had at least some revegetation take place. Moonshine, having the warmest and most temperate climate, experienced the most. A fairly heavy invasion of cheat grass (*Bromus tectorium*), bracken fern (*Pteridium aquilinum*), and scotch broom (*Cytisus scoparius*) was noted. The skid trails at Bullards and Pliocene were covered with coniferous litter, mainly in the form of pine needles. Kit-kit-dizze (*Chamaebatia foliolosa*) sprouts were common at Pliocene, while conifer seedlings and tanoak sprouted in Bullards' trails. Yuba, with its cold, harsh climate, had only a few forbs sprouting in its partially snow covered trails.

CONCLUSIONS

From the information gained on the 36 primary skid trails produced by this study, several generalizations can be made. After 20 trips by any of the vehicles, there was little difference on the portions of the trails which received direct track or wheel pressure for the soil and hydrologic properties measured. The primary distinction between vehicles was for the condition the trail centers were left in. The crawler tractor caused uniform compaction across its trails, while the torsion suspension vehicle and rubber-tired skidder had noticeably less disturbance in this zone.

Due to the large sample size used and the tight calibration obtained for the nuclear probes, bulk density provided a very good index for compaction. When trail averages were considered, significant differences between machines for the change in bulk density were found for all of the depths sampled. The crawler tractor produced larger changes than either of the other two vehicles. It must be remembered, however, that the rubber-tired skidder moved only approximately half of the load pulled by the other two machines. Had the number of trips been increased for the rubber-tired skidder to equalize the wood yarded, the results may have been significantly different. Absolute bulk density values were higher with increasing depth, but the largest change in density occurred in the surface layer.

As indexed by air permeability, the three vehicles produced very similar reductions in macropore space in the surface 2.5 cm as the number of trips increased. Approximately 75 percent of the surface macropore space reduction occurred by six trips. After 20 trips, there was no statistical difference in mean backpressure readings for any of the machines. Due to the widely ranging properties of forest soils, only 25 to 35 percent of the variability could be explained by regressing air permeability readings against bulk density values taken at the five cm depth for any given site. On the basis of this study's results, it can be concluded that the air permeameter provides a reasonably good index of compaction when the sample size is large enough to compensate for soil heterogeneity.

Infiltration capacities for the undisturbed soil at the four sites exceeded the maximum precipitation rates which could be expected. Mineral soil from the three higher elevation sites was very hydrophobic. Yuba, with its associated red fir forest and litter, had the most non-wettable soil. Metabolic products from fungal decomposition of the litter layers are thought to coat the individual soil particles and resist wetting. In the undisturbed state, this process was only observed to limit infiltration at Yuba. Macro-voids allowed water transmission at Pliocene, while well developed aggregate structure aided Bullards' infiltration. After 20 passes with the machines, the crawler tractor produced a 78 percent reduction in infiltration capacity, while the torsion suspension vehicle and the rubber-tired skidder caused a 67 percent decrease.

Suspended sediment concentrations determined from runoff collected on the infiltration plots were extremely variable and the sample population was highly skewed. A square root transformation was used to normalize the distribution. The crawler tractor trails produced approximately 40 percent higher sediment concentrations when compared to the levels measured on the trails for the other vehicles. The organic matter content in the surface five cm explained 30 percent of the variability in sediment movement in the track positions of the trails.

Saturated hydraulic conductivity measurements made from cores taken in the surface six cm of the track position showed that there was no significant difference between vehicles. The mean reduction in conductivity was 80 percent. Site differences in conductivity levels were significant, with Moonshine's cores experiencing the lowest water transmission. Conductivity was strongly correlated with percent macropore space.

Porosity measurements showed that there was mainly a conversion of macropore space to micropore space. The mean decrease in total porosity was only four percent in the surface six cm layer. The average reduction in macroporosity in the surface six cm was 43 percent; significant differences in reductions by machine type could not be found. Mean decreases by site ranged from 30 percent at Yuba to 64 percent at Moonshine. Only at this latter site was the amount of macropore space below the critical level of ten percent needed for aeration.

Measurements made after one over-wintering period indicated that there had been no measureable recovery from compaction. Air permeability plots were remeasured and no significant change was found. Selected infiltration plots were also remeasured; infiltration capacities were generally lower than immediately following skidding. Erosion was not a problem on the skid trails and varying degrees of revegetation had taken place.

The results of this study show that on the relatively sandy soils found in the western Sierra Nevada, differences in the amount of compaction produced by the three vehicle types were not extreme. Whether this would be the case on other soil types, such as heavy clay loams found in western Oregon is not known. Clearly a wet clay soil with a large percentage of 2:1 expanding montmorillonite would behave differently than any of the soils investigated in this study.

