University of Alberta

Soil and Plant Response to Compaction

By

Emmanuel Mapfumo ©

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Ay, now the plot thickens very much upon us

George Villiers 1628-1687

The Rehearsal

DEDICATION

I dedicate this dissertation to my two brothers, Amos and Samuel Mapfumo, who passed away at the time I started this program, and my uncle Johnson Toga Nxele who passed away just before completion of this program. The whole family will forever miss you. Rest in peace.

ABSTRACT

Soil compaction has adverse effects on plant growth and there is increased carbon dioxide emission associated with using deep tillage to curtail agricultural soil compaction. Techniques that could minimize compaction include determining appropriate moisture for trafficking, use of amendments, cropping system and grazing management.

The response of three different textured soils to compaction under varying soil moistures was investigated. Either field capacity or plastic limit, whichever is less, can be used as a threshold moisture content in order to indicate compaction hazard. For all three soils the addition of fly ash significantly ($p \leq 0.05$) decreased plasticity index, and thus reduced soil susceptibility to compaction. However, fly ash amendments increased water retention and the Proctor maximum density. Responses of various growth and yield components of smooth bromegrass (*Bromis inermis* L. cv. 'Magna') and alfalfa (*Medicago sativa* L. cv. 'Rambler') to subsurface compaction of sandy loam and clay loam textured soils were studied. All measured plant parameters were negatively related to increases in bulk density but the sensitivity of the response varied from one parameter to the other. For alfalfa plants the most sensitive parameter was the number of tertiary branches while for smooth bromegrass it was shoot dry biomass. A two-year field study investigated the impact of heavy, medium and light grazing of meadow bromegrass (*Bromis riparius* cv. 'Carlton) and triticale (*Triticosecale wittmack* cv. 'Pika'), on soil compaction and whether or

not any resulting compaction was alleviated by natural processes. In fall 1995, surface bulk density and penetration resistance were significantly ($p \leq 0.05$) higher for heavy than for medium and light grazing, but non-significant differences were obtained among grazing intensities in spring and fall 1996, and spring 1997. Bulk density in the top 5 cm decreased slightly over-winter, but slightly increased in the 5-10 cm depth interval, and did not change in the 10-15 cm depth interval.

These results imply that agronomic techniques such soil water management using appropriate consistency or agronomic limits, fly ash amendments, predicting 'soil compaction costs' in terms of yield reduction, and grazing management can be used individually or as combinations to minimize compaction and use of deep tillage.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

GENERAL INTRODUCTION AND OBJECTIVES

1.1 INTRODUCTION

Soil compaction is a process whereby soil bulk density increases. Compaction of agricultural soils may be caused by artificial means through use of heavy machinery currently used in agricultural and land reclamation practices and through animal grazing (O'Sullivan and Simota 1995).

There is growing evidence that soil compaction has adverse direct and indirect effects on the quality of the environment (Soane and van Ouwerkerk 1995). The term environment herein is used to represent the following components of the global environment, *viz.*, atmosphere, surface water, groundwater and soil. The increased emission of greenhouse gases into the atmosphere, in particular carbon dioxide (CO_2), methane (CH_4), ozone (O_3) and nitrous oxide (N_2O) is the main cause of global warming and the resulting anticipated changes in climate (Rolston et al. 1993). Compaction influences soil permeability, soil aeration and crop development and thus may change the fluxes of gases from soil to the atmosphere (Goldemberg 1990). Cultivation of compacted soils consumes large quantities of fuel that lead to enhanced emission of CO_2 from combustion of this fuel (Eradat and Voorhees 1990). Methane is reported to be 20 times more potent than CO_2 on a molecule for molecule basis and accounts for about 18% of the enhanced greenhouse effect (Goldemberg 1990). Methanogenic bacteria are strict anaerobes so that methane generation by these bacteria only occurs in soils that have high water contents and especially when they are waterlogged. Soil compaction reduces air-filled porosity and soil permeability so that high intensity rainfall or irrigation may result in temporary saturated conditions. Such conditions are ideal for generation of methane by methanogenic bacteria and thus result in increased emission of CH_4 and consequently enhanced greenhouse effect (Knowles 1993).

Nitrous oxide has a lifetime in the atmosphere of about 200 years and is reported to be 230 times more potent than CO_2 as a greenhouse gas (Goldemberg 1990). Denitrification involves the emission of N_2O and N_2 to the atmosphere and can be expected to accompany anaerobic conditions which occur when periods of high soil water content follow compaction. Under favorable conditions the loss of N_2O from compacted soils may be considerable.

Compaction influences both the amount and composition of runoff, owing to its reduction of infiltration rate. In areas where cattle slurry is applied, runoff tends to increase the loss of ammonia to the atmosphere as well as contribute to the pollution of surface waters. The major problem from this is that cattle slurry has a high biological oxygen demand (approximately 10-20 g O_2 L^{-1}) so that even small quantities of slurry entering surface waters may result in severe shortage of oxygen and the consequent death of many species, including fish (Soane and van Ouwerkerk 1995). However, if care is taken to avoid excessive compaction then it may be possible to prevent the decline of the infiltration rate sufficiently to permit surface application to be used without adverse environmental effects (Douglas and Crawford 1993).

Soil compaction limits root growth resulting in less uptake of NO_3 from the soil. The excess NO_3 in the soil will tend to enter groundwater through leaching or may be lost through denitrification. In most cases reducing nitrogen fertilizer application is recommended as a means of reducing nitrate levels into the groundwater. An alternative is to establish techniques for reducing the degree of soil compactness to achieve the same aim more efficiently. However such an alternative has not been examined yet (Soane and van Ouwerkerk 1995).

It is extremely important that soil quality is maintained to assure stable whole landscapes. The influence of compaction on soil may be considered in terms of physical, chemical and biological aspects. Generally compaction results in a considerably reduced saturated hydraulic conductivity leading to enhanced risks of all types of erosion by water which in extreme cases may eventually result in landscape devastation (Fullen 1985). Compaction also influences chemical processes that may adversely affect the demand and supply of plant nutrients. Because of decreased accessibility of nutrients, and increased losses of nutrients to surface waters, groundwaters and, in the case of nitrogen, to the atmosphere as a result of enhanced denitrification, fertilizer requirements on compacted soils are relatively greater than those of uncompacted soils (Boone 1988).

The soil structural alterations associated with compaction exerts a profound influence on soil biota and may cause a loss of habitat quality for macro-fauna, micro-fauna and many plant species. Of all soil fauna earthworms are probably the most important for the structure and the 'physical soil fertility' because they can move soil (Whalley et al. 1995). Compacted soils experience temporary saturation and therefore reduced oxygen supply, resulting in reduced earthworm activity that has been observed in some studies (Whalley et al. 1995).

The most common management practice for alleviating compacted soils is deep tillage or ripping. However, alleviating subsoil compaction through deep tillage is an expensive and time consuming process, and requires high powered tractors (Atkins 1990; Håkansson and Medvedev 1995). To optimize the machinery system on a farm, a farmer must be able to estimate and compare the cost of soil compaction for alternative soil management and machinery systems. For the past few years, efforts have been made to quantify these costs (Gunjal and Raghavan 1986; Arvidsson and Håkansson 1991; Oskoui and Voorhees 1991). Thus to minimize the use of deep tillage, several techniques can be adopted: 1) an understanding of the soil response to compactive forces is required and impacts of soil amendments on these responses, 2) an assessment of the growth and yield components of plants under compacted soil conditions as a way of providing guidelines for the amount of growth reduction caused by different levels of compaction and 3) an assessment of the level of compaction that can naturally be alleviated in the field, and to what degree, without the need for deep tillage.

Soil water and texture are the most important properties that determine the level of compaction, and therefore determine how susceptible soils are to compaction (Sichinga 1989). Civil and agricultural engineers have traditionally used Atterberg limits (plastic limit, liquid limit and plasticity index) to define the moisture contents between which a soil is susceptible to compaction. However, agronomists have always avoided cultivating soils when the moisture content is close to field capacity. Very little comparison has been made of the ranges of moisture of concern in agronomic versus engineering studies.

Fly ash, a by-product of coal combustion, is composed of silt-sized particles that can potentially alter soil texture when used as an amendment. Potential benefits include improved water holding capacity, water infiltration and aeration (Hammermeister 1995) and soil traffickability (Ziemkiewicz et al. 1981). A recent study of the changes in soil physical characteristics resulting from textural change induced by fly ash was conducted by Watson (1994). In his study the addition of fly ash to a silty clay soil decreased water retention while fly ash additions to a sandy loam soil increased it. However, very little information is available about the influence of fly ash on soil mechanical properties, and specifically on the compactibility of soils amended with fly ash.

Most often compaction results from frequent traffic of heavy machinery particularly when the soil is wet (Thacker et al. 1994). In Alberta many fields are put under perennial pasture for animal grazing and no cultivation practices are conducted after establishment of pastures. Others are planted to annual forages and grazed. Heavy stocking rates used in such grazing systems may lead to surface soil compaction due to trampling. Alberta has a relatively dry climate, and thus compaction is likely limited to short periods of time when the soil is wet. During winter, agricultural soils generally do not have sufficient moisture to form ice lenses that enhance soil loosening through freezing and thawing (Thacker et al. 1994). This means that once severely compacted, the soils are not likely to be ameliorated overwinter through natural processes.

This study addressed the following questions. What ranges of moisture content, in both engineering and agronomic terms, can be used to determine when soils are most vulnerable to compaction and thus can be used to indicate the 'danger zone' for soil trafficking and handling? Can soil amendments such as fly ash alter this 'danger zone' soil moisture within which soils are most susceptible to compaction? What plant parameters are most sensitive to compaction, and what degree of compaction would cause severe reduction in growth and yield of plants? What degree of compaction can be alleviated by natural processes under field conditions? Answers to these questions may help develop alternative management strategies that could be used to determine the need for deep tillage.

1.2 OBJECTIVES

The study was composed of four main objectives:

(1) To investigate the response of three soils of different textures to compaction.

(2) To investigate the response of fly-ash amended soils to compaction.

(3) To investigate the response of growth and yield components of two plant species to different levels of compaction.

(4) To investigate the response of cattle-induced field soil compaction to natural alleviation processes overwinter.

The first two objectives were accomplished in the laboratory, while the third objective was addressed in a greenhouse study and the last in the field.

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CHAPTER 2

RESPONSE OF SELECTED NON-AMENDED SOILS TO COMPACTION

2.1 INTRODUCTION

Soils are considered to be compacted when the total porosity and, in particular, air-filled porosity are so low as to restrict soil aeration and also when soil has high strength and its pores are small so as to impede root penetration and drainage (Bennie 1991). Compactibility refers to the maximum density to which a soil can be packed by a given amount of energy (Naeth et al. 1991). There are several factors that influence soil compactibility, *viz.* inherent bulk density, soil structure, organic matter content, soluble salt concentration and most importantly water content and compactive effort (Thacker et al. 1994). These factors also influence soil workability and trafficKability. Workability is defined as the mechanical manipulation of soil with little or no structural damage, while trafficKability refers to the ability of a soil to bear traffic load without structural damage (Larson et al. 1994). TrafficKability results from soil-wheel or track interactions and it determines the ability of a soil layer to react to a given implement under given conditions of initial structure and water content (Guérif 1994).

Agronomists have traditionally used water retention at field capacity as the appropriate upper limit for soil water content that provides a balance between good soil aeration and uptake of water by plants (Hillel 1980). The wilting point has been defined as the lower limit for soil water content below which plants will not be able to extract water, and thus will start to wilt and eventually die. Soil scientists define moisture content retained at 0.033 MPa as the field capacity, while water retained at 1.5 MPa is the wilting point. In the field, a working definition of field capacity is the moisture content of soil that has drained for 2-3 days after a rain or irrigation without evapotranspiration (Hillel 1980).

Farmers usually wait for at least two days after a rainfall to start cultivating the land. This implies that cultivation practices are not likely to be carried out at moisture contents above field capacity. Hence the cultivation zone moisture content is between field capacity and wilting point. However, in fine textured soils the soil is in a plastic state at moisture contents below field capacity. Cultivating the soil in its plastic state poses severe compaction hazard. In addition, given larger tractors and wider cultivators, farmers are now able to cultivate much closer to water bodies and thus under higher soil moisture contents than previously.

The soil consistency limits (also called Atterberg limits) *viz.* liquid limit, plastic limit and plasticity index have traditionally been used by engineers as guidelines for the range of moisture content that represents compaction hazard. Few agronomists use these limits in their compaction research. The liquid limit is the water content at which the soil's behavior changes from liquid to plastic. Mechanistically this limit is the water content at which sufficient water is present to allow clay particles to slip past one another under a certain applied force (Warkentin 1961). The plastic limit is the water content at which soil can be deformed without rupture or the water content at which the remolded clay passes from the plastic to a friable or brittle condition (Skempton 1970). The plasticity index is also referred to as the plasticity number, and is the difference between the liquid limit and the plastic limit. This index indicates the range of moisture content over which a soil is plastic. Soil plasticity is greatly affected by the size and shape of soil particles (Baver 1930). Since plasticity is a function of the finer soil particles, various soils will possess different plasticities according to the amount of clay or colloids they contain. Early studies of Terzaghi (1926) showed that an increase in the percentage of clay increases both liquid limit and plastic limit and increases the plasticity index.

The Atterberg limits have also been used in the estimation of other test indices useful for soil engineering interpretations, such as bearing capacity and shear strength, compactibility, swelling potential, and specific surface (McBride 1989). The Atterberg limits were used in early studies of the tillage of soils with the plastic limit being recognized as the highest possible soil water content for cultivation (de Jong et al. 1990). Some attempts have been made to relate soil workability to the ratio of the soil water contents at field capacity and at the plastic limit (Larney et al. 1988). However, few studies have attempted to investigate relationships between agronomic limits (i.e. field capacity and wilting point) and the Atterberg limits. Such information would provide a better understanding of the linkage, if any, between an engineer's view of soil as a construction material or tillage zone, and an agronomist's view of soil as a medium for plant growth.

A laboratory test was developed by Proctor (1933) for the determination of the optimum moisture content (OMC) at which a soil can be compacted to a maximum bulk density (MBD). This test is known as the Proctor Compaction test and has long been used by civil engineers for predicting the stability of road and building foundations. The moisture content at which this maximum density occurs is called 'optimum' in engineering work. This is called 'critical moisture content' (CMC) in this study following the recommendations of several researchers (Saini and Chow 1984; Ohu et al. 1989; Stone and Ekwue 1993), because in agricultural work, soil compaction is undesirable and the moisture content at which its maximum occurs should be called critical not optimum. More recently, this test has been used to determine maximum bulk density and critical moisture content in agricultural soils, so that cultivation by farm machines or vehicle traffic in land reclamation can take place at less than this moisture content (Felton and Ali 1992; Wagner et al. 1994; Ekwue and Stone 1995). At moisture contents lower than the CMC, lubrication is not complete, and soil particles under a given compactive effort will not pack closely leaving voids in the mass, and resulting in a lower density than MBD. On the other hand, if the moisture content is greater than CMC, then moisture will occupy the place which would have been occupied by the soil particles, thereby lowering the bulk density. Therefore Atterberg limits may provide a means of calculating the range of compactibility of soils.

Several studies have reported empirical relationships between bulk density, water content and penetration resistance. For example Ehlers et al. (1983) found that penetration resistance increases with an increase in bulk density and a decrease in water content for both tilled and untilled soils. In a more recent study, penetration resistance was found to vary markedly with time and was closely related to changes in soil water content (Martino and Shaykewich 1994). Thus generally it is accepted that penetration resistance is related to moisture content and bulk density. However, such a relationship may vary from one soil to another depending on soil texture (Taylor and Ratliff 1969). Cone penetrometers which measure penetration resistance (PR) provide an easy technique for assessing compaction, but the relationship of PR with moisture content and bulk density needs to be investigated.

This study was conducted to test the following hypotheses:

1) Soil consistency limits, agronomic limits and the Proctor critical moisture content are not related and cannot be used to define moisture ranges over which maximum compaction occurs.

2) There is no functional relationship between penetration resistance, bulk density, moisture content and soil texture.

2.2 MATERIALS AND METHODS

2.2.1 Soil physical and chemical properties

The three soils used in the study included two soils from a reclaimed surface mine site 80 km west of Edmonton, Alberta (a clay loam topsoil and a sandy loam subsoil), and one soil (Orthic Black Chernozem of loam texture) from a grazing site at Lacombe 130 km south of Edmonton, Alberta.

All soils were air-dried and ground to pass a 2-mm sieve. Particle size distribution was determined using the hydrometer method (Sheldrick and Wang 1993). Water retention characteristics were determined using pressure plates.

The amount of gravimetric moisture retained at pressures of 0.010, 0.033, 0.050, 0.10, 0.30 and 1.50 kPa was determined in replicates of three.

Soil chemical properties determined in replicates of five for the soils included pH, electrical conductivity (EC), sodium adsorption ratio (SAR), soluble cations (Ca, Mg, Na and K), and organic matter content (OM). The pH was determined by glass electrode in 1:2 ratios of soil to 0.01 M $CaCl_2$ and soil to distilled water suspensions (Sheldrick 1984). Saturation paste extracts (Richards 1954) were prepared and analyzed to determine electrical conductivity and soluble cations. Electrical conductivity provides a rapid and reasonably accurate determination of solute concentration and depends on the ionic composition of the solution. Soluble calcium and magnesium concentrations were measured using atomic absorption spectrophotometry while sodium and potassium concentrations were measured using flame emission. Organic carbon was determined using the modified titrimetric dichromate redox Walkley and Black method outlined by Tiessen and Moir (1993).

2.2.2 Soil compactibility and consistency limits

The Proctor test and Atterberg limits were the two approaches used in this study to determine moisture contents at which the soils are most susceptible to compaction. The standard Proctor test was used to obtain moisture-density curves for each soil sample from six specimens. Each specimen was moistened to a different moisture content with a goal that the optimum moisture content was between the lowest and highest moisture content. The amount of water to be added was determined from the average moisture content of air-dry soil and the weight of air-dry soil. The specimens were then compacted in three equal layers in molds of height 101 mm. Each layer received 25 blows from a standard Proctor hammer of weight 2.5 kg. According to Raghavan and Ohu (1985), 25 Proctor compaction blows result in an equivalent static pressure of 0.618 MPa. The mass of the mold filled with compacted wet soil was measured before the soil was removed and broken up and then oven-dried at 105 °C. Bulk density was calculated from the mass of oven-dried soil divided by the volume of the mold. The actual moisture content was determined after oven-drying.

The consistency limits determined in this study included plastic limit, liquid limit and the plasticity index. The plastic limit is the gravimetric moisture content at which the soil stiffens from a plastic to a semi-rigid and friable state. In practice this limit is the moisture content at which a sample of soil can be rolled into a thread of 3-mm diameter without breaking. In this study this test was conducted by wetting 10 g of dry-sieved soil (< 2 mm in diameter) with distilled water. The wet soil was then shaped into an ellipsoidal ball and rolled by hand on a glass plate until a thread of about 3 mm in diameter was formed. The soil was reformed into an ellipsoidal ball and rolled out again. This process was repeated until the soil could no longer be rolled into a 3-mm thread (Jumikis 1984). The crumbled soil was then oven-dried at 105 °C to determine the moisture content at the plastic limit.

The liquid limit (LL) was determined using the one-point Casagrande method (McBride 1993). A mechanical device consisting of a specified size cup made of brass and weighing about 200 g, a cam and crank mounted on a hard rubber block and a grooving tool, was used for the test. The gravimetric moisture content (w) of the soil at which between 20 and 30 blows were required to close a groove along a distance of 13 mm was determined by oven-drying. Two consecutive closures of the groove were observed before taking a sample for moisture content determination. The liquid limit (LL) was then determined from the number of blows (N) and the gravimetric moisture content (w) of the sample:

$$LL = w(N/25)^{0.12} \qquad (2.1)$$

The plasticity index (PI) was calculated as the difference between the liquid limit (LL) and the plastic limit (PL) and reflects the range of moisture content over which the soil is susceptible to compaction by external forces

(McBride 1993). The higher the PI value, the greater the range of moisture over which the soil is susceptible to compaction.

2.2.3 Functional relationships

A laboratory experiment was designed to investigate the functional relationships between penetration resistance, bulk density and moisture content for the three soils of different textures; sandy loam, loam and clay loam. For each soil, four equally spaced moisture contents were chosen in such a way that the highest and lowest moisture contents fell at field capacity (moisture content at pressure of 0.033 MPa) and wilting point (moisture content at a pressure of 1.50 MPa) respectively. Four bulk densities were selected such that the lowest density was equal to the settling density. Each treatment was replicated twice. Settling density was determined on soil samples poured into the Proctor mold and tapped 10 times on a bench. For the clay loam and loam soils, settling density was increased by 10, 20 and 30% to produce low, medium and high bulk densities used in this study. For the sandy loam, increments of 15, 30 and 45 % were used to achieve low, medium and high bulk densities respectively. These increments were based on the calculation of maximum achievable bulk densities at the four moisture contents assuming a particle density of 2.65 Mg m^{-3} for all soils. To achieve these selected densities, measured amounts of air-dried soil was compacted in a cylindrical pot of 20-cm diameter to a depth of 7.5 cm using a standard Proctor hammer to fit in a specified volume.

A small diameter cone penetrometer (30° angle and basal area of 3.2 cm^2) was used to measure penetration resistance at three locations within the pot. At each location two readings were taken, one at the surface and the other at a depth of 2.5 cm, so that a total of six penetrometer readings were taken for each treatment. Readings taken at the surface and at the 2.5-cm depth were averaged before conducting statistical analyses.

2.2.4 Statistical analyses

Statistical analyses were conducted using a SAS package (SAS Institute 1989). Analysis of variance was conducted using the Generalized Linear Models procedure for the completely randomized design. Test for normality of data distribution for each data set was conducted using the W-test (Shapiro and Wilk 1965). Multiple linear regression analysis was performed using a stepwise procedure to determine the best regression model to describe variation in the penetrometer resistance as a function of bulk density and moisture content. From this, conclusions were drawn about which variable or variables were dominant in determining the variability of penetration resistance.

2.3 RESULTS

2.3.1 Soil physical and chemical properties

The organic matter content was greatest in the loam and least in the sandy loam soil (Table 2.1). The sandy loam was slightly alkaline while the clay loam and loam were acidic.

Moisture retention for all three soils increased as matric suction decreased. However, the rate of decrease of water retention with an increase in matric suction was greater in sandy loam than in clay loam soil (Figure 2.1). Statistical analysis indicated that both field capacity and wilting point were significantly different among soils ($p \leq 0.05$) (Table 2.2). The values of FC for sandy loam and loam soils were within three percentage points of the corresponding CMC values.

2.3.2 Soil compactibility and consistency limits

As expected, starting from a relatively dry condition, the attainable bulk density at first increased with an increase in soil moisture, then reached a peak called maximal density at a wetness called optimum (or critical) moisture content, beyond which the density decreased (Figure 2.2).

The Proctor maximum bulk density, critical moisture content, liquid limit, plastic limit, field capacity and wilting point were significantly ($p \leq 0.05$) different among soils of different texture (Table 2.2). Plasticity indices for sandy loam and loam were similar. Test for normality of data distribution using the W-test (Shapiro and Wilk 1965) indicated that data each of the limits determined were normally distributed as required in parametric statistics.

The critical moisture content (CMC) for the sandy loam was significantly ($p \leq 0.05$) lower than that for either loam or clay loam soil (Table 2.2) and significantly ($p \leq 0.05$) greater for the clay loam than that for loam soil. The sandy loam had significantly greater Proctor maximum bulk density (MBD) than that for either the clay loam or loam soil. However, MBD values for loam and clay loam soils were non-significantly different.

The liquid limit (LL) for the clay loam soil was significantly ($p \leq 0.05$) greater than that for either sandy loam or loam soil (Table 2.2.). The plastic limits (PL) for sandy loam, loam and clay loam were significantly ($p \leq 0.05$) different from each other. However, the PLs for these soils were within three percentage points of each other. The plasticity index (PI) for clay loam was significantly ($p \leq 0.05$) greater than that for either sandy loam or loam while PI for sandy loam was similar to that for loam soil. This means that the clay loam is prone to compaction over a wider range of moisture contents than either the sandy loam or loam soils.

The CMC for the clay loam was lower than the PL by almost three percentage points, while that for loam and that for sandy loam was lower by seven and eleven percentage points respectively (Figure 2.3). This means that for the clay loam soil either the plastic limit or the CMC could be used to set the moisture for handling or trafficking soils without exposing them to compaction. This is in agreement with the observations of Thacker et al. (1994) who showed that generally soils of texture ranging between loam and clay have PL values that are very close to (within three percentage points) CMC values. However, for the loam and sandy loam soils this study shows that plastic limit cannot be reliably used to estimate the moisture content at which the soil is most susceptible to compaction.

