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SOIL COMPACTION AND THE COMPACTIBILITY OF CULTIVATED AGRICULTURAL SOILS

BY

AUSTIN CHARLES JOB SICHINGA

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled SOIL COMPACTION AND THE COMPACTIBILITY OF CULTIVATED AGRICULTURAL SOILS submitted by AUSTIN CHARLES JOB SICHINGA in partial fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY in SOIL MANAGEMENT.

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Date: Sept 1, 1987

Dedication

To the memory of the little boy around our home who carried a big bright smile but could not carry the tune of " kalulu a lelila". To the memory of my best friend and loving young brother the late Sichinga John Bright

Chikumbusyo cha muzuna wane na munyane, wakutemweka Sichinga John Bright

ABSTRACT

Since the early 1970s, high soil densities due to increased use of large tractors in farming have led to yield declines in soils previously considered unlikely to suffer excessive densification. Better methods of predicting densification are required to prevent its extention to new regions. Soil densification models are predominantly of the semi–empirical type because of difficulties in measuring input variables for soil stress–strain equations. The identification of impo·tant factors and conditions under which they are significant is essential for the success of such models. To identify these factors, to determine the potential for excessive densification, to establish densification patterns under tractor tires, and to investigate the influence of number of passes and moisture levels on densification, a series of laboratory and field studies were undertaken utilizing soils from three sites near Vegreville, Alberta. For the field study, a dual tired 13 t four–wheel drive tractor and a 6 t two–wheel drive tractor were used.

A 2nd order polynomial gave the best correlations between Proctor test densities and moisture contents. Approximately 50% of field density increases were explained by pre–treatment density and 20% by clay content. Soil physical properties explained density increases at low moisture contents while a combination of physical and chemical properties explained density increases at high moisture contents.

Maximum densification occurred when moisture contents were near saturation in the sandy soil from Site 1, just above plastic limit in the sandy loam soil from Site 2 and below plastic limit in the sandy clay loam soil from Site 3. Both tractors caused subsoil densification although its occurrence was highly dependent on soil moisture contents and the absence of dense layers near the profile surface. Multiple passes caused higher densities and de· ·r densification than the single

pass.

From densification patterns established by comparing densities measured in the untracked treatment with those within and between dual tire tracks, it was determined that for six–pass treatments at high moisture contents the entire area between dual tires was densified. Densification patterns followed Soehne's (1958) calculated pressure bulbs only in the cultivated surface layers.

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CHAPTER I

THE COMPACTION PROCESS AND THE COMPACTIBILITY OF AGRICULTURAL SOILS

1.1 Introduction

Soil compaction refers to the dynamic process in which soil is densified as a result of the application of mechanical energy. Soil densification occurs whenever mechanical forces applied to the soil exceed its bearing capacity. The bearing capacity of a soil manifests the soil's ability to resist densification, compression and shear and is a function of the soil's mechanical strength. The strength of a soil is made up of a frictional component, dependent on the soil's inherent physical properties, and a cohesive component, dependent on the bonding potential between soil particles. Soil strength is further influenced by soil moisture and bulk density. Soil compactibility is the qualitative measure of the ease of densifying a soil.

Several changes occur during soil densification which cause a reduction in the soil's bulk volume; the most important of these are the rearrangement and reorientation of the particles (Harris, 1971). Forces which cause densification in soils originate from two sources: (i) forces due to natural phenomena, including wetting and drying, which are less important to cultivated agriculture because they are significant only over long periods of time, and (ii) mechanical forces applied to the soil by animals and machines during agronomic practices. Land trampling by grazing and draft animals and wheel loading by farm machinery are the most important sources of agricultural land densification today (Soane et al., 1982).

Concern over the densification of agricultural soils predates the farm tractor (Soane, 1970). Studies of tractor-induced soil densification, however, started in earnest only after World War II as a result of the increase in compaction-related problems which followed dramatic increases in numbers and sizes of farm tractors. Interest in soil densification waned in the late 1960s and early 1970s but resurged in the late 1970s. The resurgence and the continued interest in densification into the late 1980s can be attributed to four reasons.

First, farms have grown bigger in size making large tractors more economical than small ones. With the increase in farm sizes, efficient and timely operations have become essential to successful farming making mechanization of most farm operations necessary. Further, time constraints have led to operations even when soils are wet and highly vulnerable to densification.

Second, the average size of farm machinery and their numbers have continued to increase. Håkansson (1985) projected that the average tractor will have a mass of 7 t by 1990 while four wheel drive tractors will average 12 t. More specialized farm equipment has emerged since 1984 with masses of over 20 t. Today manure and slurry spreaders with over 25 t masses when loaded are common while self propelled combines weighing over 21 t and large grain wagons of up to 40 t mass are also common (Erbach, 1986). This continuing increase in farm machinery size means increasing loads continue to be applied to the soil preventing the attainment of equilibrium density conditions.

Third, changing agronomic practices, the greater use of herbicides and insecticides and increased manure, fertilizer and lime spreading have raised the number of vehicle passes over the field per season. Erbach (1986) estimated that 80% of the area in the field is traversed at least once a year in soybean and corn production. The higher number of passes causes even greater soil densification.

Finally, interest in compaction has been encouraged by lower yields associated with high soil densities while costs of correcting the condition have risen. The consequences of high soil densities in both surface and subsoil layers are well documented. In the surface layers, soil structure is degraded as aggregates are crushed. The porosity of the soil, relative proportions of large pores to small ones, and soil permeability decline, reducing rates of water infiltration into the soil. As a result, surface flooding becomes common and oxygen diffusion to the seed and plant roots declines (Grable and Siemer, 1968). In the subsoil, root growth is impeded by high densities which also prevent the crop from utilising moisture and nutrients from deeper layers of the soil profile (Soane et al., 1982).

High soil densities ultimately reduce crop yields and quality. Almost all crops suffer yield declines as a result of high soil densities. Corn yields were shown by Phillips and Kirkham (1962) to decline 10% while Morris (1975) found they declined 22% as a result of high densities. Saini and Lantage found potato yields declined 22% when bulk densities rose (Raghavan et al., 1979) and Feldman and Domier (1970) found declines in the vegetative growth of wheat after increased traffic.

1.2 The soil compaction process

The soil compaction process can be broken into three phases: (i) the application of energy which induces stress, (ii) the compression of the soil, and (iii) soil strain or densification in response to the first two phases (Hillel, 1980). A soil subjected to a pressure greater than its bearing capacity undergoes a volume reduction. This reduction may occur by one or a combination of four mechanisms: (i) compression of the solid particles, (ii) compression of liquid and gases within soil pores, (iii) changes in the volumes of liquids and gases through expulsion, and (iv) rearrangement and reorientation of the soil particles.

Although soil mineral particles may be compressed at high pressures, compression is mostly elastic in nature and the particles rebound to their pre–compression size when the load is removed. As a result particle compression contributes little to the densification of agricultural soils as long as the pressures involved are not high enough to break up the particles. Compression of liquids and gasses is also insignificant in the densification of agricultural soils because both liquids and gases can escape from the bulk soil in the short time the soil is under pressure.

The reduction in the soil volume during densification is mainly the result of the expulsion of liquids and gasses and the rearrangement of the particles (Harris, 1971; Hillel, 1980). Although these two mechanisms may operate simultaneously, the expulsion of water is more important when soils are near saturation while the main mechanism of density change is particle rearrangement and gas expulsion when the soils are not saturated (Harris, 1971). Since the total soil volume includes the volume of voids and solids, a change in the soil volume affects both porosity and void ratio.

During compaction, soil particles change position and are rearranged by rolling and/or sliding over each other. Soil and particle properties and characteristics which influence the ease of particle rolling or sliding therefore significantly affect soil densification. The structural arrangement of the particles in fine grained soils, the degree of bonding, textural gradation, particle shape, roughness and soil densities and moisture contents all significantly influence soil densification.

In the densification of saturated soils, both water expulsion and particle reorientation mechanisms are operative. As a result, the time of loading and the hydraulic conductivity of the soil are important factors determining the total volume change which occurs. Low hydrauiic conductivities and short times of loading result in low volume changes.

1.3 Soil compactibility

Soil shear strength is the stress required on a shear plane to cause failure when a normal load is applied. It is dependent on the soil's physical, chemical and mineralogical properties (Lloyd and Collis–George, 1982). The most important parameters of soil strength are represented in the Mohr–Coulomb equation which is given as:

$$\tau = c + \sigma \tan \phi \quad (1)$$

where τ is the soil strength, c is the in situ soil strength called apparent soil cohesion, σ is the applied normal stress and ϕ is the effective angle of resistance also called the angle of internal friction. In the equation, τ, c, and σ are expressed as force per unit area (kPa). Soil physical and chemical properties which influence the parameters c and ϕ also influence soil strength, bearing capacity, and compactibility.

Apparent soil cohesion (c) is associated with fine grained soils and is less important in coarse grained sandy soils. Its magnitude is dependent on the number and strength of the bonds formed between soil particles and is a function of surface charge (Lambe and Whitman, 1969). The magnitude of c can range from 0 kPa in clean cohesionless sands to 30 kPa in clays (Marshall and Holmes, 1988). Through interparticle forces, apparent soil cohesion contributes up to 80% of the shear strength in montmorillonitic clays, 40 – 60% in chlorites and 20% or less in kaolinites (Grim, 1962). The apparent soil cohesion is thus related to the specific surface area of a soil and its mineralogy. Increasing the soil's apparent cohesion will increase its strength and bearing capacity.

The angle of internal friction (ϕ) is a result of attractive forces which act among the surface atoms of the particles and particle interlock. Particle interlock varies with particle surface roughness and shape and is a function of the packing density. The values of ϕ can range from zero in saturated clays to 45^0 in densely packed sands. Increasing the angle of internal friction by increasing particle surface roughness, surface charge and soil density increases soil strength. As a result smooth round soil particles have lower strength compared to angular, rough ones. As soil strength and density increase, the energy input necessary to cause progressively greater densification also rises.

Compaction is a function of four variables: soil type, dry density, water content and compactive effort (Holtz and Kovacs, 1981). Soil type refers to soil texture, its gradation and the presence of certain minerals. Resistance to densification is partly determined by grain size distribution. Since well graded soils contain a mixture of small and large particles, there are more contacts between particles and resistance to shear is proportionately greater in such soils than in uniformly graded ones. The change in density for a given load is therefore smaller in well graded soils compared to poorly graded ones. Well graded soils however can undergo relatively wider ranges of density increases and can be densified to much higher densities than uniformly graded soils.

The soil's bulk density is important in its densification because particle interlock is partly a function of particle packing density. Chancellor and Schmidt (1962) found that increasing initial bulk density increased both the cohesion and the internal friction components of the Mohr–Coulomb equation, except in loamy soils. Soils whose initial bulk densities are low undergo greater density changes following densification.

For most soils, increasing the water potential results in lower strength (Holtz and Kovacs, 1981). The decline in soil strength is due to the lubricating effect of water and the declining forces of attraction responsible for the curved water interface between the particles. Soil strength also declines because of increased hydration water layers in the interparticle zone which separates the particles. Grim (1962) and Williams and Shaykewich (1970) presented data which showed soil strength decreasing with increasing water potential in cohesive soils.

Paul and De Vries (1979) suggested soil moisture influences soil strength through surface tension forces. Negative pressure in pore water or low water potential increases the strength of sandy soils. The influence, however, varies with clay surface area, for example unsaturated montmorillonite exhibits a higher matric potential than does kaolinite at similar moisture contents. The decrease in matric potential is partly due to increasing surface tension at the air/water interface. Increasing surface tension at the air/water interface has the same effect as increasing the compressive load and increases the shear strength of the soil. Aitchison (1961) and Towner and Childs (1972) advocated an additional term in the Mohr–Coulomb equation to account for the influence of matric potential in non–swelling clays. Increases in soil strength due to surface tension at the air/water interface are important in sands and in aggregated soils in which air which is necessary for the formation of the air/water interface is likely to enter the soil matrix. It is less important in clays in which air in unlikely to enter the soil matrix for moisture contents generally encountered in field situations.

Soil hydraulic conductivity is important in densification when soils are at high moisture contents. Loading soils at high moisture contents reduces the soil volume, which generates positive pressure in the pore liquid. As a result, in confined soils, external loads can be sustained by the pore liquid alone. When the pore liquid is allowed to escape, however, the hydrostatic stress is transferred to interparticle stress. The rate and magnitude of stress transferred are dependent on the rate at which the pore liquid escapes. Stress transfer and bulk volume reduction are thus dependent on the hydraulic conductivity of the soil. The influence of pore water pressure on soil compactibility is time dependent. It is less important during soil compaction because the time of loading is short and the pore liquid is not able to escape and it is more important during consolidation, which occurs over long periods of time allowing the pore liquid to escape.

The type, valence and concentration of ions in the soil liquid have been found to influence soil strength and compactibility. Yong and Warkentin (1966) indicated that at similar moisture contents Ca–saturated montmorillonite had a lower shear strength than did Na–saturated montmorillonite. This phenomenon was attributed to the lower surface area of interaction between the clusters of Ca–saturated flocculated clay particles compared to the d.spersed Na–saturated ones. The lower surface area in the Ca–saturated clay is due to the clusters of particles behaving as units compared to the dispersed Na–saturated particles which act individually thereby allowing the development of more air/water interfaces which cause higher shear strength.

Raghavan (1985) reported that increasing the soil organic matter of some densified Quebec soils from 3% to 10% improved yields of bushbeans by 100%. The organic matter increase reduced the soils bulk densities, improved the hydraulic conductivity, the water holding capacity and the plant available moisture of the soils. Organic matter contents of 17% were found to eliminate totally the detrimental effects of densification. Organic matter may influence soil compactibility through two mechanisms. Pre–degraded organic matter reduces soil compactibility by increasing soil resilience. The organic matter absorbs and temporarily stores the energy from the load which is released upon load removal. Degraded organic matter acts as a cementing agent, increasing the number of bonds between particles and thereby increasing soil cohesion. Soil organic matter thus reduces soil compactibility and increases the soil's bearing capacity.

1.4 Energy input by agricultural machinery

In modern agriculture the energy for soil densification is predominantly supplied by farm machinery incuding combine harvesters, manure and lime spreaders, and tractors (Erbach, 1986). Farm machinery today is mostly equipped with pneumatic rubber tires as the means by which vehicle load is transferred to the soil. The size of the tire, its flexibility and the proportion of vehicle mass that each tire carries are important factors which determine the surface area of contact between the tire and the soil. The surface area of contact determines the contact pressure or the magnitude of load per unit of area.

Tire flexibility, which is greatly affected by the inflation pressure, influences the size of the contact area and the uniformity of pressure distribution within the contact area. At high inflation pressures, tires behave rigidly, resulting in relatively small areas of contact and higher contact pressures. For air–inflated tires, the pressure exerted upon the supporting surface is approximately the same as the inflation pressure of the tire (Chancellor and Schmidt, 1962).

Smith and Dickson (1988) investigated the relative contributions of vehicle mass and contact pressure to soil densification and confirmed Soehne's (1958) conclusions that increasing ground pressure increases soil densities near the surface but has little effect at depths and increasing wheel load at a given contact pressure increases soil densities at depths without changing the resultant densification in the surface layers. Contact pressure and soil moisture were also shown by Amir et al. (1976) to be important variables in equations which predict soil densification.

Recent research in soil densification has shown subsoil compaction to be primarily a function of mass per traction device (Taylor, 1985). Håkansson and Danfors (1981) found vehicle loads exceeding 6 t on a single and 8 to 10 t on tandem axles caused soil densification at depths greater than 0.4 m. In annually repeated high axle loading experiments, Gameda et al. (1984) showed that both soil density and strength continued to increase as a result of cumulative compactive loading. Duval et al. (1987), studying the effect of heavy axle loading and subsoiling on pore size distribution, found that heavy axle loading shifted the soil's pore size distribution towards smaller pores.

Davies et al. (1973), using results from field studies which involved measuring soil densification under tracors working with different wheel loads and levels of wheelslip, found the more powerful tractors had greater wheelslip and caused more surface soil densification than less powerful ones. Experiments involving proportional increases in both load and wheelslip showed that wheelslip caused more soil densification than did additional load.

1.5 Predicting soil compaction

Numerous attempts have been made to develop soil compaction models that can be used in soil management and farm machinery design. Direct cause and effect relations exist between the use of machinery and soil densification and between soil density, plant root environment and crop production. However, these relations are complex and depend on a number of soil properties and characteristics which explains why few soil compaction models are universally applicable (Vanden Berg and Gill, 1962).

Difficulties which are encountered in attempting to predict soil densification arise because soil behaves elastically at low stress levels and plastically when stress levels are high. Mathematically, solutions to soil stress–strain equations are very complex because of difficulties in measuring the input variables within the soil. Other difficulties arise because soils in their natural state exist as semi–infinite, three–dimensional mediums but loads are applied over only a portion of the soil boundary which leads to a non–uniform distribution of the load within the soil. Predicting soil densification has thus been predominantly approached from a semi–empirical view.

Boussinesq developed the first equation to describe stress distribution in semi–infinite mediums in which the load was applied at one point (Harris, 1971). The soil was assumed to be elastic, homogeneous and isotropic. Froehlich inserted a concentrating factor into Bousssinesq's equation tc correct for the fact that soils are neither perfectly elastic nor isotropic (Soehne, 1958). The concentration factor also introduced varying strengths into the equation.

Soehne (1958) extended Boussinesq's equation to describe the behaviour of soil volume elements under pressure and used the descriptions and distribution of the volume elements in the soil to predict pressure distribution in the bulk soil mass. The stress system about a volume element at a radius r from the loading point reduces to σ_r when normal stress is expressed as the polar principal stress allowing all other stresses to become zero (Soehne, 1958). The normal stress at the point r is:

$$\sigma_r = \upsilon P \;/\; 2\,\pi\, r \cos^{\upsilon - 2}\phi \qquad (2)$$

where υ is the concentration factor which Soehne (1958) defined and assigned values of 4, 5, and 6 for hard, medium and soft soils respectively and P is pressure.

The theory indicated that when soils are wet, the stress distribution extends more in the vertical direction along the load axis than when soils are dry and hard. The theory further shows that pressure was maximum directly in the center of the loaded area and decreased towards the spreading edges. The pressure felt at depth within the soil depended on the magnitude of the pressure at the surface and the area over which the pressure was applied. The stress extended to greater depths and the stress was higher at each depth when the pressure was applied to a larger area than when it was applied to a smaller one. Pressure extended more laterally than vertically when pressures was uniformly distributed across the contact surface area and it extended more vertically than horizontally when the pressure increased (Harris, 1971). Soehne (1958) concluded that the pressure in the upper soil layers was controlled by the specific pressure at the surface which depended on the tire inflation pressure and soil deformation. The pressure deeper in the soil was controlled by the magnitude of the load.

Solutions to the Boussinesq's equation show that pressure in layered soils of different densities extended deeper when Young's modulus of elasticity was higher in the surface layer (Poulos and Davis, 1974). Soehne et al. (1962), using lead shot to trace soil movement during compaction, found maximum densification did not occur at the contact surface between a plunger and the soil as would occur if the largest principal stress uniquely controlled densification but at the intersection of lines drawn at 45^0 from the edge of the plunger. The soil volume enclosed by these lines and the bottom of the plunger acted as part of the plunger.

The fact that soils are more plastic than elastic means that the assumption of elastic soil behaviour by Boussinesq leads to errors when these conditions are not satisfied. Since soils behave elastically only at very high densities and plastically at most low and medium densities, soils can be expected to be more inert than Boussinesq's equation would predict. For this reason the effect of surface loading diminishes in much shallower depths than calculated by Soehne (Eriksson, 1982).

Janbu (1970) proposed a theory where pressure decrease in the soil profile was dependent on the shape of the loaded surface (circular, rectangular, or oblong) which predicted that the effect of the load only extended to depths corresponding to four times the width of tracks. In experiments with soils at field capacity and based on a rectangular loading surface Janbu (1970) found pressure decreased most rapidily in sands and extended deepest in clays. In all cases pressure did not extend deeper than four times the width of the tires.

Using finite element methods in simulations to predict soil stress distribution and deformation, Perumpral et al. (1971) and Perumpral (1985) found results which agree with the elastic theory of Boussinesq as long as the the assumptions of isotropic and homogeneity are satisfied. Isotropic and homogeneous soil profiles, however, are rare in cultivated fields which explains the difficulties encountered when extrapolations of laboratory or soil bin results to the cultivated field are attempted. New studies of soil densification in situ are needed in order to minimize the errors due to Boussinesq's assumptions.

1.5 Study objectives

Soil densification studies to date have characteristically been designed to study the effect of single factors, with others held constant. Although such studies are necessary to provide an insight into the influence of specific factors on densification, they neither establish the relative importance of such factors nor the conditions under which the factors are important. It is neccessary therefore to undertake multivariate studies of soil densification which address these two questions.

