STUDY OF MOLDBOARD AND CHISEL PLOW ACTION ON THE PROPERTIES OF COMPACTED SOIL, CROP GROWTH AND PLANT YIELD

by

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SHORT TITLE

INFLUENCE OF TILLAGE ON PROPERTIES OF COMPACTED SOIL

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ABSTRACT

Master of Science NISAR A. MEMON Agricultural Engineering

STUDY OF MOLDBOARD AND CHISEL PLOW ACTION ON THE PROPERTIES OF COMPACTED SOIL CROP GROWTH AND PLANT YIELD

Experiments to study the behaviour of the soil and response of a Buckwheat crop due to compaction and subsequent tillage were conducted on Bearbrook clay soil in 1978 and 1979.

The results indicated an increase in soil density, penetrometer and vane shear resistance, and decrease in air-filled porosity, unsaturated hydraulic conductivity and availability of water, as the compaction level increased. This resulted in a reduction of dry matter and grain yield of 72-85 and 27 percent, respectively.

The moldboard and chisel plows were effective in decreasing soil density and the penetrometer resistance in the 0 - 0,15 and 0 - 0,25m soil layers, respectively. This resulted in an increase in air-filled pores and water conduction properties, thus augmenting plant growth. The moldboard plow treatment proved to be superior to the chisel plow treatment in producing higher yields.

Optimum yield was associated with a narrow range of average soil density in the dry season and higher range in the wet season, indicating that the environment had a greater effect on plant growth than did the soil density.

RESUME

M.Sc. NISAR A. MEMON Génie Rural

ETUDE DES EFFETS D'UNE CHARRUE A LABOUR
ET D'UN "CHISEL" SUR LES PROPRIETES
D'UN SOL COMPACTE

Des expériences pour étudier le comportement du sol dû au tassement et au labourage ont été conduites sur un sol argileux Bearbrook en 1978 et 1979.

Les résultats ont indiqués une augmentation de la densité du sol, résistance du pénétromètre et de l'aube de cisaillement; et une diminution en air dans les pores du sol, conductivité hydraulique non saturé et de la disponibilité de l'eau, dès que le niveau de compaction augmentait, une réduction des matières sèches et de la production de grain de 72-85 et 27 pourcent, respectivement, fûrent observées.

La charrue à labour et la charrue chisel étaient efficace pour diminuer la densité du sol et la résistance du pénétromètre dans les couches du sol à 0 - 0,15 et 0 - 0,25m respectivement. Ceci résulte en une augmentation d'air dans les pores du sol, améliore les propriétés de conduction et provoque une augmentation de croissance chez la plante. La charrue à labour fût prouvée supérieur à la charrue à chisel en démontrant un rendement de production supérieur à cette dernière.

La production optimum a été associé avec un écart étroit de densité du sol durant la saison sèche et un écart plus grand durant la saison pluvieuse. Ceci indiqua que l'environnement eu un plus grand effet sur la croissance des plantes que la densité du sol.

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NOMENCLATURE

A', A*	Slope of the curve
A	Harvested area, m^2
a	Intercept
Am, An) Bm, Bn)	Constants
b, b_1	Slope
C	Density counts
C'	Sensitivity constant
C.I	Cone index, kPa
Cm, Cn	Constants
Cp	Porosity obtained by unit pressure, %
Cs	Standard density counts
d	Depth, cm
Da	Distance away from the wheel centre line, cm
D , D_o	Diffusion coefficients
$D\omega$	Soil water diffusivity
$\frac{\partial H}{\partial Z}$	Hydraulic gradient
$\frac{\partial h}{\partial z}$	Suction gradient
$\frac{\partial \theta}{\partial t}$	Soil water flux
$\frac{\partial \partial}{\partial z}$	Soil moisture gradient
$\frac{\partial \Psi}{\partial \theta}$	Rate of change of matric suction with respect to moisture content
FC	Field capacity
H	Hydraulic head, m

Cont'd.

h	Suction head, m
K(θ)	Hydraulic conductivity as a function of moisture content, m/sec.
K	Hydraulic conductivity, m/sec.
L	Depth, m
ln	Natural logarithm
$\overline{M}$Cp	Average moisture content of the plants (weight basis), %
mc	Moisture content, %
N, n	Porosity, %
Na	Precompacted porosity, %
np	Contact pressure, kPa
Nv	Virgin porosity, %
P	Pressure, kPa
PEN	Penetrometer resistance, MPa
Pr	Residual pressure, kPa
PW	Permanent wilting point
R	Coefficient of correlation
S	Sink term or extraction term, m/sec.
S(z)	Flux in the plant root, m/sec.
$S_f(z)$	Soil moisture flux, m/sec.
T	Transpiration rate, m/sec.
t	Time, sec
V_t	Total volume, m^3
v	Soil water flux, m/sec.
V_v	Volume of voids, m^3

Cont'd.