2.3.3 Functional relationships

For the sandy loam soil at a moisture content of approximately 8%, penetration resistance (PR) increased 24-fold (i.e. from 0.07 to 1.66 MPa) between settling density (1.20 Mg m^{-3}) and highest density (1.74 Mg m^{-3}) (Figure 2.4). For all four moisture levels, the average penetration resistance for the highest density was at least fourteen times greater than that for the settling density.

The PR response of the loam soil to different moisture and density treatments was similar to that of the sandy loam soil (Figure 2.5). Between settling density (1.18 Mg m^{-3}) and highest density (1.53 Mg m^{-3}) the average PR increased by at least 6 fold. For each bulk density the average PR varied with moisture content. For approximately equal bulk densities and moisture contents, the average PR for a sandy loam was greater than that for a loam. However, at a gravimetric moisture content of 16% the PR for loam was greater than that for the sandy loam. This may be due to the fact that this level of moisture is greater than the field capacity of sandy loam and therefore caused comparatively less frictional resistance in the sandy loam than in the loam, as suggested by Ekwue and Stone (1995).

For the clay loam soil, PR increased with an increase in density (Figure 2.6), reaching a maximum at a moisture content close to wilting point. At this moisture content the PR for the highest density (1.50 Mg m^{-3}) was more than double that for the settling density (1.15 Mg m^{-3}). For the settling density treatment, PR decreased 12-fold between 24 and 47% gravimetric moisture contents, whereas for the maximum density treatment (1.50 Mg m^{-3}) PR decreased by 20 times within the same moisture range.

2.3.4 Regression analysis

The relationship between PR, bulk density and moisture content was significantly ($p \leq 0.05$) affected by soil texture. For the sandy loam soil, PR (MPa) was significantly ($p \leq 0.05$) positively related to bulk density (BD in Mg m^{-3}) as indicated in equation 2.2;.

$$PR = 4.19BD - 4.98 \qquad (2.2)$$

$R^2 = 0.85$, n=32

For the loam soil, PR was significantly ($p \leq 0.05$) positively dependent on BD as indicated in equation 2.3;

$$PR = 3.99BD - 4.49 \qquad (2.3)$$

$R^2 = 0.90$, n = 32

For the clay loam soil, PR was significantly positively related to BD and significantly ($p \leq 0.05$) negatively related to volumetric moisture content (VMC in $m^3/100\ m^3$) with moisture content accounting for a greater variation of PR than did bulk density (equation 2.4).

$$PR = 1.90BD - 0.05VMC - 0.43 \qquad (2.4)$$

$R^2 = 0.75$, n=32

These equations show that the slope of regression associated with bulk density decreased from coarse to fine textured soil. However, the difference in the slopes between sandy loam and loam soils was less pronounced compared to the difference in the slopes of loam and clay loam soils.

A PR of 2 MPa is often used as a threshold beyond which plant growth becomes severely restricted (Taylor et al. 1966; Naeth et al. 1991). Using the above equations for the sandy loam it is predicted that a PR of 2 MPa can be achieved at density of 1.67 Mg m^{-3} at any moisture content. For the loam soil the density at which a PR of 2 MPa can be achieved is 1.63 Mg m^{-3} and does not vary with soil moisture. For the clay loam soil at volumetric moisture contents of 10, 20 and 30%, the corresponding bulk densities at which a PR of 2 MPa can be achieved are 1.54, 1.80 and 2.07 Mg m^{-3} respectively.

2.4 DISCUSSION

The LL of soils containing high amounts of clay is primarily controlled by two factors: (1) the shearing resistance at particle level, and (2) the thickness of the diffuse double layer. In soils with high amounts of montmorillonite clays the contribution of the shearing resistance to controlling the LL is minimal compared to the contribution of the electrical double layer (Sridharan et al. 1986). The control of the LL due to the diffuse double layer comes as a result of the fact that clays are negatively charged mainly due to isomorphous substitution.

The physico-chemical mechanisms affecting the plastic limit include the amount of coarse fraction, thickness of diffuse double layer as well as the fabric of clays (Venkatappa Rao and Rekhi 1977). The PL is greater in soils with smaller fractions of coarse-sized grains and lower diffuse double layer thickness. Coarse-sized particles act as a diluent and cause the plastic limit of sandy loam and loam soils to be lower than that for the clay loam.

In this study higher PI of clay loam than that for sandy loam or loam means that the clay loam is prone to substantial compaction over a wider moisture content range than either the sandy loam or loam soils. According to Jumikis (1984) a PI < 7 indicates that a soil is of low plasticity, $7 < \text{PI} < 17$ indicates medium plasticity while PI > 17 indicates high plasticity. Using these guidelines the clay loam used in this study is highly plastic while the sandy loam and loam have low plasticity and therefore are less prone to severe compaction because of the narrow moisture range within which deformation would occur. For each soil it is not advisable to use heavy machine traffic such as that used in reclamation or to allow animal treading when the water content of the soil is between the plastic limit and liquid limit.

Thus the range of moisture content, which is the 'danger zone', within which the soils can be easily compacted when external pressure is applied, is narrower in coarse-textured soils compared to fine-textured ones, as expected. For the sandy loam and loam-textured soils, field capacity is much below this 'danger zone'. Thus cultivation of soil at field capacity would unlikely cause severe soil compaction. However, land users must be cautious since maximum densification for these soils occurs at moisture (CMC) close to field capacity. Furthermore, the determination of Atterberg limits for coarse-textured soils is not reliable, so that CMC may be used as guide to moisture content unsuitable for cultivation.

For the clay loam FC lies in the 'danger zone' for soil workability. Cultivation of this soil at or near FC could result in severe compaction. Even at moisture halfway between FC and WP, cultivation would still cause compaction since the soil water content would be within the danger zone. Furthermore, maximum densification for this soil occurs at a moisture content (CMC) below plastic limit and also between FC and WP. This means that for the clay loam, the range of moisture within which the soil is most susceptible to compaction may be wider than previously thought. This result agrees with the results of Thacker et al. (1994) who found that for seven soils ranging from loam to clay loam texture the plastic limit was within three percentage points of the CMC. According to Baver (1930) maximum compactibility occurs over a moisture range approximately the same as that over which plasticity exists. In this study this statement holds for the clay loam soil.

For the sandy loam and loam soils, the positive relationship between penetration resistance and bulk density, and lack of relationship between penetration resistance and moisture content suggests that soil lubrication due to increased water content may not have been as influential as particle rearrangement in determining the magnitude of penetration resistance (Chancellor 1971). This is probably due to the fact that sand grains in these soils interlock with a high soil-metal friction irrespective of the water content of the soil. However, for the clay loam the moisture content determined most of the variation of penetration resistance, probably because for this soil a relatively greater fraction of fine sized particles gives it a larger surface area, and thus greater water retention. Consequently the addition of water will provide lubrication between particles, and since there is a relatively smaller fraction of sand grains that cause high frictional resistance, the penetration resistance becomes dependent on the soil's cohesive status which decreases as soil water increases.

2.5 CONCLUSIONS

Field capacity for the clay loam soil is in the 'danger zone', i.e. FC is in the range within which the soil is plastic. Therefore trafficking and cultivation must be avoided when this soil is at field capacity. For the three soils used in the study either field capacity or plastic limit, whichever is less, is recommended as a threshold moisture content beyond which trafficking should be avoided.

The nature of the relationship between penetration resistance, bulk density and moisture content depends on soil texture. Bulk density is the dominant independent variable that determines penetration resistance of coarse-textured soils (sandy loam and loam), whereas for the fine-textured soils (e.g. clay loam) moisture content is the dominant independent variable that accounts for most of the variation in penetration resistance.

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Table 2.1. Physical and chemical properties of the three soils used in the study.

Soil characteristic	Sandy loam	Loam	Clay loam
Sand (%)	70	51	25
Silt (%)	14	34	35
Clay (%)	16	15	40
Organic matter (%)	0.5	9.5	3.6
pH (using 0.01M $CaCl_2$)	7.4	4.8	5.9
Electrical conductivity (dS m^{-1})	0.43	0.31	0.40
Ionic strength (moles L^{-1})	0.006	0.004	0.005
Sodium adsorption ratio	7.9	0.2	4.3

Table 2.2. Proctor maximum bulk density, critical moisture content, agronomic and Atterberg limits for three soils of different textures.

Soil characteristic	Sandy loam	Loam	Clay loam
Proctor maximum density (Mg m^{-3})	1.74a†	1.48b	1.46b
Critical moisture content (g/100g)	14.5c	20.4b	24.3a
Field capacity (g/100g)	15.2c	18.7b	34.8a
Wilting point (g/100g)	6.5c	10.8b	18.2a
Liquid limit (g/100g)	30.2c	33.9b	51.1a
Plastic limit (g/100g)	25.1c	27.9a	27.1b
Plasticity index (g/100g)	5.2b	6.0b	24.0a

† Within rows, means followed by the same letter indicate non-significant difference ($p \leq 0.05$); n=3; field capacity measured at 0.033 MPa; wilting point at 1.50 MPa.

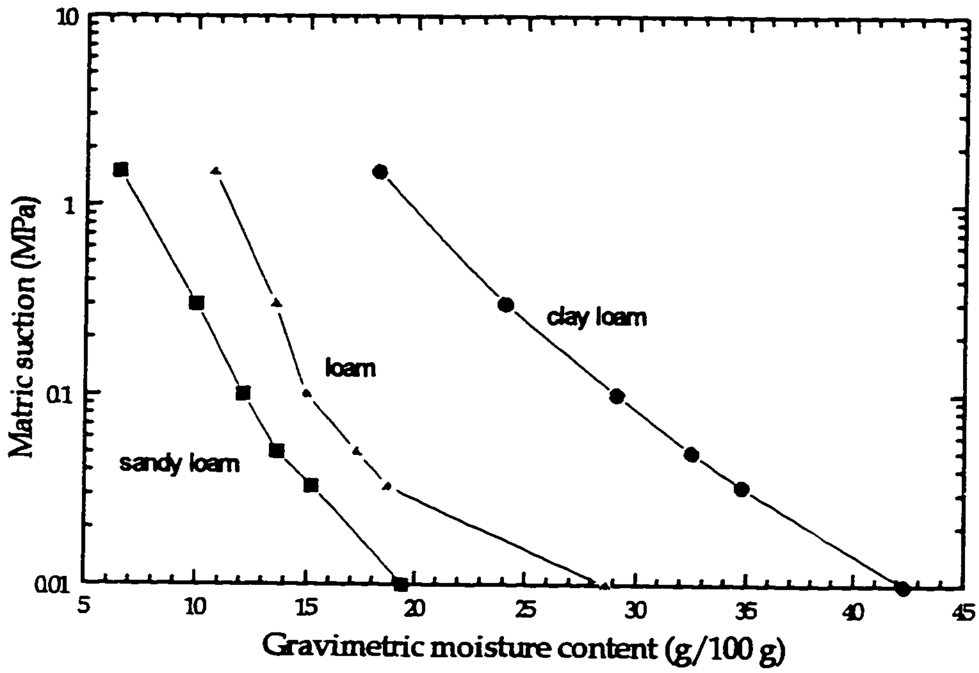

Figure 2.1. Water retention curves of the three soils used in the study.

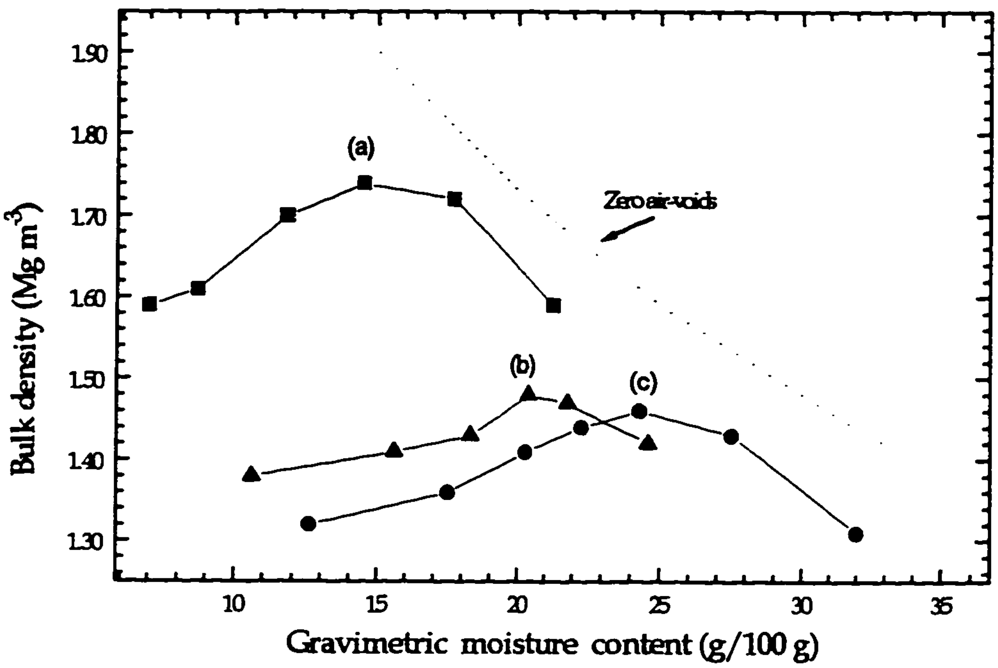

Figure 2.2. Proctor density curves for (a) sandy loam, (b) loam and (c) clay loam soils.

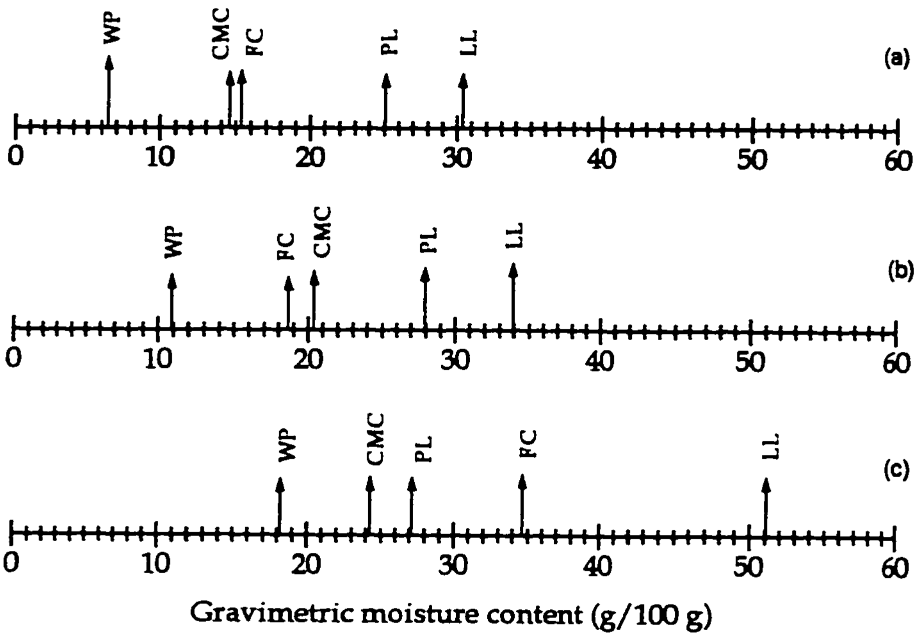

Figure 2.3. Wilting point (WP), field capacity (FC), critical moisture content (CMC), plastic limit (PL) and liquid limit (LL) of (a) sandy loam, (b) loam and (c) clay loam soils.

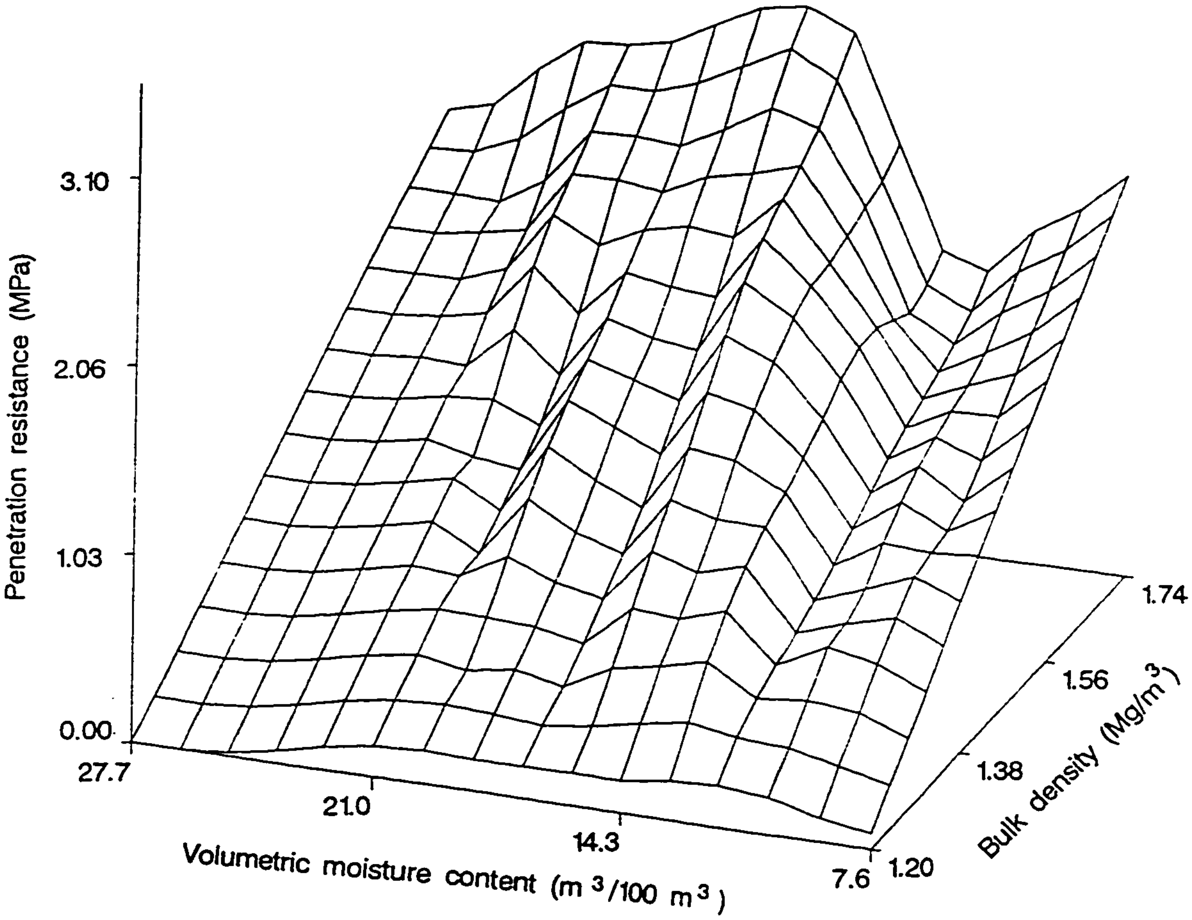

Figure 2.4 Variation of penetration resistance (MPa) of sandy loam soil with bulk density and moisture content.

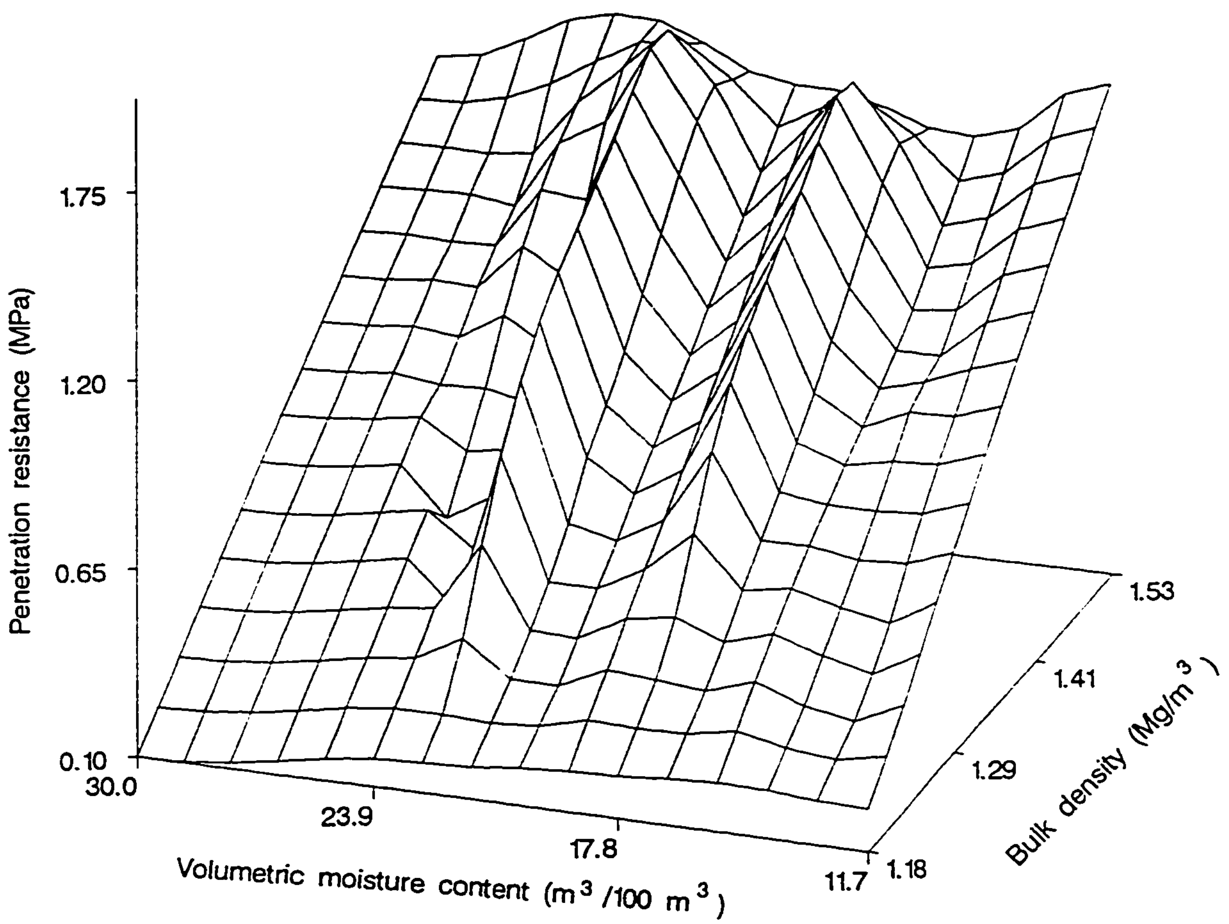

Figure 2.5 Variation of penetration resistance (MPa) of loam soil with bulk density and moisture content.

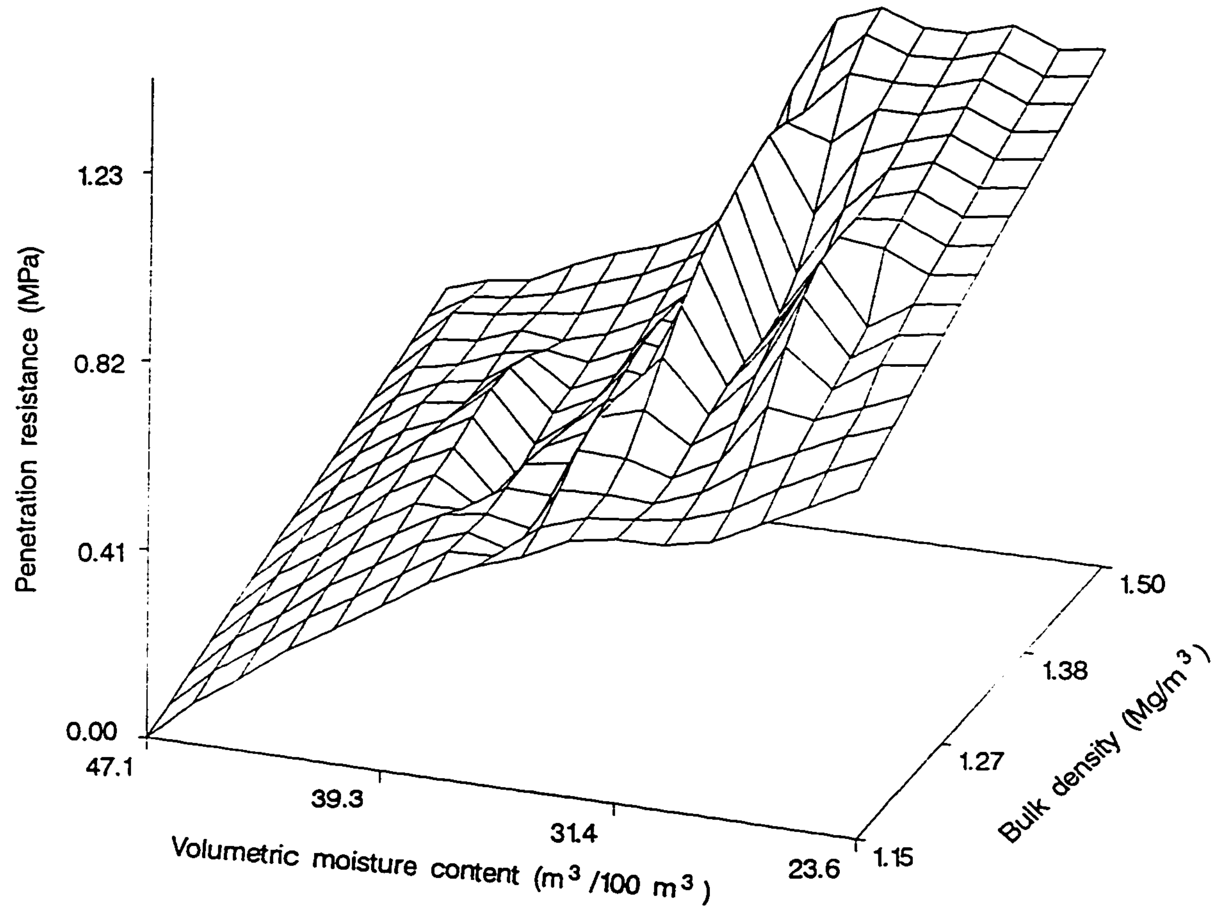

Figure 2.6 Variation of penetration resistance (MPa) of clay loam soil with bulk density and moisture content.

