

MULTIPASS EFFECTS OF WHEEL AND TRACK TYPE VEHICLES ON SOIL  
COMPACTION

by

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THIS WORK IS DEDICATED TO  
THE DEPRIVED AND POOR PEOPLE OF THE WORLD  
WHO WORK HARD AND ARE FAITHFULL,  
AND TO THOSE WHO STRUGGLE FOR EQUALITY AND JUSTICE.

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## Chapter I

### INTRODUCTION

Soil physical conditions are directly and indirectly influenced by machine operations. Heavy equipment used in agriculture and forestry can alter the soil structure and cause soil compaction to considerable depths. Compaction is the process of packing the soil particles together. During this process the soil density is increased while the total pore space is decreased. Many soil physical properties are affected by this process, which in turn affect the soil-plant relationship.

Both soil and machine factors influence the compaction process. Selected variables under both category are: moisture content, soil structure and texture, amount of organic matter, initial density, vehicle type, weight, area and shape of contact area, and frequency of travel.

Soil compaction typically increases the soil bulk density and its strength while reducing the total pore space. Generally, these changes result in a reduction of plant yield due to high mechanical impedance to root development, and due to restricted movement of air, water and nutrients. Moderate compaction may, in some cases, increase the availability of soil moisture and nutrients, but heavy compaction

can restrict movement of both water and nutrients to plant roots.

Excessive compaction of soil is shown to have detrimental effects on plant growth and yield (Taskov, 1980; Mitchel et al., 1982). Thus, a knowledge of the compaction process, the factors that influence it, and its effect on the soil physical conditions is essential for removing or minimizing the detrimental effects of soil compaction.

Many studies in the past have dealt with the effects of factors such as load application, traffic intensity, soil moisture level, and soil texture on soil compaction and effects of compaction on soil physical properties and plant growth. However, the extent and its long range effects on tree survival and growth are not well documented. Thus, a study was initiated with an overall objective of evaluating the effects of multiple passes of vehicles on soil compaction and on tree growth and survival. The study described in this thesis was conducted as a part of this overall project and its specific objectives are stated in the next chapter.

## Chapter II

### OBJECTIVES

The objectives of this study were twofold:

I. To evaluate the effects of vehicle type, soil moisture, number of vehicle passes, and interactions among these factors on soil bulk density.

II. To compare nuclear and gravimetric procedures for determining soil bulk density.

## Chapter III

### LITERATURE REVIEW

Soil compaction is a process by which bulk density of a given soil is increased due to an external force, usually due to machine operation. Raghavan and McKyess (1977) defined compaction as a process of rearrangement of the soil particles, producing changes in the soil-air-water matrix. The relationship between compaction and soil physical properties is reviewed here. The properties included are: soil structure and texture, strength, aeration, moisture, and nutrient status. Vehicular factors, depth of compaction, and the effects of compaction on plant growth and yield, and on soil erosion are also reviewed.

#### 3.1 SOIL STRUCTURE AND TEXTURE

Soil structure can influence the compaction of soil as well as being influenced by it. One of the factors influencing the compaction process is the particle size composition. Particle size distribution determines the pore space characteristics of the soil. Soils with high porosity are more compressible than those with low porosity. Poorly graded soils are composed of uniform sized particles and have a high void ratio; whereas, well graded soils, containing a

wide variety of particle sizes, have high bulk densities and can be compacted to much higher densities than soils of uniform grain size. This is because the soil particles are rearranged and smaller particles fill the voids between the large ones under compactive forces (Huberty, 1944; Klingebiel and O'Neal, 1952; Ingles, 1974).

Many workers have studied the effect of soil texture on compaction. According to Raney et al. (1955), hardpans produced by compaction are most commonly found in medium-textured soils: loams, sandy loams, and silt loams.

From his field and laboratory studies, Krynine (1951) found that maximum densities obtainable decreased proportionately in the order of decreasing grain size from gravel to clay.

Unpacked, virgin soils have granular and crumb structure forms that are associated with good tilth as well as good moisture and air relationships. Heavy compression of soil results in reduced permeability and poor drainage due to an increase in bulk density. Degraded soil structure generally influences plant growth through its effect on soil-water, soil-air relations or by affecting the mechanical impedance of the soil (Fountaine, 1958; Negi et al., 1980).

Sorochkin and Sheptukhov (1979) reported that the effects of compaction on soil structure could be traced to a depth of

50 Cm. The deterioration was accompanied by a decrease in intra-aggregate porosity, a considerable increase in mechanical strength, and a resulting adverse effect on plant development.

Gerard (1965) investigated the influence of texture and other soil physical factors on the strength of combinations of silt-clay and sand mixtures. He plotted maximum strength as a function of percent silt and clay content and showed that soil strength increases with increasing silt and clay content.

In a skidding investigation, Dickerson (1976) reported that although bulk densities of undisturbed soils were not significantly related to any of the soil components, bulk densities of soil compacted by the rubber-tired skidder were negatively correlated with the percentage of sand. Another study, conducted with a crawler tractor (Hatchell et al, 1970), showed that final density after nine trips was negatively correlated with percentage of clay in surface soil but positively correlated with percentage of silt.

Warnaars and Eavis (1972) investigated the effect of grain-size distribution , under varying mechanical impedance, on pea (Pisum sativum), corn (Zea mays), and grass seedling root growth. They reported that root elongation was restricted due to mechanical impedance in all treatments in-

cluding the very fine sands in which the longest roots were found. This effect was most pronounced in the coarse sands, where crooked swollen roots, similar in shape to the pore channels, were found. In the fine sands, when drained properly, roots were straight and evenly tapered but smaller than would be expected in unpacked soil.

### 3.2 SOIL STRENGTH

The major consequence of compaction is an increase in the shear strength of soil due to an increase in bulk density. In general, strength of a given soil, at a given moisture level, increases with increasing density (Carter and Tavernetti, 1968). The major factor influencing the soil strength - density relationship is soil moisture content (Chancellor, 1971).

At any given bulk density, soil resistance tends to pass through a maximum as soil moisture is increased. This effect is most pronounced at low bulk densities ( $1.0 \text{ g/cm}^3$ ) and disappears at high bulk densities ( $>1.6 \text{ g/cm}^3$ ). Loss of soil moisture results in a general increase in soil strength, which is due to a decrease in pressure in the pore fluid and, in some soils, a decrease in particle spacing (Hampton and Selig, 1965). Camp and Gill (1969) showed that strength parameters representing cohesion and angle of internal friction increase with a decrease in soil water content.

Soil strength increases with increasing bulk density and moisture tension but not independently. To show the interrelationship, Mirreh and Ketcheson (1972) used a three dimensional plot of soil resistance values, bulk density, and matric pressure. The plot shows that the relationship of soil resistance to bulk density tends to be slightly concave to the base with steeper slopes and increasing linearity at the higher matric pressures ( $>0.6$  Mpa).

Eavis and Payne (1968), studying penetration of sandy loam soils, also found that soil mechanical resistance was influenced by moisture tension as well as by bulk density. The effect of moisture levels was small in loose soil and large in compact soil. They investigated the growth of pea seedling roots in small soil columns for a period of 24 hours. The growth of the root length and volume was approximately inversely proportional to the level of mechanical resistance, while the mean diameter of the roots were approximately proportional to mechanical impedance.

The work of Phillips and Kirkham (1962a) indicated that corn yields were directly proportional to the weight of the roots in the top 60 cm layer of soil. This was attributed to increased mechanical impedance to root growth due to high soil strength.

Penetrometers are commonly used to characterize the strength of soils, and soil resistance is recorded in terms of pressure. Taylor et al. (1966) investigated cotton (Gossypium hirsutum) root penetration in four medium- to coarse-textured soils each at five different bulk densities and three moisture contents. The results of this study showed that only 35% of the taproots penetrated a soil layer with a resistance of 0.10 Mpa or higher. The root elongation was found to cease at a resistance of 2.2 Mpa.

When local zones of compaction are encountered, the roots spread laterally resulting in more girdled and abraded roots (Taylor and Bruce, 1968; Bakhshi et al, 1970; Pirone, 1972). Voorhees et al. (1975), studying the root elongation rates of pea seedlings, found that as soil resistance due to compaction increased, the primary root became more twisted, and more branching of the root in a limited volume of the soil occurred. They pointed out that although such increased root branching in a given volume of soil may be desirable for nutrient and water uptake, a considerable volume of soil must be explored to satisfy the plant's total water requirements. Thus, soil compaction can result in an increased rate of branching in a limited volume at the expense of primary root elongation.

Many workers have reported reductions in root growth due to excessive soil strength (Phillips and Kirkham, 1962a; Eavis and Payne, 1968; Barley, 1965).

Gerard et al. (1972) studied root growth in a Harlingen clay soil at different densities and moisture contents. Root elongation decreased with increasing soil strength. This was particularly true for soil resistance higher than 0.10 Mpa. Roots appeared to grow better in soils with moderate strength (0.04-0.09 Mpa) than in soils having lower or higher mechanical impedance. Heavily compacted clay soil with bulk densities of 1.65 and 1.67 g/cm<sup>3</sup> greatly retarded or prevented root elongation, and high soil strength caused root deformation as well as increased lateral development.

Cotton seedling root penetration in Amarillo fine sandy loam soil was investigated by Taylor and Gardner (1963). They concluded that soil strength, not bulk density, was the critical factor controlling root penetration.

### 3.3 SOIL AERATION

Soil aeration is the movement of gases through the soil by diffusion or by mass flow. It occurs mainly in air filled pores. These processes can be disrupted by alteration of soil structure. Aeration problems resulting from changes

in soil structure are related to the pore size distribution. Rearrangement or destruction of macropore space by either reducing the size of aggregates or increasing the bulk density affects gaseous exchange in the soil (Vomocil and Flocker, 1961; Hatchell et al., 1970; Eavis, 1972).

Decreases in pore space due to compaction can restrict movement of oxygen into the soil, and carbon dioxide out of the soil (Grable, 1971; Eavis and Payne, 1968; Rickman et al., 1965). In general, oxygen deficiency is more serious to plant growth than excessive carbon dioxide (Kramer, 1950; Slayter, 1967).

Gill and Miller (1956) studied the effect of oxygen supply on seedling root development under various levels of mechanical impedance. They found that the rate of growth of unimpeded roots declined when the oxygen content fell below 10% (of the pore space). Furthermore, at relatively small levels of impedance, a low oxygen content resulted in a zero growth rate. "The ability of a root to enlarge in spite of mechanical restraint was greatly impaired by relatively modest reductions in oxygen contents".

Oxygen deficiencies can cause changes in kind and rate of biological activities. According to Kempner (1937), this happens only at very low oxygen levels (below 5%).

Based on experiments on different plants, researchers have reported "critical" levels of air space at field capacity below which plant growth and productivity decline rapidly. Vomocil and Flocker (1961) cited a number of such studies and suggested that for most plants, limiting levels of soil air space appear to be in the vicinity of 10 to 15% (of the pore space).

Roots developing in poorly aerated soils are thicker, shorter, and darker in color with fewer hairs due to insufficient oxygen (Richards and Wadleigh, 1952; Eavis and Payne, 1968).

Russel (1952), Baver (1956), and Wesseling (1962) concluded that soils are basically aerated by diffusion. The rate of diffusion depends on the free pore space in the soil. Dyrness (1965) found that compaction significantly decreases porosity of the surface soil. "In the tractor-logged area, undisturbed soil had approximately 77% pore space, while compacted soil averaged only about 63%".

Six passes of a crawler tractor (Moehring and Rawls, 1970) on wet soils (moisture content near field capacity) decreased total pore space by 11%, and macropore space by 49%. Under dry conditions, however, the measured physical properties of the soil were not affected.

Many authors (Cannon and Free, 1925; Lawton ,1946; Wiersma and Mortland ,1953; and Hatchell et al. ,1970). have shown positive correlation between the growth response of several plants and soil aeration, primarily the rate of supply of oxygen to the roots.

Other investigators, however, have suggested that lack of adequate aeration is detrimental to plant growth and yield only in conjunction with other unfavorable conditions such as increased soil strength or prolonged saturation of the soil (Grable, 1966; Kramer, 1950; Tacket and Pearson, 1964a).