The majority of the densification studies have been conducted as simulations which have been verified in laboratories or soil bins in order to approximate the assumptions of isotropic and homogenous soil conditions. In verifying these studies, both soil moisture content and bulk densities have been kept artificially uniform. In contrast, soils in cultivated fields are almost never at uniform moisture content because of the influence of gravity and meteorological events. Soil profile densities are also rarely uniform in the field, tending to be lower near the soil surface due to cultivation and high organic matter content and highest just below the cultivated layers.

In densification studies of cultivated fields, abnormally heavy equipment has often been used to load the soil and/or the loads have been applied in ways not consistent with normal agronomic practices. The results obtained from such studies are thus difficult to relate directly to densification resulting from agronomic operations.

The general objectives of the studies reported in this dissertation were to study the densification of cultivated soils subjected to tractor loading under normal farming operations and to study the influence of soil physical and chemical properties on density changes. In order to achieve these objectives, the studies were conducted in cultivated field soils in which natural variations of both moisture and density were allowed. The tractors used were representative of commonly available sizes and except for the lack of load on the tractors, the soils were loaded so as to reflect the passage of tractor tires.

The specific objectives, the organization of the chapters, and their titles in the dissertation are as follows:

CHAPTER 2

TITLE: The influence of soil physical and chemical properties on soil compactibility.

Objectives: To:

(i) establish differences, if any, in the densification behaviour of the three soils in the laboratory and determine equations which best describe this behaviour, and

(ii) identify which soil properties influence soil compactibility in the field, and rank their importance in explaining density increases.

CHAPTER 3

TITLE: Tractor–induced soil densification under field conditions.

Objectives: To quantify soil density increases and depth to which these extend in the soil profile as a function of:

(i) soil pre–treatment bulk densities and moisture content, and

(ii) tractor mass and the number of passes over the field by the tractor.

CHAPTER 4

TITLE: Densification patterns under dual tractor tires.

Objectives: To determine:

(i) densification patterns under dual tractor tires,

(ii) how far lateral densification extends, and

(iii) what proportion of the area betweeen the dual tires is compacted during tractor passage.

CHAPTER 5

TITLE: Synthesis.

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CHAPTER II

THE INFLUENCE OF PHYSICAL AND CHEMICAL PROPERTIES ON SOIL COMPACTIBILTY

2.1. Introduction

Soil densification refers to the dynamic process in which the soil's density is increased as a result of the application of mechanical force which exceeds the soil's bearing strength. Densification depends on the soil's compactibility which is a soil property that depends on the soil's bearing strength and reflects a soil's capacity to support a load by resisting densification, compression and shear. It is influenced by the soil's physical and chemical properties, moisture content and bulk density (Lloyd and Collis–George, 1982). Soils are less compactible when their bearing strength is high. Important parameters of soil strength, τ, are given in the Mohr–Coulomb equation which is presented as:

$$\tau = c + \sigma \tan \phi \qquad (1)$$

where c is the apparent soil cohesion, σ is the applied normal stress, ϕ is the angle of internal friction and τ, c and σ are all expresed as force per unit area.

Apparent soil cohesion depends on the number and strength of interparticle bonds which are a function of the nature of the clay. As a result apparent soil cohesion is mostly associated with fine grained soils. Increasing the soil's apparent cohesion increases its strength. The angle of internal friction is a result of macroscopic particle interlock and the microscopic attractive forces which act among the particle's surface atoms. Particle interlock increases with particle surface roughness and is a function of the particle shape and the particle packing density.

Increasing the bulk density of a soil increases both its cohesion and its angle of internal friction (Chancellor and Schmidt, 1962).

In addition to compactive effort and the soil's bulk density, Proctor identified soil type and moisture content as other important factors in soil densification (Holtz and Kovacs, 1981). Soil type refers to the soil's texture, gradation and mineralogy. For soils of the same initial density, changes in density for given loads are smaller in well graded soils than in uniformly graded soils because of the greater number of contacts between particles and the proportionately larger shear resistance in well graded soils compared to the uniformly graded ones (Hillel, 1980).

Generally soil strength is low when soil moisture contents are high and high when soil moisture contents are low. The major influence of soil water on the soil's strength and its compactibility is through its effect on the soil water matric potential. Low soil water matric potentials in soils are a result of high surface tension at the air/water interface which raises the soil's shear strength (Paul and De Vries, 1979). Towner and Childs (1972) recommended that an additional term be added to the Mohr–Coulomb equation to account for the effect of matric potential in non–swelling clays. Increasing soil moisture content also results in reduced soil strength because the water's lubricating effect reduces friction between the soil particles causing soil strength to decline (Holtz and Kovacs, 1981). The lubricating effect of water on soil strength depends on whether the water is bonded to the soil particles, forms water of hydration around ions or is in the free state. Water that is bonded to soil particles or is in the hydration shells has a higher viscosity than free water (Sposito, 1984). Free water is thus more efficient as a lubricant. The lubricating influence of the water therefore will vary with the nature of the clay in the soil.

The type, valence and concentration of ions in the soil solution also influence soil compactibility. Yong and Warkentin (1966) indicated montimorillonite had lower shear strength when Ca was the saturating ion than when Na was the saturating ion because Ca flocculates the clay particles into clusters which behave as units. This reduces the total surface area of the clay and leads to reduced air/water interfaces compared to Na which disperses the clay particles causing them to act individually and causing greater air/water interfaces. The presence of air/water interfaces is the cause of increased soil strength. In addition, the divalent Ca–saturated clays have smaller diffuse ion–layers of hydration water compared to the monovalent Na. The diffuse double layer of Na therefore extends wider than that of the Ca ion. Since water in the diffuse double layer is of a higher viscosity and acts as part of the ion or soil particle to which it is bonded, less densification occurs in the Na–saturated clay and the Ca–saturated particles are thus more compactible.

Raw organic matter influences soil compactibility by increasing soil resilience. Degraded organic matter acts as a cementing agent and increases soil cohesion by increasing the number of bonds between the particles. (Raghavan, 1985) Increasing soil organic matter from 3% to 10% reduced densification enough for a 100% increase in bushbean yields while increasing organic matter contents to 17% eliminated the effects of densification completely (Raghavan, 1985)

2.2 Study objectives

Soil densification studies to date have concentrated on studying the effects of single factors while others are held constant. Although parameters which influence densification have been identified in this manner, their relative importance and the conditions when they are important have not been clearly established. Two studies, a laboratory one and a field one, were conducted with the specific objectives of:

(i) establishing differences, if any, in the densification behaviour of three soils in the laboratory and determining equations which best describe this behaviour, and

(ii) identifying which soil properties influence soil compactibility in the field and ranking their importance in explaining density increases.

2.3 Materials and methods

The field studies were conducted at three sites located at Warwick, 90 km east of Edmonton, Alberta. The sites, which had been cultivated for 40 years, were selected based on differences in their particle size distribution and CEC and on site accessibility. Soil descriptions and classification are summarized in Table 2.1 while select soil properties are given in Table 2.2.

The soil at Site 1 was characterized by 40 cm of wind blown sand over a buried Ahb horizon which extended from 40 to 80 cm and was underlain by a Bg horizon. Site 2 had a sandy loam Orthic Black Chernozemic soil. The profile had an Ap horizon from 0 – 15 cm, an Ah horizon from 15 – 53 cm and a Bm horizon below it. The profile had a dense layer above a stone layer at the 15 cm depth. Site 3 had a sandy clay loam soil which was classified as a Rego Black Chernozem, salinized and carbonated. The Apk horizon extended from 0 – 16 cm and was underlain from 16 – 30 cm by a Csak horizon, loam to clay loam till in texture and by a Ccasa horizon below 30 cm (Howitt, 1988).

A treatment plot, 50 m long and 40 m wide, with a 5 m buffer left between the plot and the fence line, was demarcated at each site. A plan view of the plot showing the sampling points is shown in Figure 2.1a. For the first study, each plot was divided into 6 sampling subplots. Six samples, one from each subplot were taken from the top 30 cm of each site, composited and used in a Proctor test conducted according to the standard ASTM method described by Felt (1982). The hammer had a surface area of 7.854 cm^2. The test cylinder measured 101.6 mm in diameter and 93 mm in height. Energy inputs of 6, 16, 30 and 80 kJ cm^{-3} were attained by varying the mass of the hammer, drop height and the number of blows. Moisture contents were varied in four increments over a soil water matric potential range of –33 kPa to –1500 kPa. Bulk density results from the Proctor test were correlated with energy inputs, moisture contents and matric potentials to determine densification behaviour.

For the field study, each plot was divided into 12 subplots for sampling purposes. A plan view of the plot showing the field treatment and the sampling points is shown in Figure 2.1b. A soil core to a depth of 90 cm was taken in each subplot and divided to give subsamples in 15 cm intervals. Each sample was air dried and sieved through a 2–mm sieve before being analysed. Particle size was determined with the hydrometer method using the standard ASTM No. 152H hydrometer. Sample dispersion was achieved by soaking in calgon. Samples from Site 3 were treated with HCl to remove excess Ca. Particle density was determined using the pycnometer method (Blake and Hartge, 1986). Moisture contents were determined at matric potentials of –20 kPa and –1500 kPa using the pressure plate extraction method described by Klute (1986). Plastic and liquid limits were determined using samples which had been sieved through the No. 40 sieve by the ASTM D 423–66 method as described by McKeague (1979).

Organic matter contents were determined using the microprocessor–based Leco CR 12 Carbon Analyser. Samples were combusted in an O_2 atmosphere and the resulting CO_2 measured by a solid state infrared detector. CEC and cations present in the soil were extracted with NH_4OAc and concetrations determined using the Perkin–Elmer model 503 Atomic Absorption Spectrophotometer. Sodium adsorption ratio (SAR) and soluble sodium percentage (SSP) were calculated from cation concentrations determined in the CEC analysis as follows:

$$SAR = Na / \sqrt{(Ca + Mg)/2}$$

$$SSP = Na / (Na + K + Ca + Mg)$$

A 13 t, 4–wheel drive Versatile 835 tractor was used to compact the soil in the second study. The tractor was equipped with 18.4 – 38 tires in a dual set up. The pressure in the inner "traction" tires was 103 kPa and it was 89.5 kPa in the outer "floatation" ones. The inner tires were ballasted with 420 kg of calcium chloride solution each while the outer tires were not ballasted. To standardize conditions, the sites were tilled with a cultivator to a depth of 15 cm prior to treatment application. Soil moisture contents with depth were determined immediately after treatment application. Moisture contents during treatment were considered normal for field operations.

The densities used in this field study were measured in the treatment which consisted of three multiple passes within a single track applied by the 13 t tractor operated at 8 km h^{-1}. The treatments were repeated at two different dates to give the low and the high moisture content treatments for each site. Eight sets of measurements were made in the center of each of the inner and outer tractor tracks for a total of sixteen sets of measurements. A set of measurements included control measurements taken in the untracked area of the field and the treatment measurements taken in the center of the inner "traction" track and the outer "flotation" track. Density changes at the 10 cm depth were analyzed in order to reduce the possible influence of surface disturbance at the 5 cm depth and avoid possible effects of the high density layer at the 15 cm depth.

A Nuclear Pacific Stratigauge, a combination density–moisture gauge, was used to take moisture and density count ratio (count at depth/standard count) readings. These were used to calculate the volumetric moisture content and the wet and dry bulk densities using site specific moisture calibration curves determined for the soil at each of the three sites and the manufacturer's determined density curves.

In order to determine the correlations between density changes and soil properties and also to establish which variables were significant in influencing soil compactibility, density increases from the selected treatments were correlated with soil properties from the nearest of the 12 sampling points within the plot (Fig. 2.1b). Correlations between density increases and soil properties and the selection of significant variables in the compactibility predictor model were done using multivariate stepwise regression. To test whether one variable can substitute for another in predictor models in case they are highly correlated, the variables were first correlated amongst themselves and the highly correlated variables were then substituted for each other in the compactibility model.

2.4. Results and discussion: Study I

The energy input levels, treatment moisture contents and Proctor determined densities for Sites 1, 2 and 3 are presented in Figures 2.2, 2.3 and 2.4 respectively. The equations which best describe the densification behaviour for the different energy input treatments and their correlations are presented in Tables 2.3, 2.4 and 2.6.

For the 6 kJ cm^{-3} energy input, the density–moisture relation of the soil from Site 1 was best described by a linear relation (Table 2.3). The density–matric potential correlations were best described by the 2nd order polynomial although a logarithmic relation also gave a high correlation. Density–matric potential correlations (not shown) were slightly better than the density–moisture content correlations. The maximum resultant density at Site 1 was 1.76 Mg m^{-3} attained at –10 kPa matric potential and for 80 kJ cm^{-3} energy input. The resultant densities for the 6 kJ cm^{-3} energy input appear not to have attained their peak values but this was likely the result of high moisture contents levels which were above field capacity and probably too high for compaction. The density attained at the highest moisture content appears not to be an accurate representation of densification (Fig. 2.2).

For the 16 and 30 kJ cm^{-3} energy input levels for the soil from Site 1, the density–energy input relation was also best described by the 2nd order polynomial irrespective of whether the densities were correlated against water content or matric potential (Table 2.3). For the 30 and 80 kJ cm^{-3} energy levels, bulk densities declined slightly at the two highest moisture levels compared to the lower two, indicating that peak densities had been attained. For the 30 and 80 kJ cm^{-3} energy inputs, only the 2nd order polynomial relations gave consistently high correlation coefficients because the densification curves were parabolic in nature. Densification varied with moisture content and energy input so that the peaks of the parabolas occurred at lower moisture contents and became sharper as energy input increased from 30 kJ cm^{-3} to 80 kJ cm^{-3}. With the exception of the density attained at the 6 kJ cm^{-3} energy input for the highest moisture content, the results obtained in the densification of this soil were expected. The linear correlation of the curves at Site 1 were to be expected because densification curves for sands generally do not show a pronounced parabola, tending instead to be relatively flat. The the 6 kJ cm^{-3} energy input, high moisture content density was likely inaccurate indicating that deviations should be expected when using the predictor polynomials determined.

At the 6 and 16 kJ cm^{-3} energy input levels for the soil from Site 2, the densification curves were best described by a 2nd order polynomial (Table 2.4). The curves at Site 2 had a more pronounced parabolic shape than those for the soil from Site 1 because of the increased clay content in the soil. Unlike the soil from Site 1, however, the density–matric potential correlation coefficients for the soil from Site 2 were lower than those for density–water content. This was likely a consequence of the increased number of variables which influenced matric potential for the soil from

Site 2 compared to the one from Site 1. Higher clay and organic matter contents influenced the the soil water matric potential and the compactibility of the soil from Site 2. The maximum resultant density at Site 2 was 1.81 Mg m^{-3} measured at −25 kPa matric potential and for 80 kJ cm^{-3} energy input. At the high moisture contents, the density differerences between the 6 kJ cm^{-3} and the 80 kJ cm^{-3} energy input treatments was approximately 0.05 Mg m^{-3} (Fig. 2.3) showing that increasing energy input at high moisture contents had relatively little effect on density increases because the moisture contents were too high for densification.

The Site 3 sample gave parabolic densification curves for the 16, 30 and 80 kJ cm^{-3} energy input levels (Fig. 2.4) compared to only the 30 and 80 kJ cm^{-3} energy input level treatments at Site 2 and only the 80 kJ cm^{-3} energy input level treatment at Site 1. Only the 6 kJ cm^{-3} treatment curve at Site 3 could be described by the linear relation, eventhough the correlation coefficient for the linear relation was lower than that for the first two sites. Although the 80 kJ cm^{-3} treatment densification curve for the soil from Site 3 can be described by a 2nd order polynomial (Table 2.5). The curve's peak density occurs at low moisture contents (Fig. 2.4). Increases in moisture content therefore resulted in declining densities. The maximum resultant density at Site 3 for 80 kJ cm^{-3} energy input was 1.69 Mg m^{-3} attained at −50 kPa matric potential. As for the soil from Site 2, differences in the densities attained for the 6 kJ cm^{-3} and the 80 kJ cm^{-3} energy input levels at the highest treatment moisture contents were less than 0.04 Mg m^{-3}.

Proctor densities rose with increasing energy input at low moisture contents but either did not change or declined as energy input increased from 30 kJ cm^{-3} to 80 kJ cm^{-3}. The decline in densities was small for the sandy soil from Site 1 but become more pronounced as clay content increased. As clay content increased the influence of matric potential on soil densification become more important because more air/water interface curvatures developed which increased soil strength. The linear nature of the curves for the soil from Site 1 compared to parabolic curves from Sites 2 and 3 should be expected because characteristically the densification curves for sands do not generally rise and drop as much as those of clay soils (Holtz and Kovacs, 1981). At high moisture contents the influence of energy input on densities attained was less significant because moisture contents were too high for maximum densification.

2.4. Summary

The densification behavior of the soils as given by the Proctor test followed characteristic densification patterns. At low energy inputs, (6 kJ cm^{-3}), densities increased as moisture content rose until the peak density was attained. For the medium energy inputs, 16 and 30 kJ cm^{-3}, densities increased to a peak and then declined giving the typical parabola as moisture content rose. For the highest energy input, 80 kJ cm^{-3}, densities declined as moisture increased because the soils attained their peak densities at the lowest treatment moisture content. The parabolic pattern of density versus moisture content become more pronounced as both energy input and clay content increased.

Irrespective of the energy level and whether moisture content or matric potential was used in plotting the densities, the 2nd order polynomial consistently gave higher correlation coefficients than did other relations. The densities attained for the three samples at low energy input were relatively high at 1.61, 1.54 and 1.41 Mg m^{-3} for Sites 1, 2 and 3 respectively, suggesting that these soils would densify easily even at low loading levels.

Both resultant bulk densities and matric potentials at which maximum densification occurred were different for the three soils indicating that densification behavior varied considerably as clay increased from 2% for the soil from Site 1 to 6% for the soil from Site 2 and 20% for the soil from Site 3. The variation may also have been due to differences in other soil properties.

2.5. Results: Study II

Pre–treatment bulk densities are presented in Figure 2.5. At Site 1, densities increased from 1.49 Mg m^{-3} at the 5 cm depth to 1.83 Mg m^{-3} at 20 cm. At Site 2 densities were 1.42 Mg m^{-3} at a depth of 5 cm and increased to 1.76 Mg m^{-3} at 15 cm while at Site 3 densities increased from 1.41 Mg m^{-3} at 5 cm depth to 1.65 Mg m^{-3} at 15 cm depth. Figure 2.5 shows a sharp peak at the 15 cm depth of Site 2, and a much less pronounced one at Sites 2 and 3. Maximum resultant densities after treatment were 1.88 Mg m^{-3} at Site 1, 1.78 Mg m^{-3} at Site 2 and 1.70 Mg m^{-3} at Site 3 and generrally occurred above the depth of maximum pre–treatment densities. The densities at the three sites were relatively high but as shown in Study 1, these soils tend to compact easily even at low moisture contents and low energy inputs.

Profile soil moisture contents during treatment are shown in Figure. 2.6. During treatment application, moisture contents measured at the 10 cm depth of Site 1 were 12% at the low level and 21% at the high one, both levels above –33 kPa soil water matric potential. At the same depth the low moisture content was 11%, below –33 kPa soil water matric potential plastic limit and 28% at the high level equal to –33 kPa soil water matric potential and plastic limit at Site 2. At Site 3, the low moisture levels at the 10 cm depth was 33%, closer to plastic limit than to –33 kPa soil water matric potential but below both and 45% for the high level, above both –33 kPa soil water matric potential and plastic limit but closer to –33 kPa soil water matric potential.

Two correlation tables are presented for each site. Tables 2.6a, 2.7a and 2.8a give correlations between individual soil properties and density changes for Sites 1, 2 and 3 respectively. Tables 2.6b, 2.7b and 2.8b show soil properties which were selected by the forward stepwise varible selection method for contributing significantly to the predictor models and how much of the cummulative density increase each of the properties explained when added to previously selected variables. Although the highest correlated properties are usually selected for inclusion in the model, variables which are related to each other and which therefore explain the same density change may not both be selected. Thus the first, second and third highly correlated variables are not necessarily selected in that order. The model only includes those variables which for the least number of them, explain most of the density change. Using this method, therefore, the most important variables to use in predicting a given density increase can be selected. The method can show which variables are important and the conditions when they are important. Variables forced into the model are those which improve the predicting precision (R^2) of the model but in a non–significant manner.