CHAPTER 3

RESPONSE OF FLY-ASH AMENDED SOILS TO COMPACTION

3.1 INTRODUCTION

Current energy policies worldwide consider generation of thermal power as a major source of electricity for industrial development. Fly ash generated from the combustion of coal presently comprises about 500 million tonnes every year and is expected to increase to 850 million tonnes by the year 2000 (Sivapullaiah et al. 1996). Fly ash is the residue from coal combustion that enters the flue gas stream. It is predominantly composed of fine particles and is either collected in emission control devices, such as electrostatic precipitators or mechanical filters, or released from the stack. Fly ashes are composed of small, glassy, spherical particles ranging from 0.01 to 100 μm and specific gravities of 2.1 to 2.6 (Adriano et al. 1980). Fly ash is a complex heterogeneous material consisting of both crystalline and non-crystalline phases (El-Mogazi et al. 1988).

Currently there are two methods for the disposal of fly ash: settling ponds and landfills (Carlson and Adriano 1993). The major potential adverse impacts of ash disposal on terrestrial ecosystems include: leaching of potentially toxic substances from the ash into soils and groundwater, reduction in plant establishment and growth due to the ash, changes in plant elemental composition and increased cycling of potentially toxic elements through the food chain (Carlson and Adriano 1993). Research has been conducted on utilizing fly ash for various purposes to minimize the disposal problems and requirements. Vast quantities of fly ash have been used in geotechnical engineering for construction of embankments, dams, as backfill behind retaining walls and for land reclamation (Torrey 1978; Mattigod et al. 1990). However, such uses consume a very small fraction of total fly ash production (approximately 10 to 20%), so the disposal problem is still very much at hand (Watson 1994). Very little research has been conducted on the impact of fly ash on soil workability.

The Proctor compaction test provides a standardized method of quantifying soil resistance to compaction over a range of soil water contents under a given compaction effort. According to Hillel (1980) the line connecting the peaks of all the bulk density versus wetness curves (i.e. all Proctor Compaction curves) corresponds approximately to 80% degree of saturation. Given the critical moisture content (CMC) and Proctor maximum bulk density (MBD) of a soil the degree of saturation (S) can be obtained from equation 3.1;

$$S = \frac{\rho_s * CMC}{\rho_w(\frac{\rho_s}{MBD} - 1)} \quad (3.1)$$

where ρ_s is the soil particle density (Mg m^{-3}) and ρ_w is the density of water and is equal to 1 Mg m^{-3}. This equation is a physically-based model that relates a degree of saturation (S) to the maximum bulk density obtained from the Proctor test and has been used to estimate MBD from given values of CMC for soils of various textures (Wagner et al. 1994) and for soils amended with organic materials such as peat, farmyard manure, filter press mud (Stone and Ekwue 1993) and sewage sludge (Ekwue and Stone 1997). This model has not been tested on fly ash amended soils.

Soil consistency limits (Atterberg limits) include the plastic limit, liquid limit and the plasticity index, which is the difference between the liquid limit and the plastic limit. The Atterberg limits have traditionally been used in engineering to provide guidelines for the soil moisture range that represents optimum compaction (Atterberg 1911). These limits were used in early studies of the tillage of soils with the plastic limit being recognized as the highest possible soil water content for cultivation (de Jong et al. 1990). Some attempts have been made to relate soil workability to the ratio of the soil water contents at field capacity and at the plastic limit (Larney et al. 1988). Few studies have attempted to investigate relationships between agronomic limits (i.e. field capacity and wilting point) and the Atterberg limits. Furthermore no studies have been conducted on the impact of fly ash amendments on agronomic compared to Atterberg limits. Such information would provide a better understanding of the impact of fly ash amendments on agronomic and Atterberg limits, and on the relationships between penetration resistance, bulk density and soil moisture of soils amended with fly ash.

Water retention at field capacity has traditionally been used by agronomists to indicate the upper limit for soil water that provides a good balance between good soil aeration and uptake of water by plants (Hillel 1980). Wilting point has been defined as the lower limit for soil water below which water extraction by plants ceases and plants will start to wilt and eventually die. Soil scientists have defined water retention at 0.033 MPa as the field capacity, while water retained at 1.5 MPa is the wilting point. However, the field definition of field capacity is the water retained 2-3 days after a rain or an irrigation (Hillel 1980). Land users have a tradition of waiting at least two days after a rainfall, before starting cultivation and other soil handling procedures. This means cultivation is not likely to be carried out at soil water content above field capacity, and thus the cultivation becomes limited to moisture contents between field capacity and wilting point.

Because fly ash consists mainly of silt-sized particles, ash addition to soils high in sand or clay can alter soil texture. However, few studies have examined the impact of fly ash on soil physical properties and most of these studies have focused on its effect on bulk density (Chang et al. 1977; 1989). The use of fly ash has been reported to affect all common soil physical and chemical characteristics, except for soil plasticity, compactibility and soil strength (Adriano et al. 1980). Because of its pozzolanic property, the presence of free lime and the inert state of its particles, fly ash can possibly be used to improve workability of the soil by reducing its plasticity. Sivapullaiah et al. (1996) concluded that the addition of fly ash improved the workability of an expansive soil. In their study, the addition of fly ash increased the plastic limit but decreased the liquid limit. Overall, the plasticity index decreased, i.e. fly ash decreased the range of moisture content within which the soil is most susceptible to compaction. This is the only research cited on the impact of fly ash amendment on soil plasticity.

Evidence in the literature indicates that root growth ceases after soil penetration resistance reaches some critical value (Gerard et al. 1982). Several authors have assumed this threshold value to be 2 MPa (Taylor et al. 1966; Naeth et al. 1991; Bennie 1991). Extensive research has shown that empirical relationships between penetration resistance, bulk density and moisture content vary from one soil to another depending on soil texture (Taylor and Ratliff 1969; Ehlers et al. 1983; Martino and Shaykewich 1994). The addition of fly ash to soils of different textures may potentially alter these empirical relationships. However, again no studies have been conducted on this topic. Such studies would be very useful to agronomists and reclamation specialists and would provide information about the potential use of fly ash in reducing soil workability problems while, at the same time, helping to solve a disposal problem for the generating industry.

The study reported herein was conducted to test the following hypotheses:

(1) Plasticity, compactibility and water retention do not depend on soil texture.

(2) Fly ash amendments do not affect soil plasticity, compactibility and water retention.

(3) Fly ash amendments do not affect the functional relationships between penetration resistance, bulk density and soil moisture content.

3.2 MATERIALS AND METHODS

3.2.1 Soil physical and chemical properties

The three soils used in the study included two soils from a disturbed, reclaimed surface mine site 80 km west of Edmonton, Alberta (a clay loam topsoil and a sandy loam subsoil), and one soil (Orthic Black Chernozem of loam texture) from a grazing site at Lacombe, 130 km south of Edmonton, Alberta. Particle size distribution for non-amended soils and for the fly ash used in the study was determined using the hydrometer method (Sheldrick and Wang 1993). The sandy loam contained 70% sand, 14% silt, and 16% clay. The loam soil contained 51% sand, 34% silt and 15% clay. The clay loam soil contained 25% sand, 35% silt and 40% clay. Organic carbon was determined using the modified titrimetric dichromate redox Walkley and Black method outlined by Tiessen and Moir (1993). The organic matter contents were 0.5%, 9.5% and 3.6% for the sandy loam, loam and clay loam, respectively.

The unweathered fly ash used in the study was collected from the Highvale mine. The ash contained a large amount of silt-sized particles (Table 3.1) and less than 10% clay sized particles. The fly ash was highly alkaline and it contained substantial concentrations of calcium, sodium, magnesium and potassium.

Water retention characteristics of the non-amended soils and fly ash amended soils were determined using pressures of 0.033 and 1.50 MPa. Soil chemical properties determined for the soil/fly ash mixtures included pH, electrical conductivity (EC), sodium adsorption ratio (SAR) and soluble cations (Ca, Mg, Na and K). The procedures used to determine these properties have already been described in Chapter 2 of this dissertation.

3.2.2 Soil compactibility and consistency limits

The Proctor test and measurement of Atterberg limits were the two approaches used in this study to determine moisture contents at which the fly ash-amended soils are most susceptible to compaction. The procedures used to determine maximum Proctor density and consistency limits were already described in Chapter 2 of this dissertation.

3.2.3 Functional relationships

A laboratory experiment was designed to investigate the functional relationships between penetration resistance, bulk density and moisture content for both non-amended and fly ash amended soil mixtures. The experiment consisted of three soils (sandy loam, loam and clay loam in texture), four rates of fly ash (0, 5, 10 and 20% of the original soil by volume), four bulk density levels and four levels of moisture content. For each soil or soil/fly ash mixture, four equally spaced moisture contents were chosen in such a way that the highest and lowest moisture contents fell at field capacity (0.033 MPa) and wilting point (1.50 MPa) respectively. Four bulk densities were selected such that the lowest density was equal to the settling density. For the clay loam and loam soils, settling density was increased by 10, 20 and 30% to produce low, medium and high bulk densities used in this study. For the sandy loam, increments of 15, 30 and 45 % were used to achieve low, medium and high bulk densities respectively. These increments were set based on the calculation of maximum achievable bulk densities at the four moisture contents assuming a particle density of 2.65 Mg m^{-3} for all soils. To achieve these selected densities, measured amounts of air-dried soil amended with different rates of fly ash were compacted in cylindrical pots of 20-cm diameter to a depth of 7.5 cm using a standard Proctor hammer to fit in a specified volume.

A small diameter cone penetrometer (30° angle and basal area of 3.2 cm^2) was used to measure penetration resistance at three locations within the pot. At each location two readings were taken, one at the surface and the other at a depth of 2.5 cm, so that a total of six penetrometer readings were taken for each treatment. For each treatment the readings taken at the surface and at 2.5-cm depth were averaged before performing statistical analyses. Each treatment was replicated two times.

3.2.4 Statistical analyses

Statistical analysis included correlation and multiple regression. These analyses were performed using SAS statistical package (SAS Institute 1989). Simple linear correlations were determined between engineering characteristics such as the consistency limits and critical moisture content (CMC), and the agronomic characteristics such as water held at field capacity (0.033 MPa) and water held at wilting point (1.50 MPa). Regression analysis was performed using a stepwise procedure to determine the best regression model to describe variation in penetration resistance. From this, conclusions were drawn about what variable or variables were dominant in determining the variability of penetration resistance. The regression equations obtained were used to predict threshold bulk densities required to give a penetration resistance of 2 MPa for soil/fly ash mixtures wetted to different moisture contents.

3.3 RESULTS

3.3.1 Soil chemical properties

The non-amended sandy loam was alkaline while the clay loam and loam were acidic (Table 3.2). For all three study soils, the addition of fly ash significantly ($p \leq 0.05$) increased the pH as measured by using both distilled water and 0.01 M $CaCl_2$. Increases in the calcium concentration, electrical conductivity and ionic strengths in saturation extracts of soil: fly ash mixtures were also observed. The concentrations of magnesium, sodium and potassium also increased with the addition of fly ash. For the sandy loam the increase in calcium concentration was greatest so that the sodium adsorption ratio (SAR) decreased. However, the amount of sodium in the non-amended loam was relatively much smaller than that of the extracts from fly ash amended mixtures, so that fly ash addition at 5% resulted in a slight but non-significant increase in the SAR. Sodium content at 10% and 20% fly ash rates was significantly ($p \leq 0.05$) greater than that for the non-amended loam soil.

3.3.2 Water retention properties

As expected the gravimetric moisture contents at both field capacity (FC) and permanent wilting point (WP) were significantly ($p \leq 0.05$) greater for clay loam than for either sandy loam or loam soil (Table 3.3). The moisture contents at field capacity for non-amended sandy loam and loam soils were within three percentage points of the corresponding critical moisture content values obtained from Proctor tests. It seems therefore that for the non-amended loam and sandy loam soils, maximum densification likely occurs at moisture contents near field capacity.

The addition of fly ash altered the water retention properties of all soils. For sandy loam and loam soils the addition of 5% fly ash significantly ($p \leq 0.05$) increased the water retention at FC and WP compared with non-amended soils. However, for the clay loam addition of 5% fly ash significantly ($p \leq 0.05$) decreased water retention at FC and WP. Generally, retention properties of soils amended with 10 and 20% fly ash were similar to those of soils amended with 5% fly ash.

3.3.3 Soil compactibility and consistency limits

For all the soils the addition of fly ash increased the maximum Proctor density. CMC for the non-amended sandy loam was significantly ($p \leq 0.05$) lower than that for non-amended loam and non-amended clay loam soils (Table 3.3), and was significantly higher for the non-amended clay loam than that for non-amended loam soil.

For the sandy loam and loam soils, amendment with 5% fly ash significantly ($p \leq 0.05$) increased MBD compared with the non-amended soils. However, MBDs for these soils when amended with 5, 10% and 20% fly ash were non-significantly different from each other. For the clay loam soil, the MBD for soil amended with 5% fly ash was non-significantly greater than that for the non-amended soil. However, MBDs of soils amended with higher rates of fly ash were significantly greater than those for non-amended clay loam soil.

Using equation (3.1), and assuming a particle density of 2.65 Mg m^{-3}, MBD and CMC occurred at a mean degree of saturation of 77.5% for all soils, amended and non-amended, used in this study. The mean values for soils amended with 0 to 20% fly ash ranged from 68.4 % for loam to 85.3% for clay loam. Regression analysis indicated a significant ($R^2 = 0.85$; $p \leq 0.05$) linear (1:1) relationship between maximum bulk density predicted using equation (3.1) assuming 80% saturation, and maximum bulk density obtained from the Proctor test. Therefore an 80% degree of saturation at these compaction thresholds as suggested by Hillel (1980) can be assumed.

The liquid limit (LL) for the non-amended clay loam soil was significantly ($p \leq 0.05$) greater than those for non-amended sandy loam and loam soils (Table 3.3). For all three soils, the LLs for fly-ash amended soils were significantly ($p \leq 0.05$) lower than that for non-amended soils. The plastic limit (PL) for the non-amended sandy loam was significantly ($p \leq 0.05$) higher than that for soils amended with 5, 10 and 20% fly ash. However, the PL for loam soil amended with 5% fly ash was similar to that of non-amended loam soil. PLs of loam soils amended with higher rates of fly ash (10 and 20%) were significantly lower than that of loam soil amended with 5% fly ash. PLs for fly ash amended clay loam soils were similar to those of non-amended soils. The plasticity index (PI) for clay loam was significantly ($p \leq 0.05$) greater than that for either sandy loam or loam. This means that the non-amended clay loam is prone to substantial compaction over a wider range of moisture content than either the non-amended sandy loam or loam soils. For all three soils the addition of fly ash significantly decreased PI. However, for all three soils PIs for soils amended with 10% fly ash were non-significantly different from PIs for soils amended with 20% fly ash.

The critical moisture content (CMC) for the non-amended clay loam was lower than the plastic limit (PL) by two percentage points, while that for loam and that for sandy loam was lower by seven and nine percentage points respectively (Table 3.3). This means that only for the clay loam soil either the plastic limit or the CMC from the Proctor test could be used to set the moisture for handling or trafficking soils without exposing them to the dangers of compaction. This is in agreement with the observations that generally soils of texture ranging between loam and clay have plastic limits that are very close to (within three percentage points) CMC values (Thacker et al. 1994). However, for the loam and sandy loam soils, the plastic limit cannot be reliably used to estimate the moisture content at which the soil is most susceptible to compaction.

Correlation analysis indicated that the CMC was closely and positively correlated to the FC and to the WP moisture contents (Table 3.4). This means that determination of FC and WP can provide a relatively easy means of estimating CMC at which the soil is most susceptible to compaction. The PL was significantly, positively correlated to CMC, LL, and WP ($p \leq 0.05$). Plots of gravimetric moisture content for the various limits measured in this study indicate that their location relative to each other varies depending on the texture and the amount of fly ash added to the soil (Figures 3.1, 3.2 and 3.3). Generally, for all soils the difference between plastic limit and field capacity decreased with the addition of fly ash.

3.3.4 Functional relationships

Generally the addition of fly ash altered the functional relationships between bulk density, moisture content and penetration resistance with each soil responding differently. For the sandy loam, the addition of fly ash decreased PR. The decrease was more pronounced at low bulk densities than at higher ones (e.g. Figure 3.4). For the loam soil at lower moisture contents, the addition of 5% fly ash decreased PR (e.g. Figure 3.5), but higher rates of fly ash slightly increased it. However, in general the addition of fly ash did not change penetration resistance compared with that for the non-amended loam. For the clay loam soil, the addition of fly ash increased the PR of mixtures with the same moisture and density treatments, especially for the high density treatments. On average, the addition of 5% fly ash increased the penetration resistance five fold. However, the increases were more pronounced at higher moisture contents than at lower ones (e.g. Figures 3.6).

Multiple linear regression analysis indicated that the maximal model to describe variation of penetration resistance (PR) includes bulk density (BD) and gravimetric or volumetric moisture content (VMC). The nature of this regression was significantly ($p \leq 0.05$) affected by the soil texture and fly ash amendments. Thus the generalized maximal model is a distinct lines regression;

$$PR_{ijk} = \alpha_{ij} + \beta_{ij}(BD)_{ijk} + \gamma_{ij}(VMC)_{ijk} + \varepsilon_{ijk} \qquad (3.2)$$

where α = intercept; β = regression coefficient associated with bulk density (BD); γ = regression coefficient associated with volumetric moisture content (VMC); ε = residual error; i = 1...3 soils; j = 1...4 fly ash rates; k = number of replications. For the sandy loam soil the estimated equations had bulk density as the only significant ($p \leq 0.05$) independent variable influencing penetration resistance, while volumetric moisture content did not significantly affect penetration resistance (Table 3.5). For the loam soil amended with 10 and 20% fly ash and for all clay loam/fly ash mixtures, penetration resistance was significantly ($p \leq 0.05$) dependent on both bulk density and moisture content.

Regression equations were used to predict bulk densities that gave a penetration resistance (PR) of 2 MPa for soil/fly ash mixtures wetted to 10, 20 and 30% volumetric moisture contents (data not shown). For the sandy loam soil a small increase in threshold bulk density was observed when the soil was amended with 5% fly ash. For example at all three moisture contents the predicted threshold densities at 0, 5, 10 and 20% fly ash rates were 1.67, 1.74, 1.66 and 1.64 Mg m^{-3} respectively. For the loam soil, in general, fly ash amendments did not seem to have an effect on the threshold densities, especially when soil moisture was greater than 20%. Threshold densities required to give a PR of 2 MPa for the clay loam soil increased with moisture content but decreased with fly ash addition. A major decrease in the threshold density was obtained between 0 and 5% fly ash rates for the clay loam. Thereafter no changes in threshold densities were obtained with further additions of fly ash. This means that the addition of fly ash to clay loam would increase the resistance of soil to penetration, while increasing soil water would cause the opposite effect.

3.4 DISCUSSION

The increase in EC as a result of the addition of fly ash at rates up to 20 % was small enough so that EC of the mixtures still remained below 2 dS m^{-1}, the limit beyond which plants become adversely affected by the level of salinity (Janzen 1993). Although the addition of fly ash decreased sodium adsorption ratio (SAR) for sandy loam and clay loam mixtures, and increased it for the loam mixtures, all the SAR values for non-amended and amended soils were less than 13, the critical value above which sodicity of the soil becomes a problem that could cause serious reductions in plant growth and deterioration of soil structure (Bernstein 1975). In general, the greater the ionic strength of a soil, the more likely that the soil becomes coherent after drying.

Incorporation of fly ash increased the Proctor maximum bulk density likely because the fly ash used in the study has a density of 0.95 Mg m^{-3}, which was lower than the settling densities of 1.15, 1.18 and 1.20 Mg m^{-3} for the non-amended clay loam, loam and sandy loam soils, respectively. This means that the addition of fly ash increased the porosity of the soil mixtures. However, the greater pore spaces created rendered the soils more compactible than the original control soils. The soils then lost most of the gained porosity due to the expulsion of air from the soil pores when a compactive force was applied, resulting in greater sinkage than when no fly ash was incorporated.

The physically-based model developed by Hillel (1980) may be used to estimate the Proctor maximum bulk density when the critical moisture content for fly ash amended soils is determined from other soil properties. In this study critical moisture content and Proctor maximum density were both determined from the Proctor test, and the model verified that the assumption of 80% saturation holds for fly ash amended soils. Thus if critical moisture content could be determined from other properties, then Proctor maximum density can be predicted by assuming an 80% saturation. This assumption also holds for soils of various textures (Wagner et al. 1994) and soils amended with farm yard manure (Stone and Ekwue 1993) and sewage sludge (Ekwue and Stone 1997).

The decreased liquid limit and plasticity index of amended clay loam soil agrees with the observed response to fly ash amendment of black cotton soil (Sivapullaiah et al. 1996). The liquid limit of soils containing high amounts of clay is mainly controlled by the shearing resistance at particle level, and the thickness of the diffuse double layer. In soils with high amounts of montmorillonite clays the contribution of the shearing resistance to controlling the liquid limit is minimal compared to the contribution of the electrical double layer (Sridharan et al. 1986). The control of the liquid limit by the diffuse double layer comes from negatively charged clay surfaces mainly due to isomorphous substitution. To maintain electroneutrality this charge is satisfied by adsorbed cations, such as Ca^{2+} , Mg^{2+}, Na^{+}, and K^{+}. When clay particles come in contact with water, the adsorbed cations diffuse to equalize the concentration throughout the soil solution.

The addition of fly ash increases the concentration of Ca^{2+} cations in the fly ash/soil mixtures because of the substantial amount of free lime contained in fly ash. These Ca^{2+} cations reduce the thickness of the diffuse double layer of clay particles by displacing monovalent cations such as Na^{+} on the exchange complex and by increasing the electrolyte concentration. Furthermore, fly ash has particles coarser than clay so that fly ash particles added to a soil with high clay content can act as a diluent thus decreasing the liquid limit.

The decrease in the plastic limit of the amended sandy loam and loam soils may be due to the addition of fly ash increasing the amount of coarse-sized particles which act as a diluent. The general decrease in the plasticity index with addition of fly ash to all three soils indicates improvement in the workability of the soils amended with fly ash. In other words, the range of moisture content, which is the 'danger zone' within which the soils can be badly compacted when external pressure is applied, becomes smaller so that soils become less susceptible to compaction. This result agrees with the reported continuous decrease in the plasticity indexes with an increase in the rates of fly ash added (Sivapullaiah et al. 1996). However, in their study the minimum plasticity index was achieved at 35% fly ash rate, while in our study this was achieved at 5% fly ash rate. These findings contradict the hypothesis that soil plasticity is not dependent on fly ash amendments.

The addition of fly ash altered the relationship between agronomic and engineering characteristics of the three soils. For the amended sandy loam and loam soils the difference between CMC and field capacity was still very small, irrespective of the fly ash rate, so that even for amended soils either field capacity or CMC can be used as a guide to the moisture content at which trafficking and handling must be avoided. For the non-amended and amended clay loam soils, the CMC was close to the plastic limit, while FC was much greater than either PL or CMC in all clay loam/fly ash mixtures. Therefore for these mixtures, plastic limit should be used as a limit for soil moisture beyond which trafficking and cultivation must be avoided.

Soil texture and the addition of fly ash significantly altered the relationship between penetration resistance, bulk density and moisture content. For example for both amended and non-amended sandy loam soils penetration resistance was positively, linearly dependent on the bulk density. This suggests that soil lubrication due to increased water content did not matter as much as particle rearrangement in determining the magnitude of penetrometer resistance. This is probably due to the fact that high content of sand grains in these mixtures still interlock and causes a high soil-metal friction irrespective of the water content of the soil. However, for the clay loam soil the moisture content of the soil determined most of the variation of penetration resistance. This is probably because for clay loam a relatively greater fraction of fine sized particles gives it a larger surface area, and thus greater surface tension (Jumikis 1984). Consequently the addition of water will provide lubrication between particles, and since there is a relatively smaller fraction of sand grains that cause high frictional resistance, the penetration resistance becomes dependent on the soil's cohesion which decreases as soil water increases.