Still other studies have indicated the role of aeration to be minimal compared to other factors influenced by soil compaction. In a study on corn seedling root growth, Philips and Kirkham (1962) concluded that mechanical impedance and not aeration is the primary cause for reduced corn root growth in early stages. Tacket and Pearson (1946b) also arrived at the same conclusion from a study dealing with the cotton root penetration into a compacted sandy loam subsoil. They remarked that mechanical impedance would overshadow aeration effects even though oxygen levels below 10% had a detrimental effect at low densities ( $< 1.5 \text{ g/cm}^3$ ).

### 3.4 SOIL MOISTURE

Moisture content of soil is one of the most important factors influencing the compaction process. According to proctor (1933), in dry soils the resistance of the particles to rearrangement is greatly due to the lack of lubrication by water films and the existence of high surface tension. A slightly higher moisture content improves lubrication and neutralizes the surface tension forces such that smaller particles easily rearrange and fill the voids between the larger particles. Further addition of moisture increases compactability only to a certain point - the optimum moisture content for maximum compaction - where water and a small amount of air fill the pore space, producing an arrangement which resists further compaction (Lull, 1959; Foil and Ralston, 1967; Hatchell et al. 1970).

Thus, the amount of compaction of a soil under a given force increases with increasing moisture content until it reaches a maximum, at a moisture content closer to the lower plastic limits (Weaver and Jamison, 1951), and then drops.

Hatchell et al. (1970) stated that on wet, medium- to fine-textured soils, a high degree of compaction can be induced with only one vehicle trip, while dry, coarse-textured soils are compacted only slightly by several trips. They stated that compaction of excessively moist, medium-textured

soils causes a "critical reduction in non-capillary pore space, surface runoff, and internal drainage", resulting in extended periods of poor aeration which are detrimental to the establishment and growth of pine (Pinus taeda) seedlings.

According to Warkentin's review (1971), when dry soils are subjected to compacting forces, aggregates undergo a deformation and rearrangement process which results in a void-size reduction rather than compaction of aggregates themselves (Cheng and Warkentine, 1968; Day and Holmgren, 1952). Compaction of wet soils results in more parallel orientation of clay particles within peds. In moist soil aggregates, Day and Holmgren (1952) stated, plastic deformation is the dominant mechanism of compaction.

Compaction can increase water storage and often the amount of water available to plants (Jamison, 1953; Rosenberg and Willits, 1962). This is because the micropores created by compaction retain water at field capacity.

Jamison (1965) indicated that moderate compaction can increase available moisture storage capacity in the available moisture range for most soils. However, excessive packing of soil reduces both capacity and movement of water and air, adversely affecting root growth (Lutz, 1952). In fine-textured soils, Lutz (1952) observed a reduction in pore size

to radii smaller than the thickness of the water film on the particles. Thus, practically all of the pores are filled with water, which is held with a considerable force such that there is no water or air available to the plant roots.

In a given soil, the availability of water to the plant depends, to a large degree, upon the size of the root system. Soil compaction can adversely affect plant water uptake by impeding root growth and thus limiting the volume of soil effectively explored by roots for water (Taubenhaus et al., 1931; Gill, 1971).

Taylor et al. (1964) observed more wilting of grain sorghum in high strength soil compared to that grown in low strength areas. But, in the final analysis, grain yields were not significantly reduced by compaction.

Lowry et al. (1970) attributed reduction of cotton yield, grown in artificially compacted soil, to water supply deficiency due to limited rooting volume.

Increasing soil bulk density and decreasing porosity generally causes a reduction in infiltration rate and an increase in the amount of runoff (Trimble and Weitzman, 1953) causing surface erosion and a soil moisture deficiency at deeper levels.

During an infiltration study by Parker and Jenny (1945), it was observed that 33 passes of a crawler tractor on a moist soil increased surface runoff more than 15 fold.

Steinbrenner (1955) found that on a dry soil four passes of an HD-20 tractor (weighing about 20 t) resulted in a 50% reduction in macropore space which was associated with an infiltration rate decrease from 80 to 10 cm<sup>3</sup>/min. However, when the soil was wet, only one tractor trip produced the same effect. This example clearly illustrates the influence of moisture on the compaction process and the effect of compaction on soil water.

Work of Prihar and Van Doren (1967) indicated that over 40% of the reduction in corn yield associated with soil compaction was due to the poorer infiltration of water into compacted soils.

Gumbs and Warkentin (1972) made infiltration measurements on swelling clay soil samples packed into columns and reported a considerable decrease in the rate of water movement in the soil.

The importance of soil water content to plants growing in compact soils was demonstrated by Wittsell and Hobbs (1965). Wheat yields were increased by watering soil that was compacted to a depth of 30 cm, which otherwise showed decreased yields.

### 3.5 SOIL NUTRIENTS

Availability of nutrients to the plants is one of the most important factors influencing plant-soil relationships. Nearly all of nutrients taken up by plants are in the form of ions which have to move through the soil to reach the sorbing root surfaces. Nutrient uptake involves two different processes. They are: distribution of the root system into areas where nutrients occur, and transport of nutrient ions to the absorption sites (Danielson, 1972).

Soil compaction generally affects the growth and distribution of the root system as discussed in the soil strength section. Compaction also influences nutrient movement in the soil. Available forms of soil nutrients could be divided into two groups: relatively mobile, like nitrate nitrogen; and relatively immobile nutrients, like exchangeable potassium and the adsorbed forms of phosphate. Bray (1954) suggested that there are two types of root sorption zones associated with these two available nutrient forms. One zone includes the whole volume of soil within the major part of the root system. From this zone (root system sorption zone), mobil nutrients are extracted by the roots. The other zone type are the thin volumes of soil adjacent to each root, or root hair surface, from which the roots effectively obtain the relatively immobile nutrient ions.

The removal of the immobile nutrients decreases rapidly with distance from the root surface. Since plants extract immobile ions such as phosphates and potassium only from the volume of soil with which the roots are in immediate contact, the uptake of these nutrients is dependent on the size of the root system. By reducing the size and distribution of the root system, soil compaction will reduce the amount of immobile nutrients taken up by plants. Hence, reduced root extension will result in deficiency of nutrient ions such as phosphate and potassium (Parish, 1971). Voo-rhees et al. (1975), however, found that compaction resulted in an increased root branching in a given volume of the soil, which may be desirable for uptake of nutrients in that limited volume. This is done, however, at the expense of decreased size of the root system due to an increase in soil resistance to root elongation.

The movement of relatively mobile nutrients through the soil to the root system involves two mechanisms: mass flow in the water absorbed by the plant, and diffusion (Barber, 1962). Soil compaction influences both these processes. The consequence, however, may be detrimental or beneficial to nutrient availability.

According to Kemper et al. (1971) movement of non-adsorbed ions such as nitrates and sulphates depends to a

large degree on mass flow of soil solutions. Since compaction can increase unsaturated conductivity, and thus the rate of solution movement, the nutrients in soil solution will move faster. It should, however, be noted that compaction decreases the conductivity of the soil when it is fully saturated.

The breakdown of the soil structure, due to heavy compaction, results in a reduction of pore space and blockage of pathways through which diffusion and mass flow of nutrients take place (Graham-Bryce, 1963; Parish, 1971). But since the amount of anions, such as various forms of phosphate, is directly proportional to bulk density, compaction can increase concentrations of such ions in the vicinity of the roots (Kemper et al., 1971).

Cheng et al. (1971) conducted greenhouse experiments to investigate the effect of soil physical conditions on plant growth and on uptake of trace elements by plants. They noted that oat roots in compacted soil ( $1.5 \text{ g/cm}^3$ ) were distorted, and generally shorter and thicker than those of plants in unpacked soil ( $1.2 \text{ g/cm}^3$ ). Thus, root size and distribution were affected: "Compaction invariably decreased the plant content of manganese, iron, and aluminum, but increased Mn/Fe ratio." No significant difference in the molybdenum uptake by oats between the compacted and unpacked soils were observed.

Like other limiting factors related to compaction, nutrient supply in a compacted soil can have a detrimental effect on plants only when other soil conditions are not favorable. In a fertile soil, provided adequate aeration and moisture are available and resistance levels are not prohibitive, compaction does not interfere with the nutrition of the plant (Parish,1971).

Several important factors are involved in soil compaction that need to be mentioned in this review. Machine factors such as type of the vehicle and intensity of traffic are two primary factors and depth of soil compaction is another.

### 3.6 VEHICULAR FACTORS

The vehicle related factors that influence soil compaction are: weight, area of contact with soil (hence the type of vehicle), and number of machine passes over the soil. The change in the degree of compaction a soil can experience is directly proportional to the applied force and inversely proportional to the area of contact. Thus, the heavier the vehicle and the smaller the contact area with the soil surface, the more the soil compacts.

Compaction of soil depends, to a large degree, on the intensity of travel over an area and, to a lesser degree, on the type and weight of the vehicle. As far as the type of

vehicle is concerned, wheeled or rubber-tired vehicles and crawler tractors are the two types of machines extensively used in agriculture and forestry.

Moehring and Rawls (1970) used a 57600 kg crawler tractor to skid tree lengths on a wet soil. After six passes of the tractor, bulk density in the 0- to 5-cm layer of the skid trail was 13% greater than the adjacent undisturbed area.

In most cases, the maximum increase in bulk density occurs during the first few passes of the vehicle.

In a study on a wide range of soil textures, Hatchell et al. (1970) reported that four passes of a crawler tractor resulted in 90% of the maximum compaction. In fact, on an average only 2.5 trips were needed to reach densities within 10% of the maximum attained.

Raghavan et al. (1977) reported 70% of the total density increase of a clay soil during the first five passes. The rate of density change decreased considerably during additional passes. Fifteen vehicle passes resulted in a dry density increase of  $0.35 \text{ g/cm}^3$ .

Free et al. (1947) reported a 13.6% increase in soil density due to one trip with an empty farm truck, when the soil moisture was 23.0%. At a moisture content of 19%, four passes increased the bulk density by 27.4%.

Even though it has been shown that crawler tractors compact the soil less than wheeled vehicles (Lull, 1959), studies examining the effect of tractor type have been limited to date.

Reed (1940) found that soils were compacted to lower depths by crawler tractors (30 cm) than by rubber-tired tractors (20-25 cm). Recently, more workers have compared the effects of rubber-tired and crawler tractors on soil compaction.

In a study by Miles et al. (1981), multipass compaction by a rubber-tired skidder and a crawler tractor were compared during logging operations. They found that soil bulk density measured at 15 and 25 cm depths, was mainly influenced by the moisture conditions and traffic intensity. Moisture content, however, was considered as the more influential factor. Most of the compaction occurred during the first few passes (2-4). Rate of density increase diminished rapidly with increasing traffic. The crawler tractor caused slightly less compaction than the rubber-tired skidder. At a depth of 15 cm and a moisture content of 23%, four passes of the tractor compacted the soil 20 percent, while four passes of the skidder increased the density by 24%.

Shishiuchi and Adachi (1982) studied the effect of intensive traffic on the growth of planted Japanese larch see-

dlings. They reported that soil hardness was maximum at 10-15 cm depth, increasing logarithmically with the number of tractor trips. For 80-100 trips, compaction by wheeled tractors was higher than that by crawler tractors. This pattern was reversed for treatments subjected to more than 100 trips. That is, tracked vehicles caused more compaction than wheeled vehicles when 100 trips were exceeded.

### 3.7 DEPTH OF COMPACTION

The depth of compaction as well as its severity in sub-soil layers is a factor that can be detrimental to plant root penetration and growth.

Campbell et al. (1973) reported significant compaction due to rubber-tired skidder on the top 10 cm of the soil. However, at depths 20 cm and greater, there were no significant differences in bulk density between treated and untreated areas.