At Site 1, the variables highly correlated with density increases at low moisture content were initial bulk density, clay and sand contents and the Ca:Na ratio. Variables which were poorly correlated with density increases included organic matter, CEC and SAR (Table 2.6a). Only clay and silt were significant variables in the low moisture compactibility model at Site 1. Clay gave a correlation R^2 of 0.91 while adding silt to the model improved it to 0.96. The R^2 was improved slightly to 0.98 when initial bulk density and Ca:Na ratio were forced into the model while forcing CEC into the model improved the R^2 to 0.99 (Table 2.6b).

Variables which were highly correlated with density changes in the high moisture treatment were initial bulk density, Ca:Na ratio and sand content while poorly correlated variables included organic matter, silt and CEC (Table 2.6a). Significant variables in the compactibility model were initial bulk density and CEC, which together gave an R^2 of 0.89. The R^2 was improved to 0.95 by forcing Ca:Na ratio and clay content into the model (Table 2.6b).

At Site 2, for the low moisture content, organic matter, CEC, initial bulk density, clay contents and liquid limits were highly correlated with density increases. For the same conditions, sand and silt contents, Ca:Na ratio and SAR were poorly correlated with density increases (Table 2.7a). At the low moisture content, only organic matter significantly contributed to the soil compactibility model giving an R^2 value of 0.42. Variables which improved the R^2 of the model when forced into it were initial bulk density, Ca:Na ratio and SAR. This treatment gave a maximum R^2 of 0.62, the least among the treatments (Table 2.7b).

For high moisture content at Site 2, density increases were highly correlated to initial bulk density, CEC, Ca:Na ratio and liquid limit. Soil properties which were least correlated with density change were plastic limit, sand and clay contents and SAR (Table 2.7a). The variables selected as significantly contributing to the compactibility model at high moisture content were initial bulk density, CEC and organic matter which together gave an R^2 of 0.77. Forcing clay and plastic limit into the model improved the R^2 to 0.89 while sand improved it to 0.95. Ca:Na ratio improved it further to 1.00 (Table 2.7b).

The correlations at Site 3 for the treatments at the low moisture content were high for initial density, clay content, Ca:Na ratio, silt and sand contents and low for CEC, liquid limit, SAR and plastic limit (Table 2.8a). Significant variables contributing to the compactibility model at the low treatment moisture content included initial density and clay content which together gave an R^2 of 0.96. CEC improved the R^2 to 0.99 (Table 2.8b).

At the high moisture treatment level, initial bulk density, SAR, plastic limit and clay contents were highly correlated with density increases (Table 2.9a). Significant variables in the compactibility model were initial density, Ca:Na ratio and silt content which together gave an R^2 of 0.83. Forcing CEC into the model improved the R^2 to 0.91 and liquid limit improved it further to 0.94 (Table 2.9b).

The most highly correlated variables among the soil properties are given in Table 2.9. Comparisons of these pairs with the correlations from the six treatments presented in Tables 2.6, 2.7 and 2.8 and between 2.9a and 2.9b show that the highest correlated pairs were not equally correlated with density changes observed.

2.6 Discussion

Factors which influenced soil compactibility at all three sites in treatments applied at low moisture content were initial bulk density, clay, sand and silt contents, organic matter and Ca:Na ratio. The non–physical properties which were important at low moisture contents were Ca:Na ratio and to a lesser extent organic matter content. Soil physical characteristics were thus more important in influencing soil compactibility at low moisture contents while CEC, Ca:Na ratio, SAR and organic matter together with initial bulk densities and clay contents were the important factors which influenced soil compactibility at high moisture content. The non–chemical properties which influenced soil compactibility at high moisture contents included initial bulk density and clay content. Chemical properties expained relatively more of the density increase at high moisture contents than at low ones and were thus of importance in high moisture treatments.

Initial bulk density was important at both the low and the high treatment moisture contents because its influence on soil compactibility is not moisture dependent. Generally, because of repeated pre–study loadings, the densities of the three soils in the field were likely near maximum (indicated by high bulk densities and small density changes) and the particles had assumed stable positions. Changing soil moisture content did not change the soil densities under load and hence did not change the influence of initial density on soil compactibility. Initial bulk density determined the possible density increases for given energy inputs.

Although the correlation between clay content and soil compactibility was not high, clays were correlated with soil compactibility at both the low and the high moisture contents. Physically, clay particles affect soil compactibility by fitting in the voids between the larger particles thereby increasing contacts and friction between the particles and thus increases the soil's shear strength. High clay contents therefore cause reduced soil compactibility. The physical attributes of clay were the reason for its influence at low moisture contents. In general clay also increases the bonding of the soil, its water holding capacity and increases the soil's plastic and liquid limits. It thus influenced soil cohesion and shear strength. These clay attributes were responsible for its influence on compactibility at high moisture contents.

Organic matter was correlated with density increases to a small extent both at the low and high moisture contents but only at Site 2. Organic matter influences soil compactibility by physically increasing soil resilience and chemically by increasing particle bonding which increases soil shear strength. Like clay contents increasing soil organic matter decreases soil compactibility. Organic matter likely did not significantly influence compactibility at Site 1 because it constituted only 0.9% of the soil. Organic matter was not important at Site 3 most likely because the greater influence of the higher clay content masked its effect. Although it appears to have been important at Site 2, the fact that Site 2 had the largest density increase suggests organic matter, which reduces soil compactibility, was likely too low to be important.

CEC reflects the soil's surface charge and its bonding capacity. Although the Ca:Na ratio was correlated with density increases at both the high and the low moisture contents, it was only significant in the high moisture compactibility model for Site 3. Dispersion in the soil is the result of interparticle forces. Maximum repulsion occurs in the soil when salt concentrations are low in the pore water, the exchangeable cations are monovalent and there is a high amount of water for increased interparticle distances (Yong and Warkentin, 1966). Since the Ca:Na ratio was also least at Site 3 dispersion can be expected to have been most pronounced at the high moisture content of Site 3, i.e low salt concentration in the pore water.

The importance of any given variable in the compactibility model declines as more variables enter the model because there are more variables to explain the given variation. Important variables in the compactibility model for Site 1 were physical at the low moisture content and initial bulk density and sand content at the high one. Unlike Site 1, the physical properties other than initial bulk density were less important at Sites 2 and 3, because the chemical variables had more influence than at Site 1. In the high moisture compactibilty model for Site 2, the importance of both CEC and organic matter increased as more variables entered the model. As expected, the importance of initial densities declined as more variables entered the model but especially when plastic limit and clay content did because these also reflect the soil's physical attributes and hence explain some of the same observed variation as initial density.

Highly correlated pairs of soil properties were not equally correlated with density changes observed because they did not explain the same density increases and did not neccessarily influence the compactibilty models to the same extent. Even when soil properties were highly correlated with each other, their influence on densification was not the same because they influenced compactibility differently depending on soil conditions and other properties. The substitution of even perfectly correlated variables for each other in compactibility models therefore can lead to errors in predicted density increases which explains some of the difficulties in predicting densification.

2.7. Summary

Only three soils were used in this study but the results show that the influence of soil properties, their behaviour and when they are important change with soil moisture content, energy input and the presence of other variables. Although all three soils had high sand contents, they behaved differently. It is therefore likely that predictor models would not be simple, different models are required to emphasize different variables depending on the conditions in the soil.

Although the energy levels used in the Proctor test were not the same as those used in the field treatments and the field loading was dynamic, the soil from Site 2 had the highest final density in the Proctor test. In addition the soil from Site 2 and that from Site 3 the largest density increase. In the field the density at Site 2 increased the most although Site 1 had the highest final density. When both studies are considered, Site 2 was the most compactible, Site 3 was the second most compactible and Site 1 the least even though it had the highest initial and final densities. In both the Proctor test and in the field treatments, the densities attained at all three sites were rather high indicating the Proctor test can be used to distinguish the relative compactibilities of different sites and whether they behave differently when densified.

2.8 Conclusions

Among the soil variables investigated, initial bulk density, clay and Ca:Na ratio were important at all three sites for the low moisture treatments. Initial bulk density, SAR and clay content were more important than other variables in the treatments at high moisture content.

In general soil physical properties, especially initial bulk density and clay contents, were the most important factors in the low treatment moisture compactibility models where they explained almost all the observed density change while the chemical properties, specifically CEC, SAR and Ca:Na and initial bulk density were more important in the high treatment moisture models.

Some properties, specifically, initial bulk density, clay, organic matter and Ca:Na ratio influenced the compactibility models irrespective of treatment moisture content.

In spite of being highly correlated with each other, some variables did not influence compactibility to the same degree and therefore could not substitute for each other in the compactibility models.

Table 2.1 Classification and descriptions of profile horizons of the soils used in the study.

	Site 1			Site 2			Site 3		
Classification	*			Orthic Black Chernozermic			Rego Black Chernozem salinized carbonated		
	Horizon	Texture	Depth (cm)	Horizon	Texture	Depth (cm)	Horizon	Texture	Depth (cm)
	*	S	0 – 40						
A Horizon	Ahb	S	40 – 80	Ap	SL	0 – 15	Apk	SCL	0 – 16
				Ah	SL	15 – 53			
B Horizon	Bg	S	> 80	Bm	SL	> 53			
C Horizon							Csak	SCL	16 – 30
							Ccasa	SL	> 30

* Wind deposited sand

Table 2.2 Physical and chemical properties of the soils used in the studies

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture	OM (%)	CEC $cmol(+)kg^{-1}$	SAR	Ca/Na
Site 1								
00–15	2	5	93	S	0.8	4.3	0.25	31
15–30	3	4	93	S	0.9	6.2	0.24	43
30–45	4	3	93	S	–	5.3	0.31	46
Site 2								
00–15	6	18	76	SL	2.6	14.4	0.14	130
15–30	8	18	74	SL	2.5	12.0	0.14	120
30–45	11	17	72	SL	–	9.3	0.17	130
Site 3								
00–15	20	22	58	SCL	3.8	20.0	3.2	10
15–30	20	19	61	SCL	2.6	18.0	3.2	11
30–45	17	18	65	SL	–	11.5	2.7	15

Table 2.3 Model descriptions of densification curves for the soil from Site 1

Energy kJ/cm^3	Model	Coefficients a	b	c	R^2
6	$y = 1 / (a + bx)$	0.654	–0.002	0.0000	0.95
6	$y = a + bx$	1.527	0.005	0.000	0.95
16	$y = a + b / x$	1.695	–0.608	0.0000	0.97
16	$y = a + bx + cx^2$	1.444	0.0316	–0.0012	0.97
30	$y = a + b / x$	1.790	–0.482	0.0000	0.67
30	$y = a + bx + cx^2$	1.517	0.0432	–0.0018	0.92
80	$y = a + b / x$	1.758	–0.133	0.0000	0.16
80	$y = a + bx + cx^2$	1.611	0.0293	–0.0014	0.94

y = Soil bulk density Mg m^{-3}

x = Soil moisture content (cm^3 cm^{-3} * 100)

Table 2.4 Model descriptions of densification curves for the soil from Site 2

Energy kJ/cm^3	Model	Coefficients a	b	c	R^2
6	$y = a + bx$	1.218	0.015	0.0000	0.83
6	$y = a + bx$	1.218	0.015	0.000	0.83
16	$y = 1 / (a + b / x)$	0.673	−0.002	0.0000	0.97
16	$y = a + bx + cx^2$	1.483	0.0049	0.0000	0.97
30	$y = a + b / x$	1.662	−0.372	0.0000	0.19
30	$y = a + bx + cx^2$	0.917	0.0099	−0.0032	0.88
80	$y = a + bx$	1.939	−0.014	0.0000	0.72
80	$y = a + bx + cx^2$	1.474	0.0518	−0.0021	0.96

y = Soil bulk density Mg m^{-3}

x = Soil moisture content ($cm^3\ cm^{-3}$ * 100)

Table 2.5 Model descriptions of densification curves for the soil from Site 3

Energy kJ/cm^3	Model	Coefficients a	b	c	R^2
6	$y = 1 / (a + bx)$	0.880	–0.005	0.0000	0.90
6	$y = a + bx$	1.336	0.0016	0.0058	0.96
16	$y = a + b / x$	1.553	–2.362	0.0000	0.49
16	$y = a + bx + cx^2$	0.694	0.0680	–0.0015	0.99
30	$y = x / (a + bx)$	0.474	0.659	0.0000	0.07
30	$y = a + bx + cx^2$	0.658	0.0786	–0.00018	0.82
80	$y = a + bx$	1.977	–0.019	0.0000	0.83
80	$y = a + bx + cx^2$	1.408	0.0374	–0.00127	0.92

y = Soil bulk density $Mg\ m^{-3}$

x = Soil moisture content $(cm^3\ cm^{-3} * 100)$

Table 2.6a Density change: soil physical and chemical properties multivariate correlations (R^2) for Site 1

Low Moisture Treatment		High Moisture Treatment	
Variable	Correlation	Variable	Correlation
Clay	0.9514	Initial density	0.7724
Initial density	0.9173	Ca:Na	0.5863
Sand	0.8957	Sand	0.4662
Ca:Na	0.4524	SAR	0.4245
SAR	0.3202	Clay	0.3939
Silt	0.2877	CEC	0.2841
CEC	0.1064	Silt	0.2740
SOM	0.0341	SOM	0.2162

Table 2.6b Variables which influenced the compactibility model for Site 1

Low Moisture Treatment			High Moisture Treatment		
Variable	R^2	MSE	Variable	R^2	MSE
Clay*	0.91	0.0016	Initial DB*	0.60	0.0021
& Silt*	0.96	0.0007	& CEC*	0.89	0.0006
& Initial DB	0.98	0.0005	& Ca:Na	0.92	0.0005
& CEC	0.99	0.0004	& Clay	0.95	0.0003

* Variables significant in the compactibility model based on 12 observations

MSE = mean standard error SOM = soil organic matter

Table 2.7a Density change: soil physical and chemical properties multivariate correlations (R^2) for Site 2

Low Moisture Treatment		High Moisture Treatment	
Variable	**Correlation**	**Variable**	**Correlation**
SOM	0.6492	Initial Density	0.6465
CEC	0.6479	CEC	0.4805
Initial density	0.6272	LIL	0.3705
LIL	0.5627	Ca:Na	0.2428
Clay	0.3978	SOM	0.2162
PLL	0.3866	Silt	0.2132
SAR	0.2737	SAR	0.1977
Ca:Na	0.2077	Clay	0.1905
Silt	0.1930	Sand	0.1071
Sand	0.1080	PLL	0.0069

Table 2.7b Variables which influenced the compactibility model for Site 2

Low Moisture Treatment			High Moisture Treatment		
Variable	**R^2**	**MSE**	**Variable**	**R^2**	**MSE**
SOM*	0.42	0.0028	Initial DB*	0.42	0.0019
& Initial DB	0.50	0.0027	& CEC*	0.66	0.0013
& Ca:Na	0.54	0.0027	& SOM*	0.77	0.0009
& SAR	0.63	0.0025	& PLL	0.83	0.0008
& CEC	0.70	0.0024	& Clay	0.90	0.0006

* Variables significant in the compactibility model based on 12 observations

MSE = mean standard error

SOM = soil organic matter

PLL = plastic limit

LIL = liquid limit

Table 2.8a Density change: soil physical and chemical properties multivariate correlations (R^2) for Site 3

Low Moisture Treatment		High Moisture Treatment	
Variable	Correlation	Variable	Correlation
Initial density	0.9770	Initial density	0.7174
Clay	0.7843	SAR	0.6665
Ca:Na	0.3385	PLL	0.5121
Silt	0.2648	Clay	0.4549
Sand	0.2313	Sand	0.3711
SOM	0.2081	Ca:Na	0.3215
PLL	0.1612	CEC	0.2574
SAR	0.1239	LIL	0.2061
LIL	0.1025	Silt	0.1486
CEC	0.0630	SOM	0.1192

Table 2.8b Variables which influenced the compactibility model for Site 3

Low Moisture Treatment			High Moisture Treatment		
Variable	R^2	MSE	Variable	R^2	MSE
Initial DB*	0.52	0.0007	Initial DB*	0.52	0.0059
& Clay	0.96	0.0007	& Ca:Na*	0.71	0.0039
& Silt	0.98	0.0004	& Silt*	0.83	0.0026
& CEC	0.99	0.0003	& CEC	0.91	0.0021

* Variables significant in the compactibility model based on 12 observations

MSE = mean standard error

SOM = soil organic matter

PLL = plastic limit

LIL = liquid limit

Table 2.9a Correlations (R^2) among selected pairs of soil physical and chemical properties for Sites 1, 2 and 3

Pair No.	Variable 1	Variable 2	Correlation
1	Clay	SAR	0.959
2	Clay	CEC	0.929
3	Silt	PLL	1.000
4	SAR	Ca:Na	–0.708
5	SOM	LIL	1.000

Table 2.9b Correlations (R^2) between density increases and selected pairs of highly correlated soil physical and chemical properties for low and high moisture contents at Sites 1, 2 and 3

		Site 1		Site 2		Site 3	
		Moisture contents		Moisture content		Moisture content	
Pair	Variable	Low	High	Low	High	Low	high
1	Clay	0.951	0.772	0.398	0.191	0.784	0.455
	SAR	0.320	0.425	0.274	0.198	0.124	0.667
2	Clay	0.951	0.772	0.398	0.191	0.744	0.455
	CEC	0.106	0.284	0.648	0.481	0.630	0.257
3	Silt	0.288	0.274	0.193	0.213	0.265	0.149
	PLL	–	–	0.387	0.007	0.161	0.512
4	SAR	0.320	0.125	0.274	0.198	0.124	0.667
	Ca:Na	0.452	0.586	0.208	0.243	0.339	0.322
5	SOM	0.034	0.216	0.649	0.216	0.208	0.119
	LIL	–	–	0.563	0.371	0.103	0.206

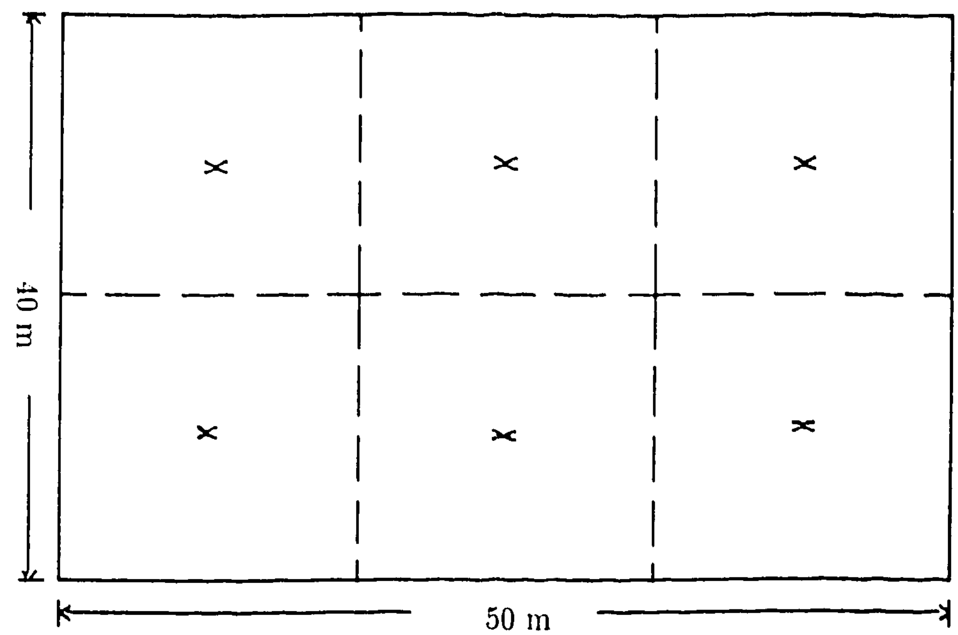

Figure 2.1a. Plan view of the plots showing the location of the 6 points where samples used in the Proctor test were taken.