The general decrease in penetration resistance with addition of fly ash may be due to the reduction in frictional resistance due to less particle interlocking in fly ash/sandy loam mixtures compared with the sandy loam soil without fly ash amendments. These findings contradict the hypothesis that soil texture and fly ash do not affect penetration resistance.

3.5 CONCLUSIONS

The maximum density as determined by the Proctor test increased, while the plasticity index decreased, due to the addition of fly ash. The decreased plasticity index of amended mixtures means that over the range tested fly ash can help reduce soil traffickability problems by reducing the range of moisture over which soils are most susceptible to compaction. Trafficking and cultivation of non-amended and fly ash-amended sandy loam and loam soils must be avoided at moisture contents close to field capacity since maximum densification occurs at these moisture contents. For the non-amended and fly ash-amended clay loam soils, maximum densification occurs between wilting point and field capacity, and at a critical moisture content close to their plastic limit. Therefore cultivation and trafficking of these soils must be avoided at moisture contents close to the plastic limit. For all soil/fly ash mixtures, either the plastic limit or field capacity, whichever is less, should be used as a guide for soil moisture above which cultivation practices and soil handling must be avoided. Overall these findings contradict the hypothesis that soil plasticity and compactibility are not affected by fly ash amendments.

In all three soils the addition of fly ash altered the relationship between penetration resistance (PR), bulk density and volumetric soil moisture. For the sandy loam, addition of fly ash decreased PR. For the loam soil fly ash did not affect PR while for the clay loam fly ash increased PR. This result contradicts the hypothesis that fly ash has no effect on functional relationships between these three parameters. For the sandy loam soil, fly ash and bulk density affected PR, while for the clay loam soil fly ash, bulk density and moisture content affected PR. Relationships for loam soil were intermediate.

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Table 3.1 Physical and chemical properties of Sundance fly ash used in the study (adapted from Sale' et al. 1996).

Chemical property	Fly ash	
	Water extractable concentration (ppm)	Total concentration (ppm)
<u>Elements</u>		
Ca	5400	70000
K	4	690
Mg	2	3900
Na	220	10000
<u>Other characteristics</u>		
pH using $CaCl_2$	9.5	
pH using H_2O	12.5	
EC (dS m^{-1})	12.5	
Sand (%)	37	
Silt (%)	54	
Clay (%)	9	

Table 3.2 Chemical properties of the non-amended and fly ash- amended soils used in the study.

Soil	Fly ash rate (%)	pH		Concentration in saturation paste extracts (ppm)				EC (dS m^{-1})	Ionic strength (M)	SAR
		1:2 H_2O	1:2 $CaCl_2$	Calcium	Magnesium	Sodium	Potassium			
Sandy loam	0	8.9c†	7.4f	12i	4d	121c	5e	0.43e	0.006e	7.9a
	5	8.6d	8.0d	37hi	18c	119c	21d	0.62d	0.008d	4.0b
	10	10.2b	9.5b	159defg	3d	194a	26d	0.94c	0.012c	4.2b
	20	10.4a	9.9a	247cdef	3d	167b	27d	1.17b	0.015b	2.9c
Loam	0	5.4j	4.8j	50ghi	13cd	7e	83c	0.31e	0.004e	0.2e
	5	6.9h	6.5h	140fgh	34b	21de	155b	0.97c	0.013c	0.4e
	10	7.4g	7.1g	383a	62a	30d	162ab	1.09bc	0.014bc	0.4e
	20	8.1e	7.7de	281abc	45b	41d	173a	1.60a	0.021a	0.6e
Clay loam	0	6.6i	5.9i	33i	9cd	108c	4e	0.40e	0.005e	4.3b
	5	7.5g	7.3fg	267bcde	69a	149b	25d	1.04bc	0.014bc	2.1d
	10	7.8f	7.5ef	157efg	35b	207a	25d	1.20b	0.016b	3.9b
	20	8.7d	8.4c	299abc	44b	113c	19d	1.61a	0.021a	1.6d

† within columns, means followed by the same letter are not significantly different from each other at 0.05 probability level, n=4 for each treatment.

Table 3.3 Critical moisture contents (CMC) and bulk densities (MBD) obtained using the Proctor tests, field capacity (FC), wilting point (WP), liquid limit (LL), plastic limit (PL) and plasticity indices (PI) of fly ash amended soils.

Soil	Fly Ash (%)	Agronomic limits (%)		Proctor		Atterberg limits (%)		
		FC	WP	CMC	MBD	LL	PL	PI
Sandy loam	0	15.2h†	6.5h	14.5d	1.74b	30.2e	25.1d	5.2d
	5	20.2e	8.2g	13.9d	1.83a	24.6h	22.3e	2.6gf
	10	17.2g	8.5g	14.1d	1.84a	24.9h	22.5e	2.3g
	20	20.3e	8.2g	13.7d	1.83a	25.2h	22.7e	2.5gf
Loam	0	18.7f	10.8e	20.4b	1.48e	33.9d	27.9ab	6.0d
	5	22.4d	12.0d	19.3c	1.54 d	30.4e	28.4a	2.0g
	10	20.2e	10.8e	19.3c	1.55d	28.3g	24.7d	3.6ef
	20	23.0d	10.0f	19.2c	1.53d	29.2f	24.5d	4.7de
Clay loam	0	34.8a	18.2a	24.3a	1.46e	51.1a	27.1bc	24.0a
	5	32.1bc	14.6c	23.8a	1.48 e	34.9c	26.7c	8.2c
	10	33.1b	16.7b	23.7a	1.51d	37.4b	27.7ab	9.7b
	20	31.8c	14.7c	19.5c	1.65c	36.8b	26.8c	10.0b

† within columns, means followed by the same letter are not significantly different from each other at 0.05 probability level, n=5-10 for each treatment.
Field capacity measured at 0.03 MPa; wilting point at 1.5 MPa.

Table 3.4 Correlation matrix between Atterberg and agronomic limits for all soil/fly ash mixtures.

Parameter	Correlation coefficients between parameters				
	CMC	PL	LL	FC	WP
CMC	–	0.80**	0.80**	0.81**	0.86***
PL		–	0.68*	0.54ns	0.66*
LL			–	0.79**	0.88***
FC				–	0.90***
WP					–

*, **, *** indicate significance at 0.05, 0.01 and 0.001 significance level respectively; n=12.

Table 3.5 Regression equations, coefficients of determination (R^2), probability levels and standard error of estimate ($SE_{Y.X}$) for penetration resistance (PR) as a dependent of bulk density (BD) and volumetric moisture content (VMC) for different soils and fly ash amendment rates.

Soil	Fly ash (%)	Regression equation	R^2	Prob.	$SE_{Y.X}$
Sandy loam	0	PR = 4.19 x BD - 4.98	0.85	0.0001	0.36
	5	PR = 4.23 x BD - 5.34	0.79	0.0001	0.47
	10	PR = 4.54 x BD - 5.54	0.87	0.0001	0.36
	20	PR = 4.70 x BD - 5.73	0.89	0.0001	0.34
Loam	0	PR = 3.99 x BD - 4.49	0.90	0.0001	0.17
	5	PR = 4.34 x BD - 5.00	0.94	0.0001	0.14
	10	PR = 4.65 x BD - 0.018 x VMC - 5.05	0.95	0.0001	0.13
	20	PR = 5.06 x BD - 0.025 x VMC - 5.45	0.95	0.0001	0.17
Clay loam	0	PR = 1.90 x BD - 0.050 x VMC - 0.43	0.75	0.0001	0.16
	5	PR = 4.73 x BD - 0.091 x VMC - 2.28	0.81	0.0001	0.30
	10	PR = 5.04 x BD - 0.096 x VMC - 2.59	0.85	0.0001	0.28
	20	PR = 4.75 x BD - 0.094 x VMC - 2.42	0.82	0.0001	0.29

BD = bulk density (in Mg m^{-3}); VMC = volumetric moisture content (in $m^3/100\ m^3$); PR = penetration resistance (MPa); n=32 for each equation.

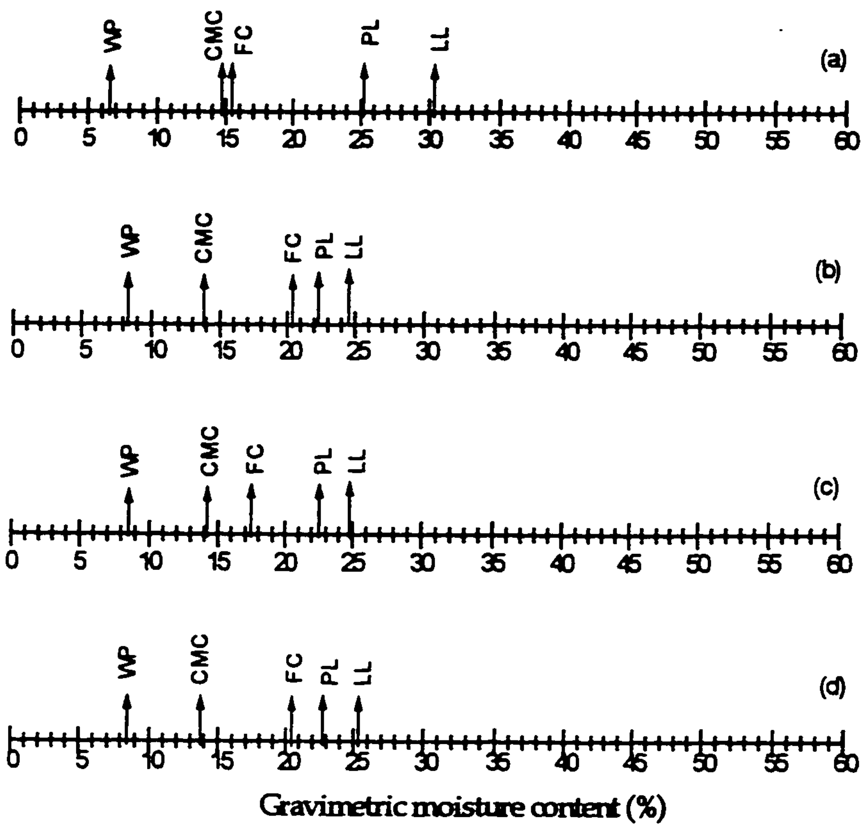

Figure 3.1 Wilting point (WP), field capacity (FC), critical moisture content (CMC), plastic limit (PL) and liquid limit (LL) of sandy loam soil amended with (a) 0%, (b) 5%, (c) 10% and (d) 20% fly ash.

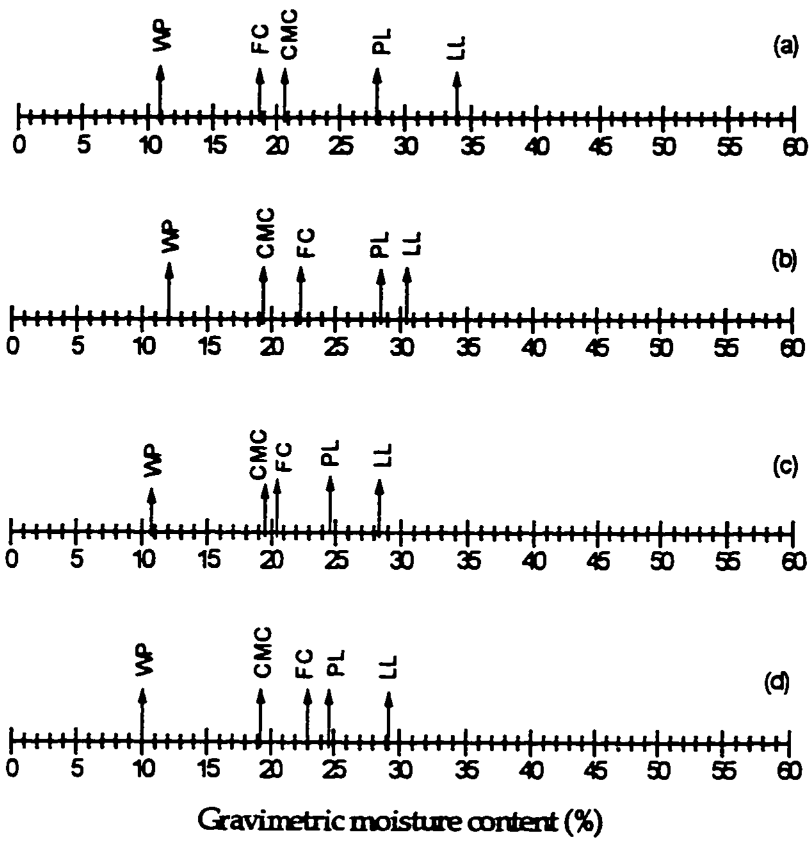

Figure 3.2 Wilting point (WP), field capacity (FC), critical moisture content (CMC), plastic limit (PL) and liquid limit (LL) of loam soil amended with (a) 0%, (b) 5%, (c) 10% and (d) 20% fly ash.

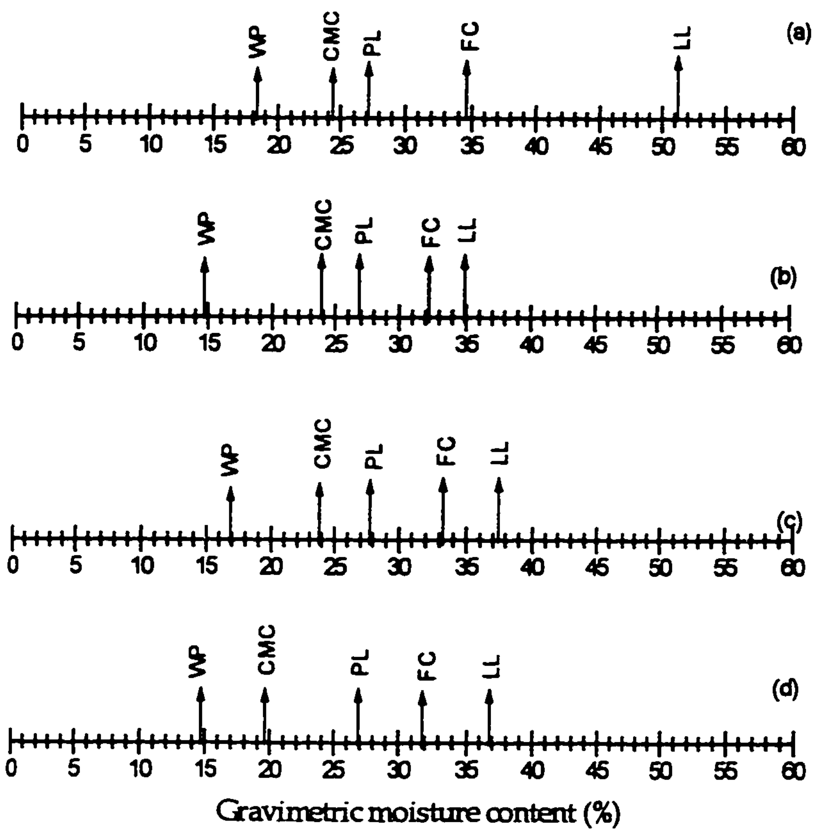

Figure 3.3 Wilting point (WP), field capacity (FC), critical moisture content (CMC), plastic limit (PL) and liquid limit (LL) of clay loam soil amended with (a) 0%, (b) 5%, (c) 10% and (d) 20% fly ash.

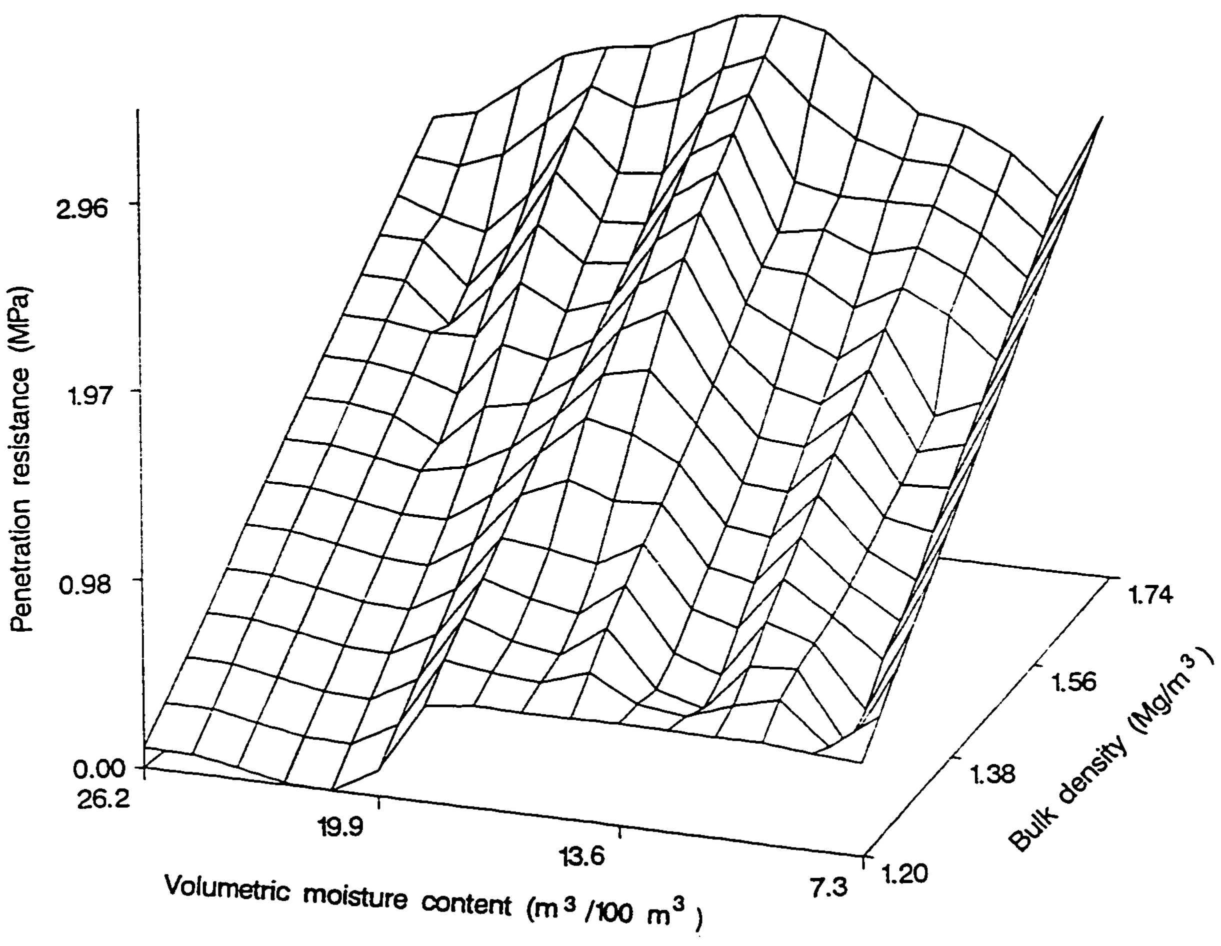

Figure 3.4 Variation of penetration resistance (MPa) with bulk density and moisture content for sandy loam soil amended with 10% fly ash (v/v).

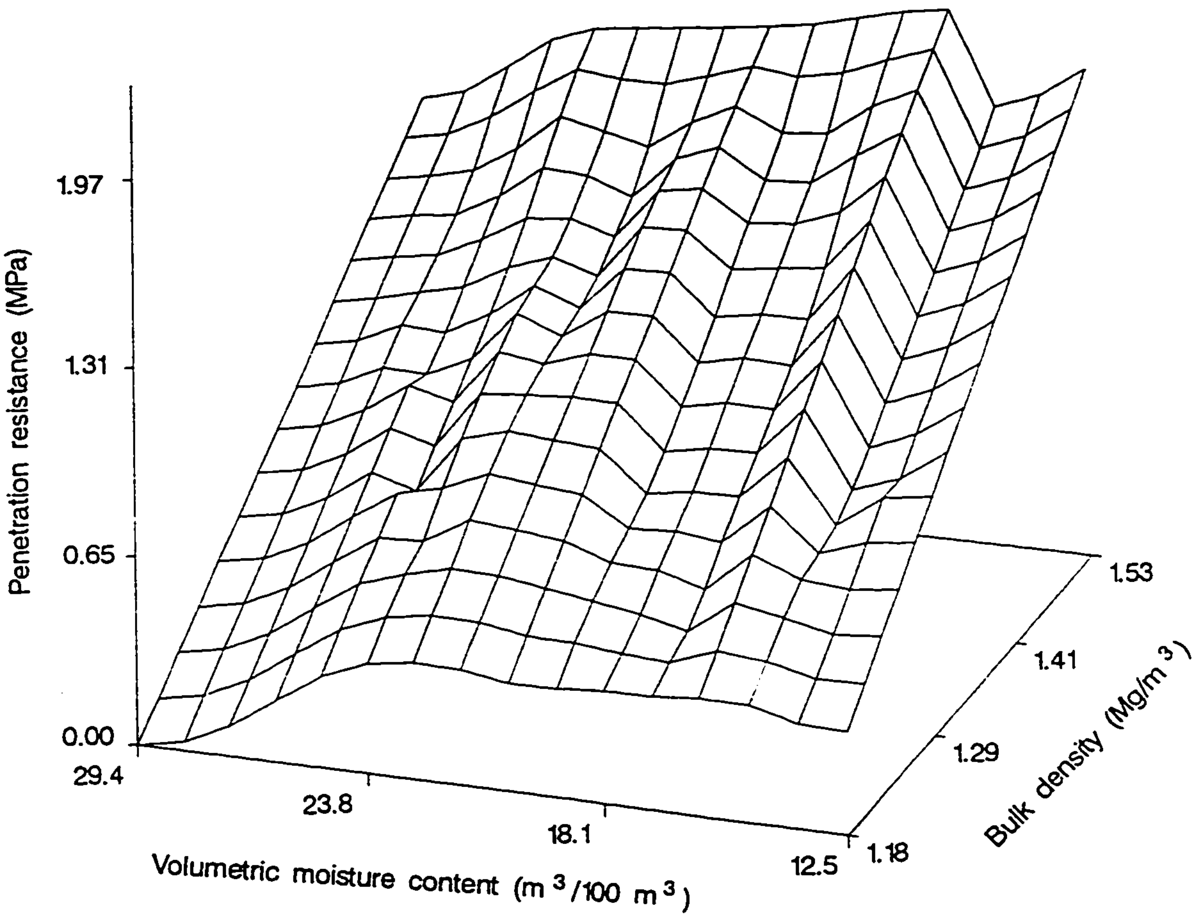

Figure 3.5 Variation of penetration resistance (MPa) with bulk density and moisture content for loam soil amended with 10% fly ash (v/v).

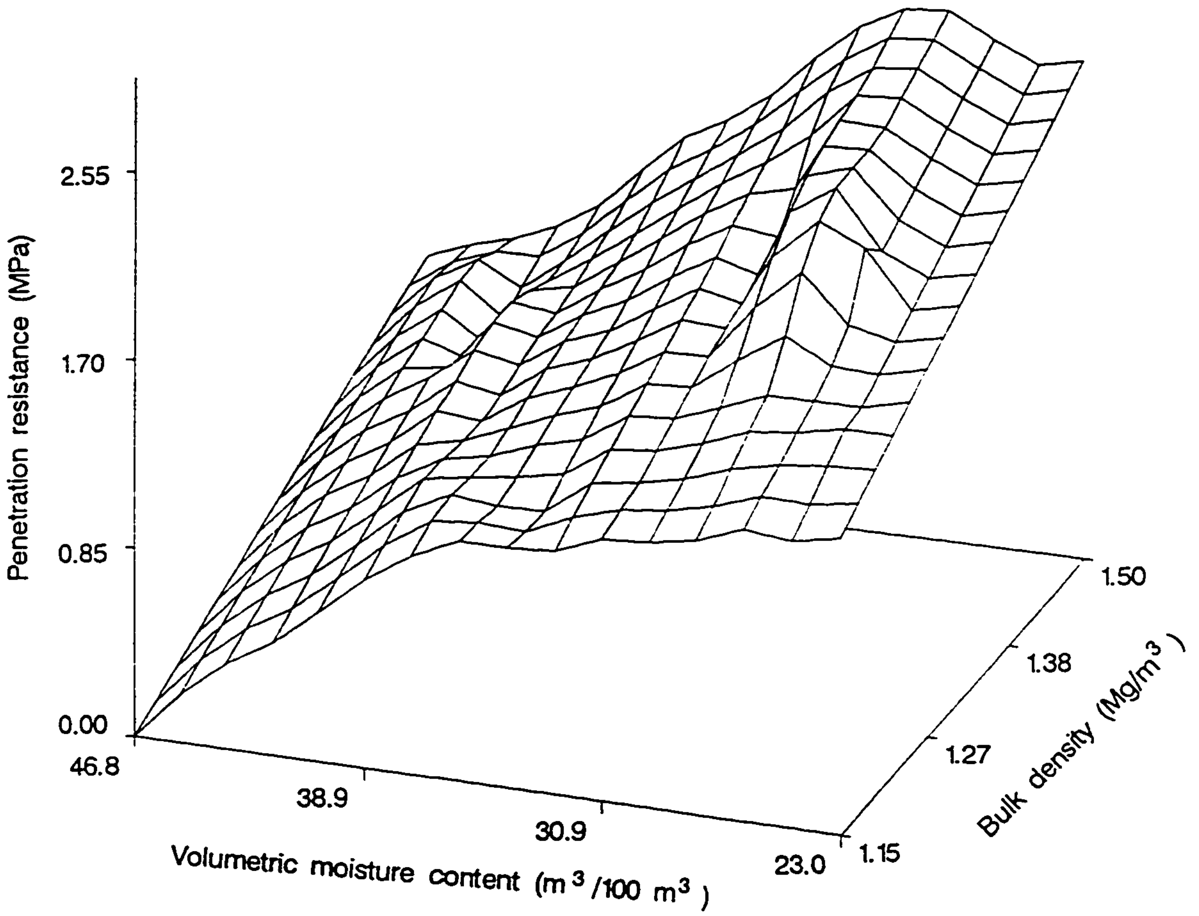

Figure 3.6 Variation of penetration resistance (MPa) with bulk density and moisture content for clay loam soil amended with 10% fly ash (v/v).