W	Weight of the moisture (dry weight basis), g
Wc	Weight of the empty container, g
Wdc	Weight of the dry sample + container, g
Wwc	Weight of the wet sample + container, g
$\overline{W}wp$	Average weight of the wet plants, g
Y	Plant yield, kg/ha
Ymr	Maximum relative yield
z	Gravitational head, m
Z	Depth, m
γ_b	Dry bulk density, g/cm^3
$\overline{\gamma}_b$	Actual average dry bulk density, g/cm^3
γ_{bo}	Optimum dry bulk density, g/cm^3
γ_p	Particle density, g/cm^3
$\overline{\gamma}_1$, $\overline{\gamma}_2$	Average dry bulk density from the surface, g/cm^3
γ_1, γ_2	Dry bulk density of the layers, g/cm^3
γ_T	Total bulk density, g/cm^3
θ	Volumetric moisture content m^3/m^3
θ_s	Volumetric moisture content at air entry value, m^3/m^3
Φ	Soil suction, cm of H_2O
Φ_e	Soil Suction at the air entry value, cm of H_2O
r	Distance from root axis, cm

CHAPTER I

INTRODUCTION

Compaction is defined as the process of changing volume of soil under a certain load applied intentionally or un-intentionally. In other words it is a change in bulk density, void ratio, or porosity. Soil, being a highly complex substance, is most variable in character. The variability includes the physical, chemical and biological properties of soils as well as environmental factors such as climate, weather, tillage and agronomic treatments, and crop use. Thus the proper understanding of the soil compaction process, and design and selection of tillage equipment, challenges the farmers and scientists for optimum crop production.

It is generally believed that excessive soil compaction can have adverse effects on soil as a medium for plant growth. These effects are (1) increasing the mechanical impedance to the growth of roots and (2) altering the extent and configuration of the pore spaces. The consequences of these changes may be complex.

Studies of Raghavan et al., (1978b, c, d, e, 1979), McKyes et al., (1977), Chassé et al., (1975) and Soane (1970, 1975) have shown detrimental effects of compaction on crop production. Soil structural damage caused by machinery traffic depends on soil type, soil moisture, contact pressure (Amir et al., 1976) and the number of passes of the wheel (Raghavan et al., 1977b).

Recent times have seen rapid changes to larger tractors and heavier implements, and an increase in the size of hauling units which transport most of agriculture and animal produce on the farm. Heavy tractors or the hauling units need wheels with greater inflation pressure in order to support maximum weights. All the necessary operations carried out on the farm, from preparation of land to harvesting, may create excessive compaction of the soil by expelling the air, water and nutrients which result in (1) moisture stress in the plants, and (2) not enough pore space for plant growth. Trouse and Humbert (1961) have compared the yields of a hand cut field with those of a heavy machinery trafficked field in Hawaii. Heavy machinery showed a detrimental effect on sugar cane production. This effect is even worse if the soil is lacking organic matter.

Indiscriminate and excessive traffic on the farm results not only in undesirable compaction, damages to the surface topography and mechanical shattering of the soil structure, but each injudicious trip puts an extra burden on energy demands in terms of fuel wastage and manpower resources, and diminishes yield returns. Traffic on moist soil especially reduces its permeability very effectively (Gill,1959).

The type of tillage also might logically affect soil physical conditions, such as granular structure, soil porosity, bulk density, soil strength, soil mixing and surface condition. These in turn can affect the soil air, water infiltration, moisture retention, temperature and compaction characteristics.

Any or all of the above factors may then affect the chemical and biological activity in the soil, including root and plant growth.

This study examined the effect of vehicle traffic and tillage of compacted soil caused by the moldboard and chisel plows on physical properties of a clay soil and plant performance in the field. The tests comprised field and laboratory studies of the compaction state and the effects of different passes of traffic on water movement, soil strength and plant growth. Tillage was applied to the compacted field plots, with different passes of a vehicle, to study effectiveness in improving the structure with respect to water movement, soil strength and plant growth. This study was continued for two seasons in which buckwheat was grown. Information regarding rainfall and water table was taken as well, and a statistical analysis was performed to observe the significant effects.

In the end, this study may result in a better understanding of the design and selection of machines and new field management practices which could be more efficient, economical and agriculturally sound.

CHAPTER II

REVIEW OF LITERATURE

2-1 General

The basic requirements for plant growth are that the soil must be aerated, the seed bed must be loose enough for the seedling to grow up and the pore space around the seed must be wide enough to allow young rootlets to grow but packed enough to promote germination. The soil must be permeable to allow enough water to infiltrate and reduce runoff, as well as to promote a favourable temperature. Besides these basic requirements, the other necessary conditions include chemical and biological activities.