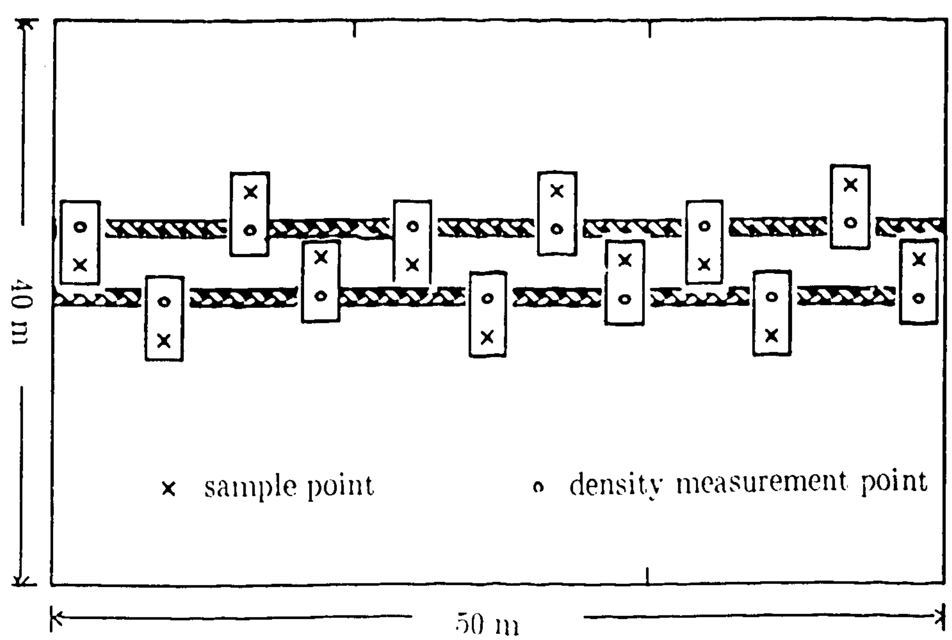

Figure 2.1b. Plan view of the plots showing the location of the three–pass treatment and the 12 points where samples used in the multivariate correlations were taken

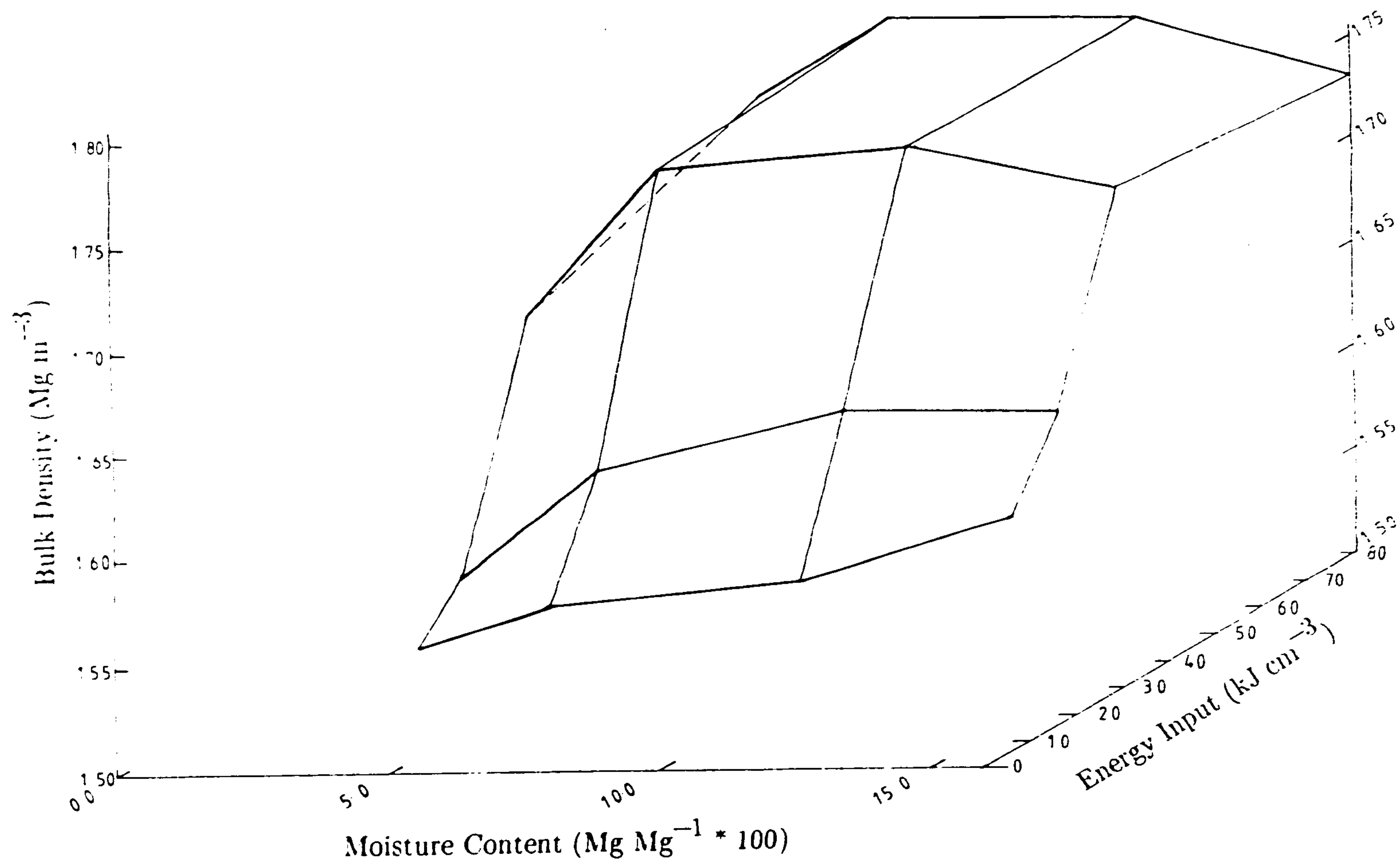

Figure 2.2. Densification curves for the soil from Site 1 for soil water potentials ranging from −33 kPa to −1500 kPa and energy inputs of 6, 16, 30 and 80 kJ cm^{-3}.

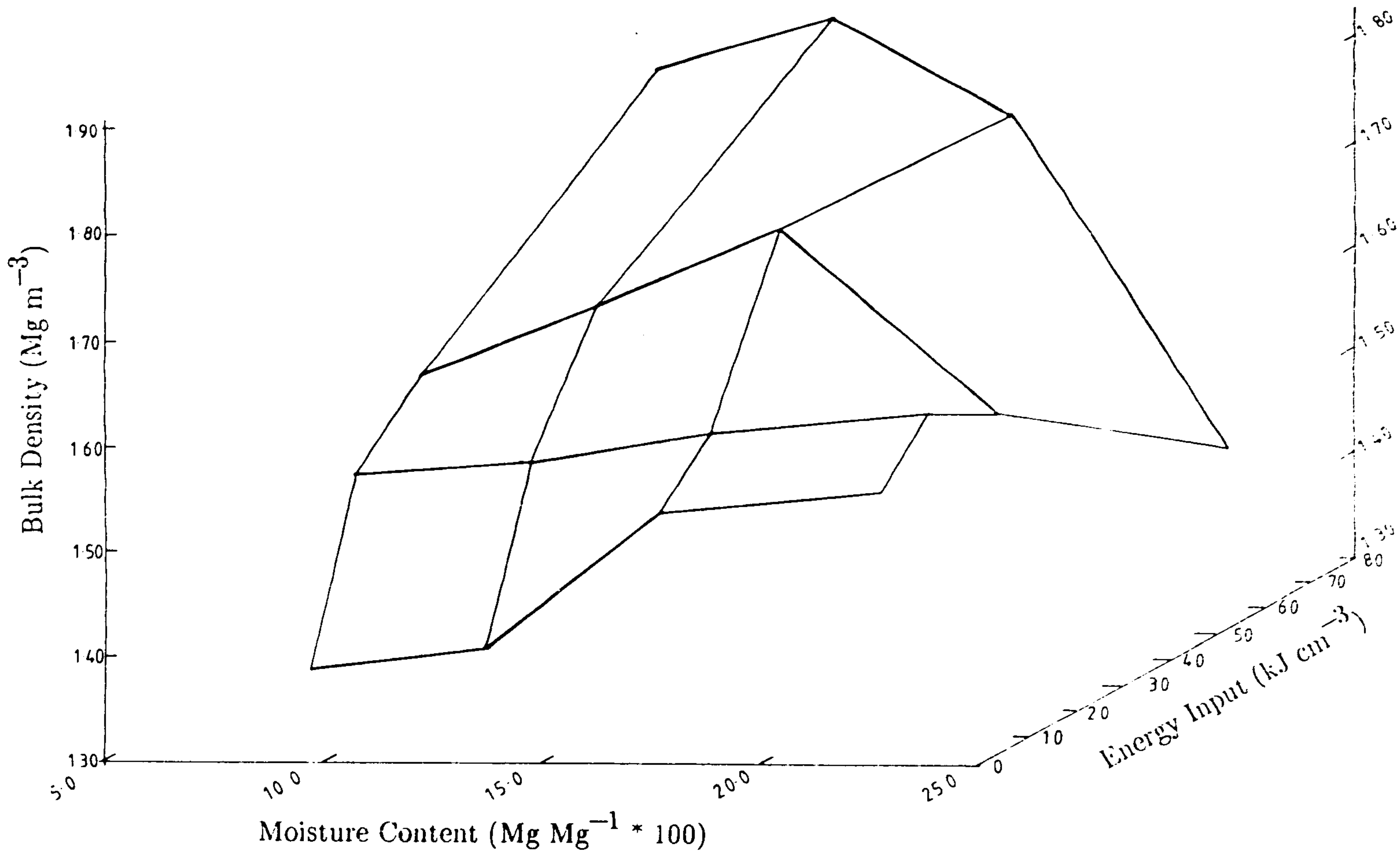

Figure 2.3. Densification curves for the soil from Site 2 for soil water potentials ranging from −33 kPa to −1500 kPa and energy inputs of 6, 16, 30 and 80 kJ cm^{-3}.

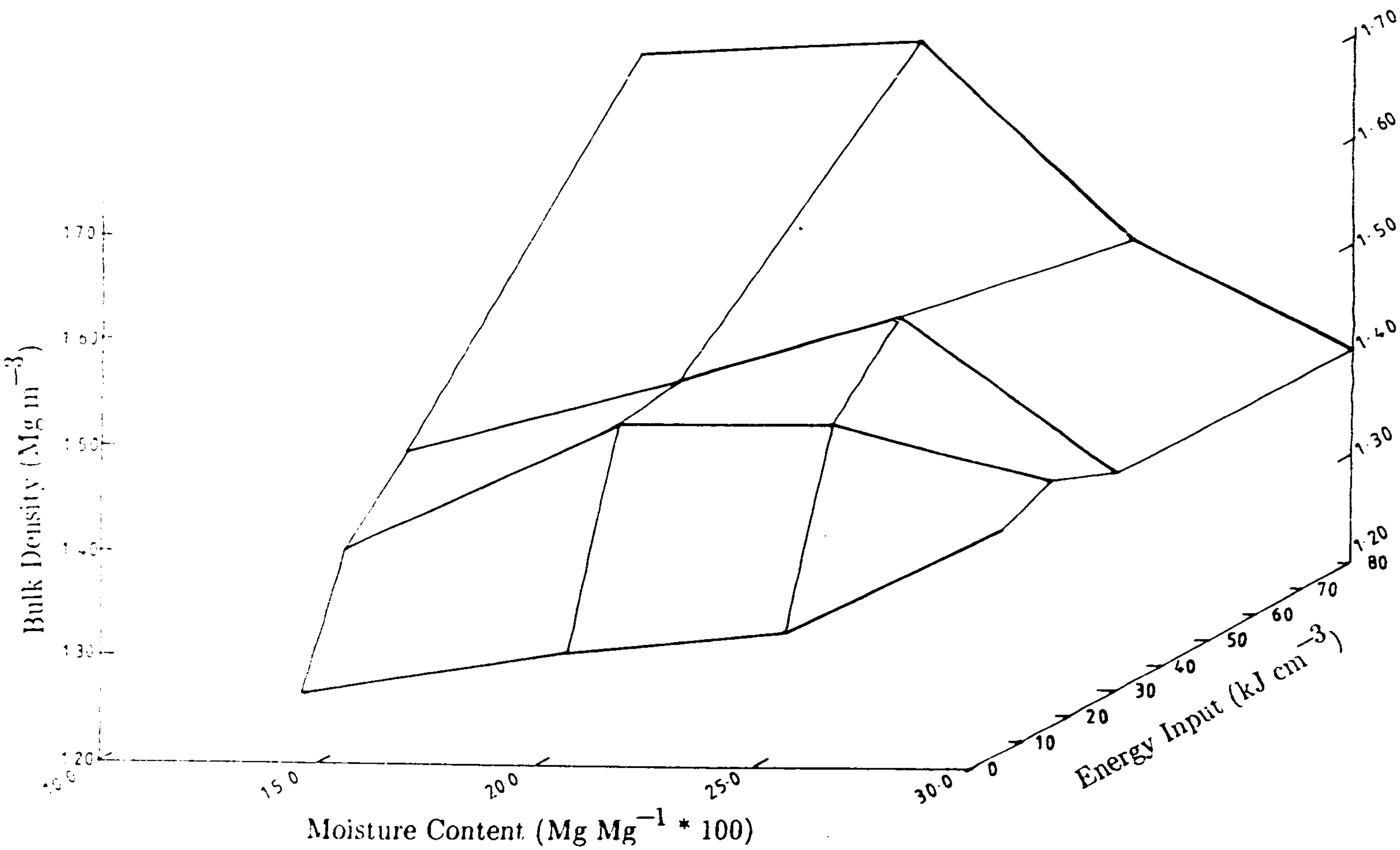

Figure 2.4. Densification curves for the soil from Site 3 for soil water potentials ranging from −33 kPa to −1500 kPa and energy inputs of 6, 16, 30 and 80 kJ cm^{-3}.

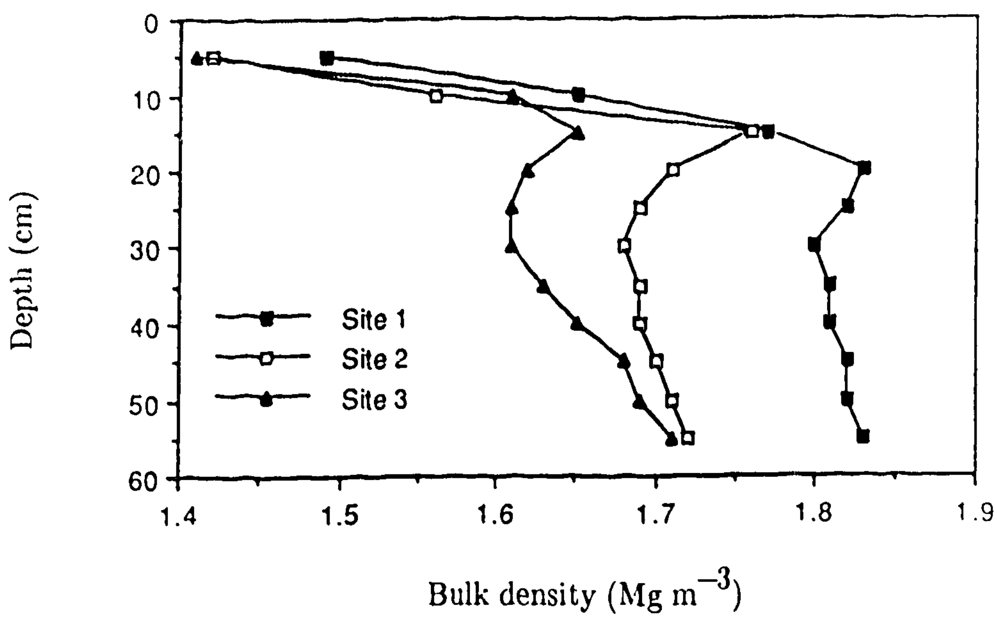

Figure 2.5. Mean soil bulk density before treatments at Sites 1, 2 and 3.

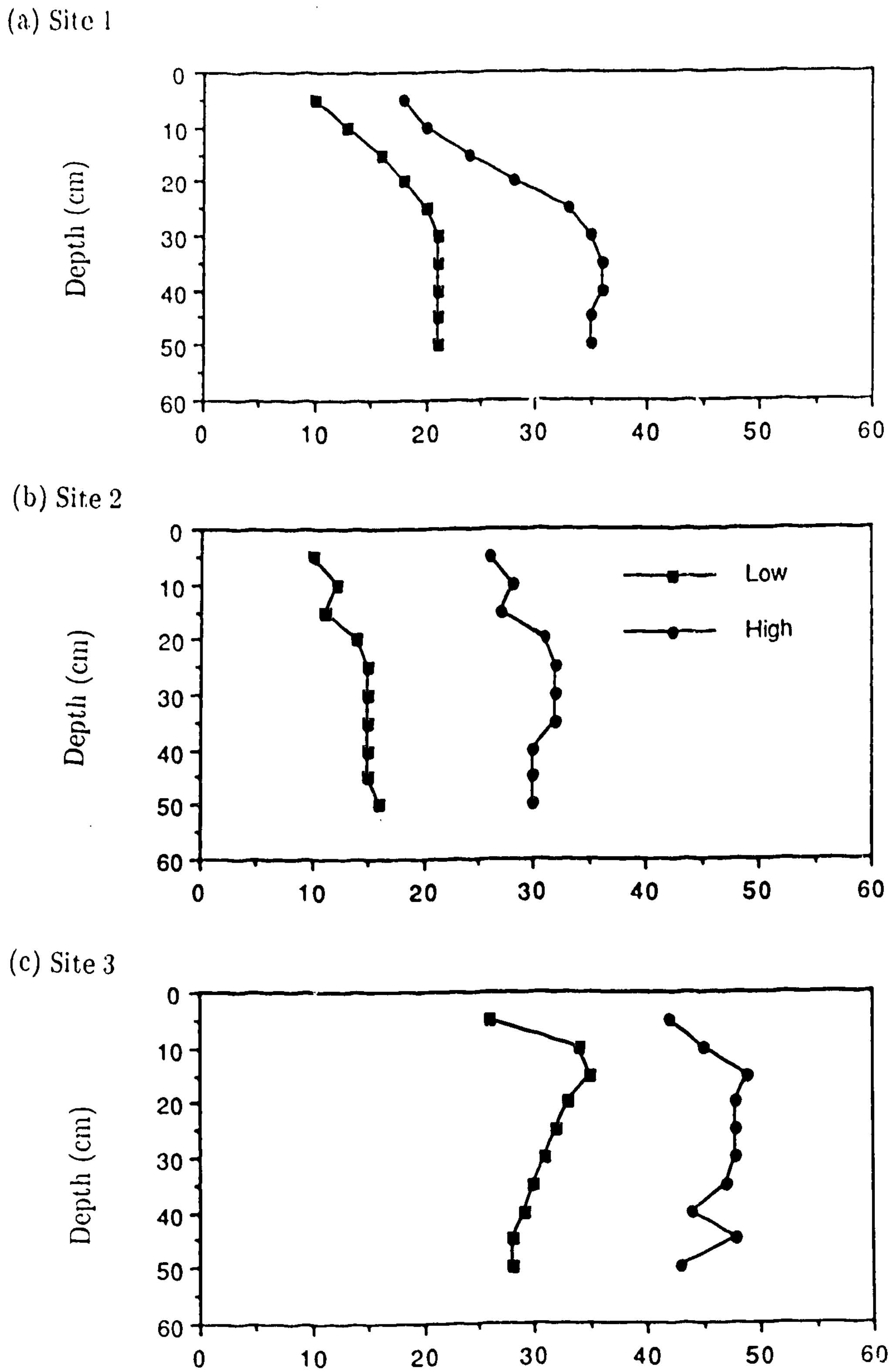

Figure 2.6. Moisture contents during treatment application at (a) Site 1 (b) Site 2 and (c) Site 3.

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CHAPTER III

TRACTOR–INDUCED SOIL DENSIFICATION UNDER FIELD CONDITIONS

3.1 The effect of soil properties and conditions

Larger farm sizes and the need for timely farm operations, especially seeding and harvesting, have made the use of large, heavy farm tractors efficient and economical, resulting in their increased use. This has led to increased incidences of excessive soil densification which result when farm operations are carried out with these tractors in moist, compactible soils. Soil properties and conditions and tractor characteristics and number of passes across the field are factors which influence soil densification.

Hovanesian (1958), Janbu (1970) and Gameda et al. (1984) all cited clay type as the most important soil property affecting its compactibility. Expanding clays were shown by Stone and Larson (1980) to be more elastic than non–expanding clays. Soil texture also has an important influence on soil compactibility. McMurdie and Day (1958) found that previously loaded sands expanded much less than clays when the load was removed. The relative proportions of clays to sands may thus be important in soil compactibility.

Particle size distribution influences soil compactibility by influencing its shear resistance. Soils characterized by high shear resistance are less compactible than those characterized by low shear resistance. Well graded soils have higher shear resistance than uniformly graded ones because in well graded soils the smaller particles fit among the larger ones, increasing the number of contact points and friction between the particles. Rough, angular soil particles also have higher shear resistance than smooth round ones because of greater friction between the particles.

Higher densities result as soil moisture increases and soil strength declines until the optimum moisture is reached, after which further increases in moisture result in lower bulk densities (Holtz and Kovacs, 1981).