CHAPTER 4

PLANT PARAMETER RESPONSE TO COMPACTION

4.1 INTRODUCTION

Compaction of agricultural soils caused by intensive traffic with tractors and other heavy vehicles has become a worldwide problem. Compaction strongly influences soil physical properties such as bulk density, pore size, pore continuity, aeration, permeability, penetration resistance, and soil water and temperature regimes, which in turn affect plant growth (Panayiotopoulos et al. 1994). Several plant characteristics are affected when roots are subjected to conditions of high soil strength as a result of compaction. These characteristics include shoot growth, crop yield, root:shoot ratio, root diameter, root morphology, root physiology and biochemistry, and root elongation (Poincelot 1986; Masle and Passioura 1987; Atwell 1990a). Most of studies have been conducted on cereal crops. For example, corn grain yields were reduced by up to 50% on compacted clay soils compared to similar uncompacted soils (Poincelot 1986). In some cases the extent of crop yield decrease has been demonstrated by measuring yields after removing the traffic pan by subsoiling. Under these conditions yield increases of up to 83% were obtained for corn and cotton (Poincelot 1986). In corn, compacted subsoil of bulk density between 1.71 and 1.82 Mg m^{-3} caused a 45 to 50% yield reduction (Gauntley et al. 1980). In wheat, grain yield, stover yield and spikes m^{-2} of wheat in compacted soil were respectively 23, 20 and 14% less than respective values for uncompacted soil (Oussible et al. 1992). Masle and Passioura (1987) found that leaf area in both compacted and uncompacted soils increased with plant age but at every stage of growth the leaf area of plants in compacted soils was smaller than that in uncompacted soils. The decrease in the plant dry weight with an increase in penetration resistance was linear for both shoots and roots, but the rate of decrease was much greater for shoots than for roots.

Elongation of roots is perhaps the most studied plant response to soil compaction and was the subject of a review by Unger and Kaspar (1994). In most studies soil resistance as measured by a penetrometer has been assumed equal to the resistance encountered by roots during growth, termed root penetration resistance (Bengough and Mullins 1990). For roots to elongate, the pressure they generate must be greater than the soil resistance. The higher the root penetration resistance, the lower the root elongation rate (Bengough and McKenzie 1994); when the root growth pressure is equal to or smaller than the root penetration resistance, elongation will stop. Misra et al. (1986) reported maximum root growth pressures between 0.9 and 1.3 MPa. However, root elongation in laboratory and field studies was curtailed by penetration resistances between 0.8 and 5 MPa (Bennie 1991; Bathke et al. 1992).

Relationships between bulk density or penetration resistance and root growth parameters in a wide range of soil textures and plant species are negative linear or curvilinear (Bengough and Mullins 1990; Bennie 1991). However, in many of these studies root elongation is linearly related to soil penetration resistance up to 2 MPa (Taylor et al. 1966; Ehlers et al. 1983). If this is reproducible for a variety of plant species and soil types, then simple linear equations may be adequate to estimate "soil compaction costs" in terms of reductions of plant parameters as a result of increases in penetration resistance or bulk density.

A bulk density at which root growth is stopped or greatly retarded is often called the critical bulk density. Evidence in literature shows that critical bulk densities vary with soil texture, soil water content and soil structure (Jones 1983). Many threshold values for soil physical and chemical properties found in the literature are theoretical, vary substantially and are not based on plant response (e.g. Naeth et al. 1991).

The most common method of alleviating soil compaction is through deep tillage. However, this process is very time consuming, requires high powered tractors and causes considerable increase in the emission of carbon dioxide due to elevated fuel consumption (Eradat and Voorhees 1990). Therefore, increased efforts must be made to minimize the use of deep tillage. One way to achieve this would be through quantification of "soil compaction costs" associated with the compaction status of the soil. Such knowledge enables making decisions on whether deep tillage is necessary, based on economic assessment, estimated growth improvement after deep tillage, and environmental consequences likely to result from it. Thus an investigation into this subject would be a unique contribution to the literature and would provide a data base for modeling. However, in order to accomplish this, the relationships between plant growth response to compaction must be quantified.

The objective of this greenhouse study was to evaluate sensitivity of growth and yield components of smooth bromegrass and alfalfa to subsurface compaction in two soils of different textural classes.

4.2 MATERIAL AND METHODS

4.2.1 Experimental design, soils and plant species

Studies of plant growth in soils of different bulk densities were conducted using 15-cm diameter cylindrical pots (20-cm height) in a greenhouse. Temperature was maintained at 20 °C and the photoperiod was 16 h. The temperature controller was set at 22 °C while the emergency vent was set at 32 °C. Caps with three holes were fitted at the bottom of the pots to allow free drainage. A completely randomized design with three replicates of a factorial arrangement of treatments (species, soil texture, soil density) was used.

Two soils, a sandy loam and a clay loam (both collected from a reclaimed mined site), were used. The sandy loam soil contained 70% sand, 14% silt, 16% clay and 0.5% organic matter. This soil had a pH of 7.4 (1:2 soil to 0.01M $CaCl_2$), electrical conductivity of 0.43 dS m^{-1} and sodium adsorption ratio of 7.9. The clay loam soil contained 25% sand, 35% silt, 40% clay and 3.6% organic matter. The soil pH was 5.9 (1:2 soil to 0.01M $CaCl_2$), electrical conductivity was 0.40 dS m^{-1} and sodium adsorption ratio was 4.3.

For each soil, four bulk densities were used. The lowest density was equal to the settling density (control) and the highest equal to the maximum bulk density determined by the Proctor test (Jumikis 1984). For the sandy loam, increments of 15, 30 and 45% above settling density were used to achieve low, medium and high bulk densities, respectively, because of the wide range between settling density (1.20 Mg m^{-3}) and maximum Proctor density (1.74 Mg m^{-3}) (Table 4.1). For the clay loam, increments of 10, 20 and 30% above settling density were used, because of a narrow range between the settling (1.15 Mg m^{-3}) and maximum Proctor density (1.50 Mg m^{-3}). Densities will subsequently be referred to as control (settling density) and low, medium and high densities (the latter being the Proctor density).

Soil in the pots was compacted at Proctor optimum moisture content to the desired bulk density using a standard Proctor hammer (2.5 kg). A line was drawn on the inside of every pot at 10 cm from the bottom. A known mass of air-dried soil of known gravimetric moisture content was wetted to the Proctor optimum moisture content before being compacted to fit a known volume to achieve a desired bulk density. In each pot, only the bottom 10 cm was compacted to the desired bulk density. This compacted soil layer was covered with a 3-cm layer of clay loam soil tapped lightly to a settling density of approximately 1.15 Mg m^{-3}.

Alfalfa (*Medicago sativa* L. cv. 'Rambler') and smooth bromegrass (*Bromis inermis* L. cv. 'Magna') were used because of postulated differences between dicotyledons and monocotyledons in penetration abilities through soils of high strength and their use in reclamation and grazing systems. Fifteen seeds per pot were planted 2 cm deep for alfalfa and 1.5 cm deep for smooth bromegrass. Alfalfa seeds were pre-inoculated with *Rhizobium meliloti* to promote nitrogen fixation. Plants were thinned to seven per pot two weeks after planting.

4.2.2 Nutrient and water supply

Nutrient solutions containing nitrogen, phosphorus, potassium and sulfur were added to each pot at 100 kg N ha^{-1} (NH_4NO_3), 40 kg P ha^{-1} ($NaH_2PO_4.H_2O$), 40 kg

K ha^{-1} (KCl) and 10 kg S ha^{-1} (Na_2SO_4) before planting. These are similar to commercial field application rates for these species. Nitrogen solution was also added to smooth bromegrass 23, 44 and 66 days after planting.

Water retention at field capacity (0.033 MPa) and at wilting point (1.50 MPa) was determined for both soils using pressure plate apparatus. Gravimetric water content for the sandy loam at field capacity was 15% and water content at wilting point was 7%, with an available water capacity (AWHC) of 8%. Gravimetric water content for the clay loam at field capacity was 35% and at wilting point was 18%, resulting in an AWHC of 17%. In the greenhouse soil water was maintained at 70% of AWHC by watering the pots every day after weighing to determine the amount of water to add. For the sandy loam soil, this was equivalent to 34% of saturation, while for the clay loam it was 60% of saturation.

4.2.3 Shoot measurements

Plant height was measured at 9, 45, 62 and 78 days after planting. Final leaf length and width was measured using a ruler marked in 0.5-mm increments. Smooth bromegrass leaf width and length measurements were taken on the third leaf blade from the bottom. Tillers for each pot were counted before harvest. The average number of tillers per plant was determined based on the number of plants in the pot. Alfalfa leaf measurements were taken on one leaflet of the third trifoliate. Shoot harvest was conducted 12 weeks after planting and shoot dry biomass was determined after oven-drying at 60 °C for 48 h.

4.2.4 Root measurements

Plants were harvested after 12 weeks. Root dry biomass was recorded in both the uncompacted topsoil and the compacted subsoil layer. The contents of a pot were sliced into three segments of 0 to 3 cm, 3 to 8 cm and 8 to 13 cm. Each segment was gently broken apart making sure that minimal soil or roots were lost in the process. A set of three sieves of sizes 6.3, 2.0, and 1.18 mm were used to collect the large roots from each segment. After collecting the large roots, the soil and attached fine roots were placed in a separate container filled with water and soaked for 10 minutes to facilitate separation. The contents were then agitated to break soil aggregates and separate the fine roots. A 250-µm sieve was used to collect the fine roots. Root dry biomass for each segment was determined after drying for 48 h at 60 °C.

4.2.5 Statistical analyses

Statistical analyses of all recorded parameters were conducted using the SAS statistical package (SAS Institute 1989). Analysis of variance for plant parameters was conducted using the Generalized Linear Models procedure for the completely randomized design. Data for number of tillers per smooth bromegrass plant and secondary and tertiary branches per alfalfa plant were analyzed separately for each plant species. Means were separated using the least squares means procedure. Test for normality using the W test (Shapiro and Wilk 1965) was performed on each of the plant parameters.

Regression analysis was performed using data averaged for three replicates. For each soil and plant parameter the average for the control was standardized as equal to 100%, so that the yield of low, medium and high density treatments were expressed as a percentage of the average yield for the control. Therefore the dependent variable was average yield of each parameter expressed as a percentage of the yield of that parameter for the control density, while the independent variable was bulk density. Thus four data points representing averages for the four density treatments were used for each regression. These regression equations were used to estimate the threshold densities that caused reductions in yields to 75, 50 and 25% of that for the control.

4.3 RESULTS

For all plant parameters measured, except for the fraction of roots in topsoil, the soil×density×species interaction was non-significant at 0.05 probability level. However, for shoot dry biomass, root dry biomass, leaf length, leaf width, plant height, at least two of the soil×density, density×species and species×soil interactions were significant ($p \leq 0.05$). In the test for normality of data distribution, probability values were all greater than the critical value of 0.05 indicating values for each parameter were normally distributed as required in parametric statistical analyses. Initial analyses of combined leaf length data for smooth bromegrass and alfalfa showed the data to be non-normally distributed, thus leaf length data were analyzed separately for each plant species.

4.3.1 Shoot parameters

In both soils and for both plant species, final plant heights generally decreased with increased bulk density (Table 4.2). For the sandy loam soil average smooth bromegrass heights under control, low, medium and high bulk density treatments were significantly different ($p \leq 0.05$). However, while average alfalfa height at control density was significantly higher than for other densities, that for low was not significantly different from that for medium density. For the clay loam soil, average heights of smooth bromegrass for the four density treatments were significantly different from each other, while for alfalfa average height in low density was non-significantly different from that in medium density.

For both plant species leaf length generally decreased with increased bulk density (Table 4.3). For both soils and both plant species average leaf lengths were greatest in the controls. For the clay loam, and in both alfalfa and smooth bromegrass, the average leaf lengths in control and low densities were non-significantly different from each other. The leaf lengths in medium and high densities were also non-significantly different from each other. For the sandy loam, leaf length for smooth bromegrass in control, low and medium densities were non-significantly different from each other, while length for high density was significantly lower than that for control density only. The same pattern was observed for leaf length of alfalfa in sandy loam. In general, increased bulk density resulted in slightly less reduction of average leaf length in sandy loam than in clay loam soil.

Generally, leaf width decreased with increasing levels of bulk density for both species (Table 4.3). For the sandy loam, average leaf width of both smooth bromegrass and alfalfa in the high density treatment was significantly lower than that for either control, low, or medium density. Non-significant differences were observed between control, low and medium densities. For smooth bromegrass in the clay loam, significant differences were obtained between leaf width in control, low and medium densities. The high density treatment was not significantly different from the medium density. However, alfalfa leaf width was significantly different for control, low and high density. Leaf width in low and medium density was non-significantly different.

Generally, in alfalfa, the number of both secondary and tertiary branches decreased with increasing level of bulk density (Table 4.4). For clay loam soil the number of secondary branches for the high density was significantly ($p \leq 0.05$) different from that of the control, low and medium density treatments. However, there were non-significant differences between control and low, and between low and medium density treatments. In the sandy loam, the secondary branches in the high density treatment was significantly lower than in other densities. The clay loam control had a significantly greater number of secondary branches than the sandy loam control. In the clay loam, the number of alfalfa tertiary branches for control was significantly different from that for low, medium and high density. However, low and medium density were non-significantly different. In the sandy loam, the tertiary branches in control were significantly different from that in other densities, but that for low, medium and high density were non-significantly different from each other.

The average number of smooth bromegrass tillers per plant decreased with increasing density (Table 4.4). Number of tillers per plant in the control, low and medium density sandy loam soil were non-significantly different from each other. However, the high density had a significantly lower number of tillers than that for other density treatments. In clay loam soil the average number of tillers per plant was generally greater than that for sandy loam of the same density. The number of tillers per plant for low density clay loam was non-significantly different from that for control and medium density treatments.

Shoot growth of both plant species in the high density treatment of either soil was severely reduced as reflected in shoot dry biomass (Table 4.5). In general, shoot dry biomass decreased with increased level of density for each soil and plant species. In clay loam soil, the shoot dry biomass for smooth bromegrass in control, low, medium and high densities were significantly different from each other ($p \leq 0.05$). However, for alfalfa there were non-significant differences between control and low, and between low and medium densities. In the sandy loam soil, smooth bromegrass shoot dry biomass in control density was significantly greater than that in low, medium and high density treatments. There was a non-significant difference between low and medium density. For alfalfa shoot dry biomass was non-significantly different between control and low, low and medium, and medium and high density treatments. In both soils, shoot dry biomass production of alfalfa was much poorer than that of smooth bromegrass at similar densities.

4.3.2 Root parameters

Within the same soil, alfalfa produced relatively higher root dry biomass than did smooth bromegrass at equal bulk densities (Table 4.5). In clay loam soil, root dry biomass for smooth bromegrass was significantly different between control, low, medium and high density treatments. However, root dry biomass for alfalfa was non-significantly different between control, low and high density treatments. In sandy loam soil, root dry biomass of smooth bromegrass in control density was significantly greater than that in low, medium and high density treatments. Low and medium densities were non-significantly different. For alfalfa, control, low and medium densities had root dry biomasses that were non-significantly different from each other. However, control density had significantly greater root dry biomass than the high density treatment.

For both soils, an increase in bulk density caused an increase in the fraction of root dry biomass in the uncompacted topsoil (Table 4.6). For example, this percentage for smooth bromegrass increased from 23% in the control to 63% in the high density treatment of the clay loam soil, and from 32% in the control to 69% in the high density treatment of the sandy loam soil. For alfalfa the increase in the percentage of root dry biomass in the uncompacted topsoil with increased bulk density was not as dramatic as that for smooth bromegrass root growth. In clay loam soil the percentage root dry biomass of alfalfa in the topsoil was 34% in the control and 51% in the high density treatment, whereas in sandy loam soil it was 36% in the control and 46% in the high density treatment. The fraction of root dry biomass in the uncompacted topsoil is equivalent to root growth restricted to the plough layer in the field.

For both soils, root:shoot ratios for smooth bromegrass were not affected by bulk density treatments (Table 4.6). The results of mean separation using the least square means procedure indicated non-significant differences between any two ratios for the control, low, medium and high density treatments. This indicates that what happened to roots affected shoots in the same proportion. For alfalfa plants root:shoot ratios were affected by bulk density level, especially in the sandy loam soil. However, the data were not normally distributed as required in parametric statistics. Several transformations were attempted, but did not yield different results. Thus inferences from the root:shoot ratios must be made with caution.

4.3.3 Regression analyses

Regression analyses were performed on all shoot growth and root growth parameters (Tables 4.7). In all regressions the dependent variable was the average relative yield of parameter as a percentage of that for the control, and the independent variable was bulk density. In both soils and for both species, the relationship between plant height or leaf length and bulk density was linear. In sandy loam soil, smooth bromegrass height decreased less rapidly with an increase in density than did alfalfa height, whereas in clay loam soil the reverse was true. Alfalfa leaf length decreased more rapidly for both soils than did smooth bromegrass leaf length.

Different types of regression equations for leaf width were obtained. While the relationship for alfalfa leaf width decreased with bulk density, the relationship was either quadratic or exponential for smooth bromegrass. For clay loam the relation between the number of secondary or tertiary branches of alfalfa with bulk density was linear, whereas in sandy loam these relationships were curvilinear. The average number of tillers per smooth bromegrass plant decreased linearly with increasing soil density for both clay loam and sandy loam soils.

In both soils regression equations relating shoot biomass to bulk density were linear. However, the slope of the equation for alfalfa was greater than that for smooth bromegrass which suggested that dry biomass of alfalfa was more sensitive to subsurface compaction than was that of smooth bromegrass. Shoot dry matter yield for smooth bromegrass would decrease by 19% for clay loam and by 12% for sandy loam for every 0.10 Mg m^{-3} increase in bulk density above settling density (i.e. above 1.15 Mg m^{-3} for clay loam and above 1.20 Mg m^{-3} for sandy loam). Alfalfa shoot biomass would decrease by 22% and 15%, respectively, for the same increase in bulk density. While shoot dry biomass reduction for smooth bromegrass was less than that for alfalfa, for every 10%

increase in bulk density for each soil, the trend for root dry biomass production was the opposite. A similar result was obtained for corn, a predicted 18% corn yield decrease for every 0.10 Mg m^{-3} increase in bulk density above 1.30 Mg m^{-3} in a soil with 30 to 40% clay (Canarache et al. 1984).

Regression equations that related root biomass to bulk density were either linear or curvilinear. In sandy loam soil for both species, these two parameters decreased linearly with increase in density. However, in clay loam soil these two parameters decreased linearly with increasing bulk density for smooth bromegrass, whereas for alfalfa the response was curvilinear.

4.3.4 Threshold density values for growth reduction

Regression analysis indicates any density greater than settling density generally decreases plant growth parameters. Threshold bulk density values at which 75%, 50% and 25% reductions in yields of various plant parameters occurred were calculated from the regression equations (Tables 4.8). These values differed with soils and plant species in this study. Generally, for a given reduction in plant parameter, the threshold bulk density for sandy loam was greater than that for clay loam suggesting variation of plant growth response to compaction is greatly influenced by soil textural class. This contradicts our hypothesis that plant growth response is not a function of soil texture.

Within each soil threshold values for a given reduction in each parameter differed for smooth bromegrass and alfalfa. For example in the sandy loam soil the threshold density value at a relative plant height of 75% was 1.43 Mg m^{-3} for alfalfa, whereas that for smooth bromegrass was 1.52 Mg m^{-3}. However, at 75% relative yield of root dry biomass threshold density was 1.38 Mg m^{-3} for alfalfa and 1.48 Mg m^{-3} for smooth bromegrass. This indicates that plant growth response to subsurface compaction is a function of plant type, soil and response parameter considered.

Generally, for both soils and plant species the threshold densities required to reduce relative yield to 75% for plant height, leaf width, average smooth bromegrass tillers per plant, number of alfalfa secondary branches and number of alfalfa tertiary branches were either lower or close to the Proctor maximum density. For the leaf length the threshold densities required to reduce relative yield to 75% were equal to or above the Proctor maximum densities. The threshold densities required to reduce number of tertiary branches of alfalfa to 25% were 1.44 Mg m^{-3} and 1.56 Mg m^{-3} for clay loam and sandy loam soils, respectively. These densities are lower than the Proctor maximum densities, indicating tertiary branch production is a very sensitive parameter to subsurface compaction. For shoot and root biomasses the threshold densities required to achieve 25% relative yields were greater than the Proctor maximum density for both soils and plant species except for alfalfa shoot biomass for sandy loam soil. Such threshold densities are impossible to achieve indicating that it is unlikely that yield of parameters such as plant height, leaf width and length, tillers and root biomass can be reduced to 25% that for the control.

For each plant and soil combination, plant parameters were ranked in decreasing order of sensitivity to subsurface compaction (Table 4.9). These rankings were based on the critical density values required to reduce parameters to 75% (Tables 4.8). For alfalfa grown in sandy loam and clay loam soils the number of tertiary branches was most sensitive to subsurface compaction, suggesting this parameter might be the best early warning sign of compaction problems for alfalfa growth. Shoot biomass was more sensitive to compaction than root biomass. This means subsurface compaction is likely to cause more severe reductions in shoot growth than root growth, thus causing an increase in root:shoot ratios as observed for alfalfa. In both soils alfalfa leaf width and length were the least sensitive parameters to subsurface compaction. For smooth bromegrass, shoot biomass was more sensitive to compaction than root biomass; number of tillers per plant and leaf length were least sensitive.

This study demonstrates clearly the negative effect of compaction on forage plant yield. While shoot dry biomass was 1st or 2nd in sensitivity in all cases, plant height was ranked 3rd, 4th or 6th in sensitivity.

4.4 DISCUSSION

The general reductions in root and shoot growth of both plant species with increasing bulk density and the greater effect of compaction on shoot than root growth is in agreement with several published results from laboratory and field studies on plant responses to soil compaction (Richards and Rowe 1977; Carmi and Heuer 1981; Atwell 1990a; Atwell 1990b). However, this is in contrast with the results from other experiments where shoot growth increased and root:shoot ratios decreased with increasing bulk density (Shierlaw and Alston 1984; Wolkowski 1991). These researchers attributed their results to shortage of water at the end of the study as plants matured within the restricted soil volume of the pots.

The reduction in plant growth measured in this study was probably related to the combination of increased root penetration resistance, oxygen deficiency and the development of a rhizosphere environment that affects plant nutrient availability. In compacted soils, especially clay or clay loam soils, O_2 flow to the root system may be too low to fully meet plant needs. Furthermore, accumulation of CO_2 and other substances in the soil may cause root death or interfere with water uptake, N_2 fixation, and microbial activity (Unger and Kaspar 1994). Nutrients which are immobile in the soil (e.g. phosphate) rely on efficient exploration of the soil by high-order lateral roots and mycorrhizae, and are therefore likely to become deficient in shoots of plants with low root length densities (Atwell 1990a). The shoot may also be limited by an insufficient supply of carbohydrates because a high proportion of the plant carbohydrate reserves is directed to the roots or because the photosynthetic rate is small due to a small stomatal conductance (Masle and Passioura 1987). The sink priority in the plant therefore determines the order of sensitivity of plant parameters to compaction.