However, soil compaction reduces the aeration of the soil, so the physiological needs of plants in terms of an adequate oxygen supply can be hampered. Compaction also reduces the permeability to water, which increases the runoff and decreases the recharge of ground water, and ultimately results in stress to the survival of the plant. Compaction alters thermal relations as well, and increases the mechanical strength of the soil to provide resistance to the proliferation of plant roots. Compaction may also affect the chemical and biological activity of the soil. All these effects may reduce the quality and quantity of crop produced.

The review of literature which covers most of the studies on compaction and tillage and their effects on agricultural soils is presented here.

2-2 Definition

Gill (1961) defined soil compaction as "the pressing of soil together to make it more dense". This definition is mostly mechanical and does not involve all aspects of soils in agriculture. Raney and Edminster (1961) defined soil compaction as the "act of moving particles closer together by external forces". Further, they specified that external forces may be falling rain, implement traffic, heavy overburden, or an excessive wet layer of surface soil. Compaction is widely used in civil engineering in order to get more compacted soils in dams, roads and around culverts. In agricultural soils, however, the interest is to reduce soil compaction in order to provide a healthy environment for roots to grow and use soil water efficiently.

2-3 History

From the Egyptian civilization to now, good tilth is recognized as an improvement of land for agricultural purposes. Tillage is provided to reduce the bulk density, increase porosity, increase the intake of water into the soil and ensure good environmental conditions for plant growth. The scientists in early times recognized that hard pans resulted in soils from artificial or natural forces. These pans might be inherently present or result from improper management practices. These hard pans are sometimes detrimental to plant root growth and water infiltration.

Studies of compaction started in the 1920's, e.g., Eden and Maskell (1928), who noticed a greater retention of moisture in hard or artificially compacted soil, which resulted in eradicated plants.

Baver (1938) compacted a Cecil clay soil and measured the percolation and pore space of compacted soil. The percolation rates in loose soil and compacted soil were found to be 127 and 5,8 cubic centimeters per ten minutes, respectively. The pore space of compacted soil was decreased from 61,8 percent to 56,8 percent. Bertramson and Rhoades (1938) showed that an increase in bulk density and decrease in porosity resulted from extended periods of cultivation.

Mckibben (1971) reported about 0,8 million ha. have already been compacted in the United States, and 0,8 to 1,2 million ha. are approaching to the same conditions in California alone.

Despite the loosening effects due to freezing and thawing in the winter, persistent excess compaction over the years may be due to increases in tractor weights. Mckibben (1971) reported that the average weight of tractor had increased from about 2700 to 4500 kg during the period of 1948 to 1968.

In the 1950's, this topic was popular and most of the research reported in the literature was conducted. A number of bibliographies and literature reviews are available on the subject (ASAE-SSAE, 1958; Gill, 1959; Raney and Edminster, 1961). In the 1960's, reviews by Gill (1961); Vomocil and Flocker (1961) and Rosenberg (1964) were published. The most recent comprehensive review on compaction is now available in an ASAE-Monograph (1971).

2-4 Traffic Effects

There are two kinds of forces by which compaction occurs, viz. external and internal forces. External forces from vehicle and tillage tools are called mechanical forces (Cohron 1971). Mechanical forces have visible sources and are easy to measure. Here the forces produced by vehicle traffic and the resultant change in compaction level on agricultural soils will be assessed.

Under modern standards of production efficiency, agricultural soil is worked by large machinery, using big plows or harrows, three or four row cultivating and harvesting equipment such as combines or cotton pickers, big hauling equipment for transportation loaded with many tons and with tires inflated at pressures of 250 to 400 kPa. Depending on specific management practices, the usual operations of machinery carried out on average farms are as follows:

1) Seed bed preparation
2) Planting and fertilizer applications
3) Herbicides or cultivation applications
4) Insecticide application if necessary
5) Harvesting and fall plowing
6) Transportation of farm produce

Voorhees (1977) pointed out that 100 percent of the surface soil may be compacted by wheel traffic under normal farming operations. Soane (1975) illustrated an example of the total area covered by traditional practice. Fertilizer distribution, harrowing twice, sowing and rolling gave about 91 percent coverage over an area 9m by 9m when a medium sized tractor was used. The study of Voorhees et al., (1978), on structural change due to a 5 year period of traffic of normal row cropping in Minnesota on silty clay loam soil, showed that the wheel traffic could compact the soil to a 45cm depth. Gill (1959) indicated some danger of soil compaction by traffic under various conditions affecting physical properties of soil. He further noticed that the design of plows could destroy the structure by requiring wheels to operate in the bottom of the furrow, which is the zone where the soil is not loosened by the plow.