Artificial compaction of a sandy loam soil increased bulk density by 27% and 10% at depths of 0-7.5 cm and 15-23 cm, respectively (Throud and Frissel, 1976). It took natural processes over 8.5 years to rejuvenate the surface layer (0-7.5 cm) bulk density to its original value. No recovery was recorded after this period for the 15-23 cm layer. The authors noted that recovery in terms of bulk density does

not necessarily indicate recovery in terms of other soil properties that may have been changed by compaction.

In general, most compaction occurs in the upper 15 cm of the soil (Hassan, 1978; Throud and Frissel, 1976), but soil layers as deep as 60 cm can be affected (Parker and Jenny, 1945). Weaver (1950) reported that tractor tires compacted the soil (Davidson Loam) to a depth of 23 cm.

Raghavan et al. (1977) found that the maximum change in density of a clay soil at various moisture levels subjected to repeated tire passes occurred between 12-26 cm below the center of the tires.

Bulk density measurement of soils compacted during mechanized harvesting in spruce-fir forests (Holman et al., 1978) indicated that compaction was greater in the top 7.5 cm of soil than in the 7.5-15 cm layer. Effects of location and bulk density of hard pans on cotton growth and yield were examined by Lowry et al. (1970). They found that growth and yield increased with increasing depth of the compacted layer.

### 3.8 GROWTH AND YIELD

Response of plants to soil compaction varies depending on soil type and climatic conditions. For example, Rosenberg and Willits (1962) examined the effect of changes in soil physical properties due to compaction on the growth of barley. On freehold loamy sand, a 37% decrease in barley yield was observed as a result of bulk density increasing from 1.3 to 1.65 g/cm<sup>3</sup>. On the other hand, in Galestown sand the yield increased by 50% due to a bulk density increase from 1.3 to 1.6 g/cm<sup>3</sup>. The yield increase was attributed to increased water availability due to soil compaction. They stated, however, that this beneficial effect of increased moisture availability in sand may be counteracted by decreased depth or volume of rooting due to increased mechanical impedance. In Penn silt loam an increase in soil density resulted in decreased yield. Oxygen deficiency was determined to be the cause of reduced yield on this soil.

Another example of the varying effect of compaction on plant growth and yield is the work of Wittsell and Hobbs (1965). They found that compaction of surface (0-15 cm) soil to a bulk density of 1.6 g/cm<sup>3</sup> reduced sorghum (Sorghum vulgare) growth more than did subsurface (15-30 cm.) compaction.

Moser (1981) presented the results of a study dealing with the effect of light and heavy machinery on the yield of three pastures. He reported that on dry soil compaction was minimal. However, in wet soil some compaction damage as well as reduced yield for a few months were observed.

Although effects of soil compaction on plants vary with varying soil type and climatic conditions, it has been proven that a high degree of compaction has detrimental effects on plant growth and yield.

Youngberg (1959) observed a highly significant decrease in the growth of planted douglas-fir (*Pseudotsuga menziesii*) seedlings on compacted tractor roads as compared with seedlings in undisturbed locations.

Working with silt loam and silty clay loam soils, Adams et al. (1960) reported significant reductions in potato (*Solanum tuberosum*), sugarbeets (*Beta vulgaris*), wheat (*Triticum aestivum*), and corn yields due to soil bulk density increasing from 1.07 to 1.19 g/cm<sup>3</sup>.

Many other studies have shown that it is difficult to separate the effects of mechanical impedance, poor aeration, and unfavorable moisture relations on plant growth (Foil and Ralston, 1967; Philips and Kirkham, 1962; Rosenburg, 1964).

Pomeroy (1949) attributed high mortality of newly germinated loblolly pine (*Pinus taeda*) seedlings in logging

trails to failure of the root to penetrate the compacted soil surface.

In another study with loblolly pine Hatchell et al. (1970) observed reduced stocking and retarded growth on primary skid trails. These effects were particularly severe on the finer textured soils where seedlings were half the size of those in undisturbed soil.

Moderate compaction has, in some cases, been found to improve plant growth, primarily due to increased moisture availability (Negi et al., 1980; Voorhees, 1977). This is accomplished through increased seed or seedling contact with moisture films. Gaultney et al. (1982), however, reported that moderate subsoil compaction of a silt loam reduced corn yields by 25%.

### 3.9 EROSION

As mentioned in the soil moisture section, compaction causes a reduction in the soil pore space. Reduction of macroporosity interrupts natural channels through the profile, decreasing infiltration and increasing surface runoff. If an adequate vegetative cover is not present, depending on the soil type and slope, this can result in considerable erosion of top soil (Dyrness, 1950; Hatchell et al. 1970).

In addition to infiltration capacity, structural stability of the soil also influences soil erodibility (Wischmeier and Mannering, 1969). Traffic can increase soil shear strength and thus its resistance to detachment during rainfall.

Voorhees et al. (1979) found that ruts formed by tractor wheels can serve as channels to concentrate the rainfall, leading to high runoff rates. At the same time, the soils compacted by tractor wheels were less susceptible to erosion due to high shear strength. However, severe erosion was observed in a rut created by a single pass of a planter wheel. It was concluded that the planter did not cause enough compaction to provide a stabilizing effect.

Johnson and Beschta (1980) stated that removal of vegetative or litter cover and the upper several centimeters of the soil horizon by tractor logging makes the soil vulnerable to erosion with the first rain storm.

Dickerson (1975) reported soil erosion of a hilly site where a rubber-tired skidder was used to skid a load of three hardwood logs a total of seven trips. Seventy five percent of the total soil loss occurred during the first six months and then it started to diminish rapidly as herbaceous vegetation occupied bared soil.

Even slightly disturbed areas are susceptible to erosion because soil movement can be increased simply by removal of the protective covering of organic matter even though bulk density changes are minimal. Dyrness (1955) stated that tractor logging results in the deposition of large amounts of loose soil such as skidroad berms. Such deposits are easily susceptible to erosion.

### 3.10 NUCLEAR DENSITOMETRY

Gamma ray density probe gauges have been used by several researchers in soil compaction studies as well as other investigations to make density measurements at incremental depths up to 30 cm (Bradshaw, 1979; McKeys et al., 1977). Such gauges are often equipped with the instrumentation needed to measure soil moisture content. There have been questions as to whether nuclear densitometry is accurate and convenient enough to replace the gravimetric method of soil density measurement.

Baker (1981) used a Campbell Pacific density/moisture nuclear gauge in a logging compaction study. He concluded that the nuclear density probe could be used to observe local changes in soil density that occurred between successive machine passes. The accuracy of the density readings were not checked against other methods of density measurement.

In a comparison between standard core sampling method and nuclear densitometry, Hassan (1978) used a Troxler 3401 unit. She stated that the neutron gamma radiation gauge indicated soil densities much higher than those obtained by the standard method. Hassan recommended that the gauge not be used for moisture determination and that a correction factor of 0.8 be used for the density measurements on organic soils.

Rawitz et al. (1982) tested a two-probe gamma gauge and concluded that laboratory calibration of the gauge by the calibration stand supplied with the instrument or by previously published methods yields erroneous results. They suggested that if valid attenuation coefficients of water and soil are developed, the double-probe gamma method would achieve better precision than core sampling. They also mentioned "the need for a practical method of keeping the access tubes parallel or measuring the angle between them to facilitate correction by calculation".

Based on laboratory performance tests on a Campbell Pacific MC-2 moisture/density gauge, Ayers and Bowen (1983) concluded that even though the gauge gives accurate wet density profiles, dry density values cannot be accurately determined using wet density and moisture readings obtained from the gauge. They suggested the use of soil moisture values

obtained by gravimetric method instead of that obtained by the nuclear gauge. They also stated that in the dual probe mode the soil density is measured one half inch shallower than the indicated probe depth. Another problem associated with nuclear gauges is "averaging" due to lack of resolution. According to Ayers and Bowen (1983) this has not been quantified and a procedure for proper compensation is not available.

## Chapter IV

### EXPERIMENTAL PROCEDURE

The field study was conducted in the fall of 1982 at the Reynolds Homestead Research Center located in Patrick county, Virginia (Figure 1). A detailed description of the test site, test-plot layout, treatments, and procedures are discussed in this chapter.

#### 4.1 SOIL DESCRIPTION AND PREPARATION OF TEST SITE

The test site included a 1.4 ha area with a mixed hardwood and pine stand. The physical layout of the test site is shown in figure 2. It consisted of two mainplots of 30 x 146 m separated by an 8 m wide vehicle corridor along the longest dimension. Two more vehicle corridors were available on the outer sides of the two mainplots. These corridors were utilized for the removal of harvested trees, maneuvering of vehicles used in the experiment, and for transporting various equipment used during the study.

The gently sloping test site was clearcut manually during the summer of 1982. All trees and limbs in the test area were winched remotely and skidded along the three machine corridors to avoid soil compaction due to the movement of harvesting equipment.

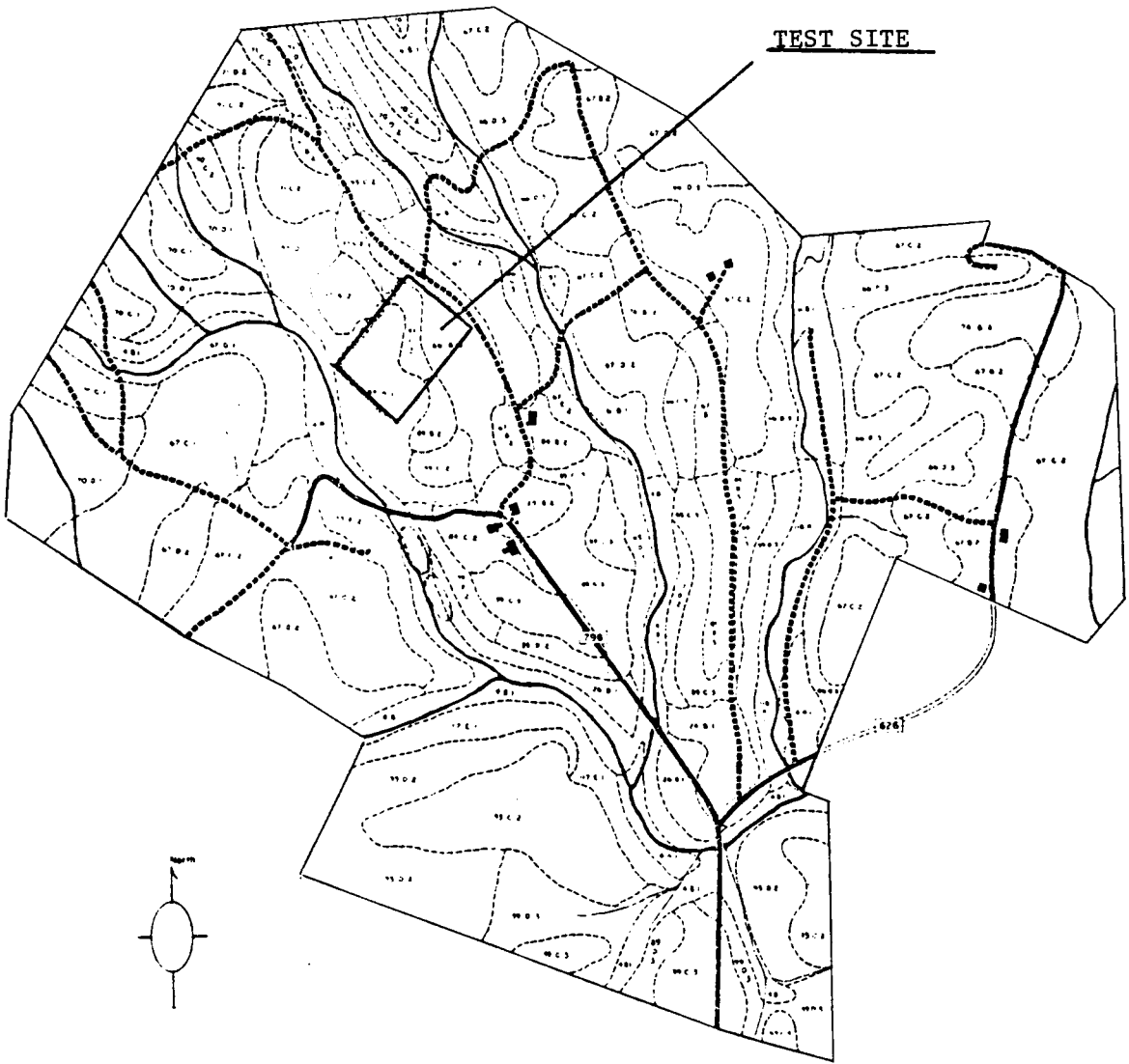


Figure 1. Location of the test site at Reynolds Homestead Research Center, Patrick county, Virginia.