In this study, although most regression equations relating response of various plant parameter yields to soil bulk density were linear, some were curvilinear (quadratic or exponential). From research covering a whole range of soil densities which can be established for a given soil, it appears that these different responses are segments of an optimum curve as suggested by Ericksson et al. (1974). This optimum curve is not unique, but shape and position greatly depend on a number of factors. Generally speaking, the optimum is shifting to lower density when soil texture is fine instead of coarse, when dicotyledons instead of monocotyledons are grown and when the soil is wetter during the growing season (Boone 1986). Furthermore, this variable response indicates that various plant parameters reach their optimum growth values at different bulk densities.

Guidelines which can be developed from the results of this study (Table 4.8) will enable prediction of plant growth parameters under different levels of compaction and will enable land users to make an economic assessment of the benefits of deep tillage for given levels of compaction. While this study was conducted for two soils with varied textures, it is expected that the response of plant parameters to compaction of soils of textures between those of these two soils would be different.

The growth response obtained in this study may be less than that observed in most field experiments on compaction. This may be partly because in our conditions soil water was maintained at pre-determined levels. Thus soil water was not limiting. However, the field situation is very complicated because of dynamic soil water regimes. There is evidence that the conditions experienced by only part of the root system may influence the behavior of the shoot (Whiteley and Dexter 1982; Masle and Passioura 1987).

Topsoil thickness in the field varies and thus for shallow topsoil signs of compaction problems might be visible in plants at early stages of growth (Masle and Passioura 1987). However, under thicker topsoil, the problems of subsurface compaction may be less pronounced because the topsoil volume could provide the necessary nutrients and water storage required for plant growth, and very few roots will grow deeper into the compacted subsoil.

4.5 CONCLUSIONS

All densities greater than settling density caused a decrease in shoot biomass and root biomass. However, the reduction in shoot dry biomass was greater than that in root dry biomass. The sensitivity of various plant parameters to subsurface compaction varied considerably with plant species. Plant growth response to subsurface compaction is not only a function of plant type, but also depends on the parameter measured. For alfalfa, the most sensitive parameter to subsurface compaction was tertiary branch production while the least sensitive was leaflet width. For smooth bromegrass the most sensitive parameter was shoot dry biomass while the least sensitive was leaf length. The number of tillers was among the least sensitive parameters. For both plant species and soil types, plant height was a relatively insensitive parameter, contrary to common assumptions. Response curves of all parameters to subsurface compaction were generally linear. The effect on specific plant parameters and hence economic costs of soil compaction can be estimated from simple empirical equations. Threshold bulk density values limiting plant growth are a function of soil type, plant type as well as plant parameter measured.

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Table 4.1 Bulk density categories, increments and packed values for sandy loam and clay loam soils at the beginning of the study.

Compacted subsoil texture	Bulk density category	Bulk density increment (%)	Bulk density ($Mg\ m^{-3}$)
Sandy loam	control	0	1.20
	low	15	1.38
	medium	30	1.56
	high	45	1.74
Clay loam	control	0	1.15
	low	10	1.27
	medium	20	1.38
	high	30	1.50

Table 4.2 Average plant height (cm) of alfalfa and smooth bromegrass during a 12-week period of growth under four different bulk densities and in two soils.

Soil texture	Bulk density	Average plant height (cm)	
		Alfalfa	Smooth brome
		9 days after planting	
Clay loam	control	7.1ab†	22.7bc
	low	7.6a	25.1a
	medium	8.1a	20.9c
	high	7.9a	23.7ab
Sandy loam	control	7.3ab	24.7ab
	low	6.6ab	23.8ab
	medium	7.2ab	23.5ab
	high	5.0b	24.2ab
		45 days after planting	
Clay loam	control	19.7b	55.3a
	low	19.6b	47.8b
	medium	19.9b	43.3c
	high	18.9b	36.0d
Sandy loam	control	23.5a	43.3c
	low	17.9b	36.6d
	medium	19.5b	32.5e
	high	14.1c	31.5e
		62 days after planting	
Clay loam	control	29.3b	70.4a
	low	30.6ab	64.2b
	medium	29.6b	57.6c
	high	24.6c	42.9e
Sandy loam	control	33.3a	58.8c
	low	23.5c	50.3d
	medium	23.1c	39.8e
	high	16.7d	35.0f
		78 days after planting	
Clay loam	control	36.6ab	76.1a
	low	32.1c	65.9b
	medium	32.8bc	60.4c
	high	27.5d	46.2e
Sandy loam	control	37.6a	62.3bc
	low	26.4d	53.2d
	medium	26.4d	45.7e
	high	17.5e	35.6f

† Within columns and for each of the days after planting (DAP), means followed by the same letter are not significantly different from each other at 0.05 probability level, n=3 replicates for each treatment.

Table 4.3 Length and width of smooth bromegrass leaf blades and alfalfa leaflets after 12 weeks under four levels of bulk density in two soils.

Soil texture	Bulk density	Average leaf length (mm)		Average leaf width (mm)	
		Smooth brome	Alfalfa	Smooth brome	Alfalfa
Clay loam	control	299.1a†	11.8a	8.4a	5.9a
	low	275.6ab	11.3a	6.9b	5.0b
	medium	235.5cd	9.4bc	6.1c	4.6b
	high	236.1cd	9.1bc	5.9c	4.5c
Sandy loam	control	247.2bc	9.9b	6.4c	5.2b
	low	241.2cd	9.1bc	6.2c	4.6b
	medium	224.0cd	9.5bc	6.2c	4.6b
	high	216.1d	7.6c	5.0d	3.9c

† Within columns, means followed by the same letter are not significantly different from each other at 0.05 probability level, n=3 replicates for each treatment.

Table 4.4 Secondary and tertiary branches produced per alfalfa plant and tillers per smooth bromegrass plant after 12 weeks under four bulk densities and two soils.

Soil texture	Bulk density	Alfalfa branches		Smooth bromegrass
		Secondary	Tertiary	tillers per plant
Clay loam	control	16.1a†	10.6a	3.2a
	low	13.9ab	7.2b	3.1a
	medium	11.3bc	5.2b	2.8ab
	high	8.2de	0.7c	2.0c
Sandy loam	control	12.6bc	6.3b	2.8ab
	low	9.8cd	2.1c	2.4bc
	medium	9.7cd	1.3c	2.3bc
	high	5.5e	0.2c	2.1c

† Within columns, means followed by the same letter are not significantly different from each other at 0.05 probability level, n=3 replicates for each treatment.

Table 4.5 Shoot and root dry biomass of smooth bromegrass and alfalfa after 12 weeks under four bulk densities and two soils.

Soil texture	Bulk density	Shoot dry biomass (g)		Root dry biomass (g)	
		Smooth brome	Alfalfa	Smooth brome	Alfalfa
Clay loam	control	25.5a†	9.3a	19.0a	3.5ab
	low	19.5b	7.6ab	16.6b	4.6a
	medium	13.8cd	5.6bc	12.2c	3.5ab
	high	7.9fg	2.0de	6.9ef	2.4bc
Sandy loam	control	15.3c	5.8bc	13.5c	3.8ab
	low	11.0e	3.6cd	9.0d	3.2abc
	medium	8.8ef	2.7de	8.1de	2.5bc
	high	5.2h	0.9e	4.3g	1.6c

† Within columns, means followed by the same letter are not significantly different from each other at 0.05 probability level, n= 3 replicates for each treatment.

Table 4.6 Fraction of total root dry biomass in the uncompacted topsoil and root:shoot ratios of smooth bromegrass and alfalfa plants after 12 weeks under four bulk densities and two soils.

Soil texture	Bulk density	Percent of total root dry biomass in topsoil (%)		Root:shoot ratio	
		Smooth brome	Alfalfa	Smooth brome	Alfalfa
Clay loam	control	23c†	34cd	0.8a	0.4d
	low	26c	28d	0.9a	0.6cd
	medium	28bc	34cd	0.9a	0.6cd
	high	63a	51a	0.9a	1.2b
Sandy loam	control	32bc	36bc	0.9a	0.7cd
	low	47b	46ab	0.8a	1.1b
	medium	68a	43abc	0.9a	0.9bc
	high	69a	46ab	0.9a	2.0a

† Within columns, means followed by the same letter are not significantly different from each other at 0.05 probability level, n=3 replicates for each treatment.

Table 4.7 Regressions, probabilities, R^2 values and standard error of estimates ($SE_{Y.X}$) for plant parameters of smooth bromegrass and alfalfa in clay loam and sandy loam soil.

Y-variate	Soil	Plant	Equation†	R^2	Prob	$SE_{Y.X}$
Plant height (%)	Clay loam	Brome	Y = 225 - 108BD	0.98	0.01	2.69
		Alfalfa	Y = 172 - 63BD	0.85	0.10	4.82
	Sandy loam	Brome	Y = 194 - 78BD	0.99	0.002	1.16
		Alfalfa	Y = 204 - 90BD	0.89	0.10	8.80
Leaf length (%)	Clay loam	Brome	Y = 174 - 65BD	0.89	0.10	4.16
		Alfalfa	Y = 184 - 73BD	0.91	0.05	4.32
	Sandy loam	Brome	Y = 132 - 26BD	0.96	0.02	1.45
		Alfalfa	Y = 144 - 36BD	0.72	0.20	6.38
Leaf width (%)	Clay loam	Brome	$Y = 117(BD)^{-1.3613}$	0.94	0.01	0.04
		Alfalfa	$Y = 113(BD)^{-1.0453}$	0.92	0.05	0.04
	Sandy loam	Brome	$Y = -115 + 326(BD) - 123(BD)^2$	0.92	0.05	4.92
		Alfalfa	Y = 151 - 43BD	0.94	0.01	3.19
Secondary branches (%)	Clay loam	Alfalfa	Y = 263 - 141BD	0.99	0.005	1.79
	Sandy loam		$Y = 33 + 156(BD) - 85(BD)^2$	0.91	0.05	11.9
Tertiary branches (%)	Clay loam	Alfalfa	Y = 401 - 260BD	0.98	0.01	5.70
	Sandy loam		Y = 285 - 167BD	0.85	0.10	4.35
Tillers per plant(%)	Clay loam	Brome	Y = 232 - 110BD	0.86	0.10	8.20
	Sandy loam		Y = 154 - 44BD	0.96	0.02	2.71
Shoot dry biomass (%)	Clay loam	Brome	Y = 327 - 197BD	0.99	0.001	0.38
		Alfalfa	Y = 362 - 223BD	0.97	0.020	7.55
	Sandy loam	Brome	Y = 240 - 118BD	0.99	0.010	3.76
		Alfalfa	Y = 276 - 150BD	0.97	0.020	6.93
Root dry biomass (%)	Clay loam	Brome	Y = 317 - 185BD	0.98	0.020	5.48
		Alfalfa	$Y = -1743 + 2918(BD) - 1141(BD)^2$	0.87	0.100	15.0
	Sandy loam	Brome	Y = 236 - 117BD	0.94	0.050	8.2
		Alfalfa	Y = 227 - 104BD	0.99	0.020	2.3

† Y = % of given parameter relative to the value of that parameter in the control density, n = 4 for each equation; BD = Bulk density ($Mg\ m^{-3}$).

Table 4.8 Estimated threshold bulk densities to reduce relative yield (%) of plant height, leaf length and width, number of alfalfa branches, shoot and root biomass of smooth bromegrass and alfalfa under clay loam and sandy loam subsurface compaction.

Parameter	Parameter as a percentage of that for control (%)	Threshold bulk density ($Mg\ m^{-3}$)			
		Clay loam		Sandy loam	
		Brome	Alfalfa	Brome	Alfalfa
Plant height	75	1.39	1.53	1.52	1.43
	50	1.62	1.93	1.84	1.71
	25	1.85	2.32	2.16	1.99
Leaf length	75	1.52	1.50	2.21	1.91
	50	1.90	1.84	3.19	2.60
	25	2.28	2.19	4.17	3.29
Leaf width	75	1.39	1.47	1.78	1.78
	50	1.87	2.17	1.96	2.36
	25	3.11	4.22	2.11	2.95
Secondary branches	75	–	1.34	–	1.50
	50	–	1.52	–	1.72
	25	–	1.69	–	1.88
Tertiary branches	75	–	1.25	–	1.26
	50	–	1.35	–	1.41
	25	–	1.44	–	1.56
Tillers per plant	75	1.43	–	1.79	–
	50	1.66	–	2.36	–
	25	1.88	–	2.93	–
Shoot dry biomass	75	1.28	1.28	1.39	1.34
	50	1.40	1.40	1.60	1.51
	25	1.53	1.51	1.81	1.67
Root dry biomass	75	1.31	1.48	1.38	1.45
	50	1.44	1.53	1.59	1.69
	25	1.58	1.57	1.81	1.93

Proctor density for sandy loam = 1.74 $Mg\ m^{-3}$, Proctor density for clay loam = 1.50 $Mg\ m^{-3}$.

Table 4.9 Decreasing order of sensitivity of plant parameters to subsurface compaction after 12 weeks of growth.

Rank	Clay loam		Sandy loam	
	Smooth brome	Alfalfa	Smooth brome	Alfalfa
1	Shoot dry biomass	Tertiary branches	Root dry biomass	Tertiary branches
2	Root dry biomass	Shoot dry biomass	Shoot dry biomass	Shoot dry biomass
3	Plant height	Secondary branches	Plant height	Root dry biomass
4	Leaf width	Root dry biomass	Leaf width	Plant height
5	Tillers per plant	Leaf length	Tillers per plant	Secondary branches
6	Leaf length	Plant height	Leaf length	Leaf width
7	–	Leaf width	–	Leaf length

CHAPTER 5

SOIL COMPACTION AND ITS NATURAL ALLEVIATION UNDER GRAZING MANAGEMENT

5.1 INTRODUCTION

Livestock trampling has both direct and indirect effects on vegetation and soils. The physical effects of grazing animals' hoof action include mechanical injury to or loss of vegetation as well as compaction of the surface soil. However, the extent of livestock-induced soil compaction depends on the grazing management system, soil moisture content, vegetation cover and soil type.

Grazing management is based on balancing timing, intensity, frequency, duration and selectivity of grazing animals. Mismanagement of livestock, especially with high stocking rates, has caused severe degradation in much of the world's rangelands (Bari et al. 1993). Moderate stocking rates designed to use about half the current year's forage production are generally accepted as proper grazing management (Stoddart et al. 1975).

Proponents of intensive rotational grazing believe that livestock hoof actions that result in chipping and trampling may increase water infiltration rates (Savory 1978). However, many researchers do not support this hypothesis considering soil pressures from animal hooves might be as much as 200 kPa which is considerably greater than the pressure exerted on the soil surface by a tractor which can range from 30 to 150 kPa (Profitt et al. 1993). Cattle exert static or standing pressures (averaged over entire surface area of the hoof) of 10.9 kg cm^{-2} (Lull 1959) and 13.6 kg cm^{-2} (Busby and Gifford 1981). However, pressures can be 2 to 4 times higher when an animal travels. In an artificial trampling study, Frame (1971) reported that cattle with a hoof print size of 60 to 90 cm^2 exerted pressures between 2.8 and 4.2 kg cm^{-2} on the soil surface while traveling. Abdel-Magib et al. (1987) argued that this variation is due to variation in the fraction of total hoof surface assumed to be in contact with the ground.

Alderfer and Robinson (1947) evaluated compaction due to different grazing intensities on soils ranging from clay loams to sandy loams. Compaction occurred to a depth of 5 cm and bulk density increased greatly on heavily grazed sites compared with ungrazed sites. Rhoades et al. (1964) reported bulk densities of 1.72 Mg m^{-3} on heavily grazed soil and 1.56 Mg m^{-3} on ungrazed soil, with depth of compaction limited to within 15 cm from the surface. Krenzer et al. (1989) showed increases in bulk density by as much as 16% and soil strength by 270% in the near-surface soil as a result of animal traffic. However, compaction was deeper in a sandy loam than a silt loam. In the former, the bulk density increased to a depth of 20 cm and the soil strength to 30 cm while in the latter the bulk density increased only to a depth of 12 cm.

Compaction due to animal traffic also has adverse effects on soil structure and hydrologic condition. For example Warren et al. (1986) found that trampling of dry soil caused disruption of naturally occurring aggregates while trampling moist soil deformed existing aggregates and led to creation of an impermeable layer composed of dense unstable clods. Heavy stocking rates may reduce infiltration and the extent of this reduction may be affected by the duration of grazing (Weltz et al. 1989).

Aggregate stability is an important physical property controlling resistance to erosion in many soils. Aggregate size distribution and stability in surface soils are determined by a number of soil and environmental parameters. The beneficial effects of freezing and thawing on the water-stability of soil aggregates has been a subject of controversy. Some researchers have shown that freezing and thawing disintegrates soil structure and reduces aggregation (Leo 1963; Bisal and Nielsen 1967). In these studies the degree of disintegration was directly related to soil water content and freezing rate. Contrasting results have been presented where freeze-thaw cycles promoted soil aggregation (Sillanpaa 1961; Sillanpaa and Webber 1961). However, other studies showed that freeze-thaw action tends to break down large aggregates and to aggregate fine particles to intermediate size aggregates (Benoit 1973). Thus the total effect depends on the soil type and degree of initial aggregation.

Soil properties such as texture, organic matter, water content and other factors such as environmental conditions and grazing intensities govern the degree to which compaction occurs. These factors are also responsible for the differences in the time required for recovery from compaction (Warren et al. 1986). The variation of these factors makes it difficult to transfer results from one site to another.

The main goal of amelioration of soil compaction should be to re-establish the necessary network of continuous macropores for root development, soil aeration and adequate infiltration. The main processes of natural alleviation of surface soil compaction include freeze-thaw cycles especially in cold climates, wetting-drying cycles and earthworm activity.

The effects of freeze-thaw action are expected to be greater on soils whose texture makes them frost susceptible, and which have abundant water during freezing (Kay et al. 1985). Soils with high contents of silt are most susceptible to frost heaving and this process may have a significant contribution in alleviating surface compacted soils provided there is enough water to form ice lenses. In some cases annual freezing has been inadequate in alleviating soil compaction. For example Swedish experiments indicate that two to four years may be needed to restore crop yield levels on clay soils after excessive compaction and much longer to reduce the bulk density or vane shear strength to the same level as uncompacted soils. Several studies conducted in the laboratory showed that some compacted soils need ten to fifteen cycles of freezing and thawing to attain equilibrium bulk density (Heinonen 1986). These studies, however, assume the dominance of freeze-thaw cycles as a natural alleviation process for compacted soils. In reality it is not uncommon under field conditions for natural processes of alleviation to occur simultaneously.

Most surface soils in Alberta are frozen during the winter months. However, very little information is available on how soil structural properties are affected by freezing during winter and subsequent thawing during spring especially in compacted soils as a result of animal trampling. Furthermore, the results of aggregate stability research in general are inconsistent (Mostaghimi et al. 1988). Information concerning the influence of animal traffic on soil compaction and the possible amelioration through freeze-thaw action would provide useful clues for determining appropriate grazing management systems that would minimize deterioration of the physical and hydrologic quality of the soil.

Dexter (1991) suggested that allowing a soil to dry as much as possible (i.e. to -1.5 MPa or beyond) is the most effective form of soil amelioration because when a soil with medium to high clay content dries, it shrinks and vertical desiccation cracks form. When a cracked soil is wetted rapidly it swells and the desiccation cracks close. However, the combined effects of differential swelling and pressure build-up in entrapped air can cause mechanical failure of the soil, and thus may loosen compacted soils.

Earthworms can have a profound effect on soil structure, both through the casts which they excrete and through their tunnels. They can have considerable positive effects on the soil, such as reduced bulk density, increased infiltration rate and increased hydraulic conductivity (Joschko et al. 1989; Whalley et al. 1995).

Based on the above information we tested the hypothesis that grazing would not compact the soil. We also hypothesized that natural processes would not alleviate this compaction. The objective of this study was to investigate the impact of intensity of grazing and season on soil bulk density and penetrometer resistance in selected annual and perennial forages.

5.2 MATERIALS AND METHODS

5.2.1 Experimental site

The study was conducted at the Lacombe Research Station, Lacombe, Alberta. The study site elevation ranges between 866 m and 873 m above sea level. The soil on the site is an Orthic Black Chernozem of silt loam to loam texture. On average the soil contained 15% clay, 34% silt, 51% sand and 9.5% organic matter. Soil pH determined using distilled water was 5.4, electrical conductivity (EC) was 0.31 dS m^{-1} and the sodium adsorption ratio (SAR) was 0.2.

5.2.2 Meteorological conditions

Total precipitation between April and October 1995 and 1996 was 408 mm and 383 mm, respectively. However, total precipitation in September in the respective years was 9 and 82 mm. Mean monthly temperature between April and October ranged between 5.8 and 15.9 °C in 1995, and between 2.8 and 16.1 °C in 1996. During winter months (November to March) the total precipitation in 1995/96 was 88 mm while average snow depth was 180 mm. For 1996/1997 winter precipitation was 235 mm with an average snow depth of 180 mm.

5.2.3 Experimental design

The experimental design is a 3x2 factorial design with four replications as blocks. Each plot is 33 m long and 9 m wide (297 m^2) and is subjected to one of three grazing treatments (heavy, medium, light). The upper two experimental blocks are eastfacing and on a 4-6% slope, while the other two blocks are on flat land.

5.2.4 Plant species

Two forages, meadow bromegrass (*Bromus riparius* cv. 'Paddock') and triticale (*Triticosecale wittmack* cv. 'Pika'), were chosen for study under grazing. Meadow bromegrass is a perennial forage bunch grass. Triticale is a winter cereal, when planted in spring remains vegetative until vernalized the following winter. Thus triticale was vegetative during the study period.

Meadow bromegrass was seeded on May 31, 1993. Seedbed preparation consisted of a fertilizer application (112 kg ha^{-1}), one pass with a rototiller, followed by a diamond spike harrow and finally a crowfoot packer. Meadow bromegrass was seeded at 16.8 kg ha^{-1}. *Medicago sativa* cv. 'Spreader II' (alfalfa) was seeded with it at 1 kg ha^{-1}. The seeding was done by broadcasting followed by one pass with a diamond harrow and one pass with a crowfoot packer. In 1994 and 1995 meadow bromegrass was fertilized in mid-April at 112 kg ha^{-1}.

Seedbeds were prepared for triticale in June 1993 by rototilling, harrowing and fertilizer application at 112 kg ha^{-1}. Triticale was seeded at 135 kg ha^{-1} using a plot seeder with press wheels at the front and back of double disk openers. A final packing operation was performed using a crowfoot packer. In early May, 1994 and 1995, with residue from the last fall, annual seedbeds were prepared in a similar manner to 1993 and seeding rates were the same.

5.2.5 Grazing systems

One year old crossbred beef replacement heifers were used to graze plots. In 1993, unquantified light grazing was used to reduce forage on all treatments to an even height for study commencement in spring 1994.

Forage height was used to define grazing intensity. Grazing started when forages reached a target maximum height and ceased when a target minimum height was reached. Target heights varied among species and were set according to the species morphology, the desired amount of litter and the amount of bare ground decided appropriate for that treatment. Forage heights were determined as the average of 10 disk heights (Bransby et al. 1977).

For meadow bromegrass heavy grazing commenced when plants were 8-10 cm in height and ended at 2-5 cm. Medium grazing began at 12-15 cm and ceased at 8-10 cm, while light grazing started at 15-20 cm and stopped at 12-15 cm. For triticale, heavy grazing started at a forage height of 8-12 cm and ended at 2-5 cm, medium grazing was initiated at a height of 12-15 cm and stopped at 8-10 cm, and light grazing started at a height of 15-20 cm and stopped when plants reached a height of 12-15 cm.

For both meadow bromegrass and triticale, heavy grazing represented an over-grazed condition with significant bare ground and minimum litter. Medium grazing represented an intermediate condition (near that used for rotational grazing by good producers) without excessive bare ground and with a moderate amount of litter. Light grazing allowed forages to reach an advanced stage of maturity with seedhead emergence where possible, and was intended to produce large amounts of litter.

Because forage height was used to define grazing intensity, different amounts of forage regrowth were required for different grazing intensities and forages. This resulted in variation in the number of grazings per season among treatments. For meadow bromegrass, heavy, moderate and light grazing treatments the average number of grazings per season were 7, 5 and 3 respectively, while for triticale the respective grazings were 4, 4 and 2 times per season. In the 1995 grazing season the product of number of cows and the duration of grazing (i.e. cow-days) was 37, 19 and 15 for meadow bromegrass under heavy, medium and light grazing, respectively. For triticale total cow-days were 19, 10 and 9 for heavy, medium and light grazing, respectively. In the grazing season of 1996 the cow-days for meadow bromegrass were 27, 16 and 14, while those for triticale were 13, 9 and 6 for heavy, medium and light grazing respectively.