Arndt and Rose (1966) illustrated the cultural operation effects on soil properties. In a draught animal system, the units of soil compaction are randomly distributed; small discs of more than 15cm diameter, produce small hydrologically closed depressions. In mechanized systems, the compaction is a wide band spaced at regular intervals. In a row cropping mechanical cultivation system, traffic bands are formed following the use of a variety of row cropping systems (Fig. 2.1). Arndt and Rose (1966) also presented a theory by considering the changes in the overall relative magnitude of soil properties due to the changes in the degree of compaction due to traffic. This theory can also be used in designing tillage systems, where the effect of soil compaction is severe because of soil factors. It becomes necessary to reduce traffic by designing the best possible tillage system.

Chesness et al., (1972) indicated the effects of traffic in a peach orchard soil on soil strength. The soil between trees was treated with herbicides and disk tillage. More strength was found in trafficked plots, which could hamper tree root development.

Swanson and Jacobson (1956) showed four compaction zones in a cultivated area. These zones are divided into two main zones, namely horizontal zones and vertical zones. The horizontal zones comprise (i) soil surface crust, (ii) loosened seed bed due to cultivation up to 7,62 to 10cm depth, (iii) plow layer compacted below the depth of the plow sole. The vertical zones consist of (iv) the area compacted due to wheel traffic between rows. There are two other horizontal compaction zones, (v) in the plow sole area and (vi) in the area immediately below the plow sole (Swanson 1954).

2-5 Compaction

The state of compaction changes as the volume of soil changes (Harris, 1971) and this change is attributed to the action of forces. Gill and Vandenberg (1967) defined these forces as mechanical (machines and animals) and natural (drying and genetic processes). They further defined the compaction behaviour equations; for example, as the stress increases the volume decreases, or as the stress decreases the volume increases. These input and output variables are uniquely related only for certain circumstances.

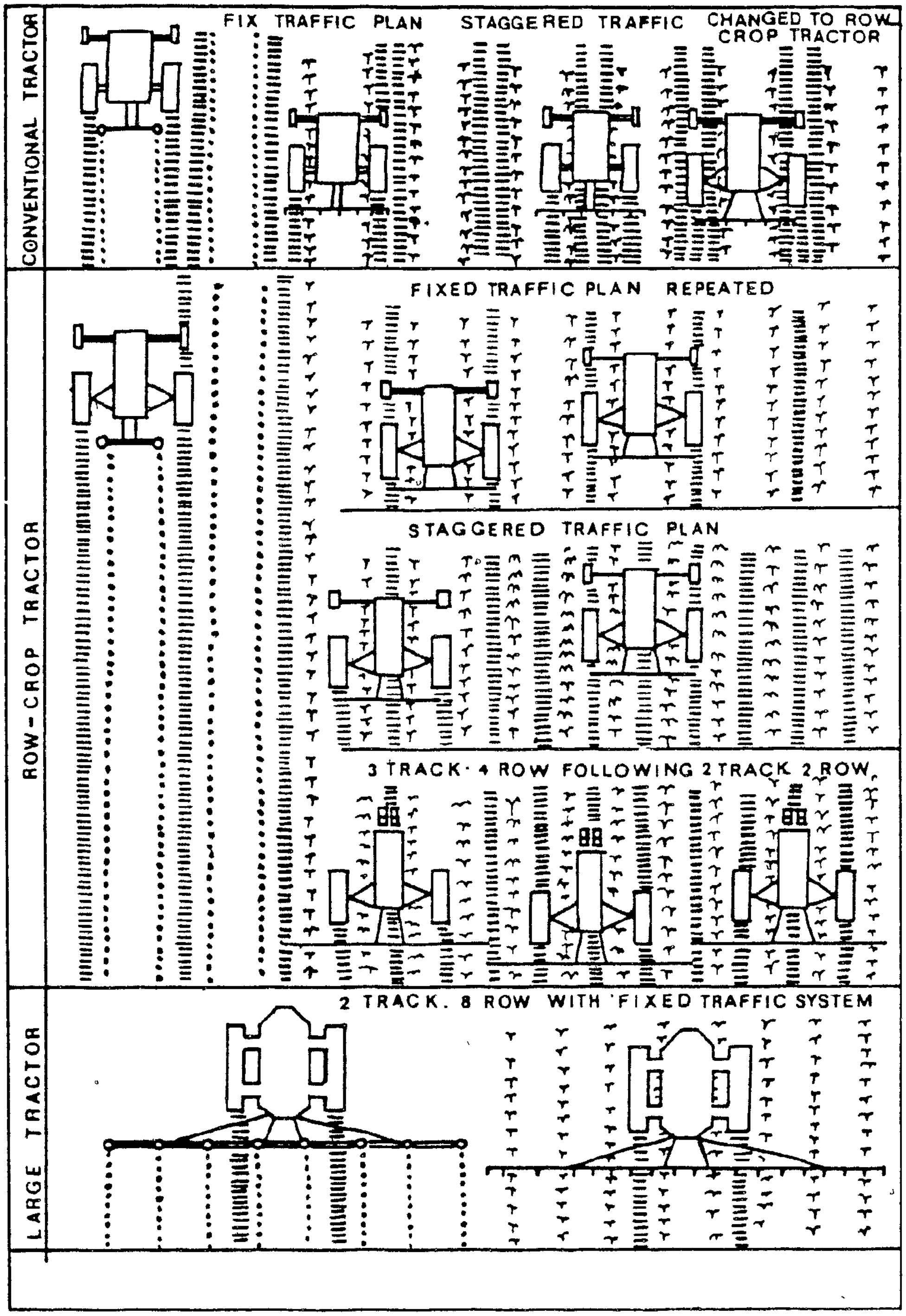


Figure 2.1 Distribution of traffic and crop bands for a variety of cropping systems (redrawn from Arndt and Rose, 1966).