Gameda et al. (1984) and Hovanesian (1958) found the interaction between clay type and water to be important in soil densification. The effect of water on soil compactibility depends on whether the water molecules are in a free state or bonded to the interparticle cations or soil particles. The major mechanism by which water molecules are bonded to the soil particles is hydrogen bonding. Water in the interparticle zone may also be linked to soil particles through their association with interparticle cations. Hydration water shells surrounding the cations are linked to the soil particles through bonds which are formed between the cation and the particles (Sposito, 1984). When bonded to the cations or soil particles, H_2O molecules behave differently from those of free water and they act as part of the cations or soil particles respectively. In the free state, water lowers soil strength by acting as a lubricant between the particles which increases soil compactibility.

When a soil at a high moisture content is loaded, water is forced from the interparticle zone as the particles move closer to each other. At low water contents, the amount of water forced out is less for a given load if the soil surface area is high because of the greater number and strength of bonds to be broken. On removal of the load, water molecules are drawn back into the interparticle space, attracted in part by the surface bonding and ion hydration. This movement of water molecules into the interparticle zone forces soil particles apart, reducing soil densities (Sposito 1984).

The moisture content at which a soil is most compactible is called its optimum moisture for compaction. Soane (1970) suggested the soil's optimum moisture for compaction is just below the soil's plastic limit, half way between field capacity and wilting point while Erbach (1986) suggested that it occurs at field capacity. Steinhardt and Trafford (1974) found that densification is least at matric potentials below −25 to −35 kPa.

Field capacity refers to a soil's unique water retention value at which the soil's matrix attraction is just able to oppose the force of gravity on the water. It arises from soil matric forces and is dependent on the capillary conductivity of the soil. The plastic limit on the other hand refers to the soil moisture content at which the soil changes state from a solid and becomes plastic. Plastic limit reflects the ease with which particles are able to slide over each other when subjected to shear stress and is influenced by the viscosity of the water films surrounding the soil particles. Plastic limit would appear therefore to be more related to soil compactibility than field capacity.

Chancellor and Schmidt (1962) found that bulk density increases extend deeper into the profile as moisture increases until a critical level is reached when the soil starts to spread laterally. Hovanesian (1958) showed that bulk density did not increase in saturated, confined soils. Koger et al. (1982) and Amir et al. (1976) determined that the initial bulk densities and the magnitude of the load can be used to predict the post-reloading densities of soils. Low density soils suffer more permanent deformation when loaded and show relatively larger density increases than high density soils which suffer mostly elastic deformation under similar loads (Eriksson, 1982). Raghavan (1985) found increasing soil organic matter contents from 3% to 10% reduced soil compactibility enough for a 100% increase in bushbean yields while increasing organic matter to 17% totally eliminated soil densification effects. In the treatments soil bulk densities declined as a result of the increased organic matter contents, the hydraulic conductivities of the soils, the water infiltration rates into the soil and the soil's water holding capacity all increased.

3.2 The effect of tractor mass and number of passes

Soane (1970) identified total load, pressure distribution, shape and size of the loaded area, rate of application and duration of stress, shear stress, impact effects and vibration components as load characteristics which influence soil densification. Taylor et al. (1980) and Koger et al. (1982) included mass per axle and tire size.

Soehne (1958) using Froehlich's modification of Boussinesq's equation found solutions for the pressure distribution under tractor tires in isotropic soils and concluded that the pressure distribution in the soil surface layers was controlled by the tire/soil contact pressure while in the subsurface layers it was primarily controlled by total load. Janbu (1970) suggested that pressure in the soil did not extend to depths predicted by Soehne's solutions because soil behavior was largely plastic and not elastic as assumed in Boussinesq's equation. Taylor et al. (1980) found that Soehne's solutions underestimated pressures above dense layers and overestimated them below. Smith (1985) found good agreement between Soehne's solutions and measured pressures, except in proximity to underlying dense layers where Soehne's solutions underestimated pressures. Taylor et al. (1980) and Smith (1985) further concluded that there was more lateral flow of soil at high dynamic loads than at low ones.

Håkansson and Danfors (1981) suggested mass per axle was a better predictor of soil densification than total load and recommended maintaining tire inflation pressures below 80 kPa to prevent excessive soil densification. Irrespective of the tire inflation pressure, larger diameter and wider tires cause deeper extending soil densification (Koger et al. 1982). Soehne et al. (1962) and Janbu (1970) showed wider tires have their point of maximum stress and maximum densification, deeper in the soil profile than narrow tires.

Multiple passes increase soil bulk densities by causing greater particle reorientation (Eriksson, 1982). Davies et al (1973) showed that particle reorientation was greater when wheelslip and smearing occurred. They found both wheelslip and smearing were greater when large tractors were used. Although particle reorientation extends deeper into the soil with each extra pass, the effect has been found not to extend beyond the surface 10 cm of the soil.

Gill and Reaves (1956) found that soil strength continued to increase with each extra pass even when the bulk density did not. Koger et al. (1982) found that the first tractor pass increased bulk densities the most but additional passes caused further density increases. They also found the effect of multiple passes on bulk density was dependent on soil type and the total dynamic load. When total dynamic loads were kept below 20 kN, density increases ceased after the first pass. Gameda et al. (1984) found multiple passes increased bulk densities, but not the depth to which compaction extended.

Although large agricultural tractors are in common use, compaction is largely unresearched on the Canadian prairies due to an unsubstantiated belief that it is not a problem (Chanasyk, 1988). Recent studies by Rickman and Chanasyk (1988) conducted at the Ellerslie Research Station near Edmonton found grain yields were dependent on soil densities which were related to tire inflation pressures. Domier studying plots in Manitoba that had been packed with a tractor, found reduced yields on early seeded plots although some treatments on late seeded plots improved yields (Feldman and Domier, 1970). These studies appear to contradict the belief that compaction is not a problem on the Canadian prairies and underline the need to investigate it.

3.3 Study objectives

Information on the field-densification of agricultural soils has come largely from simulations or extrapolations of results from controlled soil bin studies. This information is critical to the understanding of soil densification but has not been sufficient for the management of excessive farm soil densification. Densification in agricultural soils, the magnitude of bulk density increases and the depth to which the increases extend in the profile are factors that need to be assessed in on–farm studies.

In this study, the in situ densification of three soils subjected to loading by commonly used tractors was investigated with the specific objective of quantifying soil density increases and the depth to which these extend in the soil profile as a function of:

(i) soil pre–treatment bulk densities and moisture content, and

(ii) tractor mass and the number of passes over the field by the tractor.

3.3 Materials and methods

Three sites, which have been in cultivation for about 40 years, were selected for use in the study on the basis of their particle size distribution and CEC and on site accessibility. The sites were located at Warwick, 90 km east of Edmonton, Alberta and were cultivated but not cropped during the study years. Except for Site 1, cattle had not been allowed in the fields at any time prior to or during the study. Soil textures and the classification of the soils used in the study are summarized in Table 2.1 while the physical and chemical properties are given in Table 2.2. Site 1 was characterized by 40 cm of wind blown sand over a buried Ahb horizon. The Site 2 soil was an Orthic Black Chernozemic. The profile at Site 2 had a dense layer above a stone layer at the 15 cm depth. Site 3 was located in a shallow dipression and had a Rego Black Chernozem, salinized and carbonated soil (Howitt, 1988).

A treatment plot, 50 m long and 10 m wide, was marked out at each site. A 5 m buffer was left between the treatments and the fence lines. Each plot was divided into 12 equal subplots for purposes of sampling. A soil core was taken to a depth of 90 cm in each subplot using a truck–mounted corer and divided to give subsamples in 15 cm intervals. Each sample was air dried and ground to pass a 2–mm sieve before being independently analysed.

Clay, silt and sand contents were determined using the hydrometer method. Sample dispersion was achieved by soaking in calgon. Samples from Site 3 were treated with HCl to remove excess Ca. Gravimetric moisture contents at –33 kPa and –1500 kPa were determined using the pressure plate apparatus and converted to volumetric moisture contents using mean field bulk densities. Liquid and plastic limits were determined by the method described by McKeague (1979). Organic matter was determined using the microprocessor–based Leco CR 12 Carbon Analyser. Samples were combusted in an O_2 atmosphere and the resulting CO_2 measured by a solid state infrared detector. CEC and cations present in the soil were extracted with NH_4OAc and the cations determined using the Perkin--Elmer model 503 Atomic Absorption Spectrophotometer.

The sites were tilled with a cultivator to a depth of 15 cm prior to treatment application to standardize surface conditions. Soil moisture contents with depth were determined just prior to, or immediately after, treatment application. Moisture contents during treatment were considered reasonable for normal field operations.

Three treatments consisting of a single pass, three and six multiple passes each were applied by each of two tractors operated at 8 km h^{-1}. The treatments were repeated at three different dates between summer 1985 and fall 1987 to ensure that moisture contents during the three treatment appiications were reasonably different at each site. There were thus a total of 9 moisture–pass combinations at each site.

A 13 t Versatile 835 tractor and a 6 t Deutz 120 tractor were used to apply the treatments in the study. Specifications for the two tractors are given in Table 3.1. The inner "traction" tires on the Versatile were each ballasted with 420 kg of calcium chloride solution. The outer "floatation" tires were not ballasted.

Four sets of measurements of moisture and density were made in each of the two tractor tracks for a total of eight sets of measurements. A set of measurements included readings taken in the untracked area of the field adjacent to the tracks and served as the control measurements. Other measurements were in the center of the rear 2–wheel drive tractor track and the inner "traction" track of the 4–wheel drive tractor. Two extra measurements were made in the center of the outer "floatation" tire track and in between the two dual tire tracks of the 4–wheel drive tractor. Schematic side views of density measurement points for the single–tired 6 t tractor and the dual–tired 13 t tractor are given in Figures 3.1a and 3.1b respectively.

A Nuclear Pacific Stratigauge, a combination density–moisture gauge, was used to take moisture and density count ratios (count at depth/standard count) at 5 cm intervals, starting at the 5 cm depth and extending to 60 cm. The count ratios were used to calculate volumetric moisture content and wet bulk density using site specific moisture calibration curves and the manufacturer's determined density curves. Dry bulk densities were then calculated by subtracting volumetric moisture contents from wet bulk densities.

Tire track trough depths were measured in the center of each trough by placing a straight rod across the track (on top of the disturbed soil mounds alongside the tracks) from one edge to the other and measuring the depth from the rod to the bottom of the trough. Height above the undisturbed surface was determined by measuring the height from the rod to the original undisturbed surface. Actual height of the troughs below the original surface was then determined by subtracting the height above the undisturbed surface from the total height (the top of the disturbed mounds to the trough bottom).

3.4 Results

Increased bulk density in this paper is used to describe post–treatment densities which were significantly higher ($p < 0.05$) than the pre–treatment ones and where the LSD test for homogeneity showed them to be from different populations. Instances where density increases or depth compacted were not statistically significant are also indicated. Subsoil in this paper refers to the soil in the profile which was below the cultivated surface: 20 cm at Site 1, 15 cm at Site 2 and 13 cm depth at Site 3.

The textures, physical and chemical properties for the soils are given in Table 2.2. Clay contents were lowest at Site 1 (2%) and highest at Site 3 (20%). Sand contents ranged from 93% at Site 1 to 58% at Site 3. Organic matter contents were 0.8% at Site 1, 2.6% at Site 2 and 3.8% at Site 3. Cation exchange capacities (CECs) were lowest at Site 1 and highest at Site 3; sodium adsorption ratios were least at Site 2 and were highest at Site 3. Ca:Na ratios were 31 at Site 1, 130 at Site 2 and 10 at Site 3.

Plot mean pre–treatment bulk densities at Site 1 increased from 1.49 Mg m^{-3} at the 5 cm depth to a peak 1.83 Mg m^{-3} at the 20 cm depth and remained between 1.81 Mg m^{-3} and 1.83 Mg m^{-3} in the rest of the profile (Fig 2.5). At Site 2 pre–treatment plot mean bulk densities increased from 1.42 Mg m^{-3} at the 5 cm depth to a peak 1.76 Mg m^{-3} at the 15 cm depth and declined to 1.69 Mg m^{-3} below 20 cm. At Site 3, the plot mean pre–treatment bulk density for the site was 1.41 Mg m^{-3} at the 5 cm depth, increased to 1.65 Mg m^{-3} at the 15 cm depth and declined to 1.61 Mg m^{-3} at the 25 cm depth before gradually increasing again.

Mean pre–treatment densities for the three sites were different from the means measured at the time of the individual treatments at the sites probably because of the wide fluctuations in the densities, the direction of the tracks and the location of the specific treatments within the plots. As a result of the wide variations in pre–treatment bulk densities, both density increases and final densities were used to evaluate the effects of the variables on soil densification.

Volumetric moisture contents during treatment application at the three sites are presented in Figure 2.6. Mean profile moisture contents during treatment application and moisture contents at –33 kPa, –1500 kPa, at plastic and liquid limits are givenn in Table 3.2.

Site 1

Moisture contents during treatment application at Site 1 were all above 7.5% (at –33 kPa) (Figure 3.2). The high treatment moisture contents at Site 1 were the result of the shallow depth to the water table.

Tractor size influenced the depth of the profiles compacted. The 13 t tractor caused deeper extending densification than did the 6 t tractor in the 3 treatments where increased subsoil densities were recorded (Table 3.3). The two tractors caused increased densities to the same depth in all other treatments except the 1 pass treatment at low moisture where the 6 t tractor caused deeper densification. Increased post–treatment bulk densities at Site 1 extended the deepest in treatments applied at the high moisture content and the least in treatments applied at the low moisture content and extended to the subsoil only in the 6 treatments at the high moisture content (Table 3.3).

Maximum density increases as a result of treatment at Site 1 were greater for the 13 t Versatile than for the 6 t Deutz. Density increases grew larger as the treatment moisture content and number of passes increased. The largest density increases for the 13 t tractor at the low moisture content were 0.10 Mg m^{-3} for the single pass and 0.15 Mg m^{-3} for the three and six pass treatments. Density increases at the medium moisture content were 0.15 Mg m^{-3} for the single pass 0.18 and 0.20 Mg m^{-3} for the three and the six pass treatments respectively. At the high moisture content the increases were 0.27 Mg m^{-3} for the single pass and 0.40 Mg m^{-3} for the six pass treatment (Table 3.5a and 3.5b). The largest density increases for the 6 t tractor were only half those caused by the 13 t tractor at the low moisture content and three quarters those at the high moisture content for the same number of passes (Table 3.5a and 3.5b). In those treatments in which increased densities extended to the subsoil, the bulk densities measured in the 13 t Versatile tracks were higher, though not statistically so, than those measured in the 6 t Deutz tracks.

Trough depths for the low and medium treatment moisture contents ranged from 2.5 cm to 10 cm with a mean of 5 cm (Table 3.4). The troughs were deeper in treatments at the high moisture content with a mean of 7.5 cm but were not different for the two sizes of tractors.

Site 2

Mean treatment moisture contents at Site 2 were 12% at the low level, 26% at the medium level and 28% at the high level (Fig. 3.2 and Table 3.2) compared with soil moisture contents of 26% at –33 kPa and 11% at –1500 kPa, 28% at the plastic limit and 36% at the liquid limit (Table 3.2).

At Site 2 significant densification only extended to the subsoil in the 13 t tractor three–pass treatments and in the six–pass treatments at high moisture content (Table 3.3). The 13 t tractor caused deeper densification than did the 6 t tractor in 6 cases while the 6 t tractor caused deeper densification than the 13 t tractor in a single case (Table 3.3). The densification caused by the two tractors extended to the same depth in 2 single pass treatments at low moisture content and the three–pass treatment at the high moisture content (Table 3.3). Profile depths compacted were grea' in three–pass and six–pass treatments applied at the medium and high moisture contents than in the single–pass and in treatments applied at low moisture content.

`ulk density increases caused by the 13 t tractor at the low moisture content ranged from 0.23 Mg m^{-3} to 0.26 Mg m^{-3} and 0.06 Mg m^{-3} to 0.28 Mg m^{-3}at the medium moisture content. At the high moisture content density increases ranged from 0.32 Mg m^{-3} to 0.49 Mg m^{-3} (Table 3.6a). Bulk density increases were largest at the 5 cm depth in the three and six pass treatments at the medium and high moisture contents. Although density increases at the 5 cm depth were larger at higher moisture contents than at low ones, density increases at the 10 cm depth and deeper declined from a maximum of 0.30 Mg m^{-3} at the low moisture content to 0.15 Mg m^{-3} at the medium and 0.20 Mg m^{-3} at the high moisture content. Density increases were one and a half times higher in the 13 t tractor tracks in treatment at the high moisture content than in the 6 t tractor tracks (Table 3.6a and 3.6b).

Trough depths for the low moisture content treatments at Site 2 ranged from 1.0 cm to 7.5 cm with a mean of 5.0 cm (Table 3.4). With means of 2.5 cm, troughs were shallower at the medium and high treatment moisture contents.

Site 3

Mean treatment moisture contents at Site 3 were 33% at the low level, 42% at the medium level and 45% at the high level (Table 3.2 and Fig. 3.2) compared with soil moisture contents of 41% at –33 kPa and 19% at –1500 kPa, 36% at the plastic limit and 63% at the liquid limit (Table 3.2).

Increased densities extended deepest in treatments applied at the low moisture level and depths compacted were least in treatment applied at the high moisture level. Significant subsoil compaction only occurred in the six–pass treatments at the low moisture content (Table 3.3). Where subsoil compaction occurred, the 13 t tractor caused deeper extending compaction than did the 6 t tractor (Table 3.3).

In measurements at the 5 cm depth, the density increases in the 6 t tractor tracks were slightly higher than those in the 13 t tractor tracks in 6 of 9 treatments while density increases were higher in the 13 t tracks than in the 6 t tracks in only 3 cases (Table 3.7aand 3.7b). Maximum density increases caused by the 13 t tractor ranged from 0.18 Mg m^{-3} to 0.22 Mg m^{-3} at low moisture contents. At the medium moisture content density increases declined from 0.19 Mg m^{-3} to 0.06 Mg m^{-3} for the three pass treatment while at the high moisture content density increases ranged from 0.09 Mg m^{-3} to 0.18 Mg m^{-3} (Table 3.7a). Increases in densities were least at high moisture contents. As for the 13 t tractor, maximum bulk density increases for the 6 t tractor were highest (0.26 Mg m^{-3}) in the treatment conducted at the low moisture content compared to 0.15 Mg m^{-3} at medium moisture content and 0.23 Mg m^{-3} at high moisture content (Tables 3.7a and 3.7b).

Trough depths for the low treatment moisture content at Site 3 ranged from 1.0 cm to 5.0 cm with a mean of 3.5 cm (Table 3.4). The troughs were shallower at the medium and high treatment moisture contents with means of 2.5 cm and 1.5 cm respectively.

3.5 Discussion

The depth of the soil profile compacted and the resultant bulk densities resulting from densification may have been influenced by a number of factors including: (i) soil properties and conditions, and (ii) load characteristics including tractor mass, mass per axle, tire inflation pressure and the number of tractor passes across the field.

Based on soil texture, CEC and organic matter contents of the three soils, Site 3 should have had the highest moisture contents at −33 kPa and plastic limit and should have had a high optimum moisture content for compaction. Site 3 should also have been the most compactible of the three sites because of its high clay and relatively low sand contents. Results confirm Site 3 had the highest field capacity and plastic limit moisture contents although based on density increases it was not the most compactible (Tables 3.5, 3.6 and 3.7). Densification results do show however that the optimum moisture content for compaction at Site 3 was at the low moisture content (Table 3.3 and 3.7). Although the 3.8% organic matter at Site 3 was higher than at both Sites 1 and 2, the amount was not likely high enough to reduce densification. Raghavan (1985) found that amounts in excess of 3% were necessary before compaction was reduced. Of the soil properties, clay contents and CEC appear to have influenced densification the most.

The effect of water on soil compactibilty as a lubricant was likely more pronounced at high moisture contents when hydration requirements had been satisfied and free water was present in the soil. The moisture content at which maximum field densification occurred at Site 1 was 26%, much higher than the 7.5% moisture contents at –33 kPa soil water matric potential suggesting most of the soil water was in the free state. The total porosity of the soil at Site 1 was 34%. Based on this porosity, the soil profile at Site 1 was saturated below 20 cm during the high moisture treatment.

At Site 2, soil density increased the most at the high moisture treatment, a level slightly lower than –33 kPa soil matric water potential value. Although unlike at Sites 1 and 3, the soil at Site 2 was never saturated during treatment application, relatively high resultant densities show that optimum moisture levels had been attained. Densification only extends 5 cm into the subsoil in spite of the soil generally having suffered the highest density increases of the three sites because of the presence, at the 15 cm depth, of the most pronounced dense layer among the three sites.

Dense pre–treatment layers in the profile reduced the pressure and densification below them but caused higher resultant densities in horizons overlying them. This tendency was also reported by Taylor et al. (1980). The effect of the dense layer was most important at Site 2 because there was a stone layer just below the dense layer. The relatively high contents of silt (18%) relative to clay at Site 2 may have further reduced densification because silt is difficult to densify.