5.2.6 Bulk density, moisture content and penetration resistance

Bulk density, gravimetric moisture content and penetration resistance were measured four times: fall 1995, spring 1996, fall 1996 and spring 1997. In each plot three sample sites were randomly chosen for core sampling. Around each sample site penetration resistance was measured to a 15-cm depth at three different positions within a radius of 0.5 m using a small hand-pushed cone penetrometer (30° angle and basal area of 3.2 cm^2). A hand-driven Uhland core sampler was used to collect 15-cm long samples for bulk density measurements. Each sample was sectioned into six segments each of 2.5 cm length. Each sample was put in a plastic bag to avoid water loss. The moist samples were weighed within two days after sampling before oven drying at 105 °C to determine both bulk density and gravimetric moisture content. A Proctor compaction test of the loam soil showed a maximum bulk density of 1.48 Mg m^{-3} at a critical moisture content of approximately 21%. Statistical analyses of bulk density, gravimetric moisture content and penetration resistance were conducted using SAS generalized linear procedure (SAS Institute 1989). Mean separation was conducted using the least squares means procedure.

5.2.7 Benchmark site

The benchmark site, adjacent to the grazing plots, is composed of 25-year old pasture grasses including smooth bromegrass (*Bromis inermis* L.), kentucky bluegrass (*Poa pratensis* L), quackgrass (*Elytrigia repens* L.), bluegrass species (*Poa spp.*) with common occurrence of dandelion (*Taraxacum officinale* L.). This site represents the effect of long-term continuous (season-long) grazing which is commonly practised in the area. The bulk densities and gravimetric moisture contents measured in the benchmark site were compared with corresponding values obtained in the heavy, medium and lightly grazed meadow bromegrass and triticale using Kruskall-Wallis (H) test (Siegel 1956). This test is a non-parametric equivalent of one-way analysis of variance (usually referred to as analysis of variance by ranks), and therefore does not have to satisfy the assumptions of homogeneity of variance and normality of data distribution as required in parametric statistics. This test was appropriate considering that the benchmark site was established separately from the rotational grazing experimental plots. Using this test, the data set for each depth from all seven grazing-species treatment combinations was ranked in ascending order and the sum of ranks and average for each treatment were computed. A chi-square (χ^2) value was computed from average ranks for treatments and the number of units for each treatment. This χ^2-value was compared with the critical χ^2-value at 0.05 probability level to establish whether at least one of the grazing treatments was significantly different from the others.

5.2.8 Soil aggregate analysis

Soil aggregate analysis was conducted for samples collected at the end of the grazing season, fall 1996, using the wet-sieving procedure (Kemper and Rosenau 1986). Three randomly selected samples per plot were collected in the upper 5 cm and gently broken apart before being passed through an 8-mm sieve. To avoid slaking, aggregate analysis using wet-sieving was done on field moist aggregates. A nest of six sieves was used for each sample to determine water-stable aggregates in each of the aggregate size classes: 0.125-0.25 mm, 0.25-0.5 mm, 0.5-1 mm, 1-2 mm, 2-4 mm and 4-8 mm. Aggregates retained by each sieve were collected, oven-dried at 105 °C and weighed. For each sample the mean weight diameter (MWD) was calculated using equation 5.1 below (Hillel 1980);

$$MWD = \sum_{i=1}^{n} x_i w_i \qquad (5.1).$$

where x_i is the mean diameter of any particular size range of aggregates separated by sieving, and w_i is the weight of aggregates in that size range as a fraction of the total dry weight of the sample analyzed. MWD was used as an index of aggregate size distribution.

An alternative index of aggregate size distribution, geometric mean diameter (GMD) was also calculated for each sample using equation 5.2 below (Hillel 1980):

$$GMD = \exp[(\sum_{i=1}^{n} w_i \log x_i)/(\sum_{i=1}^{n} w_i)] \qquad (5.2)$$

where x_i and w_i are as defined for equation 5.1.

Statistical analyses to compare fractions of aggregates in each size class, MWD and GMD for heavy, medium and light grazed meadow bromegrass and triticale were conducted using SAS generalized linear model procedure (SAS Institute 1989). Separation of means was conducted using the least squares means procedure.

5.3 RESULTS

5.3.1 Seasonal changes in bulk density

For meadow bromegrass, the average surface (0-2.5 cm) bulk density determined in fall 1995 was significantly greater for heavy compared to light grazing (Table 5.1). There was no significant difference between bulk densities of heavily and medium grazed areas. The surface bulk density for heavy grazing was 22% greater than that for light grazing. For triticale the surface bulk densities were similar among grazing treatments. Significant ($p \leq 0.05$) differences in the densities among plant species were observed only in the top 5 cm.

The average bulk densities for all depths intervals for meadow bromegrass and triticale under heavy, medium and light grazing intensities in spring 1996 were similar (Table 5.2).

In fall 1996 significant ($p \leq 0.05$) differences in surface bulk densities were obtained only between triticale medium and meadow bromegrass lightly grazed (Table 5.3). Generally, for each grazing treatment, the average surface density was lower in fall 1996 than fall 1995. At soil depths between 2.5 and 10 cm, the average bulk densities from meadow bromegrass and triticale under heavy, medium and light grazing were similar.

In spring 1997, and for each forage, surface bulk densities among grazing treatments were similar (Table 5.4). However, medium grazed triticale had significantly ($p \leq 0.05$) greater surface bulk density than light grazed meadow bromegrass. At soil depths greater than 2.5 cm the average bulk densities were similar among grazing treatments and for both forages.

Changes in average bulk density between fall 1995 and spring 1996, and between fall 1996 and spring 1997 were calculated to determine whether bulk density had increased or decreased overwinter (Table 5.5). For the surface 5 cm, 67% of the average bulk densities in spring were lower than those in fall. However, in the 5-10 cm depth interval 58% of the average densities were higher in spring compared to fall. For the 10-15 cm depth interval, average bulk density did not change between fall and winter. Overall, the average differences between spring and fall densities were small: -0.03, +0.02, 0.00 Mg m^{-3} for depth intervals of 0-5, 5-10 and 10-15 cm, respectively.

The data to 15 cm across depths demonstrated minimal variation in changes in densities from year to year. Between fall 1995 and spring 1996, 44% of the average densities decreased while 50% of average densities increased. Between fall 1996 and spring 1997, 50% of the average densities decreased while 36% increased. However, the rather high bulk densities for the surface 2.5 cm in fall 1995 appear anomalous and make the comparison from year to year across all depths complicated.

5.3.2 Seasonal changes in moisture content

In fall 1995, the average surface (0-2.5 cm) gravimetric moisture content for meadow bromegrass under medium grazing was significantly ($p \leq 0.05$) greater than that for heavily and lightly grazed treatments (Table 5.6). For triticale, the moisture content for heavy, medium and light grazing were not significantly different. As expected, moisture content for each grazing treatment was lower for the surface 2.5 cm compared with moisture content at greater depths. Generally, the gravimetric moisture contents at depths greater than 2.5 cm for meadow bromegrass and for triticale under heavy, medium and light grazing were not significantly different.

In spring 1996, the average surface gravimetric moisture content for light grazing was significantly ($p \leq 0.05$) greater than that for heavy grazing of triticale (Table 5.7). For the 2.5-5 cm depth interval the moisture content for the light grazed triticale was significantly greater than that for the heavily grazed meadow bromegrass. At depths below 5 cm, except for the 7.5-10 cm depth interval, gravimetric moisture contents for different grazing treatments and forages were similar.

In fall 1996 the surface gravimetric moisture content for both triticale and meadow bromegrass was significantly greater for light than for heavy and medium grazing (Table 5.8). A similar result was obtained for the 2.5-5 cm depth interval. Generally, for both forage species and all grazing treatments, moisture content was higher in the surface compared to that at greater depths.

In spring 1997, and for both forages, surface (0-2.5 cm) gravimetric moisture content for light grazing was significantly greater than that for heavy grazing (Table 5.9). Significant differences ($p \leq 0.05$) between gravimetric moisture contents for different grazing treatments were observed between depths of 0 to 12.5 cm. Unlike in Fall 1996, the moisture content for each grazing treatment was lower in the surface soil than at greater depths.

5.3.3 Seasonal changes in penetration resistance

The surface penetration resistances measured in fall 1995 varied substantially with grazing treatment (Table 5.10). Surface penetration resistance for heavily grazed meadow bromegrass was significantly greater than that for lightly grazed meadow bromegrass, and heavily grazed and lightly grazed triticale. The same trend was observed for penetration resistances measured at a depth of 2.5 cm. In the heavily grazed meadow bromegrass, penetration resistance could not be determined for depths greater than 5 cm due to very high resistances that were beyond the maximum (5.3 MPa) reading that could be measured using the penetrometer.

In spring 1996 the average surface penetration resistance for heavily grazed meadow bromegrass was still significantly ($p \leq 0.05$) greater than that for lightly grazed meadow bromegrass, and that for triticale under heavy, medium or light grazing (Table 5.11). However, because of high moisture content at the time of sampling the penetration resistances were generally lower than those measured in fall 1995. Penetration resistances among grazing intensities were significantly different for all depths intervals between 0 and 15 cm. However, for all depths penetration resistances for heavy, medium and light grazed triticale were similar.

Penetration resistances at the end of the second grazing season (fall 1996) were all lower than 2 MPa (Table 5.12). Penetration resistances for heavily grazed meadow bromegrass determined below the soil surface were significantly greater than that for lightly grazed meadow bromegrass, or heavy, medium or lightly grazed triticale. At all soil depths penetration resistances for triticale under heavy, medium and light were similar. Many earthworms were observed during sampling: on average at least one earthworm for every two core samples (approximately 125 worms m^{-2}). The numbers were greater in the heavily grazed treatments ranging between 2 and 3 worms for every three core samples collected (i.e. 170-250 worms m^{-2}).

In spring 1997 penetration resistance for heavily grazed meadow bromegrass at all depths, except at 12.5 and 15 cm, was significantly ($p \le 0.05$) greater than that for lightly grazed meadow bromegrass or triticale under heavy, medium or light grazing (Table 5.13). Penetration resistances for medium and heavy grazed meadow bromegrass were similar for depths between 0 and 2.5 cm. During sampling large numbers of earthworms were observed at approximately the same density as that observed at the end of the fall 1996 grazing season (approximately 125 worms m^{-2}).

Multiple linear regression analysis indicated the best model to describe the penetration resistance (PR) to a 15-cm depth must include bulk density (BD) and either gravimetric moisture content (GMC) or volumetric moisture content (VMC). Grazing intensity did not significantly affect this relationship. Also, plant species did not affect the slopes of this regression model. However, the season in which the data were collected significantly ($p \le 0.05$) affected the regression model so that the best generalized model was a distinct regression;

$$PR_{ijkl} = \alpha_i + \beta_i (BD)_{ijkl} + \gamma_i (GMC \text{ or } VMC)_{ijkl} + \varepsilon_{ijkl} \quad (5.3)$$

where α = intercept, β = regression coefficient associated with bulk density, γ = regression coefficient associated with gravimetric or volumetric moisture content, ε = residual error, i= 1...4 for four seasons, j=1...3 grazing intensities, k = 1...2 plant species and l = number of replications. Thus the equations had different regression coefficients for fall 1995, spring 1996, fall 1996 and spring 1997 (Table 5.14). All terms in the equation are significant ($p \leq 0.05$). However, both bulk density and either gravimetric moisture content or volumetric moisture content accounted for a very small variation in penetration resistance as reflected by a small coefficient of determination (R^2 value).

5.3.4 Benchmark

Bulk density in the benchmark was lower at the surface (0-2.5 cm) compared to that at greater depths (Table 5.15). However, moisture content at the surface was higher than that at greater depths. Bulk densities obtained in spring 1996 were either equal to or greater than those for fall 1995. However, the bulk densities in spring 1997 were lower than those for fall 1996, except for the surface bulk density.

Non-parametric statistical analysis conducted using the Kruskall-Wallis test indicated that the average surface bulk density (0-2.5 cm) for the benchmark site in fall 1995 was significantly ($p \leq 0.05$) lower than that for heavy, medium or lightly grazed meadow bromegrass or triticale (Table 5.16), presumably due to high soil organic matter and rhizomatous root systems generated by naturalized grasses on the site. At depths between 2.5 and 10 cm the average density for the benchmark site was significantly greater than that for any forage species-grazing intensity treatment combinations, as reflected by the high mean scores (ranks) for the benchmark. At depths beyond 10 cm the average bulk densities for the benchmark were similar to those for either meadow bromegrass or triticale under heavy, medium or light grazing.

In spring 1996, the average surface bulk density for the benchmark site was similar to that for either meadow bromegrass or triticale subjected to heavy, medium or light grazing (Table 5.16). However, at depths between 2.5 and 10 cm the average bulk density in each depth increment for the benchmark site was significantly ($p \leq 0.05$) greater than that for meadow bromegrass and triticale under any of the three grazing intensities.

In fall 1996, the average surface bulk density for the benchmark was significantly ($p \leq 0.05$) lower than that for the other two forages under heavy, medium and light grazing (Table 5.16). However, between depths of 2.5 and 12.5 cm, except for the 7.5-10 cm depth interval, the results of the Kruskall-Wallis test indicated significantly ($p \leq 0.05$) greater densities for the benchmark site compared with that for meadow bromegrass and triticale under heavy, medium and light grazing.

In spring 1997, the average surface bulk density for the benchmark was significantly lower than that for meadow bromegrass and triticale under any of the three grazing treatments (Table 5.16). The average bulk density in the 2.5 - 5 cm depth increment for the benchmark was similar to that for the forages under heavy, medium and light grazing. At depths increments between 5 and 10 cm, the average bulk densities between treatments were significantly ($p \leq 0.05$) different.

Gravimetric moisture content followed a reverse trend compared to bulk density. At all four measuring times the moisture content in the top 2.5 cm of the benchmark was similar to that for heavy, medium and light grazing, whereas between 2.5 and 15 cm, moisture content for the benchmark was significantly ($p \leq 0.05$) lower than that for heavy, medium and light grazing (Table 5.16).

5.3.5 Aggregate analysis

Analysis of variance of percentages of aggregates in various size classes indicated that there were non-significant differences in the fractions of small aggregates (0.125-0.25 mm and 0.25-0.5 mm) in heavy, medium and light grazed plots of meadow bromegrass and triticale (Table 5.17). However, for the 0.5-1 mm aggregate size class, triticale under light grazing had a significantly smaller fraction of these aggregates compared with other grazing and forage treatments. For aggregates in the 1-2 mm and 2-4 mm class, meadow bromegrass under light grazing had a significantly ($p \leq 0.05$) greater fraction than triticale under heavy, medium and light grazing. There were no significant differences between fractions of this aggregate class for meadow bromegrass under heavy, medium or light grazing. However, for the 4-8 mm class, meadow bromegrass under light grazing had a significantly smaller fraction than triticale under heavy, medium or light grazing.

Triticale under light grazing had a significantly greater mean weight diameter (MWD) and geometric mean diameter (GMD) compared to respective values for meadow bromegrass under light grazing (Table 5.17). There were non-significant differences between MWDs and GMDs for meadow bromegrass under heavy and medium grazing and for triticale under heavy, medium and light grazing. Generally there were few differences in percent aggregates in a given size range across plant species, except for 1-2 and 2-4 mm classes where the fraction of aggregates was significantly lower under triticale than meadow bromegrass. This higher but non-significant percentage of aggregates in small sizes may be a remnant of the annual cultivation of the triticale plots. Also the slightly higher but non-significant percentage of aggregates in the 4-8 mm class for triticale may be due to the formation of clods because of annual cultivation.

5.4 DISCUSSION

The high animal traffic associated with heavy grazing caused an increase in bulk density and penetration resistance of surface (0-5 cm) soil, due to trampling, especially during the 1995 grazing season. The greater the grazing intensity, the greater the surface area trampled and the greater the removal of vegetation. This was reflected by a greater amount of litter and a smaller percentage of bare ground reported for light grazing compared to heavy and medium grazing treatments observed in fall 1995 (Gill 1997). This vegetation removal means that the soil is less cushioned and becomes more susceptible to compaction resulting in greater surface runoff and total sediment yield obtained at the end of fall 1995 (Gill 1997). This result is in agreement with the results of Krenzer et al. (1989) who reported bulk density increases by as much as 16% due to animal traffic. Naeth et al. (1990) found that trampling due to very heavy grazing caused significantly higher bulk densities in the top 7.5 cm compared with moderate and light grazing. In our study, compaction caused by animal traffic appeared to be restricted in the top 5 cm of the soil. This result contradicts the principal foundation upon which many proponents of intensive rotational grazing systems base their conclusions, that animal hooves chip or churn the soil surface and may break up surface crusting without compacting the soil and thus improving infiltration and reducing soil erosion (Savory 1978).

The non-significant differences between bulk densities of heavy, medium and light grazed meadow bromegrass and triticale for spring 1996, fall 1996 and spring 1997 may have been due to the cumulative effect of natural amelioration processes such as, freeze-thaw action, wet-dry cycles and earthworm tunneling. During winter, soils are generally dry, but occasional thawing of snow may provide sufficient moisture to form ice lenses that create the loosening effect of surface compacted soils. In this study, it is possible that because of the soil's high silt content, the contribution of freezing-thawing phenomena in alleviating surface compaction was quite substantial, especially in the top 5 cm. However, soil moisture contents in fall 1995 were very low but quite high in fall 1996. Thus the potential for freeze-thaw amelioration in 1995 would have been low (lack of water needed for ice lens formation) but high in 1996. Similar observations have been made in forest soils (Thacker et al. 1994). Overall, the observed general decrease in bulk density in the top 5 cm overwinter and the general increase in bulk density in the 5-10 cm depth interval indicate that freeze-thaw action can cause positive or negative effects on soil physical properties. According to Larson and Allmaras (1971), ice lens formation in soils that do not get moisture recharge from the water table results in heaving of the topsoil whereas shrinkage occurs at lower depths due to partial desiccation of the soil as water moves upward to form ice lenses. This loss of water may have caused soil drying in lower depths and consequently closer packing of soil particles that gave higher bulk densities in spring compared to fall.

It is highly possible that the large number of earthworms observed in plots during sampling may have partially contributed to the observed reduction of bulk densities of heavily and medium grazed plots due to soil ingestion and tunneling. Furthermore, it is possible that the high amounts of animal waste associated with heavy grazing might have promoted earthworm activity as has been reported in the literature (Curry 1976; Lee 1985). As a result this may have slightly offset the increased bulk density associated with this grazing system.

The greater subsurface (5-10 cm) bulk densities of continuously grazed naturalized grasses compared with meadow bromegrass and triticale under rotational grazing systems means that continuous grazing systems are likely to have long-term subsurface compaction problems that limit downward water movement compared to rotational grazing systems. Although the continuously grazed naturalized grasses have rhizomatous root systems that produce high organic matter in the surface, this does not safeguard the soil profile from long-term subsurface compaction.

Penetration resistance is frequently used as a measure of soil strength. This property is a compound parameter involving components of shear, compressive and tensile strength and soil-metal friction. For each of the four seasons an empirical linear relationship was obtained between penetration resistance, bulk density and gravimetric moisture content or volumetric moisture content. This result agrees with several other experimental studies that reported that penetration resistance increases with increasing density and decreases with increasing moisture content (Malqueen et al. 1977; Ehlers et al. 1983; Busscher et al. 1987; Perumpral 1987). Cohesive strength of a soil is substantially inversely influenced by soil moisture content and is directly proportional to the ratio of clay to silt and sand (Elbanna and Witney 1987). In heavy clays penetration resistance is mainly controlled by soil cohesion, while in sandy soils it is the frictional component that controls penetration resistance. In our study the soil was loam-textured with 15% clay, 34% silt and 51% sand. Thus the high penetration resistances observed at low moisture contents were mainly due to a combination of both cohesion and friction.

The non-significant differences between regression equations for heavy, medium and light grazing indicate that compactive effort does not influence the nature of the relationship between penetration resistance, bulk density and moisture content. Also the non-significant difference between regression models for meadow bromegrass and triticale suggests that neither of these root systems was dense enough to alter the relationship between penetration resistance, bulk density and moisture content. However, the significant differences between regression equations for the four seasons may be due to soil particle rearrangement brought about during ice lens formation in winter, earthworm activity in fall and spring and loss of fine soil particles due to erosion during snowmelt. As a result of these processes slight changes in soil structure can be expected from one season to another.

Maximum root growth pressures have been reported to range between 0.9 and 1.3 MPa (Misra et al. 1986). Penetration resistances that limit root growth range between 0.8 and 8 MPa and are plant species specific (Glinski and Lipiec 1990; Bathke et al. 1992). In many studies root elongation has been linearly related to penetration resistance up to 2 MPa so that a resistance of 2 MPa has been used as the threshold beyond which root growth becomes severely restricted (Taylor et al. 1966; Naeth et al. 1991). If we accept this value as critical for limiting growth, then root growth was most likely affected in fall 1995 for all grazing treatments. However, in spring 1996 and spring 1997 only root growth of the heavy grazed meadow bromegrass was likely affected because of penetration resistances greater than 2 MPa.

Aggregate stability strongly depends on soil organic matter content (Harris et al. 1966). In some studies, aggregation in surface horizons has been predominantly affected by microbial populations and degradation of soil binding materials. High microbial populations associated with pasture grass rhizospheres produce polysaccharide mucigels that promote aggregation in short term, while in the long-term humic materials build-up will stabilize aggregates (Naeth et al. 1991). The tunneling and production of casts by earthworms, especially in heavily grazed treatments of this study, may also have masked differences between water stable aggregate size distribution among grazing treatments.

Apart from the contributions of freeze-thaw action, wet-dry cycles and earthworm activity in alleviating soil compaction, it is also possible that the general lack of significant deterioration of soil due to grazing may be attributed to the very good quality of the soil (moderate clay content and high organic matter) even after three seasons of grazing.

5.5 CONCLUSIONS

Effects of heavy grazing on soil bulk density and penetration resistance were manifested only in fall 1995. In general grazing effects of soil were mostly confined to the top 5 cm of the soil. Natural alleviation processes such as freeze-thaw action, wet-dry cycles and earthworm activity likely reduced the effects of animal trampling. Generally, at depths between 5 and 10 cm bulk density increased slightly overwinter. Continuous grazing resulted in greater subsurface densities and lower moisture contents than rotationally grazed meadow bromegrass and triticale. Thus, in the long-term, continuous grazing may cause serious subsurface compaction problems that restrict water movement. A positive relationship was found between penetration resistance and bulk density, and a negative one between penetration resistance and moisture content. Grazing intensity did not affect distribution of water-stable aggregates measured in fall 1996. A very slight plant species effect on distribution of water-stable aggregates was obtained likely due to cultivation and shallower rooting of triticale compared to meadow bromegrass.

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Table 5.1 Average bulk densities at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Fall 1995)

Grazing intensity	Bulk density ($Mg\ m^{-3}$) at depth intervals (cm) of:					
	0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow bromegrass			
Heavy	1.38a†	1.24a	1.13a	1.27a	1.25a	1.29a
Medium	1.20abc	1.20ab	1.14a	1.18ab	1.22a	1.20a
Light	1.06c	1.19ab	1.11a	1.19ab	1.27a	1.25a
			Triticale			
Heavy	1.33ab	1.08b	1.14a	1.14b	1.25a	1.27a
Medium	1.30ab	1.17ab	1.07a	1.11b	1.21a	1.23a
Light	1.16bc	1.09b	1.13a	1.14b	1.28a	1.29a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.2 Average bulk densities at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Spring 1996)

Grazing intensity	Bulk density ($Mg\ m^{-3}$) at depth intervals (cm) of:					
	0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow bromegrass			
Heavy	1.19a†	1.24a	1.18a	1.24a	1.31a	1.25a
Medium	1.14a	1.17a	1.15a	1.18a	1.27a	1.19a
Light	1.17a	1.21a	1.20a	1.23a	1.22a	1.23a
			Triticale			
Heavy	1.12a	1.12a	1.08a	1.21a	1.23a	1.25a
Medium	1.15a	1.15a	1.14a	1.21a	1.26a	1.25a
Light	1.12a	1.19a	1.17a	1.20a	1.32a	1.28a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.3 Average bulk densities at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Fall 1996)

Grazing intensity	Bulk density ($Mg\ m^{-3}$) at depth intervals (cm) of: 0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow bromegrass			
Heavy	1.02b†	1.21a	1.19a	1.20a	1.29a	1.25a
Medium	1.10ab	1.22a	1.19a	1.17a	1.23ab	1.17a
Light	1.01b	1.17a	1.14a	1.17a	1.18b	1.19a
			Triticale			
Heavy	1.10ab	1.21a	1.14a	1.09a	1.15b	1.15a
Medium	1.28a	1.27a	1.18a	1.12a	1.25ab	1.23a
Light	1.17ab	1.25a	1.20a	1.19a	1.25ab	1.29a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.4 Average bulk densities at different depths for meadow bromegrass and triticale subjected to heavy, medium and light grazing (Spring 1997)

Grazing intensity	Bulk density ($Mg\ m^{-3}$) at depth intervals (cm) of: 0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow bromegrass			
Heavy	1.05ab†	1.24a	1.22a	1.20a	1.25a	1.24a
Medium	1.11ab	1.16a	1.14a	1.17a	1.26a	1.20a
Light	0.98b	1.13a	1.15a	1.17a	1.22a	1.25a
			Triticale			
Heavy	1.06ab	1.18a	1.14a	1.14a	1.17a	1.17a
Medium	1.19a	1.25a	1.15a	1.16a	1.13a	1.22a
Light	1.03ab	1.23a	1.20a	1.16a	1.20a	1.26a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.5 Changes in average bulk densities overwinter at different depth intervals for meadow bromegrass and triticale under heavy, medium and light grazing

Plant species	Grazing intensity	Change in bulk density ($Mg\ m^{-3}$) for depth intervals (cm) of:					
		0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
		Fall 1995 vs. Spring 1996					
Meadow	Heavy	-0.19†	0.00	+0.05	-0.03	+0.06	-0.04
	Medium	-0.06	-0.03	+0.01	0.00	+0.05	-0.01
	Light	+0.11	+0.02	+0.09	+0.04	-0.05	-0.02
Triticale	Heavy	-0.21	+0.04	-0.06	+0.07	-0.02	-0.02
	Medium	-0.15	-0.02	+0.07	+0.10	+0.05	+0.02
	Light	-0.04	+0.10	+0.04	+0.06	+0.04	-0.01
	Average	-0.09	+0.02	+0.03	+0.04	+0.02	-0.01
		Fall 1996 vs Spring 1997					
Meadow	Heavy	+0.03	+0.03	+0.03	0.00	-0.04	-0.01
	Medium	+0.01	-0.06	-0.05	0.00	+0.03	+0.03
	Light	-0.03	-0.04	+0.01	0.00	+0.04	+0.06
Triticale	Heavy	-0.04	-0.03	0.00	+0.05	+0.02	+0.02
	Medium	-0.09	-0.02	-0.03	+0.04	-0.12	-0.01
	Light	-0.14	-0.02	0.00	-0.03	-0.05	-0.03
	Average	-0.04	-0.02	-0.01	+0.01	-0.02	+0.01

† change in bulk density = spring bulk density - fall bulk density for a given depth interval.