Lambe (1951) described this behaviour by compacting soils in cylinders under certain applied loads (input variable) and observing respective changes in volume and bulk density (output variable). This compaction behaviour depends on the moisture condition of the soil.

Harris (1971) has discussed the process of compaction involving forces, and relating the forces to describe the behaviour of soil by soil physical properties. He concluded that the behaviour of the soil due to applied loads is dependent on the static state and material properties of the soil.

Cohron (1971) discussed the external forces applied by vehicular traffic, animals and rainfall, and their effects on agricultural soils. The pressure distributions by tractor tires on different types of soils were also discussed, quantifying the state of compaction. Finally he indicated that more work is needed to derive a satisfactory theory relating compaction of soil to vehicles and implements.

Soil is a three dimensional medium in the natural state and forces are not applied over an infinite area, according to Gill and Vandenberg (1967). The question they asked was whether the force in a confined area could be related to the compaction behaviour in an unconfined soil state.

Harris (1971) described the concept of stress in three dimensional infinitesimal area, considering the cubical element of the soil where nine quantities of three stress vectors are the components of the stress tensor. From equilibrium conditions, the shear stresses $Txy = Tyz$, $Txz = Tzx$ and $Tyz = Tzy$. Therefore, out of nine variables six can be described to know the stresses at a point.

Soehne (1958), using a piston to compress the soil in a cylinder, related compression behaviour as a function of major principal compressive stress:

$$n = -A' \ln P + Cp$$
or
$$n = -A^{*} \log P + Cp \qquad \text{------------(2.1)}$$

where n = porosity

P = applied pressure

Cp = porosity which was obtained by compacting loose soil at a unit pressure

A' & A^{*} = slope of the respective plotted curves

However, two errors are associated with the above assumptions. Frictional characteristics in the cylinder described non-uniform stress distributions and the irregular changes over the entire sample (Harris, 1971). Chancellor et al., (1962) showed that the major principal stress does not uniquely cause compaction. There is always volumetric and shear deformation due to the applied load (McKyes et al., 1975). This indicates that the normal and shearing stress cause compaction. Vandenberg (1966) used a triaxial test and related compaction empirically as a function of mean normal stress and maximum natural shearing strain.

Kumar and Weber (1974) illustrated the compaction of unsaturated clay soil by applying hydrostatic pressure and different stress paths in a specially built triaxial cell. They assumed that the intermediate and minor principal stresses were equal to the confining pressure applied. The results gave equations defining compaction behaviour. They also examined the effects of different unidirectional stress paths during deviatoric stress application, unloading-reloading, rotation of the principal stress axes and changes in the relative value of the intermediate principal stress.

Coleman and Perumpral (1974) illustrated the compaction behaviour of sand by numerical methods. They applied the finite element method, which assumes that the elements are connected together at a finite number of points.

They developed the equation fitting the experimental data to a fifth order polynomial. They concluded that this method can be used with calibration by triaxial tests. It appears from force compaction relationships, accurate behaviour is still to be described. The aforesaid studies failed to formulate accurate compaction behaviour equations because stress volume relations are not linear, and absolute magnitude of the state of compaction is not defined.

Many studies have been conducted on compaction by vehicles. Gill and Vandenberg (1967) examined the effect of tires and tracks on compaction. Tires caused more compaction due to slippage than tracks. Wheel slip on the soil depends upon tire size, tire shape, tire flexibility, inflation pressure, wheel load, soil type and varying degree of moisture content (Raghavan et al., 1978a). Further, their study on clay soil showed that the compaction was increased most between 10 and 50 percent slip, and the minimum was at 92 percent slip. On sandy and sandy loam soils, the maximum compaction was obtained between 15 and 25 percent slip. Further slippage reduced compaction (Raghavan et al., 1977a). Nichols (1957) reported that German farmers are reluctant to use tractors for spring cultivation because the soils at that time are moist, and slippage may badly seal off subsoil by smearing action on moist soil. McKyes et al., (1975) discussed the effect of slippage and rolling resistance in humid soils of eastern Canada and suggested some precautions. They indicated that moist soil is poorer in strength, the tire will sink and shear more to reach the maximum soil strength. This produces higher slip and increased rolling resistance. These conditions may reduce power efficiency, increase tire wear and cause more damage to the soil structure. Finally they suggested larger tires, which reduce contact pressure thereby reducing wheel slip and damage to soil structure.