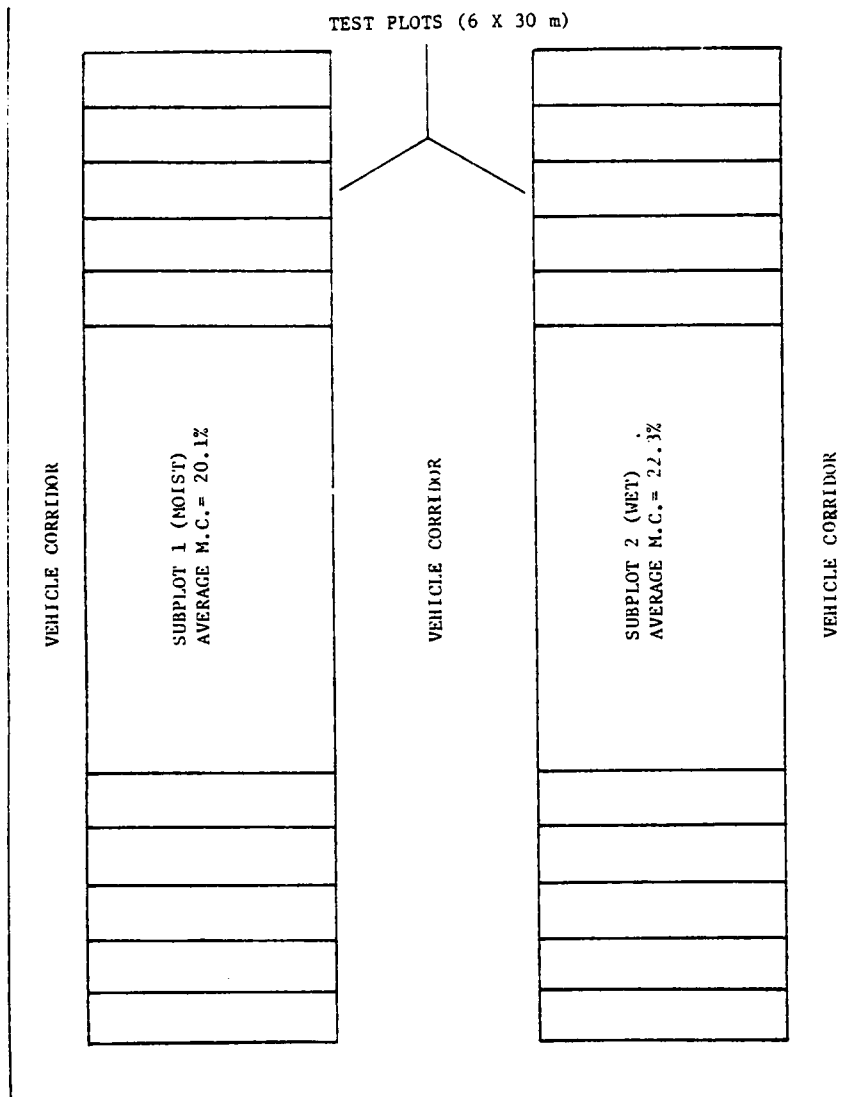


Figure 2. Layout of the test site

The soils at the test area are classified as Haysville loam and Cecil loam series.<sup>1</sup> The Haysville series is a member of a clayey, oxidic, mesic family of typic hapludults, and is a deep, well-drained soil. It is strongly acidic, medium in fertility, and medium in organic-matter content. It is moderately permeable and has good available moisture capacity. The surface layer is loam or cobbly loam, and the subsoil is clay loam to clay.

The Cecil series consists of moderately deep to deep, well drained soil with moderately high moisture holding capacity. It is a member of the calyey, kaolinitic, thermic family of typic hapludults. The surface soil generally is fine sandy loam and subsoil consists of firm yellowish red clay. Permeability of the surface soil is good while it is moderate for the subsoil. Based on laboratory tests the soil at the test site was classified according to USDA classification. The top (0-15 cm) and lower (15-30 cm) layer soils were found to be sandy clay loam and clay respectively.

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<sup>1</sup> National Cooperative Soil Survey, USDA Soil Conservation Service. Unpublished data, 1974.

#### 4.2 EXPERIMENTAL DESIGN AND INSTALLATION OF TREATMENTS

The effects of two vehicle types, four levels of passes, two levels of soil moisture, and interaction among these factors on soil compaction were evaluated. The experimental design was a split plot. Vehicle type times number of passes combinations were applied as subplots within mainplots. The experiment was replicated three times.

The two vehicles used in the study included a John Deere model 540B wheeled skidder equipped with 23.1-26 tires and a Komatsu model D53A bulldozer with 50x239 cm tracks and no blade. They are shown in figures 3 and 4, respectively. The vehicle specifications are included in table 1. The weights of the crawler tractor and the wheel skidder were 14210 kg and 7580 kg, respectively. The estimated wheel contact pressure was three times higher than that of the crawler tracks (table 1) under static conditions. The number of passes over the same area were 0, 1, 3, and 9.

Effect of moisture level on compaction was evaluated by adjusting the moisture content to two levels in the two mainplots. The mainplots were irrigated to obtain the desired moisture levels. A portable irrigation system was used for this purpose. It consisted of a 113550 L tank, a self-propelled centrifugal pump with a capacity of 14.5 L/s at 640 kPa head (Figure 5), and thirteen sprinklers spaced



Figure 3. John Deere model 540B log skidder.



Figure 4. Komatsu model D53A tractor.

TABLE 1

Specification of vehicles used in the field study

| VEHICLE<br>TYPE &<br>MODEL        | VEHICLE<br>WEIGHT<br>(kg) | ESTIMATED<br>CONTACT *<br>AREA (cm <sup>2</sup> ) | ESTIMATED<br>CONTACT *<br>PRESSURE (kPa) |
|-----------------------------------|---------------------------|---|--|
| WHEELED<br>SKIDDER<br>(J.D. 540B) | 7580                      | 3200  | 230                                      |
| BULLDOZER<br>KOMATSU<br>(D53A)    | 14210                     | 23900   | 60                                       |

\* The procedure for estimating these values is described in appendix A.



Figure 5. A self-propelled centrifugal pump used for irrigating the test site.

evenly along the longest dimension of each mainplot. Water was pumped from a stream to the tank located next to the study area (Figure 6). Sprinklers were spaced at 12 m intervals so that the areas they covered overlapped to obtain a uniform moisture distribution (Figure 7). Water was applied at a rate less than the infiltration capacity of the soil to avoid runoff. The mainplots were irrigated over a period of 24 hours, such that one plot received approximately 10 cm of water and the other 7 cm.

Each mainplot was divided into 24 test plots of 6 x 30 m to install the eight treatments with three replications. The treatments were assigned to each test plot in random order. For convenience in installing the treatments, same random order was maintained for the treatment in both mainplots having two different moisture levels.

The treatments were installed 8 hours after the plots were irrigated, on October 8, 1982. The vehicles were unloaded and traveled at constant speed. Each vehicle trip covered a strip extending over both mainplots. For multipass plots (3 and 9), the operator was guided to travel over the track made by the previous traverse by placing flags along the track. After treatment, the boundaries of each test plot was marked with flags bearing its identification number. New flags were also located on each track to help identify the three sampling locations along the track.



Figure 6. A portable storage tank used for irrigating the test site.

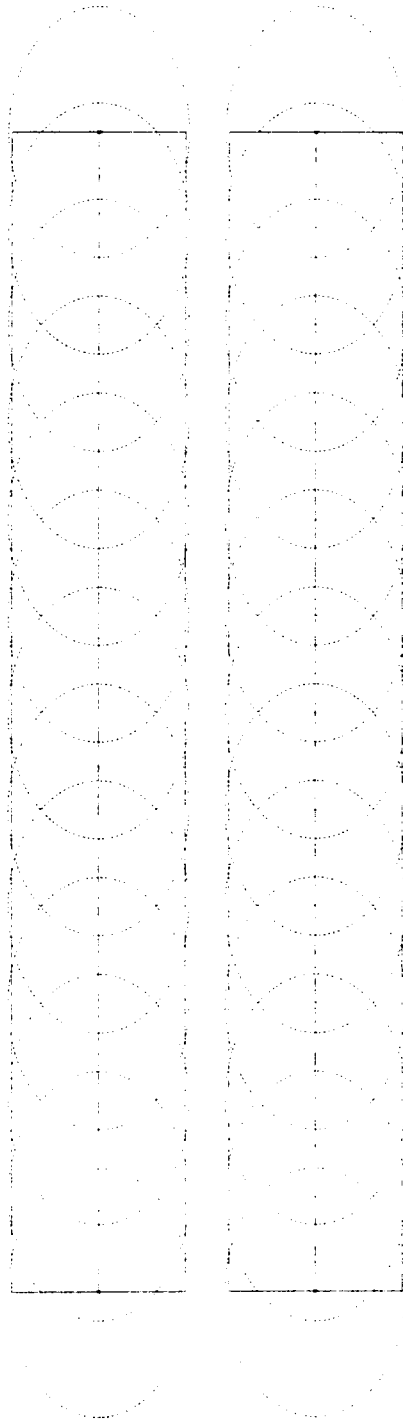


Figure 7. Sprinkler locations and area covered by each sprinkler.

### 4.3 FIELD MEASUREMENTS

Three different field measurements were made during the study. These included soil moisture measurements, and density measurements by two procedures: gravimetric and nuclear densitometry. Details of these measurements are included in this section.

#### 4.3.1 Soil Moisture

Immediately after compaction treatments were applied, soil samples were taken at two depths (0-15 cm and 15-30 cm) to determine the average moisture level. Three sets of samples (two depths at each location) were taken beside each track in each test plot. The sampling points were spaced 6 m apart as shown in figure 8. A total of 1138 samples were collected in this manner. They were weighed before and after drying at 110 C for 24 hours or more to determine the soil moisture content. The average moisture levels at two depths in each mainplot are given in table 2.

#### 4.3.2 Soil Density

Soil density measurements were taken using gravimetric and nuclear densitometry procedures.

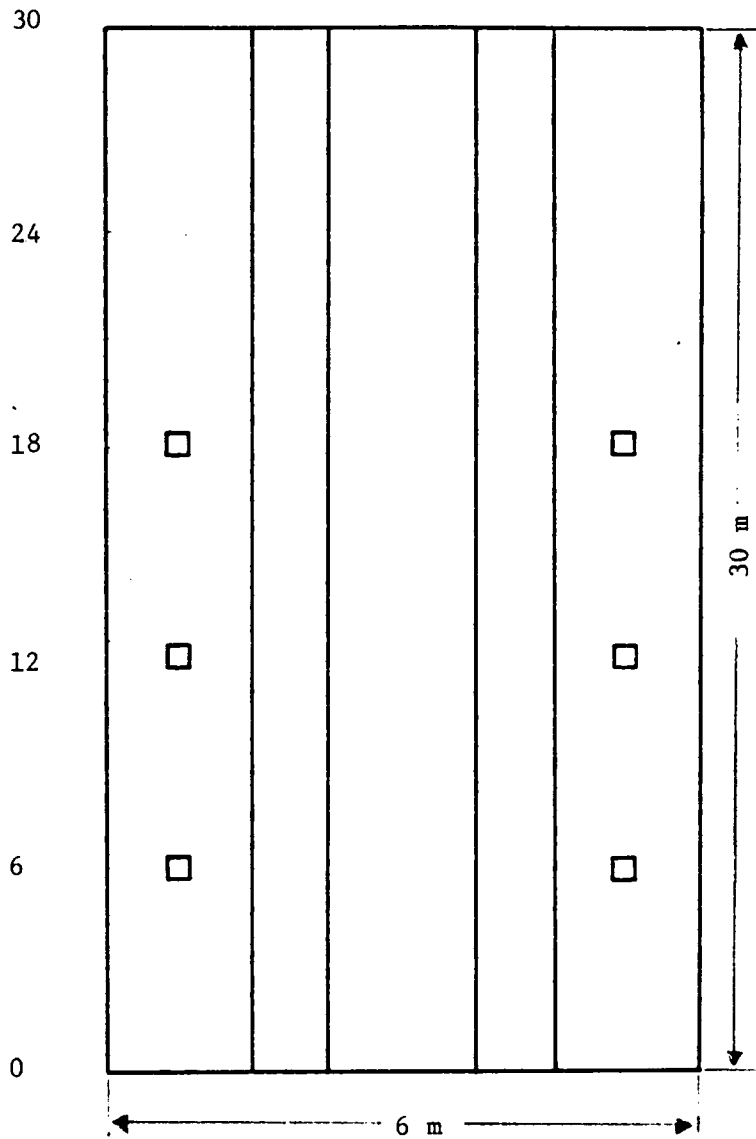


Figure 8. Locations at which soil samples were taken for moisture determination at two depths.