Table 5.6 Average gravimetric moisture contents at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Fall 1995)

Grazing intensity	Gravimetric moisture content (g/100 g) at depth intervals (cm) of: 0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow bromegrass			
Heavy	9.2b†	11.9a	12.6a	12.4a	12.2ab	12.1a
Medium	13.0a	13.5a	13.6a	13.2a	13.4ab	12.8a
Light	9.6b	11.3a	11.9a	11.5a	11.0b	10.8a
			Triticale			
Heavy	8.6b	12.6a	14.1a	14.2a	13.8ab	13.5a
Medium	8.5b	11.3a	12.0a	11.7a	11.2b	10.9a
Light	9.9b	13.5a	14.3a	14.1a	14.9a	13.2a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.7 Average gravimetric moisture contents at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Spring 1996)

Grazing Intensity	Gravimetric moisture content (g/100 g) at depth intervals (cm) of: 0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow Bromegrass			
Heavy	29.4ab†	27.3b	26.8a	25.8ab	25.0a	24.1a
Medium	31.8ab	29.3ab	27.6a	24.3b	24.0a	22.8a
Light	31.9ab	28.8ab	27.1a	25.3ab	23.8a	22.5a
			Triticale			
Heavy	27.8b	27.9ab	27.5a	26.3ab	24.6a	24.0a
Medium	29.2ab	27.9ab	27.2a	25.4ab	22.8a	22.2a
Light	34.1a	32.6a	30.7a	28.6a	26.7a	25.0a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.8 Average gravimetric moisture contents at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Fall 1996)

Grazing intensity	Gravimetric moisture content (g/100 g) at depth intervals (cm) of:					
	0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow bromegrass			
Heavy	36.3ab†	29.8b	28.1ab	26.0a	24.4ab	24.5a
Medium	36.0abc	29.4b	27.4b	26.0a	24.6ab	24.1a
Light	34.5abc	30.7ab	28.7ab	24.7a	21.9b	20.2a
			Triticale			
Heavy	30.7c	29.7b	29.1ab	27.8a	26.1ab	25.5a
Medium	31.1bc	28.6b	26.6b	24.6a	22.6ab	21.6a
Light	37.0a	33.6a	31.3a	28.3a	26.3a	24.8a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.9 Average gravimetric moisture contents at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Spring 1997)

Grazing intensity	Gravimetric moisture content (g/100 g) at depth intervals (cm) of:					
	0-2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15
			Meadow bromegrass			
Heavy	14.6c†	21.6b	22.5b	22.4c	21.8b	22.3a
Medium	22.1ab	25.4ab	23.2ab	22.8bc	23.4ab	23.2a
Light	24.2a	25.0ab	24.7ab	22.2abc	22.9ab	21.9a
			Triticale			
Heavy	15.3c	23.8ab	25.7ab	26.1a	25.5a	23.2a
Medium	16.7bc	21.6b	22.7b	23.1abc	23.1ab	21.8a
Light	21.8ab	26.3a	26.4a	25.8ab	25.2ab	23.9a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

Table 5.10 Average penetration resistance at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Fall 1995)

Grazing intensity	Penetration resistance (MPa) at depths (cm) of:						
	Surface	2.5	5	7.5	10	12.5	15
				Meadow bromegrass			
Heavy	3.43a[†]	5.05a	–	–	–	–	–
Medium	2.84ab	4.34ab	3.19b	2.99b	3.08b	3.03b	3.12b
Light	1.91bc	3.56bc	3.84a	3.90a	4.01a	4.00a	4.05a
				Triticale			
Heavy	1.76c	3.54bc	3.13b	2.83b	3.00b	3.14b	3.25b
Medium	2.62abc	3.86b	3.19b	2.96b	3.23b	3.53ab	3.68ab
Light	1.69c	2.81b	2.74b	2.74b	3.00b	3.30b	3.47ab

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 36 for each treatment.

Table 5.11 Average penetration resistance at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Spring 1996)

Grazing intensity	Penetration resistance (MPa) at depths (cm) of:						
	Surface	2.5	5	7.5	10	12.5	15
				Meadow bromegrass			
Heavy	0.96a[†]	2.10a	1.85a	1.61a	1.73a	1.76a	1.82ab
Medium	0.90a	1.70a	1.59ab	1.49a	1.59ab	1.75a	1.88a
Light	0.64b	1.24b	1.30bc	1.28b	1.39b	1.44b	1.50abc
				Triticale			
Heavy	0.59b	1.18bc	1.07cd	0.98c	1.14c	1.39b	1.45bc
Medium	0.64b	1.16bc	1.05cd	0.94c	1.11c	1.42b	1.60abc
Light	0.45b	0.84c	0.84d	0.85c	1.02c	1.29b	1.41c

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 36 for each treatment.

Table 5.12 Average penetration resistance at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Fall 1996)

Grazing intensity	Penetration resistance (MPa) at depths (cm) of:						
	Surface	2.5	5	7.5	10	12.5	15
				Meadow bromegrass			
Heavy	0.91b[†]	1.67a	1.55a	1.52a	1.59ab	1.66ab	1.72a
Medium	1.27a	1.48ab	1.44a	1.47a	1.60a	1.75a	1.80a
Light	0.77b	1.10cd	1.11b	1.11b	1.34abc	1.52ab	1.63a
				Triticale			
Heavy	0.76b	1.06d	1.05b	1.04b	1.62bc	1.35b	1.45a
Medium	0.92b	1.31bc	1.13b	1.15b	1.35abc	1.58ab	1.67a
Light	0.69b	1.02d	1.10b	1.09b	1.23c	1.39ab	1.58a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 36 for each treatment.

Table 5.13 Average penetration resistance at different depths for meadow bromegrass and triticale under heavy, medium and light grazing (Spring 1997)

Grazing intensity	Penetration resistance (MPa) at depths (cm) of:						
	Surface	2.5	5	7.5	10	12.5	15
				Meadow bromegrass			
Heavy	1.91a[†]	2.62a	2.10a	1.82a	1.79a	1.80a	1.76a
Medium	1.98a	2.21ab	1.69b	1.54b	1.55b	1.63ab	1.67ab
Light	1.38bc	1.60d	1.53b	1.45b	1.45bc	1.54abc	1.62ab
				Triticale			
Heavy	1.11c	1.42d	1.18c	1.03d	1.14d	1.30c	1.37b
Medium	1.55b	2.03bc	1.49b	1.18cd	1.18d	1.37c	1.51ab
Light	1.23c	1.63cd	1.44bc	1.24c	1.25cd	1.44bc	1.48ab

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 36 for each treatment.

Table 5.14 Regression equations relating penetration resistance (PR in MPa) to bulk density (BD in Mg m^{-3}) and gravimetric (GMC in g/100 g) or volumetric (VMC in $m^3/100\ m^3$) moisture content, and coefficients of determination (R^2), probabilities and standard errors of estimated values ($SE_{Y.X}$).

Season	Regression equation†	R^2 value	Prob.	$SE_{Y.X}$
Fall 1995	PR = 2.935 + 1.288BD - 0.041GMC	0.17	0.0001	0.73
	PR = 1.767 + 2.236BD - 0.034VMC	0.17	0.0001	0.73
Spring 1996	PR = 1.850 + 0.334BD - 0.035GMC	0.25	0.0001	0.36
	PR = 0.913 + 1.148BD - 0.031VMC	0.25	0.0001	0.36
Fall 1996	PR = 2.295 - 0.030GMC	0.21	0.0001	0.32
	PR = 1.456 + 0.645BD - 0.028VMC	0.24	0.0001	0.31
Spring 1997	PR = 1.666 + 0.393BD - 0.025GMC	0.12	0.0001	0.38
	PR = 1.138 + 0.906BD - 0.024VMC	0.13	0.0001	0.38
Combined	PR = 1.343 + 0.828BD - 0.018GMC	0.03	0.0001	0.97
	PR = 0.886 + 1.246BD - 0.017VMC	0.03	0.0001	0.97

† data for 0-15 cm depth combined; n = 397, 432, 432 and 433 for fall 1995, spring and fall 1996, and spring 1997 respectively.

Table 5.15 Average bulk densities and gravimetric moisture contents for the benchmark treatment at different depth intervals and sampling times.

Season	Depth interval (cm)	Bulk density ($Mg\ m^{-3}$)	Gravimetric moisture content (g/100 g)
Fall 95	0-2.5	0.95	9.0
	2.5-5	1.33	7.4
	5-7.5	1.25	7.3
	7.5-10	1.26	7.3
	10-12.5	1.27	7.2
	12.5-15	1.30	7.4
Spring 96	0-2.5	1.02	28.6
	2.5-5	1.36	16.9
	5-7.5	1.30	15.6
	7.5-10	1.34	15.2
	10-12.5	1.36	14.8
	12.5-15	1.30	14.1
Fall 96	0-2.5	0.84	44.0
	2.5-5	1.28	21.6
	5-7.5	1.38	17.9
	7.5-10	1.32	17.4
	10-12.5	1.37	17.1
	12.5-15	1.25	17.9
Spring 97	0-2.5	0.90	19.3
	2.5-5	1.23	18.6
	5-7.5	1.28	19.0
	7.5-10	1.30	18.9
	10-12.5	1.24	19.1
	12.5-15	1.23	19.3

n = 6 for each depth interval.

Table 5.16 Kruskall-Wallis test χ^2-values, and significance (α) levels obtained by comparing bulk densities and gravimetric moisture contents from the benchmark (naturalized grass under unmanaged grazing) with that from meadow bromegrass and triticale under heavy, medium and light grazing

Season	Depth (cm)	Bulk density χ^2 value	Bulk density Probability	Gravimetric moisture χ^2 value	Gravimetric moisture Probability
Fall 95	0-2.5	25.2	**0.0003**†	11.2	0.0822
	2.5-5	18.2	**0.0056**	23.3	**0.0007**
	5-7.5	10.8	0.0942	25.9	**0.0002**
	7.5-10	15.0	**0.0200**	25.8	**0.0002**
	10-12.5	2.8	0.8352	24.6	**0.0004**
	12.5-15	8.5	0.2007	22.6	**0.0009**
Spring 96	0-2.5	4.9	0.5569	11.6	0.0724
	2.5-5	13.7	**0.0333**	23.6	**0.0006**
	5-7.5	15.2	**0.0184**	21.4	**0.0015**
	7.5-10	12.1	0.0605	19.5	**0.0034**
	10-12.5	8.3	0.2179	16.9	**0.0097**
	12.5-15	6.0	0.4186	13.6	**0.0346**
Fall 96	0-2.5	27.6	**0.0001**	21.7	**0.0014**
	2.5-5	11.4	0.0781	21.4	**0.0016**
	5-7.5	17.6	**0.0072**	22.6	**0.0010**
	7.5-10	19.7	**0.0031**	18.9	**0.0044**
	10-12.5	20.6	**0.0021**	17.2	**0.0087**
	12.5-15	8.5	0.2038	12.6	**0.0494**
Spring 97	0-2.5	15.4	**0.0177**	22.0	**0.0012**
	2.5-5	10.1	0.1205	19.0	**0.0041**
	5-7.5	12.4	0.0530	17.5	**0.0077**
	7.5-10	13.9	**0.0307**	17.3	**0.0081**
	10-12.5	11.3	0.0786	12.6	**0.0495**
	12.5-15	6.1	0.4084	4.9	0.5523

† Values in bold are significant (Kruskall-Wallis test, $p \leq 0.05$).

Table 5.17 Average percentage of aggregates of various size ranges (mm), mean weight diameter (MWD) and geometric mean diameter (GMD) for heavy, medium and light grazed meadow bromegrass and triticale plots taken at the end of the fall 1996 grazing season.

Grazing intensity	% of soil sample within size range (mm) of:						MWD (mm)	GMD (mm)
	0.125-0.25	0.25-0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0		
				Meadow bromegrass				
Heavy	4.8a†	7.2a	11.4a	15.5ab	25.4ab	35.7ab	3.3ab	1.4ab
Medium	5.4a	8.0a	11.1a	15.1abc	24.8ab	35.6ab	3.2ab	1.4ab
Light	6.2a	8.6a	11.8a	16.2a	27.0a	30.2b	3.0b	1.3b
				Triticale				
Heavy	6.1a	8.5a	10.6ab	13.8bc	22.0bc	39.0a	3.3ab	1.4ab
Medium	6.9a	9.1a	10.6ab	13.1c	21.2c	39.2a	3.3ab	1.4ab
Light	4.5a	7.1a	9.1b	13.2c	22.2bc	43.8a	3.6a	1.5a

† Within columns, means followed by the same letter are not significantly different (LSmeans test, $p \leq 0.05$); n = 12 for each treatment.

CHAPTER 6.

SYNTHESIS

6.1 GENERAL DISCUSSION

Soil compaction is a worldwide, multi-disciplinary problem that has adverse effects on plant growth and the environment. The costs associated with deep tillage to alleviate compaction are enormous and the increased fuel consumption associated with this practice enhances emission of carbon dioxide. Thus every effort must be made to minimize or prevent compaction, and to reduce use of deep tillage. Investigating agronomic techniques such as using appropriate tests to determine 'danger zone' moisture content for soil trafficking, cropping system, use of amendments such as fly ash and grazing management may provide alternatives to deep tillage. Individual studies were conducted to investigate these techniques.

6.1.1 Threshold moisture for soil trafficking and cultivation

Engineers view soil as a construction material or cultivation medium, and they use consistency limits and critical moisture content as determined by the Proctor test for determining bearing capacity, shear strength and for predicting stability of foundations (McBride 1993). Agronomists view soil as a medium for plant growth and use field capacity to indicate a good balance between adequate water uptake and aeration, and wilting point to determine the lowest moisture content before plants begin to wilt (Hillel 1980). This study on the response of non-amended soils to compaction indicates that there is a close relationship between consistency limits and agronomic limits. Sandy loam and loam textured soils were most susceptible to compaction at soil moistures close to field capacity or critical moisture content. For a clay loam soil, maximum densification occurred at a moisture content much lower than field capacity and closer to the plastic limit. This means that, either field capacity or plastic limit, whichever is less, can be used to indicate soil moisture above which soils are most susceptible to compaction. Under field conditions, field capacity would be the best indicator of moisture content above which trafficking of sandy loam and loam soils must be avoided, whereas plastic limit would be the best indicator of 'danger zone' for trafficking clay loam soils.

6.1.2 Use of fly ash as a soil amendment and its limitations

Soil amendments such as organic matter and lime have been widely used to prevent or alleviate compaction (Larson et al. 1994). Fly ash, a by product of coal combustion, is produced in large quantities annually, and faces disposal problems worldwide (Carlson and Adriano 1993). A very small fraction of fly ash has been used in dam construction and embankments but not enough to solve the disposal problem. While studies have been conducted on using fly ash to improve water retention, few studies (e.g. Sivapullaiah et al. 1996) have been conducted on the use of fly ash as an amendment to reduce susceptibility to compaction. The study of the response of fly ash-amended soils to compaction indicated that fly ash influenced several soil physical and chemical properties such as pH, calcium, magnesium, sodium and potassium content. However, while fly ash additions increased electrical conductivity and ionic strength of soil solutions, they decreased the soil's sodium adsorption ratio (SAR). For sandy loam and loam soils, fly ash additions increased field capacity, wilting point, and maximum Proctor density but decreased liquid limit and plasticity index. For the clay loam, fly ash additions decreased field capacity, wilting point, liquid limit and plasticity index. These results support the results of Watson (1994) who observed addition of fly ash to sandy loam and silty clay textured soils at rates up to 20% increased FC and WP, but available water holding capacity did not change significantly. For soils that are most susceptible to compaction, the addition of fly ash reduces the range of moisture over which the soil is plastic, and therefore reduces the soil's susceptibility to compaction. Sivapullaiah et al. (1996) reached the same conclusion studying fly ash addition on index properties of a black soil in India.

The use of fly ash as a soil amendment may have adverse effects on soil nutrient status, plants and animals. Fly ash is substantially enriched with trace elements including As, B, Ba, Cd, Mo, Se and Sr which are potentially toxic to plants or animals (Carlson and Adriano 1993). The addition of more than 30% fly ash by weight reduced yield of beans by 48% (Aitken and Bell 1985). Whereas grain yield of barley decreased linearly with the addition of fly ash up to 50% by volume, beyond which most plants died when more fly ash was added (Salé 1995). In these studies yield decrease was attributed to boron toxicity. Selenium, also found in fly ash, is an essential element for animals, but the range between deficient and toxic levels is very narrow (Adriano 1986). The addition of high amounts of fly ash may potentially increase Se concentrations in animal feeds and subsequently cause Se toxicity. Salé (1995) suggested that fly ash amendments should not exceed 50% to avoid plant and animal toxicity.

6.1.3 Field vs remolded soil penetration resistance

The measurement of penetration resistance using cone penetrometers has been widely applied in the study of the ability of soil to support traffic, root impedance and stratification of soils and is now commonly used to assess soil compaction in agriculture and land reclamation (Naeth et al. 1991). For a non-amended loam soil much lower penetration resistance occurred in the laboratory than in the field at the same density and moisture content. For example at a bulk density of 1.20 Mg m^{-3} and a gravimetric moisture content of 20%, the penetration resistance predicted using a regression equation for combined data collected over four field seasons was 2.88 MPa. However, the predicted penetration resistance from the laboratory study at the same density and moisture content was 0.30 MPa, which is only 10% of that in the field. This discrepancy is probably due to soil being thixotropic, that is, soil which has been sheared or molded is weaker than undisturbed soil at the same density and water content. This occurs mainly because cementing bonds between soil particles become broken by mechanical disturbance and partly because clay particles become displaced from their equilibrium positions to positions of higher free energy (Dexter 1991). With time disturbed soils regain their strength, partly by rearrangement of the clay particles to assume new positions of lower free energy, and partly by the reformation of cementing bonds between soil particles (Dexter et al. 1988). Furthermore, field soils contain stones and cracks such that temporal and spatial variation of penetration resistance occurs in the field to a great extent.

The use of cone penetrometers to provide estimates of resistance to root growth in soil is limited by the fact that roots are physically different from cone penetrometers. Roots are flexible and often grow through cracks and holes in the soil, or follow planes of weakness between soil peds. They extract water from the soil, excrete mucilage from around their tips, and expand radially when physically impeded. In contrast, penetrometers are rigid metal probes constrained to a linear path through the soil. Direct comparison of root and penetrometer resistance indicate that penetrometers measure resistances that are two to eight times greater than resistances encountered by roots penetrating the soil (Bengough and Mullins 1990). This may explain why root growth in the field did not stop even at penetration resistances greater than 5 MPa. The physical differences between penetrometers and roots has raised controversy over the usefulness of penetrometers, but despite their limitations they remain the best available method for estimating resistance to root growth in the soil (Bengough and Mullins 1990; Naeth et al. 1991).

6.1.4 Sensitivity of plant parameters to compaction

All plant parameters measured (plant height, leaf length, leaf width, number of smooth bromegrass tillers, number of alfalfa secondary and tertiary branches, shoot dry biomass, and root dry biomass) were affected by compaction. The nature of the response was either negatively linear or negatively curvilinear and has been widely reported in the literature (Ericksson et al. 1974; Bengough and Mullins 1990; Bennie 1991). The linear or curvilinear nature of response has been suggested to reflect different segments of an optimum curve that vary in shape and position depending on soil texture, plant species, plant parameter measured and soil water content (Boone 1986). In this study only the effects of soil texture, plant species and plant parameter measured on the shape of the response curve were evaluated. For alfalfa plants, tertiary branch production was most sensitive to compaction while for smooth bromegrass it was shoot dry biomass. In general leaf width was the least sensitive parameter to compaction. This study not only reflected the differences in response to compaction by different plant parameters, but also provided estimates of threshold densities that are likely to cause specific reductions in plant growth.

Differences in the responses of plant parameters to compaction may be explained as sink-source relations. Allocation of photoassimilates to various parts of the plant are dynamic, changing with stage of development and affected by the environment (Wardlaw 1990). When plants are subjected to mechanical stress their carbon requirements for maintenance respiration become higher, and a very small fraction of carbon is used for growth respiration. This means that the allocation of photoassimilates to development of new plant organs such as branches and tillers would be limited under soil compaction. Instead the recently fixed and mobilized photosynthates would be used for growth and maintenance respiration of the roots to ensure adequate uptake of water and nutrients required to maintain photosynthetic activity (Siddique et al. 1990; Minchin et al. 1994). This would result in the observed greater sensitivity of shoot biomass to compaction than root biomass.

The response of plant parameters to compaction in this study may be less than that which would be observed in the field partly because in this study soil water was maintained at pre-determined levels, and thus water was not limiting, whereas in the field, soil water regimes are dynamic. It is also likely that the penetration resistances encountered by roots in the pots were much lower than those encountered in the field at the same bulk density and moisture content, due to field soil thixotropy or age hardening (Dexter 1991). Furthermore, for compacted soils under field conditions, it is practically impossible to separate the effects of penetration resistance, temperature stress and oxygen deficiency on plant growth and yield components (Unger and Kaspar 1994).

Information obtained in this study may be used in deciding whether or not to use deep tillage. The two plants used represent grasses and legumes (monocotyledons and dicotyledons) and with caution may be used for extrapolating responses of other plant species to different levels of compaction.

6.1.5 Cattle-induced soil compaction and its natural alleviation

Heavy grazing caused a substantial increase in near-surface bulk density and penetration resistance at the end of the grazing season of fall 1995. Another season of grazing did not have a significant effect on bulk density and penetration resistance. Overall, a combination of natural alleviation processes, freeze-thaw overwinter, wet-dry cycles and earthworm activity reduced soil bulk densities of grazed plots in the top 5 cm. However, bulk density at depths of 5 to 10 cm increased overwinter. These results indicate the positive and negative effects that freeze-thaw action may have on soil properties. This response depends on whether or not the soil zone under consideration gains or loses water during ice lens formation, as suggested by Larson and Allmaras (1971).

A comparison of rotationally grazed plots with the benchmark site (under season-long or continuous grazing) reflected the higher bulk densities between 2.5 and 15 cm, likely indicative of compaction due to long-term continuous grazing which is commonly practised in southern Alberta. Soil compaction induced by rotational grazing of annual and perennial forages is relatively shallow and may be alleviated naturally.

6.2 FUTURE RESEARCH

Our research is an attempt to answer questions related to various approaches from soil and plant perspectives that could be taken to minimize the use of deep tillage. Further research is needed to understand the effect of non-uniform field soil compaction on plant growth and yield components. Also research involving soils with clay contents intermediate to those used in the study and responses of growth and yield components of plant species other than alfalfa and smooth bromegrass to levels of compaction may provide a valuable contribution to the literature. Determination of soil compaction alleviation by plant roots is also a subject that requires attention given the results of a few studies that suggest that roots of some plants can grow through compacted soil zones that prevent root growth of other plants (Unger and Kaspar 1994).

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