The soil condition after compaction depends on a number of variables including the characteristics of load applied, soil type, compactness status at the time of loading and moisture condition of the soil. Meredith and Patrick (1961) examined the state of compaction of three different soils with different optimum moisture contents. The maximum compaction varied for all three soils. Jamison et al., (1950) working with Cecil clay, showed the effect of 10 passes of an Olive standard 70 tractor with 28 - 96.5cm tires (11-38 in.) inflated to 83 kPa pressure. The maximum compaction occurred in a zone which had 25 percent moisture content. Raghavan et al., (1977b) observed the effect on compaction of vehicle type, tire size, tire configuration and load, with 1, 5, 10 and 15 passes on a clay soil. The higher compaction was found in the case of larger contact pressures. 70 percent of maximum compaction was attained with the first five passes and the rate of compaction decreased for further increases of passes. The state of compaction varied with moisture conditions of the soil.

Flocker et al., (1958) indicated that soils, even when subjected to a given compactive load, show considerable inherent differences in the state of compaction due to variations in distribution of particle size and shape, and differences in organic matter content. Compaction test data from 5 montmorillonitic clay soils were compared to those from 5 kaolinitic clay soils. These comparisons failed to indicate that the montmorillonitic clay soils were more susceptible to compaction from mechanical forces than were the kaolinitic clays. Montmorillonitic clays did, however, have significantly higher liquid limits and plastic indices.

Compaction does not only damage the soil structure, but increases cost and energy expenditures. Many field trips cause compaction, but also increase the consumption of fuel and working hours in the field. Compaction increases the cloddiness, thereby increasing the cost of operation especially when a fine seed bed is required for seeded crops (Flocker et al., 1958). Bateman et al., (1965) reported that soils require greater energy to pulverize when they have been compacted above 1,2 grams per cubic centimeter bulk density.

a) Soil Density

The state of compaction is mostly described in terms of smaller volume or higher bulk density. Increases in bulk density may increase the strength of a soil, decrease larger pores into smaller pores and decrease the void ratio. Extreme compaction may result in ruts with low permeability and provide channels for water runoff to be stored in low lying areas for longer periods of time, thus creating flooding conditions for plant growth.

The density to which a given soil can be compacted varies with the water content, initial density and the force of compaction. Field tests made by U.S. Army of Engineers, Corps of Engineers, Turbul and Foster, and the Road Research Laboratory of England referred by Earl (1965), have shown that the density of soil compacted in the field depends not only on the water content and nature of the soil material, but also on the type of compaction equipment, the pressure per unit area, the air pressure in tires and other factors. Vomocil et al., (1958) measured a bulk density of 1,50 grams per cubic centimeter in Yolo loam soil after one pass of a Ford 740 tractor. The moisture content was at field capacity. The tractor had 27,5-40cm (11-16 in.) tires with inflation pressure of 83 kPa. Flocker et al., (1958) compacted a soil by using a jeep of 908 kg mass followed by a Ford 740 tractor having 182 kg of water in each rear tire. This was followed by two trips with a cultipacker pulled by the same tractor, and again trafficked by jeep loaded with 363 kg of sand. This field then had an applied pressure of 207 kPa, and was a Yolo loam soil with moisture content 19.6 percent and field capacity 17,5 percent The resulting bulk density was 1,56 grams per cubic centimeter in the top 20cm. Weaver and Jamison (1951) compacted a Davidson loam soil with an Oliver standard 70 tractor having 27,5 - 95 cm (11-38 in.) tires inflated to 83 kPa with a draft of 5,227 Newtons per wheel, to a density of 1,8 grams per cubic centimeter by four passes The moisture content was 11.4 percent McKyes et al , (1975) have shown in Fig 2.2 the contours of dry density under the passage of a 42,9 x 71,1cm(16,9 x 28 in) tire

Raghavan et al., (1976a) compared the dry densities caused by a Ford 5000 tractor of mass 4670 kg equipped with lugged tires 46,7 x 76,2cm having inflation pressure of 69 kPa, towing a loaded sprayer of mass 3474 kg with 28,6 x 61,0cm tires inflated to 132 kPa The tractor and sprayer were passed over the ground 1, 5, 10 and 15 times on a sandy loam The maximum bulk density achieved in both the cases was approximately 1,65 gram per cubic centimeter, same as with the Proctor test Many efforts were made to determine the effect of different contact pressures with combination of load at different times, (Raghavan et al , 1977b), vehicle size and tire configuration on dry density The above authors found that the maximum dry density was obtained when the moisture content was at the optimum Contours of dry density with single and multiple passes in their study is shown in Fig 2.3.