TABLE 2

Average moisture content values based on depth

| MOISTURE<br>LEVEL | DEPTH (cm)        |                  |
|-------------------|-------------------|------------------|
|                   | 0-15              | 15-30            |
| 1 (MOIST)         | 17.86%<br>[0.20]* | 22.43%<br>[0.30] |
| 2 (WET)           | 20.66%<br>[0.23]  | 24.02%<br>[0.25] |

\* Number in the square brackets represents Standard Error of Mean.

#### 4.3.2.1 Core Sampling

A hammer-type core sampler (Figure 9) was used to extract samples for density measurement. The core sampler consists of a cylindrical handle with a removable cylindrical cup and a drop-hammer. The stainless steel cup has a sharp edge and contains four removable brass rings. The large ring is 5.4x6.0 cm and the remaining three smaller rings are 5.4x0.9 cm.

To obtain soil samples, the sampler was driven into the soil using the hammer. After driving the sampler to the desired depth, it was withdrawn and the cup with the sample was removed. The soil sample enclosed within the brass rings was taken out carefully. Small rings on both ends of the large ring were then removed and excess soil was shaved off with a sharp blade. Thus, a soil sample of 137 cm<sup>3</sup>, confined within the large ring, was obtained to determine the weight and the dry bulk density.

Core samples at two depths (2-8 cm and 17-23 cm) were extracted at three locations within and outside each track in each test plot. Thus, from each test plot 24 core samples were drawn for bulk density determination. These samples were taken at 6, 12, and 18 m from the center corridor (Figure 10). To minimize the influence of vehicle load on control samples (samples taken beside the rut), they were taken approximately 1.5 times the track width away from the

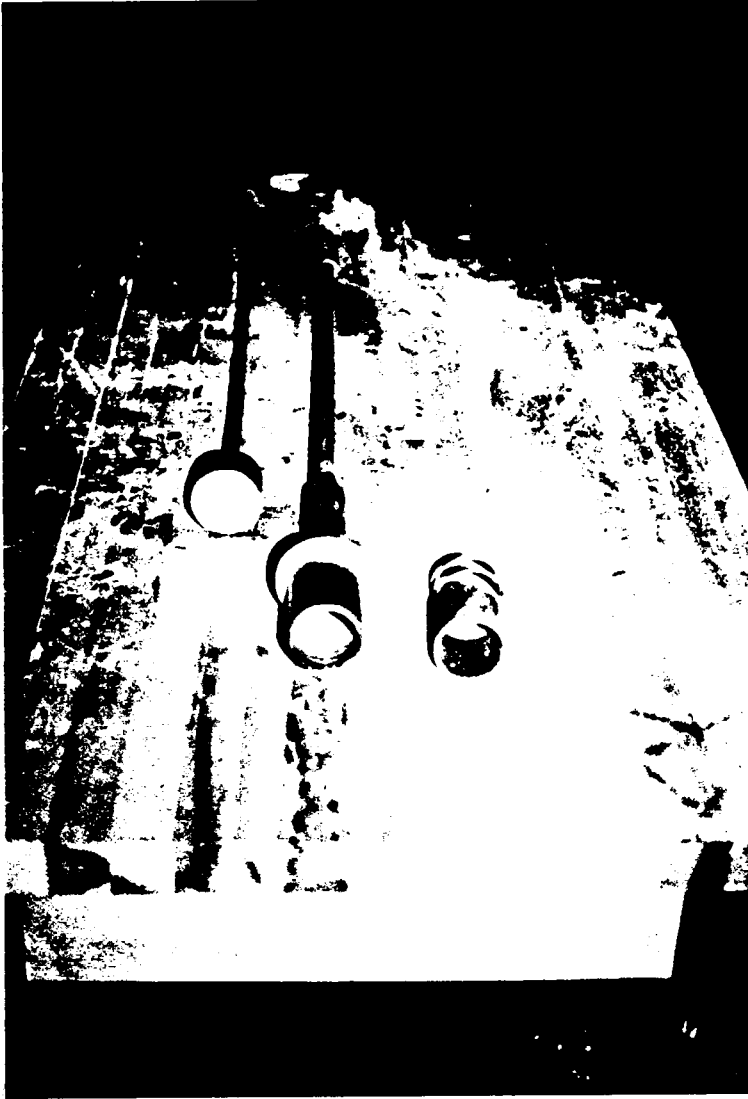


Figure 9. A hammer-type core sampler used to extract soil samples for bulk density determination.

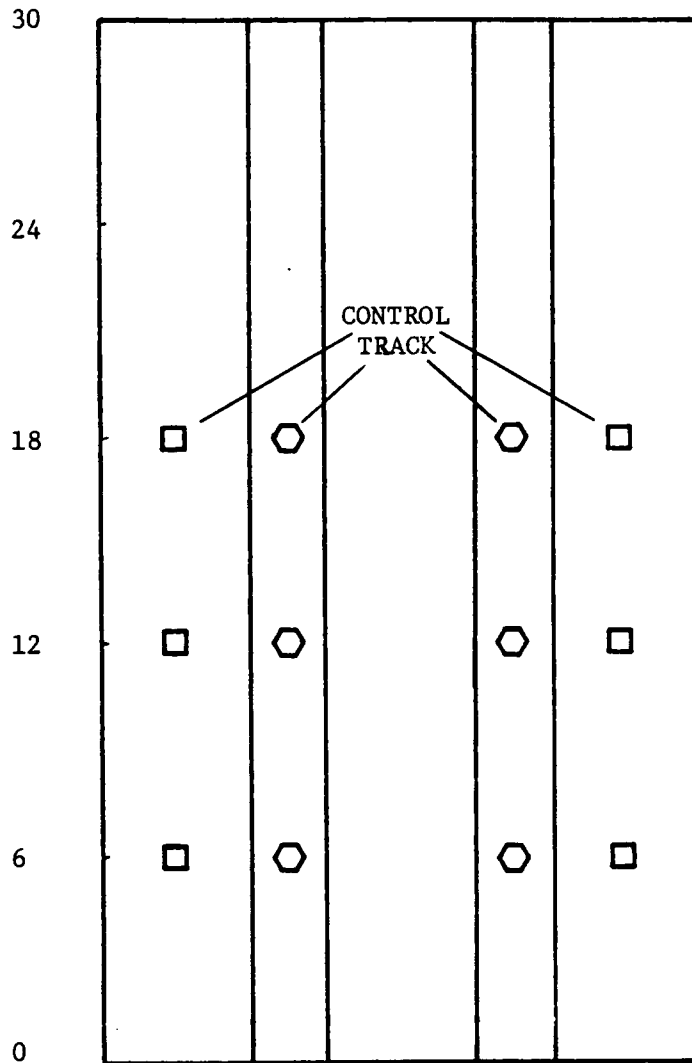


Figure 10. Locations at which core samples were taken for bulk density determination.

rut. A total of 1142 core samples were collected. They were oven-dried at 110 C and weighed to determine the dry bulk density.

#### 4.3.2.2 Nuclear Densitometry

A double probe (Campbell Pacific MC-2) moisture/density gauge (Figure 11) was used for collecting density counts. The MC-2 gauge uses two probes to determine soil wet density. One contains a cesium 137 source and the other a Geiger Mueller reciever. When the probes are lowered into the soil, the high energy photons emitted by the cesium source are either absorbed or deflected by the electrons in the soil mass. The higher the soil density, the greater the number of electrons in the soil mass, resulting in a lower count rate at the reciever. This inverse relationship between bulk density and count rate is the basis for nuclear density gauge measurements (Ayers and Bowen, 1983).

Density readings were taken within and outside each track on each test plot at a distance of approximately 13 m from the center corridor (Figure 12). At each location, readings were taken at 5.0 and 17.5 cm depths so that the density data obtained using the densitometer could be compared against similar data obtained gravimetrically. For density measurements using the nuclear gauge, litter and organic



Figure 11. Campbell Pacific MC-2 gauge used for density measurements.

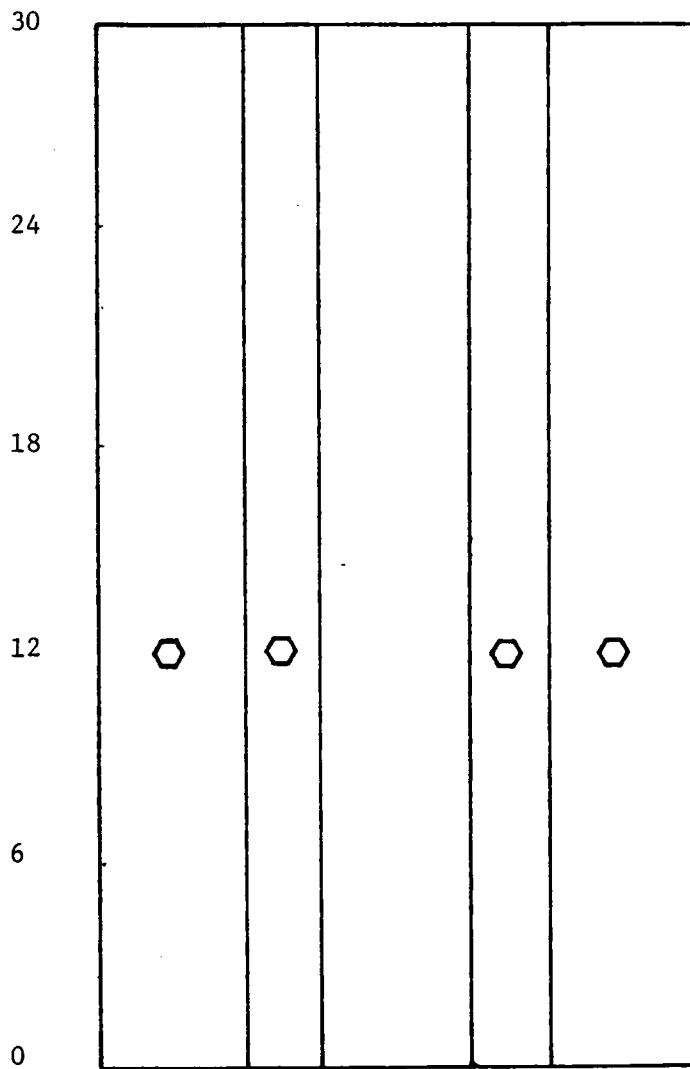


Figure 12. Locations at which nuclear density readings were taken at two depths.

material were removed from the soil surface before two 1.6 cm holes were made for inserting the two probes. The instrument was then located over the holes. The readings at previously mentioned depths were taken by lowering the probes into the holes. A total of 372 wet bulk density measurements were obtained in this manner. Dry bulk density values were then computed from the wet bulk density data.

#### 4.4 DATA ANALYSIS

An analysis of variance was conducted on the density data obtained gravimetrically to test for the effect of various treatments and their interactions at each depth. Variables contained in the model included: moisture level, tractor type, number of machine passes, and replications.