The changes in hydrologic properties of these soils were similar to those reported in several earlier studies. The establishment of primary skid trails by any of the machines will change the hydrologic regime of the soils greatly. When this occurs on 20 to 45 percent of a logging unit, the negative impacts on water and air movement can seriously alter site potential. Therefore, logging engineers and equipment operators should attempt to minimize the number of skid trails made. Winching felled timber from pre-planned skid trails is the best method of reducing harvesting impacts on the soil resource.

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APPENDICES

APPENDIX A

Soil Profile Descriptions[11]

Yuba Pass

Soil Classification: frigid Dystric Xerochrept

Soil Series: Kriest

Parent Material: Granodiorite

Horizon	Depth, cm	Description
O_1	3-0	Red fir needles, twigs; matted condition.
A_{11}	0-5	Very dark grayish brown (10YR 3/2 moist) loamy sand; weak very fine grannular structure; soft, very friable, nonsticky, nonplastic; many very fine roots; many very fine irregular pores; 25 percent pebbles; very slightly acid (pH 6.4); abrupt wavy boundary.
A_{12}	5-12	Very dark grayish brown (10YR 3/2 moist) loamy sand; massive structure; soft, very friable, nonsticky, nonplastic; common very fine and many fine roots; many very fine irregular pores; very slightly acid (pH 6.4); clear wavy boundary.
B_1	12-45	Brown (10YR 4/3 moist) loamy sand; massive structure; soft, very friable, nonsticky, nonplastic; common very fine and fine roots; many very fine irregular pores; very slightly acid (pH 6.6); gradual and smooth boundary.
B_2	45-96	Brown (10YR 4/3 moist) loamy sand; weak fine subangular blocky structure; soft, friable, nonsticky, nonplastic; few fine to coarse roots; common very fine irregular pores; 15 percent pebbles; very slightly acid (pH 6.6), clear wavy boundary.
C_1	96-180+	Light olive brown (2.5Y 5/4 moist) loamy sand; massive structure; hard, friable, nonsticky, nonplastic; very few fine to coarse roots; few fine to coarse tubular pores; 15 percent pebbles; medium acid (pH 5.6).

[11]The soil profile descriptions were done by Dr. Earl Alexander, USFS Regional Soil Scientist, Region 5.

Pliocene Ridge

Soil Classification:	mesic Andic Xerumbrept
Soil Series:	McCarthy
Parent Material:	Andesitic Lahar

Horizon	Depth, cm	Description
O_1	8-3	Mixed conifer needles, twigs.
O_2	3-0	Partially decomposed needles, twigs.
A_{11}	0-9	Very dark grayish brown (10YR 3/2 moist) gravelly sandy loam; weak very fine granular structure; soft, very friable, nonsticky, nonplastic; common very fine and fine roots; many fine irregular pores, 30 percent pebbles; medium acid (pH 5.8); clear smooth boundary.
A_{12}	9-36	Dark brown (7.5 YR 3/2 moist) gravelly sandy loam; weak very fine granular structure; soft, very friable, nonsticky, nonplastic; common fine and medium, few coarse roots; many very fine irregular pores; 30 percent pebbles and 5 percent cobbles; medium acid (pH 6.0); gradual wavy boundary.
B_2	36-75	Dark brown (7.5 YR 4/4 moist) very gravelly sandy loam; massive structure; soft, very friable, nonsticky, nonplastic; few fine, medium, and coarse roots; many very fine irregular pores; 40 percent pebbles and 10 percent cobbles; medium acid (pH 5.6), abrupt irregular boundary.
C_r	70-80+	Soft, weathered tuff breccia mudflow.

Bullards Bar

Soil Classification: mesic Xeric Haplohumult

Soil Series: Sites

Parent Material: Metamorphosed Schist

Horizon	Depth, cm	Description
O_1	12-0	Mixed conifer matted needles, twigs.
A_1	0-6	Dark brown (7.5YR 3/3 moist) loam; moderate fine granular structure; soft, friable, slightly sticky, slightly plastic; common very fine and few fine roots; common medium and many fine irregular pores; 10 percent pebbles; medium acid (pH 5.8); clear smooth boundary.
A_3	6-21	Dark reddish brown (5YR 3/4 moist) loam; strong medium granular structure; slightly hard, friable, sticky, slightly plastic; common very fine, fine, and few medium, coarse roots; common medium and many fine irregular pores; 10 percent pebbles; medium acid (pH 6.0); clear wavy boundary.
B_{1t}	21-42	Reddish brown (2.5YR 4/5 moist) clay loam; moderate very fine and fine subangular blocky structure; slightly hard, friable, sticky, plastic; few thin discontinuous clay films; few fine and common medium and coarse roots; common fine and few medium tubular pores; 8 percent pebbles; medium acid (pH 5.6); gradual wavy boundary.
B_{21t}	42-75	Red (2.5YR 4/6 moist) clay loam; moderate fine and medium subangular blocky structure; hard, friable, very sticky, plastic; moderate continuous clay films; few fine, medium, coarse roots; common fine and few medium tubular pores; 7 percent pebbles; medium acid (pH 5.8); diffuse boundary.
B_{22t}	75-125	Red (2.5YR 4/6 moist) silty clay loam; moderate fine and medium angular blocky structure; hard, friable, sticky, plastic; moderate continuous clay films; very few fine, medium, coarse roots; common fine and few medium tubular pores; 4 percent pebbles, medium acid (pH 5.8); abrupt irregular boundary.
C_r	125-150+	Soft, weathered schist; contact ranges from 100 to greater than 150 cm deep.