A maximum density at optimum moisture content can be shown by the Proctor test (Lambe, 1951). This laboratory test can characterize soil types with different textures as to maximum density at different optimum moisture contents One can use this moisture index to make a decision before going on the field with machinery Meredith and Patrick 1961) obtained different maximum dry bulk densities and optimum moisture contents for three soils they used There was very little increase in dry bulk density beyond the compactive effort of 1,3 kPa. Flocker et al , (1958) showed that

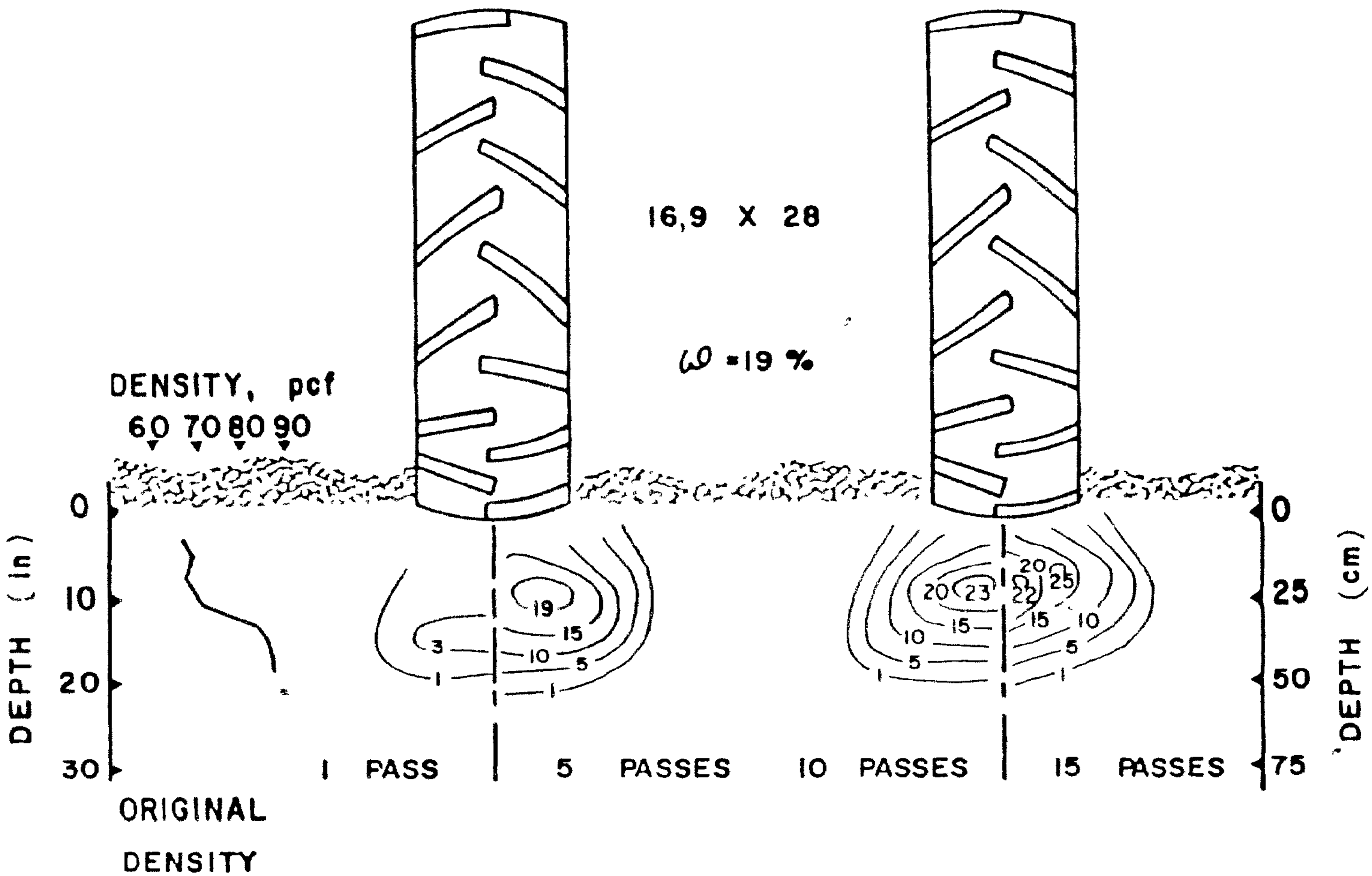


Figure 2.2 Contours of dry density increase due to tractor tire (42,9 X 71,1cm) single pass and multiple passes (after McKyes et al., 1975).