At each sample location, for each depth, compaction was calculated by subtracting the control observation (density reading beside the track) from the treatment observation (density reading within the track). The six compaction values obtained from each test plot were combined to arrive at an average value. This data was statistically analyzed to determine the treatment and interaction effects. Duncan's multiple range test was used to test for significant differences among mean compaction values due to each treatment at each depth.

A Paired Student's t-test was conducted to compare the density data obtained using the two procedures. A linear regression model was developed to describe soil density obtained using the nuclear densitometer as a function of the density obtained gravimetrically.

## Chapter V

### RESULTS AND DISCUSSION

#### 5.1 EFFECTS OF TEST FACTORS ON SOIL COMPACTION

Soil compaction resulting from multiple passes of vehicles was evaluated by analyzing the density data obtained gravimetrically. The results of this analysis are summarized in table 3.

At a depth of 15-30 cm, none of the variables considered, nor their interactions, had a significant effect on soil compaction. However, for the surface soil (0-15 cm), the following treatment and interactions were found to have a significant effect on soil compaction as indicated by the change in bulk density either at the 1% or 5% significance level:

- i) Number of passes,
- ii) Interaction between moisture level and vehicle type (M X V),
- iii) Interaction between vehicle type and number of passes (V X P).

The effect of each treatment and interaction on the compaction of the top soil layer is discussed below.

TABLE 3

Results of analysis of variance conducted to determine the effect of treatments and interactions on soil compaction

|  |                   | DEPTH > | 1      | 2       |
|--|-------------------|---------|--------|---------|
|  |                   | (cm) >  | (0-15) | (15-30) |
| T<br>R<br>E<br>A<br>T<br>M<br>E<br>N<br>T<br>S           | Moisture (M)      |         | III    | III     |
|  | Vehicle Type (V)  |         | III    | III     |
|  | No. Of Passes (P) |         | I      | III     |
|  | Replica-<br>tions |         | III    | III     |
| I<br>N<br>T<br>E<br>R<br>A<br>C<br>T<br>I<br>O<br>N<br>S | M x V             |         | I      | III     |
|  | M x P             |         | III    | III     |
|  | M x P x V         |         | III    | III     |
|  | V x P             |         | II     | III     |

I = SIGNIFICANT AT 0.01 LEVEL  
 II = SIGNIFICANT AT 0.05 LEVEL  
 III = NOT SIGNIFICANT AT 0.05 LEVEL

### 5.1.1 Main Treatment Effects

#### 5.1.1.1 Moisture Level

Soil moisture levels in the two mainplots were not appreciably different. The average moisture content in the moist and wet mainplots were 20.14% and 22.35%, respectively. The moisture data in the two plots based on depth are presented in table 2. On the average, the difference in moisture level for the top layer was 2.8% . Duncan's multiple range test performed to determine the effect of moisture levels on soil compaction, indicated that it had no significant influence on the bulk density change (table 4).

The difference in the two moisture levels was apparently not large enough to cause a significant difference in the resulting compaction.

From a similar study Miles et al. (1981) concluded that soil compaction was more sensitive to moisture level than other variables considered. Thier results showed that the compaction for a sandy loam soil at 31% moisture content was 1.5 times greater than the compaction observed at 25% moisture level.

#### 5.1.1.2 Number OF Passes

Of the three factors considered in this study, only the number of machine passes was found to have a significant in-

TABLE 4

Results of Duncan's multiple range test to determine the effect of moisture level on soil compaction (0-15 cm depth)

| GROUPING | MOISTURE<br>CONTENT | MEAN<br>COMPACTION<br>(g/cm <sup>3</sup> ) |
|----------|---------------------|--|
| A        | 17.86%              | 0.072<br>[0.015]*                          |
| A        | 20.66%              | 0.098<br>[0.013]                           |

Means with the same letter are not significantly different (0.05 level)

\* Number in the square brackets represents Standard Error of Mean.

fluence on the compaction of the top soil layer (0-15 cm). Plots of compaction as a function of number of passes are shown in figures 13 and 14 for the two moisture levels considered. From these figures it is clear that, at the lower depth (15-30 cm) in both mainplots, very little change in the bulk density was induced due to vehicle traffic. The changes were not significant (Table 3). However, on the surface layer (0-15 cm), a significant increase in compaction was observed as the number of passes increased. The effect was the same for both vehicle types.

Results of Duncan's multiple range test (table 5) showed significant differences among mean compaction values obtained from test plots exposed to different numbers of passes. One vehicle pass did not cause significant compaction. On the other hand, three passes had a quadrupling effect on the bulk density increase. Even though the compaction resulting from nine machine passes was approximately five times that of the control (no traffic), the density after nine passes was not significantly different than after three passes. This means that a major percentage (nearly 79%) of the compaction that can be expected from multiple vehicle passes occurred during the first three passes. After that, soil deformation decreased because of soil stiffness due to reduction in pore space.

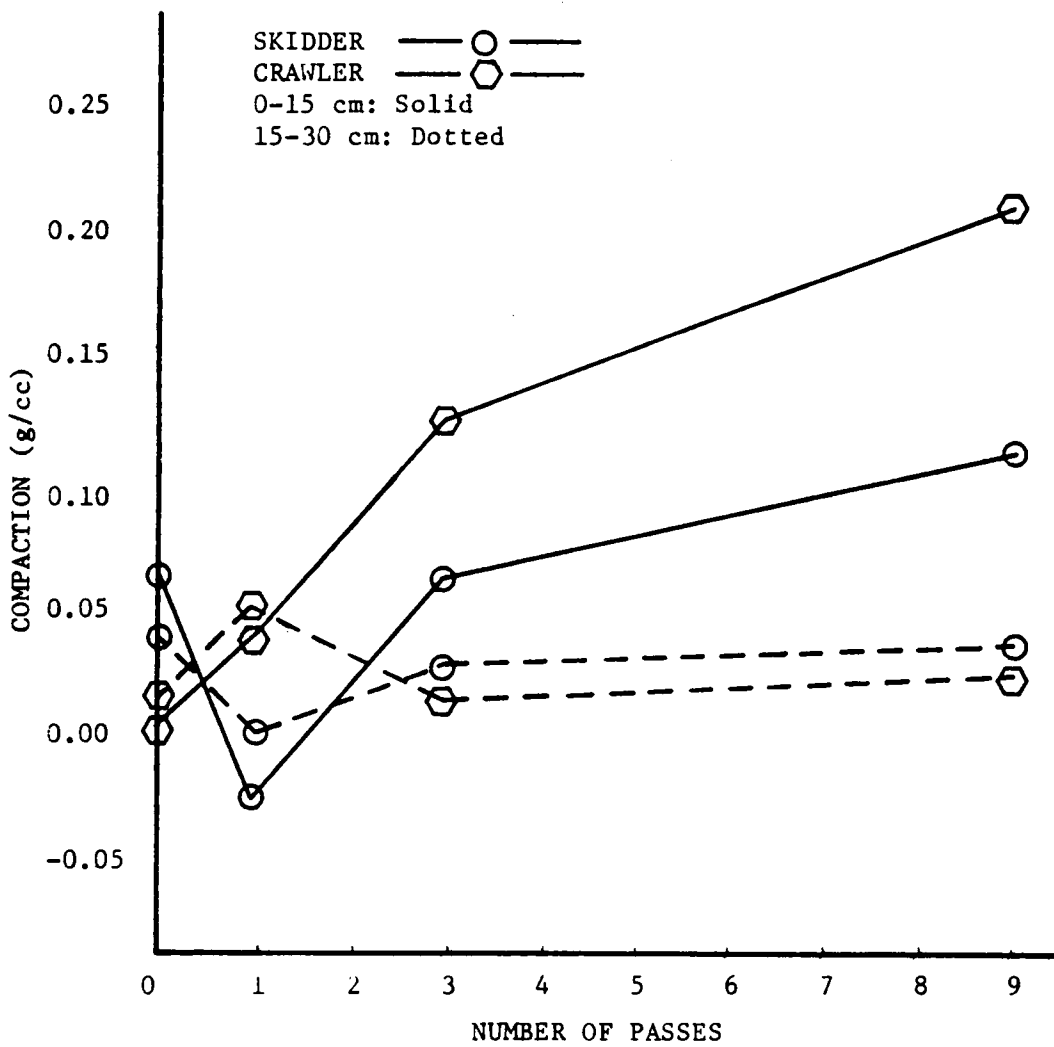


Figure 13. Effect of number of machine passes on soil compaction (soil moisture level- 22.35%).

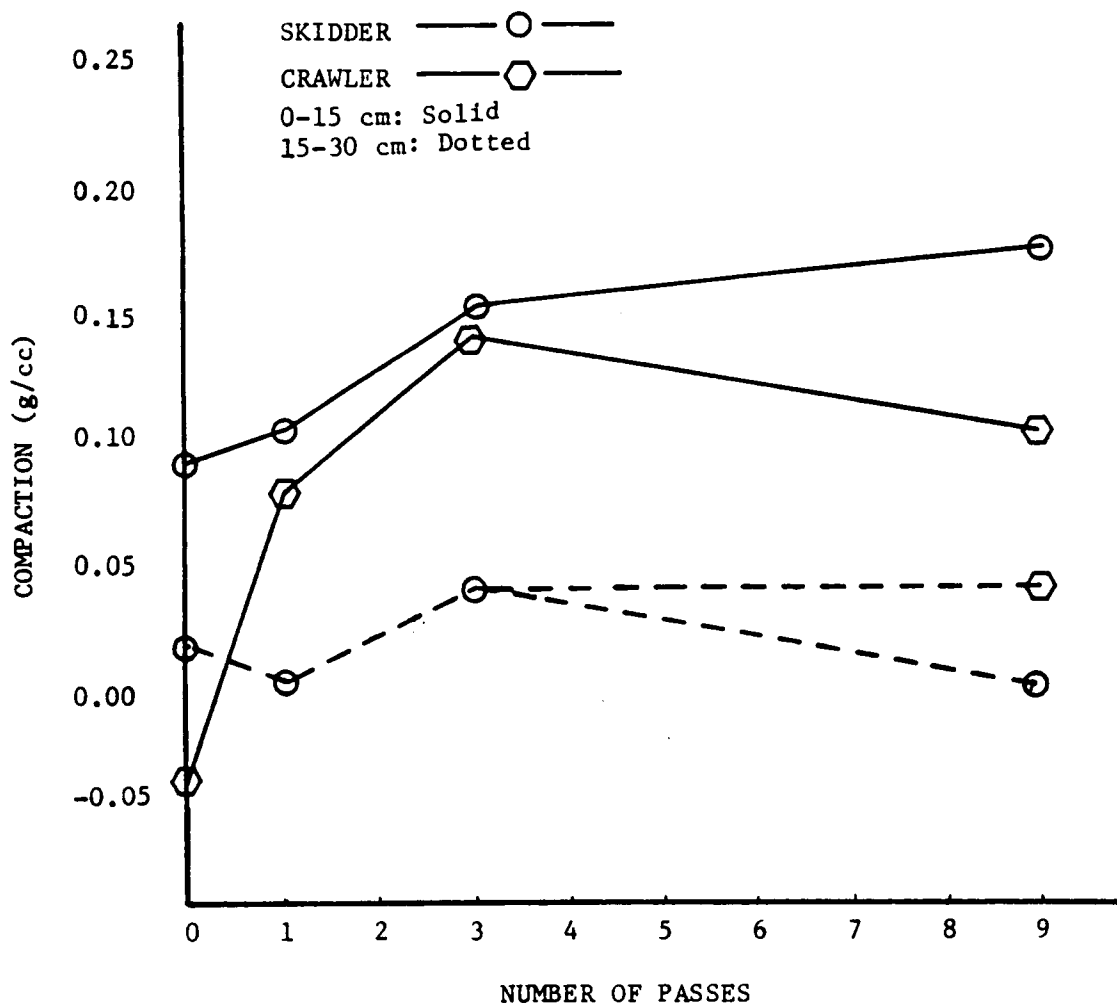


Figure 14. Effect of number of machine passes on soil compaction (soil moisture level- 20.14%).