At Site 3, compaction extended deepest and density increases were largest in the low moisture treatment which coincided with the plastic limit. When the soil was compacted at moisture contents above the plastic limit, water took a greater proportion of the total bulk volume of the soil thereby reducing its bulk density. The soil profile was saturated below the 15 cm depth during the high moisture treatment. During the short time when he soil was loaded, water was unable to escape from under the tires and hence the pore water likely supported the load, preventing densification (Hovanesian, 1958).

The optimum moisture content for densification occurred above field capacity in the low charge, sandy soil at Site 1, above the plastic limit in the silty soil at Site 2 and just below the plastic limit in the Site 3 soil. Optimum moisture content for the three soils varied with soil properties.

The relatively high pre–treatment bulk densities at all three sites may explain the relatively small density increases and why the changes were mostly confined to the low density, tilled surface layers. Similar pre–treatment and post–treatment densities below the tilled surface perhaps indicate that the soils have attained equilibrium with respect to density as a result of pre–study compaction. This may be expected in soils that have been in production as long as these sites have. Extra compaction would only occur when the soils were compacted at very high moisture levels and probably would occur if larger tractors are used.

Among the tractor characteristics which influence densification is tire–soil contact pressure. Densities used in comparing the two tractors in this study were measured in the 47 cm wide inner "traction" tire tracks of the 13 t Versatile tractor and in the 52 cm wide rear tire track of the 6 t Deutz tractor (Table 3.3). The differences in profile depth compacted and resultant densities caused by the two tractors were likely not the result of contact pressure differences because the inflation pressure difference (18 kPa) between the two tires was rather small. A concomitant comparison of the densities in the separate inner "traction" tire tracks and the outer "floatation" tire tracks, the pressure difference of 13 kPa resulted in no significant bulk density difference while Koger et al. (1982) found a difference of at least 70 kPa was necessary before significant differences were detected in the resultant densities after tractor compaction.

In comparisons between wide and narrow tires of equal contact pressures, Taylor et al. (1980) showed that wider tires caused deeper densification. Although the 52 cm wide rear tires on the 6 t Deutz used in this study were wider than the 47 cm wide dual tires on the 13 t tractor, they carried similar total mass and had lower mass per axle than did the duals (Table 3.1). For these reasons and because of their lower inflation pressure, the Deutz tires likely had lower tire/soil contact pressure and hence were not likely to have caused greater densification.

The front steering tires on the 6 t Deutz were 26 cm wide and were inflated to a pressure of 280 kPa. This high pressure may have been high enough to result in significantly higher soil densities. The effect, however, was likely limited to the surface layers because the front tires were offset and tracked along the inner edge of the rear tire tracks in whose center the densities were measured. Soehne et al. (1962) in a study of soil movement under tires traced using x-ray techniques and Taylor et al. (1980) in soil bin studies found the depth under the tires at which maximum densification occurred was equal to half the tire width. For the front tires in this study this depth would be 13 cm, indicating a shallow effect of the high pressure tires.

The 13 t Versatile caused deeper compaction than did the 6 t Deutz in 80% of cases where subsoil compaction occurred. Theoretically maximum densification should have occurred at the 23 cm depth in the 13 t tractor tracks and at 26 cm in the 6 t tractor tracks (half the tire width). Maximum densification actually occurred at the 5 to 10 cm depth indicating factors other than tire width alone controlled the depth at which maximum densification occurred. The results can be explained in part by the presence of dense layers above the theoretical depths for maximum densification. These observations show that when total load or load per axle was high, densification extended deeper than when the total load or mass per axle was low. The results however, show subsoil compaction in the 6 t Deutz treatments was also occurring.

The higher though non–significant densities in the surface 5 cm of the 6 t tractor tracks compared to those in the 13 t tractor tracks at Sites 2 and 3 were probably the result of the highly inflated front tires on the 6 t Deutz. Similar results were reported by Soehne (1958) who found that the contact pressure controlled pressure distribution in the surface layers. Density changes below the 5 cm depth were higher in the 13 t tractor tracks than in the 6 t tractor tracks. The contrasting results between the 5 cm and the 10 cm depth densities can be explained by the higher pressures below the 5 cm depth which developed in the 13 t tracks as a result of higher mass per axle than the 6 t tractor tracks and the presence in the profiles of dense layers whose effect was discussed earlier.

Increasing the number of passes from 1 to 3 resulted in higher density increases at Sites 1 and 2 but only affected depths of compaction at the high moisture content. At Site 3 density increases were smaller at high moisture contents than at low moisture levels indicating the moisture contents were higher than the optimum levels for compaction. Increasing the number of passes from 3 to 6 increased depths compacted even at low and medium moisture contents although the largest differences between the number of passes occurred at high moisture contents. Increasing the number of passes influenced density changes more than depths compacted because depths compacted were also affected by dense layers in the profile. The influence of number of passes on densification was significantly dependent on soil moisture content.

The use of the larger tractor to cultivate the plots prior to treatment application loaded the soil and may have increased densities. The case can be made that the passes made during cultivation be included in the n umber of treatment passes, especially since shear loading was likely higher during cultivation because the tractor was pulling the cultivator. This may explain the higher pre–treatment densities measured at Site 1 for treatments at the high moisture levels. Loading the soils during cultivation, however, followed no set pattern and since the treatments were randomly allocated and the density measurements made at randomly selected points, and because the figures used in the analysis were based on the means of eight measurements, the error introduced by the pre–treatment loading should have been equally random and should not alter the conclusions drawn from the treatment comparisons. It is likely that the direction of the tracks or some other unidentified factors caused the observed increase in pre–treatment densities at the high moisture level.

The high natural variation in pre–treatment bulk densities complicated the results. Even though means of eight measurements were used in comparisons, some treatment effects were likely masked by the wide bulk density variations.

3.6 Conclusions

The depths of the profiles compacted and the magnitude of bulk density increases as a result of tractor traffic in the study were influenced by complex interactions between soil physical and chemical properties, moisture content, pre–treatment denstics, the presence of dense layers below the cultivated depth and tractor size and number of passes.

Tractor size was more critical in determining depth compacted than in determining change in bulk density. The 13 t tractor with greater mass per axle and total mass caused deeper densification than did the 6 t tractor with lower mass per axle and smaller total mass.

There were no significant differences in densities caused by the "inner" traction and the "outer " floatation" tires on the dual wheels. Dual tires on the 13 t Versatile allowed the use of inflation pressures low enough to cause density increases in the soil which were comparable to those caused by the 6 t Deutz.

Increasing the number of passes, especially from three to six, significantly influenced the depth of the profile compacted, especially at high moisture contents. Generally more passes caused greater density increases at all three sites.

The deepest extending densification occurred at moisture contents near saturation, higher than field capacity at Site 1, above the plastic limit at Site 2 and just below plastic limit at Site 3. The optimum moisture content for densification varied with soil surface charge and texture.

Dense layers within the profile and pre–treatment bulk densities critically influenced both the depth of the profiles compacted and the resultant bulk densities. The presence of dense layers near the profile surface led to shallower profile densification especially at low moisture contents. At high moisture contents and for high numbers of passes, the dense layers were not as effective in restricting densification to the surface layers as at low moisture contents.

The silty soil at Site 2 suffered the shallowest but highest density increase of the three sites because of the presence of a stone layer above the dense layer at the 15 cm depth.

Table 3.1 Specifications and characteristics of the tractors used in the study.

Tractor make	Drive system	Total mass (t)	Mass distribution	Tire set up	Tire size		Tire pressure (kPa)		Tire pressure (kPa)	
			front : rear		front	rear	inner	outer	front	rear
Versatile 835	4–wheel	13	60 : 30	dual	18.4 – 38	18.4 – 38	103	89.5		
Deutz 120	2–wheel	6	35 : 65	single	11 – 16	20.8 – 32			280	84.5

Table 3.2 Mean moisture contents ($cm^3\ cm^{-3} * 100$) at −33 kPa and −1500 kPa soil water potential, liquid and plastic limits for the soils used in the study and and during treatments at Sites 1, 2 and 3

Site	Depth (cm)	−33 (kPa)	−1500 (kPa)	Liquid limit	Plastic limit	Low level	Medium level	High level
1	00 – 15	6	4	ND	5	12	16	20
1	15 – 30	8	5	ND	7	20	24	32
2	00 – 15	26	11	36	30	10	22	27
2	15 – 30	26	11	36	28	14	29	32
3	00 – 15	41	17	66	38	34	43	43
3	15 – 30	43	22	60	35	31	42	47

Table 3.3 Depths (cm) significantly densified at three different moisture levels at Sites 1, 2 and 3

		Site 1			Site 2			Site 3		
		Moisture level			Moisture level			Moisture level		
Tractor	Passes	L	M	H	L	M	H	L	M	H
13 t	1	10	15	25	15	15	15	5	15	15
6 t	1	5	15	20	15	10	10	5	5	10
13 t	3	5	20	30	10	15	20	10	10	50
6 t	3	5	20	20	15	10	15	5	5	40
13 t	6	10	15	40	20	15	30	40	10	35
6 t	6	15	15	35	15	15	25	15	10	30

L = low M = medium H= high

Table 3.4 Tractor tire–induced mean trough depths (cm) at Sites 1, 2 and 3

(a) Site 1

	Low moisture			Medium moisture			High moisture		
13 t Versatile									
Passes	1	3	6	1	3	6	1	3	6
Depth	5	5	5	7.5	5	5	7.5	7.5	10
6 t Deutz									
Passes	1	3	6	1	3	6	1	3	6
Depth	5	5	5	5	5	5	7.5	7.5	7.5

(b) Site 2

13 t Versatile									
Passes		3	6	1	3	6	1	3	6
Depth	5	5	5	2.5	2.5	2.5	2.5	2.5	2.5
6 t Deutz									
Passes	1	3	6	1	3	6	1	3	6
Depth	5	5	5	2.5	2.5	2.5	2.5	2.5	2.5

(c) Site 3

13 t Versatile									
Passes	1	3	6	1	3	6	1	3	6
Depth	5	5	5	2.5	2.5	2.5	1.0	1.5	1.5
6 t Deutz									
Passes	1	3	6	1	3	6	1	3	6
Depth	2.5	2.5	2.5	2.5	2.5	2.5	1	1.5	1.5

Table 3.5 Mean tractor–induced bulk density increases (Mg m^{-3}) as affected by moisture status and number of passes for tractors of 13 t and 6 t mass at Site 1

(a) 13 t Versatile

	Low moisture			Medium moisture			High moisture		
Passes	1	3	6	1	3	6	1	3	6
Depth									
5 cm	0.10	0.14	0.15	0.15	0.18	0.20	0.18	0.16	0.16
10 cm	0.09	–	0.09	0.10	0.10	0.14	0.27	0.23	0.39
15 cm	–	–	0.01	0.01	0.07	0.02	0.24	0.20	0.24
20 cm	–	–	–	–	0.04	–	0.01	0.11	0.02
25 cm	–	–	–	–	–	–	0.01	0.03	0.02
30 cm	–	–	–	–	–	–	–	0.01	0.03
35 cm	–	–	–	–	–	–	–	–	0.03
40 cm	–	–	–	–	–	–	–	–	0.01

(b) 6 t Deutz

	Low moisture			Medium moisture			High moisture		
Passes	1	3	6	1	3	6	1	3	6
Depth									
5 cm	0.06	0.10	0.08	0.11	0.14	0.20	0.17	0.18	0.22
10 cm	0.05	–	0.03	0.09	0.11	0.11	0.13	0.32	0.31
15 cm	0.03	0.03	0.02	–	0.02	0.02	0.09	0.21	0.18
20 cm	–	–	0.03	–	–	0.01	–	0.01	–
25 cm	–	–	–	–	–	–	–	–	–
30 cm	–	–	–	–	–	–	–	–	–

Table 3.6 Mean tractor–induced bulk density increases (Mg m^{-3}) as affected by moisture status and number of passes for tractors of 13 t and 6 t mass at Site 2

(a) 13 t Versatile

	Low moisture			Medium moisture			High moisture		
Passes	1	3	6	1	3	6	1	3	6
Depth									
5 cm	0.18	0.24	0.26	0.06	0.28	0.26	0.32	0.49	0.39
10 cm	0.23	0.13	0.26	–	0.12	0.09	0.15	0.16	0.22
15 cm	0.03	–	–	–	0.04	0.01	0.01	0.06	0.01
20 cm	–	–	–	–	–	–	–	0.03	0.02
25 cm	–		–	–	–	–	–	–	0.02
30 cm	–	–	–	–	–	–	–	–	0.03
35 cm	–	–	–	–	–	–	–	–	–

(b) 6 t Deutz

	Low moisture			Medium moisture			High moisture		
Passes	1	3	6	1	3	6	1	3	6
Depth									
5 cm	0.14	0.28	0.28	0.18	0.25	0.24	0.19	0.37	0.30
10 cm	0.16	0.26	0.18	0.15	0.16	0.09	0.08	0.21	0.18
15 cm	–	–	0.02		0.02	–	0.04	–	–
20 cm	–	–	–	–	–	–	0.04	–	–
25 cm	–	–	–	–	–	–	–	–	–
30 cm	–	–	–	–	–	–	–	–	–

Table 3.7 Mean tractor–induced bulk density increases (Mg m^{-3}) as affected by moisture status and number of passes for tractors of 13 t and 6 t mass at Site 3

(a) 13 t Versatile

	Low moisture			Medium moisture			High moisture		
Passes	1	3	6	1	3	6	1	3	6
Depth									
5 cm	0.22	0.18	0.18	0.19	0.06	0.14	0.09	0.14	0.18
10 cm	–	0.10	0.02	0.10	0.02	0.11	0.09	0.07	0.02
15 cm	–	0.05	0.02	0.05	–	–	0.02	–	–
20 cm	–	–	0.09	–	–	–	–	–	–
25 cm	–	–	0.06	–	–	–	–	–	–
30 cm	–	–	0.03	–	–	–	–	–	–
35 cm	–	–	0.04	–	–	–	–	–	–
40 cm		–	0.06	–	–	–	–	–	–

(b) 6 t Deutz

	Low moisture			Medium moisture			High moisture		
Passes	1	3	6	1	3	6	1	3	6
Depth									
5 cm	0.11	0.26	0.21	0.15	0.12	0.12	0.11	0.23	0.23
10 cm	0.02	0.03	0.04	0.03	–	–	0.03	0.11	0.10
15 cm	–	–	–		–	–	–	–	–
20 cm	–	–	–	–	–	–	–		–

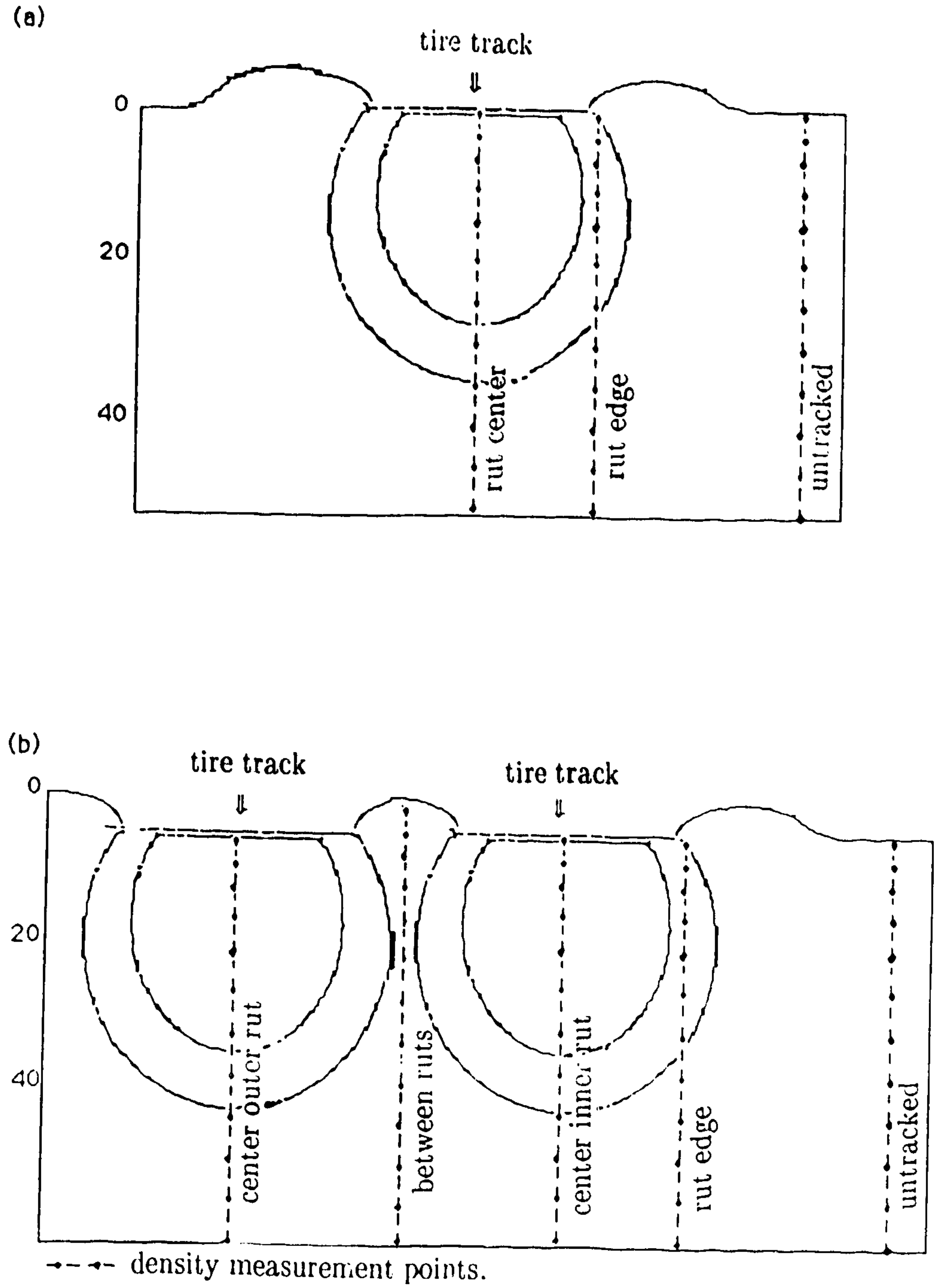

Figure 3.1. Schematic side view of the profile showing the points where densities were measured relative to the location of the tire track centers for (a) the single–tired and (b) the dual–tired tractors.

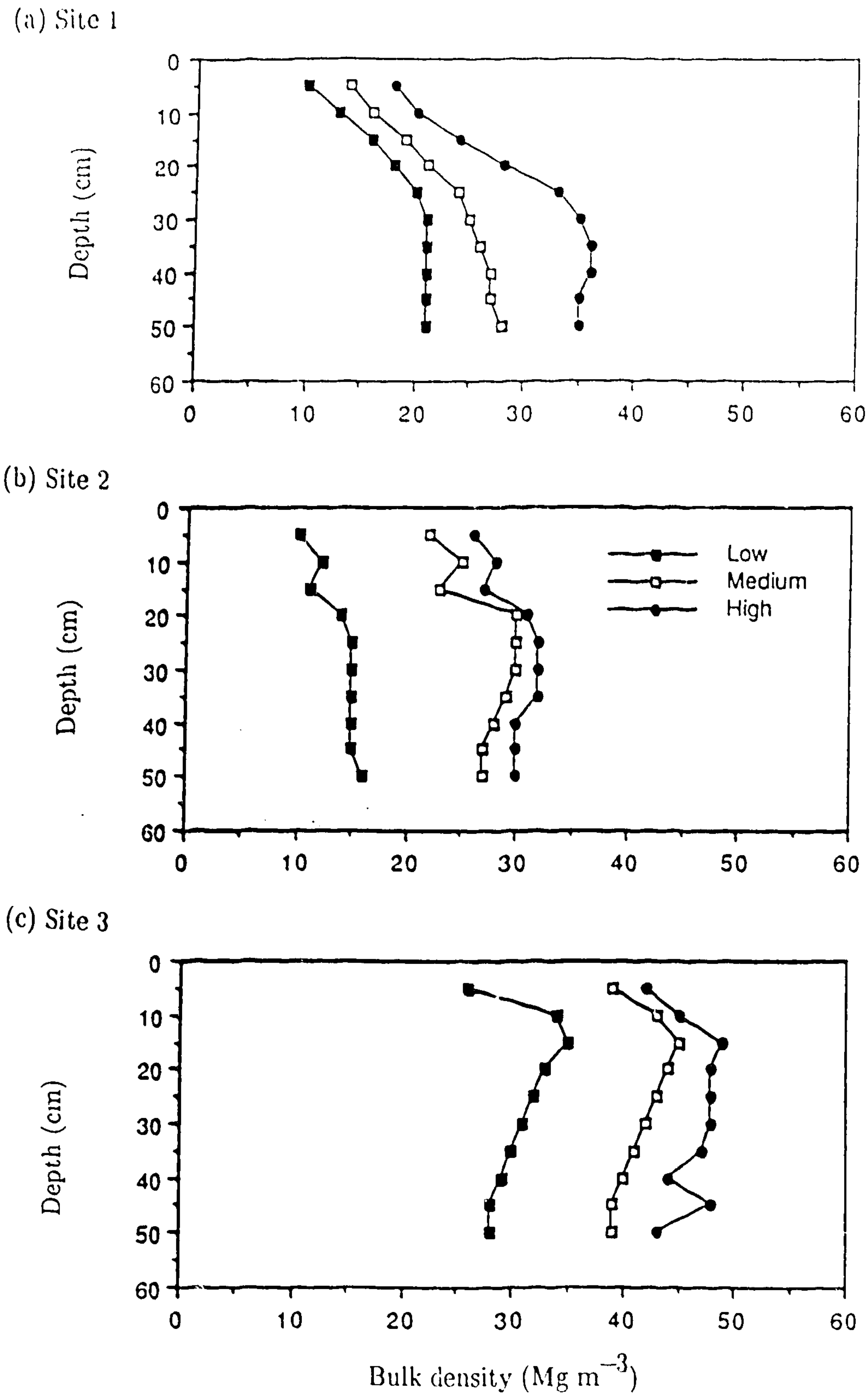

Figure 3.2. Moisture contents during treatment application at (a) Site 1 (b) Site 2 and (c) Site 3.