Moonshine Road

Soil Classification: mesic Ultic Haploxeralf

Soil Series: Musick

Parent Material: Siliceous Plutonic

Horizon	Depth, cm	Description
O_1	3-0	Mixed conifer needles, some hardwood leaves and twigs.
A_{11}	0-3	Dark brown (10YR 3/3 moist) sandy loam; weak very fine granular structure; soft, friable, slightly sticky, slightly plastic; common very fine roots; few medium and many fine irregular pores; very slightly acid (pH 6.4); clear wavy boundary.
A_{12}	3-16	Dark yellowish brown (10YR 4/4 moist) sandy loam; weak very fine to medium subangular blocky structure; soft, friable, slightly sticky, slightly plastic; few very fine to fine and common medium roots; many very fine irregular pores; very slightly acid (pH 6.4); gradual smooth boundary.
A_3	16-30	Dark brown (7.5YR 4/4 moist) loam; weak very fine and fine to medium subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; common fine and medium roots; common very fine irregular pores; slightly acid (pH 6.2); clear wavy boundary.
B_{21t}	30-52	Yellowish red (5YR 4/8 moist) clay loam; moderate fine subangular blocky structure; hard, friable, sticky, plastic; moderate continuous clay films; few fine and common medium to coarse roots; common very fine and few fine tubular pores; slightly acid (pH 6.2); clear smooth boundary.
B_{22t}	52-80	Yellowish red (5YR 4/8 moist) clay loam; moderate medium subangular blocky structure; hard friable, sticky, plastic; thick continuous clay films; few fine roots; common very fine and few fine tubular pores; slightly acid (pH 6.2); diffuse smooth boundary.
B_{3t}	80-150+	Yellowish red (5YR 5/6 moist) loam; weak subangular blocky structure; slightly hard, friable, slightly sticky, plastic; discontinuous clay films; very few roots; common very fine tubular pores; slightly acid (pH 6.2).

APPENDIX B

Sample Calculations

Bulk Density

I. Core Method

$$\text{Bulk Density } (g/cm^3) = \frac{\text{mass of dry soil particles}}{\text{total volume of the soil}}$$

$$= \frac{\text{oven dry wt (105°C) - soil can tare wt}}{\text{volume of soil retaining ring}}$$

Example:

$$\text{Bulk Density} = \frac{143.82 \text{ g} - 51.67 \text{ g}}{135.4 \text{ g}}$$

$$= 0.681 \text{ g/cm}^3 \quad \text{(Pliocene, pre-dist.)}$$

II. Probe Method

Three separate curvilinear equations were determined for converting nuclear probe readings into wet bulk density values: one for the five cm depth, one for the ten cm depth, and one for the 15, 20, and 30 cm depths.[12]

Infiltration

Infiltration Capacity (cm/hr) = rate of rainfall application - rate on constant runoff

The regression equation used to determine the application rate was:

$$Y = 9.349\ X - 55.779$$

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[12] For the specific equations and further details, see Azevedo and Froehlich (incomplete paper to be submitted to Soil Sci. Soc. Amer. J. in 1981).

where: Y = rainfall rate, ml/min
X = flow gauge reading (Froehlich and Hess 1976)

For a rainfall rate of 7.6 cm/hr (3.0 in/hr):

$X = 48$ and $Y = 392.98$ ml/min or cm^3/min

Conversion to cm/hr:

$$\frac{392.98\ cm^3}{min} \times \frac{1}{3122.6\ cm^{2}} \times \frac{60\ min}{hr} = 7.6\ cm/hr$$

Example:

Infiltration Capacity = 392.98 ml/min - 274.23 ml/min
= 118.75 ml/min
= 2.28 cm/hr (Yuba, post-dist.)