TABLE 5

Results of Duncan's multiple range test to determine effect of number of passes on soil compaction (0-15 cm depth)

| GROUPING   | NO. OF PASSES | MEAN COMPACTION (g/cm <sup>3</sup> ) |
|--|---------------|--------------------------------------|
| A  | 9             | 0.149<br>[0.019]*                    |
| A  | 3             | 0.117<br>[0.016]                     |
| B  | 1             | 0.045<br>[0.021]                     |
| B  | 0             | 0.029<br>[0.020]                     |
| Means with the same letter are not significantly different (.05 level) |               |                                      |

\* Number in square brackets represents Standard Error of Mean.

These results are in agreement with the findings of other workers (Hatchell et al., 1970; Campbell, 1973). Hatchell et al., for instance, observed that, on an average only 2.5 trips of a crawler tractor were needed to reach densities within 10% of the maximum attained. Raghavan et al. (1977) found that 70% of the total compaction was induced by the first five passes, and that the rate of density increase diminished with increasing number of passes.

#### 5.1.1.3 Vehicle Type

Despite a considerable difference in static contact pressure, the results of the analysis showed no significant difference in compaction based on vehicle type (Table 6). This observation suggests that in addition to static contact pressure there may be other factors influencing the change in bulk density in a significant fashion. A few examples of such factors may be contact pressure distribution under moving track or wheel, slip, and reaction of soil to dynamic loading. Contact pressure under a moving track or wheel can be quite different from the uniform pressure distribution assumed for computing the static contact pressure. Previous studies have shown pressure peaks directly underneath the rollers through which the crawler weight is transmitted to the track (Turner, 1982). Apparently, the magnitude of these

TABLE 6

Results of Duncan's multiple range test to determine effect of vehicle type on soil compaction (0-15 cm depth)

| GROUPING  | TRACTOR TYPE | MEAN COMPACTION (g/cm <sup>3</sup> ) |
|---|--------------|--------------------------------------|
| A   | SKIDDER      | 0.092<br>[0.014]*                    |
| A   | CRAWLER      | 0.078<br>[0.014]                     |
| Means with the same letter are not significantly different (0.05 level) |              |                                      |

\* Number in square brackets represents Standard Error of Mean.

pressure peaks was nearly the same as the maximum pressure under the pneumatic tire. Thus, the resulting compaction by the two vehicles were not significantly different.

Generally, wheeled vehicles are considered to cause more compaction than tracked vehicles of comparable weight. Lull (1959) stated that, other factors being equal, crawler tractors cause less compaction than wheeled vehicles. Because, they exert lower ground pressures than rubber-tired skidders, since crawler tractors have a much larger contact area with soil.

#### 5.1.1.4 Depth

Anticipating that soil compaction will vary as a function of depth, it was included as an independent variable in a separate ANOVA test. The results of this test indicated that compaction of the top soil layer was significantly higher than that of the lower layer.

Campbell (1973) had observed a similar compaction pattern due to a wheeled skidder. He reported a significant bulk density increase in the top 10 cm of soil and no significant compaction at or below 20 cm. Other researchers have also stated that most compaction occurs in the upper 15 cm of soil (Throud and Frissel, 1976; Hassan, 1978).

As shown in Table 3, while there was a noticeable density increase in the top 15 cm of the soil, density of the lower depth did not change significantly.

### 5.1.2 Effect of Interactions

Interactions between moisture level and vehicle type and between the number of passes and vehicle type had a significant influence on compaction of the top soil layer (Table 3). Therefore, analyses of variance were used to delineate differences in compaction among moisture level times vehicle type, and number of passes times vehicle type combinations.

#### 5.1.2.1 Moisture Level-Vehicle Type Interaction

According to Duncan's Multiple Range Test, there was a significant difference in compaction at the two moisture levels due to skidder traffic (Table 7). The amount of compaction, due to the skidder, on the surface layer at higher moisture was about 2.5 times greater than the corresponding compaction in less moist soil. In the case of the crawler, however, the difference was not statistically significant. Furthermore, compaction due to crawler traffic at the two moisture levels was not significantly different from that due to the skidder traffic on the moist soil.

TABLE 7

Results of Duncan's multiple range test to determine the effect of moisture level-vehicle type interaction on soil compaction (0-15 cm depth)

| GROUPING | MOISTURE<br>LEVEL<br>(M) | VEHICLE<br>TYPE<br>(M) | MXV | MEAN<br>COMPACTION<br>(g/cm <sup>3</sup> ) |
|----------|--------------------------|------------------------|-----|--|
| A        | MOIST                    | SKIDDER                | 1   | 0.053                                      |
| B        | WET                      | SKIDDER                | 3   | 0.130                                      |
| AB       | MOIST                    | CRAWLER                | 2   | 0.091                                      |
| A        | WET                      | CRAWLER                | 4   | 0.065                                      |

Means with the same letter are not significantly different (0.05 level)

Similar findings were reported by Miles et al. (1981). After four skidder passes, soil at a 15 cm depth experienced 20% and 40% increase in bulk density at moisture contents of 16% and 31% , respectively. Under the same conditions, compaction by the crawler traffic was 15% and 24% . Thus, it appears that the soil at certain moisture levels is more compactable by the skidder than by the crawler tractor.

#### 5.1.2.2 Vehicle Type-Number of Passes Interaction

A significant interaction between the vehicle type and number of passes was observed in the upper soil layer (0-15 cm). The interactive effect of these two factors on soil compaction is shown in figure 15. An increase in compaction with increasing number of passes of both vehicles is indicated when 1, 3, and 9 passes are considered. In this range no interaction effect is evident between vehicle type and number of passes. However, the significant interaction between number of passes and vehicle type indicated by ANOVA test (Table 3), can be attributed to the large difference in mean compaction for zero pass of the vehicles. For zero pass, the mean compaction value should theoretically be zero for both cases. Large variations within the test site and sampling are probably the primary reasons for this discrepancy in mean compaction value at zero pass.

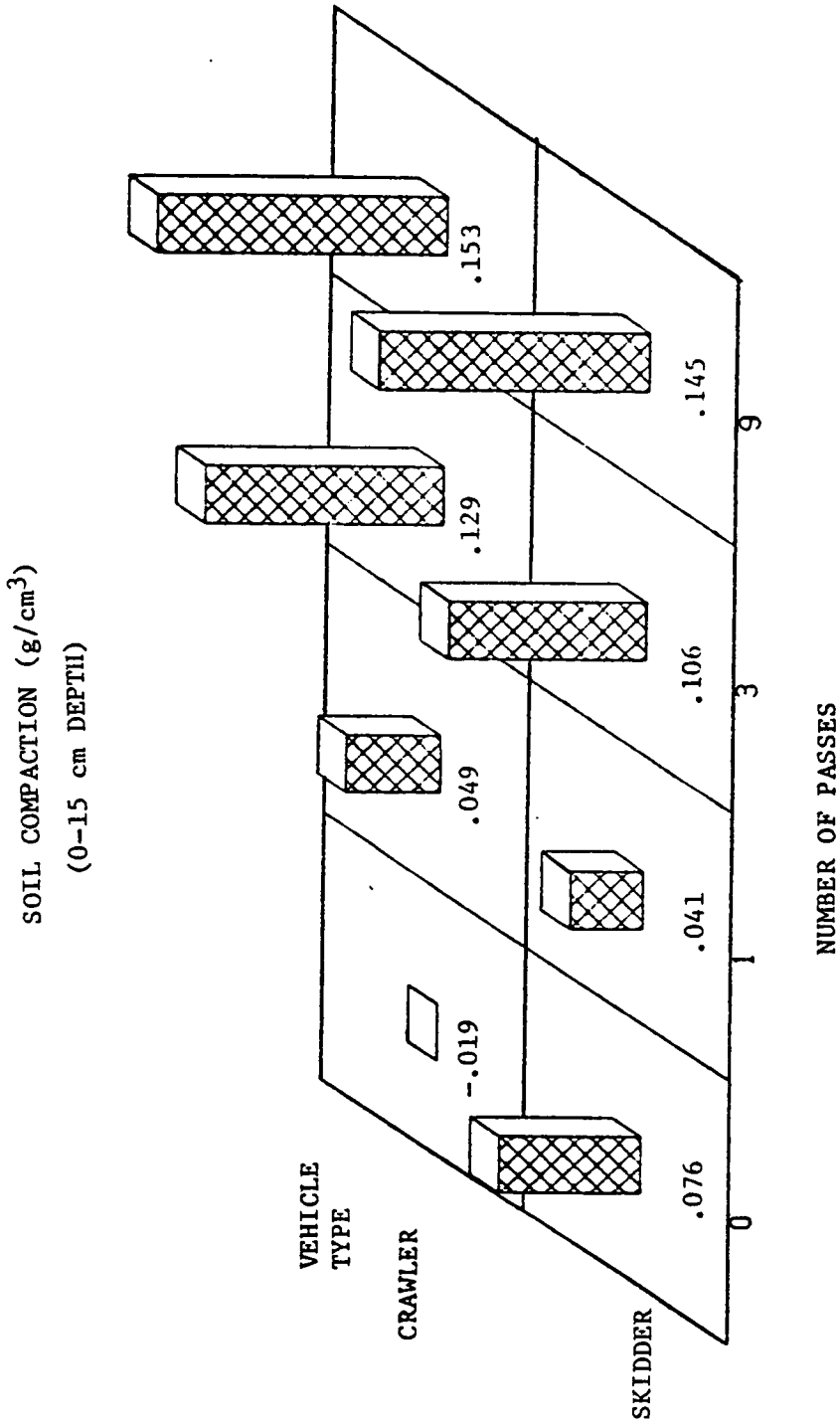


Figure 15: Interactive effect of vehicle type and number of passes on soil compaction.

## 5.2 COMPARISON OF DENSITY DATA FROM NUCLEAR AND GRAVIMETRIC METHODS

To compare the nuclear method with the standard core sampling procedure of density measurement, wet bulk densities obtained by the nuclear gauge were converted to dry bulk densities, using the moisture content data, as follows:

$$\text{Dry Bulk Density} = \frac{\text{Wet Bulk Density}}{\text{Moisture Content} + 1.0} \quad (1)$$

Dry density data were then paired with core bulk density data by location and depth. The statistical analysis consisted of a paired difference t-test which indicated a highly significant difference between compaction measured by the two methods.