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CHAPTER IV

DENSIFICATION PATTERNS UNDER DUAL TRACTOR TIRES.

4.1 Introduction

During the last two decades, reduced crop yields as a result of excessive soil densification have extended to regions traditionally not considered vulnerable to compaction problems (Taylor, 1981). This has been attributed to increases in both the number of tractor passes per crop season and the average size of farm tractor used (Erbach, 1986). Time constraints, especially during seeding and harvesting, have further encouraged farm operations when soils are wet and vulnerable to densification. The increase in excessive densification incidences has been accompanied by a decline in farm profits from crop prduction. The decline in farm profits due to excessive densification must be estimated in order to ascertain whether the problem warrants corrective measures.

A number of inputs are required to estimate the cost of excessive densification. They include crop yield declines per unit area and the proportion of each unit area densified during operations. Håkansson (1985) proposed the use of tonne km ha^{-1}, the mass of the tractor or machine in tonnes multiplied by distance in km travelled ha^{-1}, or the wheel track area in percent of field area to represent the proportion of each unit area densified during operations. Irrespective of the method used, the area densified per tractor pass and the number of passes per operation are necessary to estimate the area compacted.

The load due to vehicle mass for most farm machinery today is transferred to the soil by means of pneumatic rubber tires. Tire size, tire flexibility and the proportion of vehicle mass carried by each tire determine the surface area of contact between it and the soil and thus rut width. Tire flexibility, which is greatly affected by its inflation pressure, determines the uniformity of pressure distribution within the area of contact, pressure in the soil under the tire and the magnitude of density increases. At high inflation pressures, tires behave rigidly, causing high contact pressures and relatively small areas of contact compared to tires at low inflation pressures (Chancellor, 1976). According to Chancellor and Schmidt (1962) and Hillel (1980), pressure exerted on the soil surface by air–inflated tires is approximately equal to the tire's inflation pressure.

Soil exists as a semi–infinite, three–dimensional medium to which loads are applied over only a portion. As a result, non–uniform distribution of the load in the soil mass results. There are also difficulties in measuring stress–strain variables within the soil and furthermore, soils behave elastically at low stress levels and plastically at high ones. For these reasons mathematical solutions to the soil stress–strain problems are rather complex. Predicting densification and the area of soil densified during tractor passage, therefore, is achieved semi–empirically, by relating load inputs to density increases.

The Boussinesq's equation (equation 2 in chapter 1) is commonly used to predict pressure distribution in soils. Soehne (1958) extended this equation to describe the behaviour of soil volume elements under pressure and to predict pressure distribution in the bulk soil mass. Soehne also redefined the concentration factors so that they related to soil conditions and assigned them values of 4, 5, and 6 for hard, medium and soft soils respectively. From this theory when soils are soft (large v values), the load distribution is concentrated more along the load axis meaning that pressure extends deeper in the soil. The theory also indicates that pressure in the soil is maximum directly in the center of the loaded area and decreases towards the edges. When surface pressures in the contact area are uniform, pressure extends more laterally than vertically but when the load increases, pressure extended more vertically and less laterally (Soehne, 1958).

To develop the theory of pressure distribution in the soil, Soehne assumed that the largest principal stress uniquely caused soil densification (Soehne, 1958). Later, Soehne et al. (1962) found that soil compaction was not controlled by principal stress alone but by both shear and normal stress.

During densification, the soil's bearing capacity rises as its density increases until the soil is able to support the load, at which point density increases cease. As this happens, pressure due to the load causes soil particles to move laterally from under tires. The material moved in this manner piles along the tire rut when at the surface but causes lateral densification when it occurs below the soil surface. Although this phenomenon is known, the lateral extent of densification and the magnitudes of bulk densities the laterally densified material have not been quantified in the field.

Trough depths reflect both soil compactibility and the ease of soil movement. Trough depths are deeper when the soils are highly compactible or when relatively more soil material moves from under the tires to the edge. Soils that are less cohesive can thus be expected to have deep troughs on account of the soil material moving to the tire edges and piling alongside the tracks. This effect can be expected to be more pronounced when soils are dry than when they are wet since the particles are not bound together.

Although the occurrence of lateral densification during tire passage is discussed in the literature, tire rut width continues as the major means of estimating area compacted by tires with the assumption that only the area directly under the rut is densified. It is important therefore to establish how much, if any, lateral densification occurs as a consequence of lateral flow of soil during tire passage in order to assess accurately the area compacted. For tractors fitted with dual tires, an estimate of the proportion of the area compacted between the duals also needs to be established.

4.2. Study objectives

The objectives of this study were to determine densification patterns under dual tractor tires in order to determine how far lateral densification extends and to determine what proportion of the area between the dual tires is compacted during tractor passage. The influence of increasing the number of passes and the soil moisture contents on the lateral extent of densification and the resultant densities in the densified area adjacent to the tire ruts were also investigated.

4.3. Materials and methods

The study was conducted at three cultivated sites located at Warwick, 90 km east of Edmonton, Alberta. Soil classifications and profile horizons are presented in Table 2.1. The properties of the three soils are given in Table 2.2.

A plan view of treatment plots is presented in Figure 2.1. A 5 m buffer was left between the treatments and the fence lines.A soil core to a depth of 90 cm was taken in each of 12 subplots at each site using a truck–mounted corer and divided to give subsamples in 15 cm intervals. Samples were used to determine soil textures using the hydrometer method. Calgon was used to disperse the samples while samples from Site 3 were treated with HCl to remove excess Ca.

A 13 t, 4–wheel drive Versatile 835 tractor with a 60:40 front to rear mass distribution ratio was used to compact the soil. The tractor was equipped with 18.4 38 tires in a dual set up. The inner "traction" tires were ballasted with 420 kg of calcium chloride each and were inflated to a pressure of 103 kPa. The outer "floatation" tires were inflated to a pressure of 89.5 kPa but were not ballasted.

The sites were tilled with a cultivator to a depth of 15 cm prior to treatment application to standardize surface conditions. Soil moisture contents with depth were determined immediately after treatment application. Moisture contents during treatment were considered within the normal range for agrononmic field operations. Two treatments of a single pass and six multiple passes, each superimposed on the first, were applied by the tractor operated at 8 km h^{-1}. The treatments were repeated at two different dates between summer 1985 and fall 1987 to correspond to a low and a high treatment moisture content. There were 4 moisture–passes combinations at each site.

Four sets of measurements were made in each of the two tractor tracks for a total of eight sets of measurements for each treatment. A set of measurements included control measurements taken in the untracked area of the field adjacent to the tracks and measurements taken in the center of both the inner and the outer tracks and at the edge of the inner track and measurements were also taken between the two tracks. A side view of the points relative to the tracks at which densities were measured is shown in Figure 3.1.

A Nuclear Pacific Stratigauge, a combination density–moisture gauge, was used to take moisture and density count ratio (count at depth/standard count) readings at 5 cm intervals, starting at the 5 cm depth and extending to 60 cm. These were used to calculate the volumetric moisture contents and wet densities. Dry bulk densities were determined by deducting moisture from the wet bulk densities. Site specific moisture calibration curves used in the study were determined for each of the three sites while the manufacturer's determined density curves were used.

The F test was used to determine if significant density changes occurred at a given depth and the LSD (least squares difference) method was used to determine which densities were homogeneous and which were different. Comparisons between the untracked measurement and the density measurements at the edge of the rut established if densification extended to the edge of the tire rut (approximately 125 mm from the centre) while comparisons between the control measurement, the measurement between the ruts and the measurements in both the inner and the outer ruts centers established if the area between the ruts was densified. The LSD established whether the magnitude of densification at the edge and in between the ruts was less than or equal to that in the center of the two tracks.

4.4 Results

In Table 3.1, the moisture contents during treatment for each of the three sites together with the moisture contents at −33 kPa and −1500 kPa matric potential and liquid and plastic limits are presented. Moisture contents during the two treatments at Site 1 were above both the moisture content at −33 kPa matric potential and plastic limit. At Site 2, the moisture content during low moisture treatment application was equivalent to −1500 kPa soil water matric potential while it was equivalent to −33 kPa and plastic limit during the high moisture content treatments. For Site 3, the low moisture treatments were applied when soil moisture content was 2% above the plastic limit while the moisture content was 2% above −30 kPa matric potential during the high moisture treatments.

Trough depths for the various treatments are presented in Table 4.1. At Site 1 trough depths at low moisture averaged 5 cm and 7.5 cm at high moisture content. At Site 2 mean trough depths were 5 cm and 2.5 cm deep at low and high moisture contents respectively while at Site 3 the mean trough depths were 4.5 cm at low moisture content and 1.5 cm at high levels.

Rut edge densitities vs track centre densities

Irrespective of moisture content, densities measured at the rut edge at Site 1 were lower at the 5 cm depth than densities measured in the center of the track but were higher than the control densities. At depths of 10 and 15 cm, the densities measured at the ruts' edge were significantly higher than the untracked control densities and equal to densities measured in both the outer and the inner track centers. At depths greater than 20 cm all densities were the same (Tables 4.2 and 4.3).

At low moisture content, densities measured at the edge of the tire ruts at Site 2 were higher than the untracked control treatment densities for the single pass. The densities at high moisture content were higher than those measured in the untracked area although lower than those measured in the rut centers at the 5 cm depth for the single–pass. For the low moisture content, densities measured in the center of the tracks at the 10 and 15 cm depths were higher than both the control and edge densities. For the high moisture content, the edge densities at the 10 and 15 cm depths were significantly higher than the control and equal to densities measured in the centers of both the outer and the inner tracks. At depths greater than 20 cm all densities were the same (Tables 4.4 and 4.5).

At Site 3 densities measured at the edge equalled control densities at the 5 cm depth but edge densities at the 10 and 15 cm depths were higher than the control ones but less than those measured in the rut centers irrespective of moisture content (Table 4.6 and 4.7).

Track centre densities vs densities between tracks.

Irrespective of treatment moisture content, the densities measured between the dual tires at Site 1 wer. higher than those measured in the control treatment for both the single and six pass treatments. At the 5 and 10 cm depths, for low moisture treatments, densities measured between the dual tire ruts were higher than those in the control but lower than densities measured in the center of the dual tire ruts. They were equal or slightly less than densities in the center of the tracks at high moisture content and for six passes. Low moisture density increases measured in the six pass treatments at Site 1 extended 5 cm deeper than those in the single pass treatment. For treatments at high moisture content at Site 1, densities between the dual tire ruts were significantly higher than densities in the control treatment but lower than densities in the center of the dual tire ruts for the single pass. Densities between the dual tire ruts equalled those in the rut centers for the six pass treatment (Tables 4.2 and 4.3).

At Site 2 for both the single and six pass treatments, the densities between the dual tracks were higher than densities in the control treatment but less than densities in the center of the track for the low moisture treatment. Resultant densities were higher in the six pass treatments than in the single pass treatments although the two treatment results were statistically homogeneous (Tables 4.4). For high moisture treatments the densities between the tracks were higher than in the control and equalled those in the center of the tracks (Table 4.5). The treatment results were all homogeneous from the 20 cm depth indicating there was no treatment effect at these depths.

The results at Site 3 were similar to those at Sites 1 and 2 with the region between the dual ruts being densified in all 4 treatments. Except for the 6 pass, high moisture treatment the 5 cm densities between the dual ruts were the same as the control treatment densities. The measured densities at the 10 cm depth were significantly higher than the control densities but less than the densities in the centers of the two tracks (Table 4.6 and 4.7). There were no differences in resultant densities below the 5 cm depths for the 6 pass treatment at high moisture content.

4.5 Discussion

In order to establish whether the densification pattern under the individual tires was similar to the bulb concept suggested by Soehne in 1958 and shown in Figure 4.1, densities measured at the edge of the rut were compared to those measured in the untracked control treatment and in the center of the ruts. For Soehne's pressure bulb concept to be valid, the densities at the edge should be the same as the control ones near the surface, should be greater that the control densities at a depth equal to half the tire width before declining as depth increases to equal those in the untracked control treatment again. This would suggest the densified soil under the tire forms a parabola–shaped bulb.

The presure distribution bulb concept was true only in the surface 15 cm at Sites 2 and 3 and in the surface 20 cm at Site 1. The lack of differences between the untracked control densities and densities measured at the edge of the tire rut and between the dual tire ruts below these depths shows that the lower part of the pressure bulb did not develop, probably because stress at these depths was not high enough to cause significant density changes. The density bulb shown in Fig. 4.1 developed only in the cultivated surface layers of the soil but did not extend into deeper dense layers. The densities measured between the dual tracks show that lateral densification in all treatments extended across the area between the dual tire ruts from the 10 cm to the 15 cm depth at Sites 2 and 3 and from the 10 cm to the 20 cm depth at Site 1.

Pre–treatment dense layers in the profile have been shown by Taylor (1980) to cause relatively high pressures in overlying horizons than would develop if they were absent. Lateral densification occurred because the soil between the tires and the dense layers could not be compacted further, nor could it be moved into the underlying dense layers. The soil material hence moved laterally either plastically in the case of wet cohesive soils or as grains in the dry soil. Soil moved sidewards in this manner either piled along side the ruts if at the surface or increased the densities of the adjacent layers when below the surface.

The lateral spread of densified soil was most pronounced for six passes and for high moisture contents. This explains why densities measured between the dual tire ruts in the six pass treatments at high moisture contents were equal to those in the center of the tire ruts. When the single pass treatment is compared to the six pass treatment at each site, not only were densities higher for the six pass teatments but there was a tendency for densification to extend closer to the soil surface, such that densification in the six pass treatments occurred at the 5 cm depth compared to 10 cm depth for the single pass at all three sites.

Direct site comparisons are not possible since moisture contents during treatments were different for the three sites. Generally, lateral densification appears to have extended the most for the sand at Site 1 and the least for the sandy clay loam at Site 3. Trough depths were deeper at Sites 1 and to a lesser extent Site 2 partly because the soil material moved from under the tire to pile alongside it. Less soil moved in this manner at Site 3 because the soil was much more cohesive due to its high clay contents and relativel higher surface charge. Trough depths appear to have further been influenced by the depth to the dense layer, being deeper when the dense layers were found deeper in the profile. More soil material moved from under the tires at low moisture contents than at high ones increasing the depth of the troughs.

The pattern of density increases below the tire tracks at all three sites can only be described by the shape calculated from Soehne's (1958) equation in the cultivated surface layers. Only the top third of the bulbs developed. The partially developed bulbs had a sharp lower boundary at the depth where high density layers are encountered (Fig. 4.2) suggesting the development in deeper profiles was prevented by the presence of dense layers. The density increase pattern resembled two partially developed bulbs at [illegible] from each other with the [illegible] between them [illegible] (Fig. [illegible]).

[illegible]

the untracked densities. In the dual–tired tractor, the area densified included the entire region between the dual tires. This meant a total area of at least 125% the area directly under the dual tire ruts was densified. The resultant densities between the tires and at the edges continue to increase as the number of passes increase such that for six passes (especially at high moisture contents) they may equal densities in the center of the ruts.

4.6 Conclusions

The patterns of soil compacted under tractor tire ruts in this study followed the pressure distribution bulb concept calculated by Soehne (1958) only in the low density cultivated surface layers. Density did not increase in and below high density layers.

The area compacted under tires extended at least 12.5% of the tire rut widths further than the rut edges, suggesting that an area at of least 125% of the tire rut width was compacted during tractor tire passage.

The resultant bulk densities in the densified areas adjacent to the tire ruts were dependent on moisture conditions and the number of passes, being greater at high moisture contents and for greater numbers of passes.

Lateral extention of densification was greater in the sandy soil than in the sandy clay loam soil.

Table 4.1 Mean trough depths induced by the 13 t tractor at Sites 1, 2 and 3

	Low moisture			High moisture		
(a) Site 1						
No. passes	1	3	6	1	3	6
Depth (cm)	5	5	5	7.5	7.5	10
(b) Site 2						
No. passes	1	3	6	1	3	6
Depth (cm)	5	5	5	2.5	2.5	2.5
(c) Site 3						
No. passes	1	3	6	1	3	6
Depth (cm)	5	5	5	1.0	1.5	1.5

Table 4.2 Site 1 LSD homogeneity test results comparing the untracked profile with the tracked profiles under the dual tires and the profile between tracks for (a) 1 pass (b) 6 passes at low moisture content

(a) 1 pass

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	c	ba	cb	ba	cb
10	c	a	cba	ba	cb
15	cb	b	cb	cb	c
20	c	cb	b	cb	b
25	c	c	c	c	c
30	–	–	–	–	–

(b) 6 passes

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	c	a	a	a	cb
10	c	b	b	b	b
15	cb	b	cb	b	cb
20	c	c	c	c	c
25	–	–	–	–	–
30	–	–	–	–	–

Columns having the same letter within a given row are not significantly different ($p < 0.05$)

Table 4.3 Site 1 LSD homogeneity test results comparing the untracked profile with the tracked profiles under the dual tires and the profile between tracks for (a) 1 pass (b) 6 passes at high moisture content

(a) 1 pass

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	d	c	c	b	c
10	d	ba	cb	a	c
15	d	b	c	b	c
20	d	d	d	d	d
25	–	–	–	–	–
30	–	–	–	–	–

(b) 6 passes

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	d	c	c	b	dc
10	d	ba	cb	a	c
15	d	b	c	b	c
20	–	–	–	–	–
25	–	–	–	–	–
30	–	–	–	–	–

Columns having the same letter within a given row are not significantly different ($p < 0.05$)

Table 4.4 Site 2 LSD homogeneity test results comparing the untracked profile with the tracked profiles under the dual tires and the profile between tracks for (a) 1 pass (b) 6 passes at low moisture content

(a) 1 pass

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	c	b	c	c	c
10	c	a	cb	cb	b
15	c	c	c	c	c
20	–	–	–	–	–
25	–	–	–	–	–
30	–	–	–	–	–

(b) 6 passes

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	d	b	c	c	c
10	d	ba	cb	cb	dc
15	d	d	d	d	d
20	d	d	d	d	d
25	–	–	–	–	–
30	–	–	–	–	–

Columns having the same letter within a given row are not significantly different ($p < 0.05$)

Table 4.5 Site 2 LSD homogeneity test results comparing the untracked profile with the tracked profiles under the dual tires and the profile between tracks for (a) 1 pass (b) 6 passes at high moisture content

(a) 1 pass

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	d	a	c	a	b
10	d	b	dc	b	cb
15	–	–	–	–	–
20	–	–	–	–	–
25	–	–	–	–	–
30	–	–	–	–	–

(b) 6 passes

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	c	a	b	a	b
10	c	ba	b	ba	c
15	c	c	c	c	c
20	c	c	c	c	c
25	–	–	–	–	–
30	–	–	–	–	–

Columns having the same letter within a given row are not significantly different ($p < 0.05$)

Table 4.6 Site 3 LSD homogeneity test results comparing the untracked profile with the tracked profiles under the dual tires and the profile between tracks for (a) 1 pass (b) 6 passes at low moisture content

(a) 1 pass

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	b	a	b	a	b
10	b	ba	a	a	b
15	b	ba	a	ba	ba
20	–	–	–	–	–
25	–	–	–	–	–
30	–	–	–	–	–

(b) 6 passes

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	b	a	b	a	b
10	b	b	b	b	b
15	b	b	ba	b	a
20	b	b	b	b	b
25	b	ba	ba	a	a
30	b	b	b	b	b

Columns having the same letter within a given row are not significantly different ($p < 0.05$)

Table 4.7 Site 3 LSD homogeneity test results comparing the untracked profile with the tracked profiles under the dual tires and the profile between tracks for (a) 1 pass (b) 6 passes at high moisture content

(a) 1 pass

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	c	a	cb	ba	cb
10	cb	ba	c	a	cb
15	c	c	c	c	b
20	–	–	–	–	–
25	–	–	–	–	–
30	–	–	–	–	–

(b) 6 passes

Depth cm	Untracked	Centre Outer rut	Between ruts	Centre Inner rut	Rut edge
5	c	a	b	ba	c
10	–	–	–	–	–
15	–	–	–	–	–
20	–	–	–	–	–
25	–	–	–	–	–
30	–	–	–	–	–

Columns having the same letter within a given row are not significantly different ($p < 0.05$)

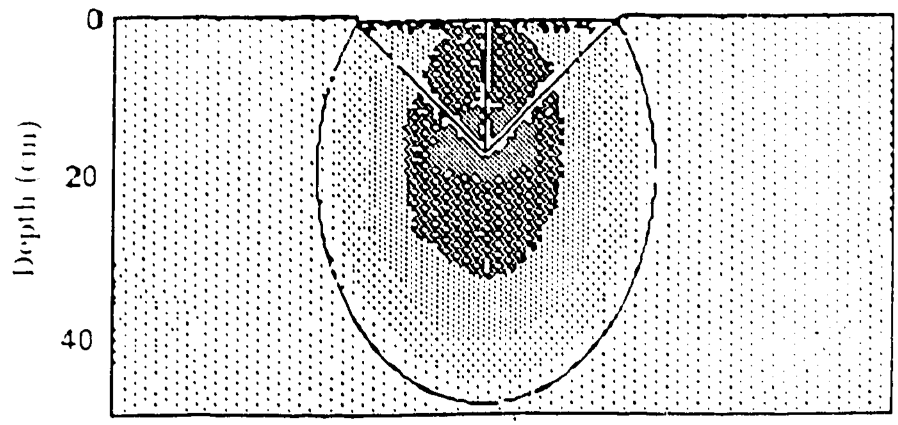

Figure 4.1. Schematic diagram of pressure distribution under tractor tires based on the pressure distribution bulb concept of Soehne (1958).