Saturated Hydraulic Conductivity

From Darcy's Law, we know-

$$q = K\frac{\Delta H}{L}$$

where: q = water flux
K = hydraulic conductivity
ΔH = the change in hydraulic head
L = length of the soil sample

The flux can also be written-

$$q = \frac{V}{a\ t}$$

where: V = a given volume of water
a = the cross sectional area
t = the time allowed for water passage (Hillel 1971)

Rearranging terms after substituting in the new flux term-

$$K = \frac{V\ L}{\Delta H\ a\ t}$$

Example:

$$K = \frac{26\ ml \times 6\ cm}{10\ cm \times 22.56\ cm^2 \times 180\ sec}$$

$= 0.00384$ cm/sec at 19°C

Correction for temperature:

$$K_{20} = \frac{\mu_{19}}{\mu_{20}} \times K_{19°}$$

$$K_{20} = \frac{1.0362}{1.0064} \times 0.00384 = 0.00395 \text{ cm/sec}$$
(Bullards, post-dist.)

Total Pore Space

By assuming complete saturation of the soil core samples, total porosity can be found by determining the volume of water present in a given core between 0 cm tension and the oven dry state-

$$\text{Total Porosity} = \frac{\text{volume of pore space}}{\text{total volume of soil ring}} \times 100\%$$

$$= \frac{\text{saturated wt} - \text{tare wt} - \text{clamp wt} - \text{oven dry wt}}{\text{volume of soil retaining ring}}$$

$$\times \text{ specific volume of water } \times 100\%$$

Example:

$$\text{Total Porosity} = \frac{1027.2 \text{ g} - 149.5 \text{ g} - 702.1 \text{ g} - 91.4 \text{ g}}{}$$

$$\times 1 \text{ cm}^3/\text{g} \times 100\%$$

$$= 62.2 \text{ percent}$$ (Bullards, pre-dist.)

Moisture Contents from the Tension Table

To determine the moisture content of a soil sample after each level of tension had been applied, the following equation was utilized:

$$\text{Moisture Content} = \frac{\text{tension wt} - \text{tare wt} - \text{oven dry soil wt}}{\text{volume of soil retaining ring}}$$

$$\times \text{ specific volume of water } \times 100\%$$

Example:

Moisture Content (30 cm tension) $= \dfrac{322.2 \text{ g} - 149.1 \text{ g} - 125.9 \text{ g}}{135.4 \text{ cm}^3}$

$$\times 1 \text{ cm}^3/\text{g} \times 100\%$$

$$= 34.9 \text{ percent}$$ (Moonshine, pre-dist.)

Macropore Space Determination

Macropore Space = total porosity(%) - 60 cm tension moisture content

Example: Macropore Space = 56.6 - 31.3

= 25.3 percent (Moonshine, pre-dist.)

Pore Size Distribution

The capillary rise equation is used to calculate the pore diameter sizes-

$$r = \frac{2\ T_s \cos a}{p\ g\ h}$$

where:
r = the pore radius
T_s= the surface tension of water
a = the contact angle
p = the density of water
g = the acceleration of gravity
h = the height of capillary rise (Hillel 1971)

Assuming the contact angle equals zero for water and the surface tension equals 72.7 dynes/cm at 20°C, the minimum radius of a pore which will be drained for a given tension can be solved.

Example:

$$r = \frac{2 \times 72.7 \text{ dynes/cm} \times 1}{1 \text{ g/cm}^3 \times 980 \text{ cm/sec}^2 \times 10 \text{ cm}}$$

$$= 0.148 \text{ mm}$$

$$d = 0.296 \text{ mm}$$

Thus, those pores draining with ten cm tension applied will have a diameter of 0.296 mm or larger. A table with the tensions used in this thesis and the corresponding minimum pore diameters drained follows:

Tension	Pore Diameter, mm
10	0.296
20	0.148
30	0.099
50	0.059
60	0.049
80	0.037

To calculate the percentage of pores in each size class, the mass of water drained at each tension was utilized (Ranken 1974).

Examples:

Percentage of pores greater than 0.296 mm =

$$\frac{\text{saturated wt} - \text{10 cm wt}}{\text{saturated wt} - \text{tare wt} - \text{oven dry wt}} \times 100\%$$

$$= \frac{356.4\text{ g} - 344.5\text{ g}}{356.4\text{ g} - 154.8\text{ g} - 126.8\text{ g}} \times 100\%$$

= 15.9 percent (Moonshine, pre-dist.)

Percentage of pores from 0.148 mm to 0.296 mm =

$$\frac{\text{10 cm wt} - \text{20 cm wt}}{\text{saturated wt} - \text{tare wt} - \text{oven dry wt}} \times 100\%$$

$$= \frac{344.5\text{ g} - 335.1\text{ g}}{356.4\text{ g} - 154.8 - 126.8\text{ g}} \times 100\%$$

= 12.6 percent (Moonshine, pre-dist.)