Using a linear regression model, a curve was fitted relating the density values obtained by the two measurement methods as shown in figure 16 . The equation for the curve fitted to the data is:

$$DN = 0.66 DG + 0.45 \quad (2)$$

where:

DN = Dry bulk density obtained  
using nuclear densitometer

DG = Dry bulk density obtained  
using Gravimetric method

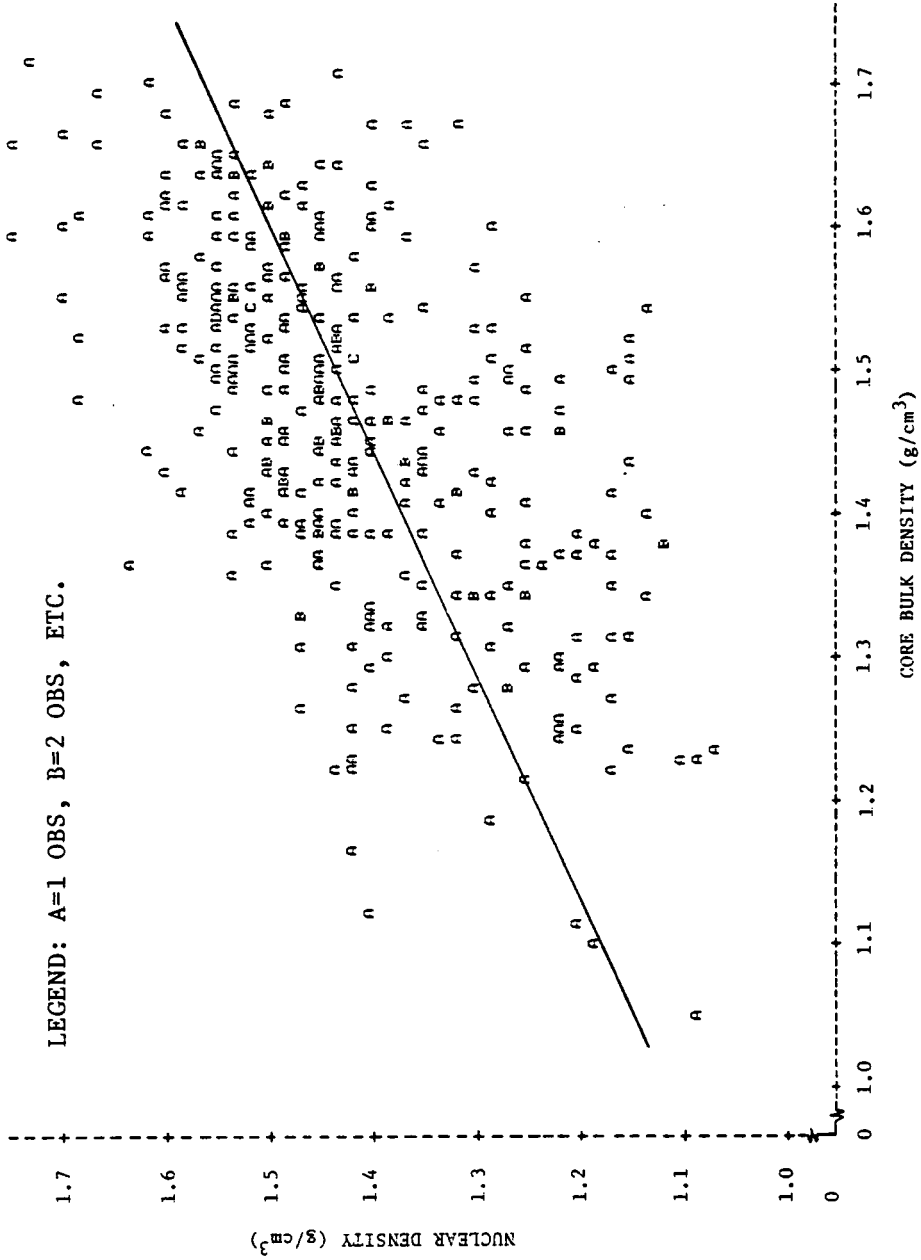


Figure 16. Comparison of density measurements using nuclear and gravimetric methods.

For majority of the observations, density measurements made by the nuclear gauge were lower than those made gravimetrically.

A similar result was reported by Gameda et al. (1983) who used a Campbell Pacific Nuclear Stragauge for density measurements.

Hassan (1978) compared gravimetric and nuclear methods and found that the nuclear gauge densities were higher than those obtained using core sampling. She suggested that a factor of 0.8 be used with density values obtained using the nuclear densitometer.

Greene (1983) developed regression equations to convert a recorded nuclear count into a field bulk density value. In comparing the bulk densities obtained from core sampling, he found that nuclear counts tended to overestimate core bulk density at values below  $1.45 \text{ g/cm}^3$  while underestimating it at values above  $1.70 \text{ g/cm}^3$ .

## Chapter VI

### SUMMARY AND CONCLUSIONS

A field study was conducted in the fall of 1982 to investigate the effect of selected factors on machine-induced soil compaction. The factors considered were: vehicle type, traffic intensity, soil moisture level, and their interactions. During the study two procedures commonly used for soil bulk density determination were also compared.

The test site, located in Patrick county, Virginia, had a mixed pine and hardwood stand which was clearcut and remotely skidded to avoid soil compaction due to traffic of harvesting equipment. Soil texture was classified based on depth. The textural classes were sandy clay loam and clay in the top (0-15 cm) and lower (15-30 cm) depths, respectively.

Treatments at the following levels were applied:

- i) Soil moisture: Two levels
- ii) Vehicle type: wheel and track type
- iii) Traffic intensity: 0, 1, 3, and 9 passes.

Each treatment combination was replicated three times and these were installed in random order on 48, 6 x 30 m test plots.

Immediately after installing the treatments, soil samples were taken from each test plot at two depths (0-15 cm and 15-30 cm) for the determination of moisture level. During the next several days following the treatment, core samples were taken in and outside the rut at three locations along each track for bulk density determination. Bulk density data using a double probe nuclear densitometer were taken at one location along the track.

The density data collected were statistically analyzed and the following conclusions were drawn from the results of these analyses:

1. Maximum change in bulk density and, thus, maximum compaction was observed in the top (0-15 cm) layer of the soil. No significant change in bulk density was observed at the lower (15-30 cm) depth.
2. Soil bulk density on the surface layer was highly correlated with the number of vehicle passes. A significant increase in compaction was observed as the number of passes of both vehicle types increased. While one machine pass did not cause a significant increase in compaction, three and nine passes did. However, no significant compaction resulting from three and nine passes was observed. The rate of bulk density increase diminished with increasing number of passes.

3. Soil moisture level did not have a significant influence on soil compaction. Apparently the 2.8% difference in the average moisture content of the two moisture levels was not large enough to cause a significant difference in the resulting compaction.
4. Despite the fact that the skidder contact pressure was over three times that of the crawler tractor, soil compaction by the two vehicles were not significantly different. The contact pressures were estimated based on uniform, static load distribution assumption.
5. There was a significant interaction between moisture-level and vehicle-type in the top soil layer. The rubber-tired vehicle, on an average, caused more compaction in the wet soil (average MC= 20.66%) than in the moist soil (average MC= 17.86%). Compaction of the wet and moist soils by the crawler tractor was not significantly different.
6. A significant interaction between the vehicle type and number of passes was found in the upper soil layer. No interaction was observed between 1, 3, and 9 passes and vehicle type. The significance indicated by the ANOVA test, may be attributed to the variability in the test site and in sampling.

7. Comparison of density data obtained using the gravimetric and nuclear methods indicated a highly significant difference between the two. For the majority of observations made during this study, density values measured by the nuclear densitometer were lower than those obtained using the gravimetric method.

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## Appendix A

### CONTACT PRESSURE CALCULATIONS

The tire contact area was estimated based on load-contact area relationship (Figure 17) provided by a manufacturer for 23.1-26 tires on flat surface. The tire contact area, estimated based on the assumption that the skidder weight is evenly distributed on the four wheels, was used to calculate the static contact pressure under the pneumatic tires. The procedure used to calculate the contact pressure for both vehicles is as follows:

#### A.1 WHEEL CONTACT PRESSURE

Total Load = 74330 N (7580 kg)

Load per tire = 18580 N

From figure 17 estimated contact area per tire = 800 cm<sup>2</sup>.

Static Contact Pressure = 230 kPa

#### A.2 TRACK CONTACT PRESSURE

Total Load = 139340 N (14210 kg)

Load per track = 69670 N

Contact Area per track = 50 cm x 239 cm = 11950 cm<sup>2</sup>

Contact Pressure = 60 kPa

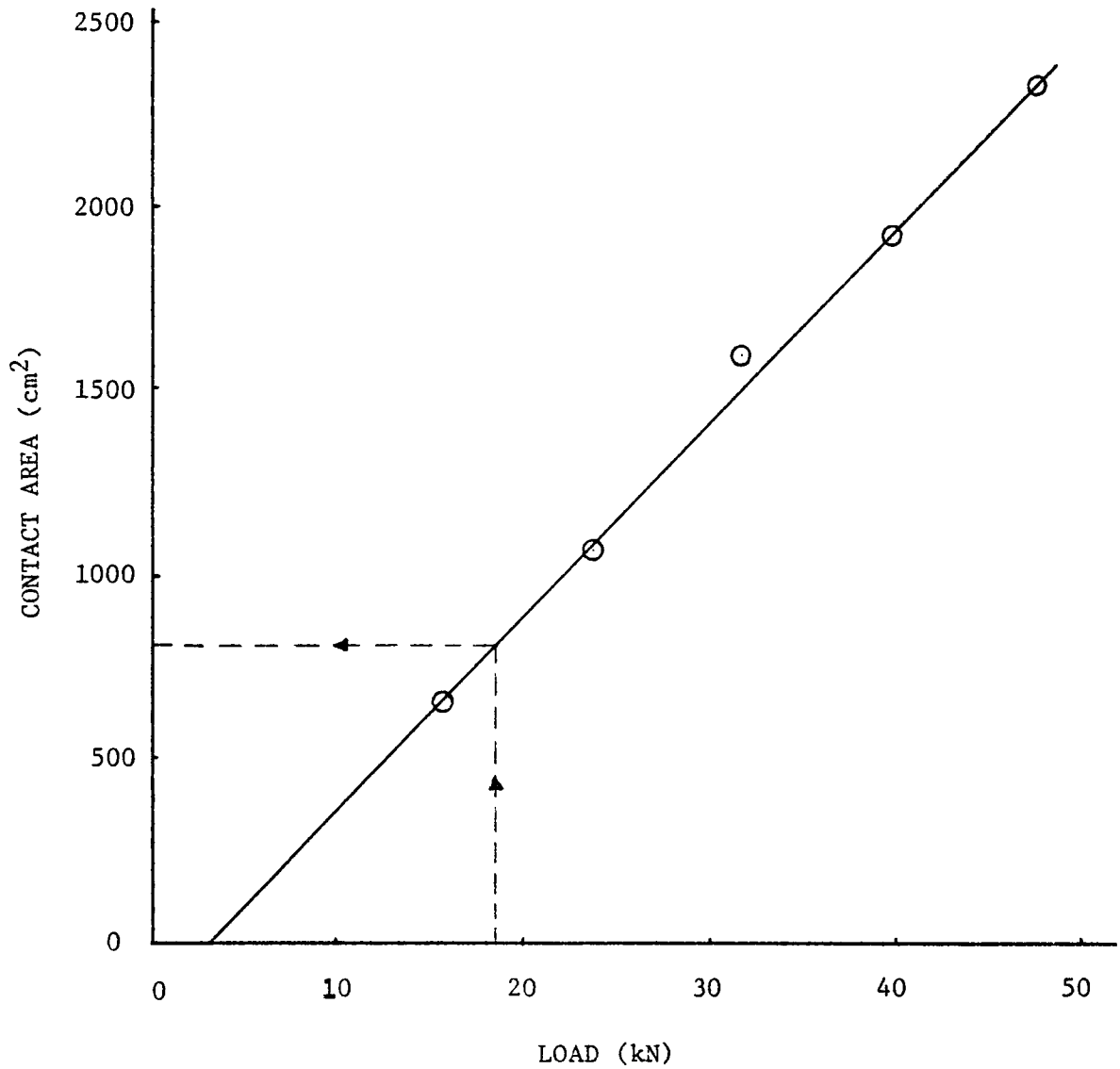


Figure 17. Load-contact area relationship for 23.1-26 tire on a flat surface.

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MULTIPASS EFFECTS OF WHEEL AND  
TRACK TYPE VEHICLES ON SOIL COMPACTION

by

Saeid Minaei

(ABSTRACT)

A field study was conducted in the fall of 1982 to investigate the effect of vehicle type, traffic intensity, soil moisture level, and their interactions on soil compaction. During the study two procedures commonly used for soil bulk density determination were also compared.

Treatments at the following levels were applied:

- i) Soil moisture: Two levels
- ii) Vehicle type: wheel and track type
- iii) Traffic intensity: 0, 1, 3, and 9 passes.

Each treatment combination was replicated three times and these were installed in random order on 48, 6 x 30 m test plots.

Soil samples were taken at three locations from each test plot for the determination of moisture level. Core samples were taken in and outside the rut at three locations along

each track for bulk density determination. Bulk density data using a double probe nuclear densitometer were taken at one location along the track.

Statistical analysis of the data indicated that, of the factors considered in the study, number of vehicle passes and interactions between moisture level and vehicle type and number of passes and vehicle type had a significant effect on the compaction of the top soil layer. The two methods for measuring soil density were compared using the paired student's t-test and an equation was developed relating the density values obtained by nuclear and gravimetric procedures. Comparison of the data from the two methods indicated that the nuclear densitometer underestimated the core bulk density.