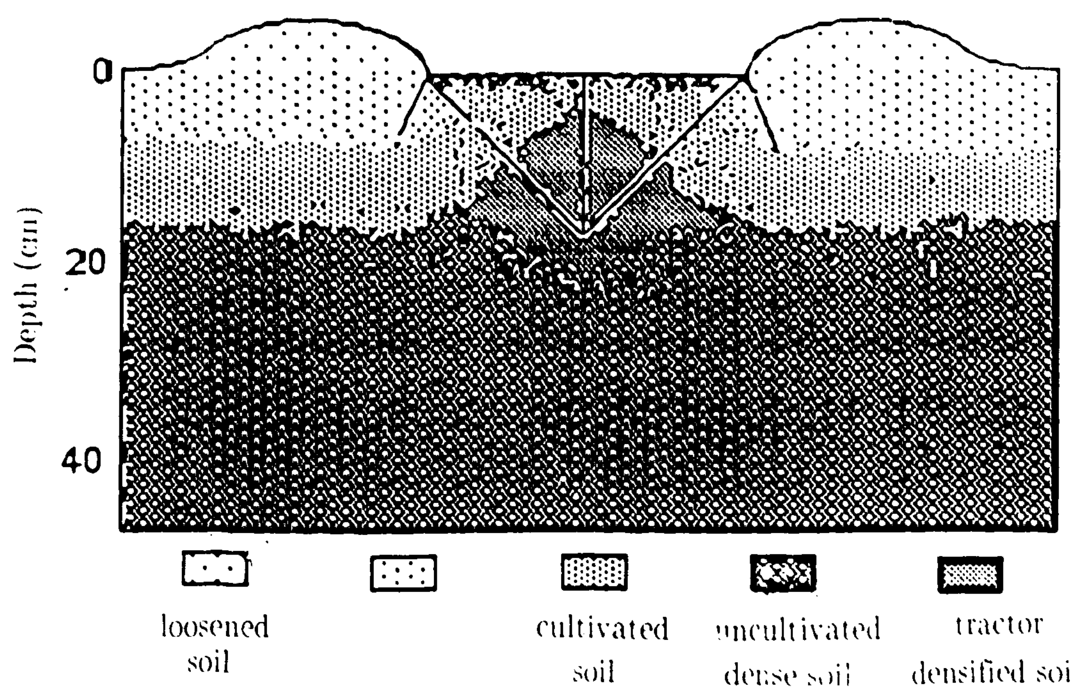

Figure 4.2. Schematic diagram of densification under tractor tires deduced from densities measured in the untracked, at the edge and in the center of the tire ruts.

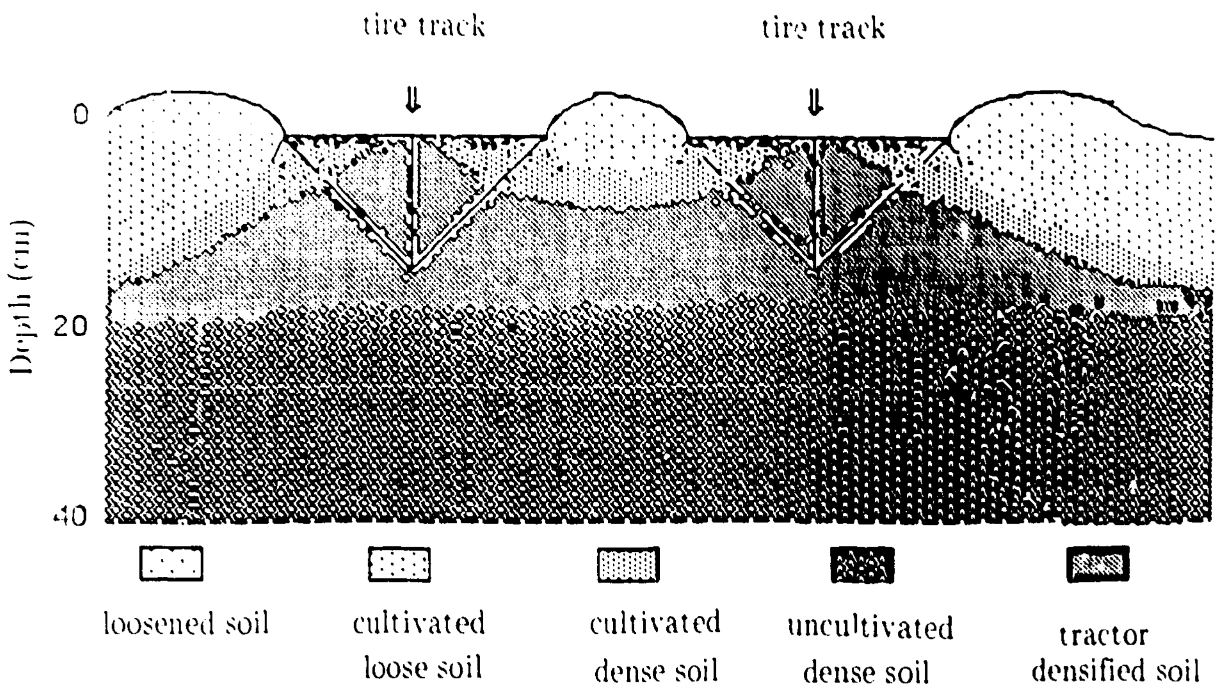

Figure 4.3. Schematic diagram of densification under and between dual tractor tire tracks deduced from homogeneity test results of the measured densities.

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CHAPTER V

SYNTHESIS

5.1. Introduction

Reduced crop yields as a result of high soil densities and expanding regions of soils suffering high machinery–induced densities is the reason for continuing research in soil compaction. Two approaches have been adopted to manage and control soil densification and its effects on crop production. The first approach divides fields into crop producing land and and semi or permanent traffic lanes. By adjusting the wheel spans of farm machinery to the same width, traffic can be restricted to these semi–permanent lanes and densification in crop producing land avoided (Taylor, 1981). This approach has had limited success because land is taken out of production and not all machinery can have their wheel spans adjusted to the same width. Some densification thus occurs in the crop producing land. The alternative approach with the objective of minimizing densification during agronomic operations remains the most viable. Once the densification process is understood, conditions when soils are vulnerable to densification can be identified and operations managed such that densification is minimized.

The studies reported in this dissertation confirm that soil densification behaviour is complex and is influenced by interactions of factors and conditions. Knowledge of these factors, especially under field conditions and their relative importance, is essential in the development of densification management systems. The first study showed that different soils have different densification behavior. Although the densification behavior of the three soils used in the studies were best decribed by the 2nd order polynomial, the densities attained during both laboratory and field densification were different for each soil. The influence of soil conditions, which change over short periods of time, were not only different for each soil but changed as the conditions varied. This creates a fundamental problem when predicting soil densification.

The first study demonstrated that in studies which allow natural variations to occur in the soil, multivariate analysis, as suggested by Hillel (1978), can not only identify the important factors influencing field soil densification and when they are important but also help establish their relative importance. Soil densification models developed from such findings are likely to be of more practical value than those based on artificially controlled studies. The study further suggested practical soil densification models have to emphasize different variables depending on moisture content, soil density, organic matter content, clay content and soil texture, soil surface charge and cations present in the soil. For example, a greater number of varaibles were required to explain density changes in the soil with 20% clay when it was at high moisture content than when it was at low moisture content.

Soil physical properties explained almost all the soil density increase at low moisture contents while chemical properties explained some of the density increases at high moisture contents. Some factors including initial bulk density, clay and organic matter were as influential at low moisture contents as at high ones. A soil density model would thus have to emphasize physical properties in sandy, dry soils and chemical properies in clayey, wet soils and emphasize certain properties irrespective of the soil moisture content.

From his laboratory studies and by solving Boussinesq's equation, Soehne (1958) concluded tire inflation pressure determined densification in surface layers while total load determined the depth to which densification extends in the soil. Taylor (1985) using results from soil bin studies found total load predominantly determines the extent of densification in the profile. These findings were based on the assumptions that soils were elastic, homogenous and isotropic. To establish how well these results compared to the densification of field soils, the influence of soil properties and tractor characteristics on soil densification were studied in cultivated field soils.

Initial bulk densities and the presence of high density layers in the soil profile were found, in this study, to have a significant influence on densification, preventing its extension to underlying horizons except under certain conditions. Density increases were restricted to the surface horizons when soils were at low and medium moisture contents in the sandy soil at Site 1 and below the plastic limit in the sandy loam soil at Site 2. Subsoil densification only occurred when the soil was nearly saturated at Site 1 and when the soil moisture content was at −33 kPa soil water matric potential in the loam soil at Site 2. In the sandy clay loam soil at Site 3, subsoil densification occurred at moisture contents slightly lower than plastic limit.

Although Håkansson (1985) suggested that tractors of mass less than 8 t per axle are unlikely to cause subsoil densification, this study showed both the 13 t (maximum mass per axle 7.8 t) and the 6 t tractor (maximum mass per axle 3.9 t) caused subsoil densification. The 13 t tractor, however, caused a greater number of subsoil densification cases. The cases of subsoil densification were higher in multiple pass treatments compared to the single pass ones. The resultant bulk densities caused by the two tractors showed no significant differences. Density increases were greater for three–pass treatments than for one–pass treatments but were not very different when three–pass treatments were compared to six–pass treatments. Increases in resultant densities were greater at high moisture contents in the sandy and the loam soils at Sites 1 and 2, but smaller in the sandy clay loam at, Site 3.

Tractor size, while important in determining whether subsoil densification occurred or not and how much density increase was likely to occur, was not as critical as soil moisture content and pre–treatment density in determining soil depth densified and resultant densities. The optimum moisture content for densification varied for each soil suggesting that in management systems, it has to be established for each specific soil, the tractor being used and for given pre–treatment soil densities.

It is necessary to calculate the cost of densification in order for farmers to make economically based decisions to correct problems of high densities and to adopt densification management techniques. To estimate this cost the proportion of the field densified during operations is required. The lateral extent of densification during compaction and the proportion of the area between the dual tires compacted during tractor passage are essential in this estimation. This study found densification extended laterally beyond tire width at least 12.5 % and covered the whole region between the dual tires. This implies a total width of 125% of the two dual tire ruts was compacted during tractor passage. Resultant density increases were greater for the high moisture treatments and for six–pass treatments than for the low moisture content and for single–pass treatments. Not only would resultant densities be higher but field areas compacted during tractor passage would be greater if operations are carried out in wet soils.

The soil densification patterns approximated from the third study appear to follow the pressure distribution pattern calculated by Soehne's 1958 model only in the surface cultivated layers. Densities below the cultivated layers were the same between treatments and the control, showing that the pressure distribution pattern calculated by Soehne and confirmed by Perumpral et al. (1971) does not translate into density increases in the presence of high density layers.

6.2 Assessment of compactibility of the three sites

Soil compactibility expresses a qualitative measure of the ease of densifying a soil at a given energy input. For equal energy inputs, soils with high compactibilities undergo greater density increases than those with low compactibilities. The compactibility of a soil is determined by its properties and prevailing conditions. Although the three soils studied in this dissertation were relatively similar there were enough differences in their properties and profile characteristics to cause the different compactibilities observed.

Both pre–treatment and post–treatment densities were highest at Site 1 and were least at Site 3. Field pre–treatment soil densities averaged 1.65 Mg m^{-3} in the surface 20 cm and 1.80 Mg m^{-3} between the 20 cm and the 60 cm depth. At Site 2, field densities averaged 1.60 Mg m^{-3} in the surface 15 cm and 1.70 Mg m^{-3} between the depths of 15 and 60 cm while at Site 3 densities avaraged 1.50 Mg m^{-3} in the surface 15cm and 1.65 Mg m^{-3} from the 15 cm to the 60 cm depth. In the Proctor test, maximum densities were 1.76 Mg m^{-3} for Site 1, 1.81 Mg $m^{-3}$for site 2 and 1.69 Mg m^{-3} for Site 3 and densities increased by a maximum 0.19 Mg m^{-3} for the soil from Site 1, 0.44 Mg m^{-3} for the soil from Site 2 and 0.40 Mg m^{-3} for the soil from Site 3 as energy inputs increased from 6 kJ cm^{-3} to 80 kJ cm $^{-3}$. In both the Proctor test and the tractor–induced field compaction, the Site 2 soil was the most compactible since maximum density incieases in the field were 0.26 Mg m^{-3} at Site 1, 0.49 Mg m^{-3} at Site 2 and 0.39 Mg m^{-3} at Site 3. The Site 3 soil was slightly less compactible than the Site 2 soil while the Site 1 soil was the least compactible.

The objective of assessing soil compactibility is to determine densities which may cause reduced crop yields. High soil densities reduce yields through increasing soil resistance to root growth and reducing O_2 supply to the roots. Although the soils from Sites 1 and 2 had relatively high densities, the strength of these soils were likely lower than that in the Site 3 soil because they both had low clay contents, low water holding capacities and were generally non–cohesive. Even though the Site 3 soil had the lowest densities of the three sites, this soil had the highest clay and Ca contents and was likely the most cohesive, likely indicating high soil strength.

Potential for restricted O_2 supplies to the root system was also higher at Site 3 than at Sites 1 and 2 because the Site 3 soil had poorer drainage characteristics and higher water holding capacity than both the soils from sites 1 and 2. Thus, although the Site 3 soil was not as compactible as that from Site 2, it likely had higher strength, greater potential for reduced O_2 supply to the roots and higher potential for subsoil densification than the soil from Site 2. Potential for reduced yields as a result of compaction, therefore, was greatest in the Site 3 soil.

The presence of a pronounced dense layer at the 15 cm depth of the profile at Site 2 not only lead to high surface layer densities, but may have impeded root growth into deeper horizons. In the absence of uncultivated profiles for comparisons, the role of machinery in causing high density layers in the profiles is difficult to establish. In the studies, the 13 t tractor caused slightly higher densities in the surface layers and a greater number of subsoil densification cases than did the 6 t tractor. In addition, the proportion of the field compacted by each tractor pass appears larger for the 13 t dual tired tractor. Because the larger tractor pulls wider implements and covers proportionately larger areas during each pass, however, calculations of areas densified per pass by the two tractors are necessary before conclusions can be drawn on which tractor compacts greater tracts. In general more caution is required when using the larger tractor if chances of high resultant densities and deeper extending densification are to be minimized.

Yield declines as a result of densification caused during agronomic operations are also needed before profit reductions due to densification can be determined. Assuming that current crop yields have not been affected by soil densification, the findings of this study suggest that fewer passes for each agronomic operation and avoiding operations when moisture contents are very high, are necessary to prevent densification problems from developing.

6.3 Conclusions

Although the three soils densification behavior was best described by a 2nd degree order polynomial, the variables important in describing this behavior varied from one soil to another and with changes in the soil moisture, density and energy input.

The importance of each variable in predicting soil densification changed as soil conditions and energy input varied. Soil compactibility was most influenced by initial density, clay content, and Ca:Na ratio. At low moisture contents soil physical properties, clay and silt contents, were the most important variables in predicting soil densification while mineralogical and chemical properties including nature of clay surface, CEC and SAR were more important at high moisture contents.

Subsoil densification in the soils studied was possible even in treatments by the 6 t mass tractor but occured more frequently in treatments applied with the 13 t tractor.
The occurrence of subsoil densification was greatly dependent on soil moisture content, generally occuring at moisture contents near saturation in the very coarse soils but at moisture contents at or lower than field capacity in soils containing higher clay contents.

Increasing the number of passes caused both greater density increases and deeper extending densification but influenced the magnitude of density increase more than depth densified.

Densification patterns under tractor tires were similar to those expected from Soehne's calculations but only in the surface cultivated layers.

The presence of high density layers in the soil profile influenced the depth of soil compacted and the densification patterns under tractor tires preventing both from extending to the deeper lying soil horizons.

The area of soil densified under tractor tires was at least 125 % of the width of the tire ruts.

6.4 Future research needs

For research in soil compactibility to be of practical value, densification models are needed which tie agronomic operations, machinery characteristics, soil conditions and profile characteristics with resultant densities and crop yields. This requires the development of computer models which can select the appropriate predictor variables for given machinery characteristics and soil conditions. To be effective such models have to emphasize different variables as soil conditions change. The development of such models requires information on which variables are important for different soil conditions and equipment.

In view of the limited number of soils used in the studies reported in this dissertation the immediate research objective should be to verify the findings of the studies in this dissertation, in soils of different properties and using larger loads such as those applied by loaded combines. The findings that physical properties were more important in predicting densification at low moisture contents and chemical properties more important at high moisture contents need to be confirmed in soils of higher clay, CEC, Ca, and Na contents and for soils of different mineralogies. Studies are also required in which soil moisture contents are increased gradually to establish whether a thresh–hold moisture content exists at which the important variables explaining the densification increase change from physical to chemical properties and whether this change is gradual or abrupt. This information would be essential in any soil densification models.

Either natural or anthropogenically–induced high density layers in the profiles influence both the depth of the profile densified and the resultant densities in surface horizons. Dense layers also influence the lateral extension of the densified soil under the tires. It is necessary, therefore, first to determine whether these layers are a result of agronomic practices in order to prevent their reoccurance should ripping be undertaken. Secondly, the critical bulk density values at which dense layers become important in profile densification need to be established. The effects of ripping to break up the dense layers need to be assessed too. In Mississipi ripping dense layers in "cotton" soils resulted in redensification to the depth of ripping which caused the dense layer to extend progressively deeper with each consecutive ripping (Taylor, 1985). A study of ripping dense layers in fall and letting the soil settle naturally over winter to increase its strength prior to soil working in spring may reduce redensification enough to give a more favorable pore size distribution.

Although rather high densities were measured at the three sites studied, it can not be ascertained if crop yields have suffered. In order to do so, there is need to use bulk densities with some indicator of soil resistance to root growth, since bulk densities alone do not give an indication of soil strength or yield reduction potential. Some relation between bulk density and potential yields needs to be established if bulk density readings are to be meaningful measures of densification. A combination of bulk densities, porosities and some measure of soil strength to reflect soil resistance to root growth appears an attractive approach for relating yields to densification.

Research is necessary to improve further the estimates of areas densified under tractor tires to estimate more accurately the soil area densified per pass. More readings at various distances from the tire's edge would indicate how far densification extends and the densities reached. The findings also need to be verified in soils of different properties and for different profile characteristics.

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