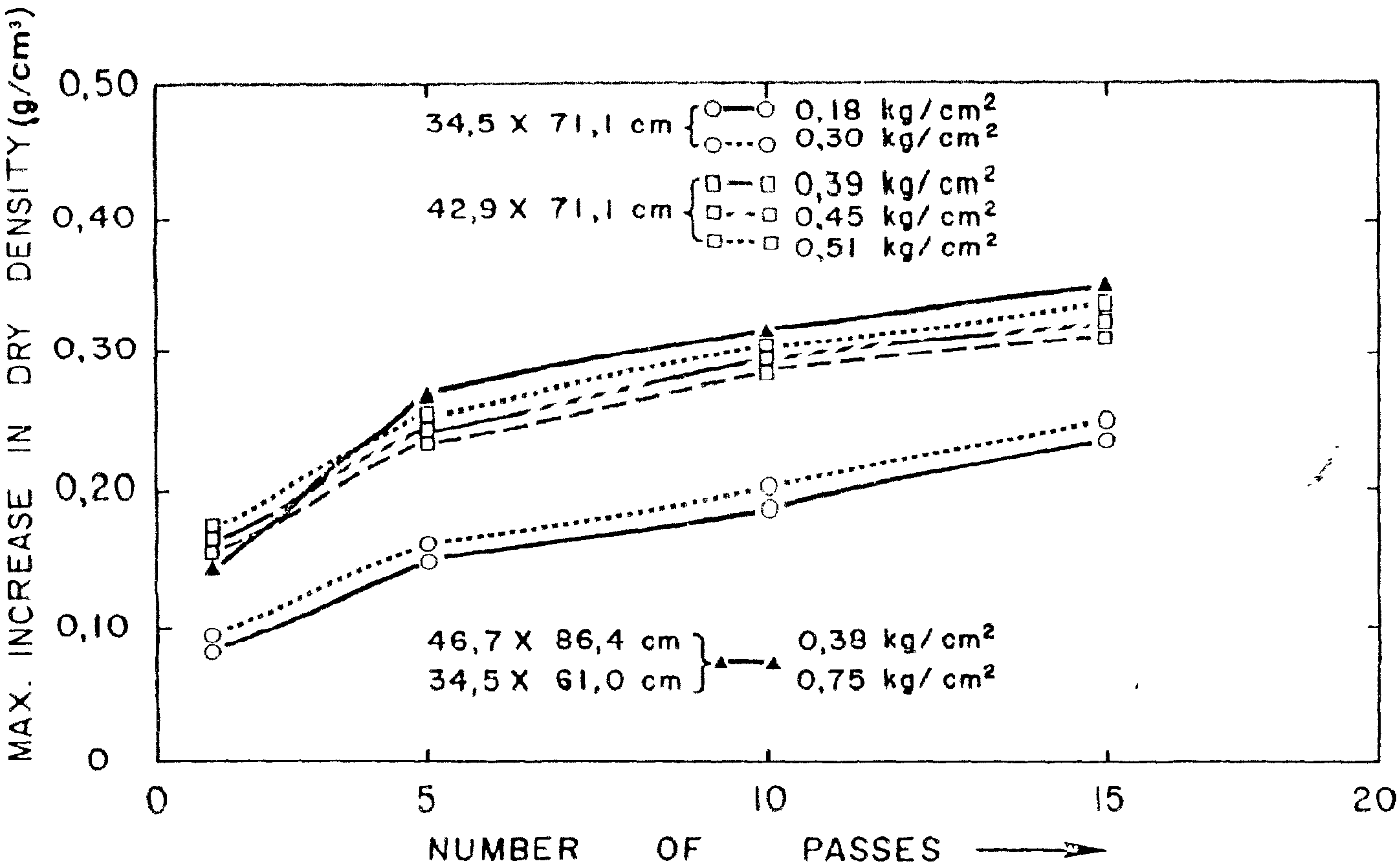


Figure 2.3 Effect of increase in number of passes on compaction for different tires (after Raghavan <u>et al.</u>, 1977b)

variations exist in dry bulk density of soils subjected to a compactive load. These variations are due to the differences of particle size distribution, size, shape and organic matter content. Elder (1958) defined structural and bulk density indices in his study, the structural index being defined as the drops of liquid absorbed by a sample in one minute.

Many efforts have been made to predict dry density from contact pressure, porosity and moisture content. Amir et al., (1976) used experimental and published data and worked out following equations for loose virgin soil to calculate virgin porosity 'Nv' and for pre-compacted soil to calculate pre-compacted porosity 'Na'

$$Nv = An - Bn\,(\ln(P)) - Cn\,(\ln(\theta)) \quad \text{----------} (2.2)$$

$$Na = An - Bn\,(\ln(P_r + P)) - Cn\,(\ln(\theta)) \quad \text{-------} (2.3)$$

θ for eq (2.2 or 2.3) = (0.4-0.9) of saturation

Pr = residual pressure which is 0

P = applied pressure

θ = volumètric moisture content at saturation

An, Bn and Cn = Constants

The authors claimed that these equations can (a) predict the amount of soil compaction, (b) evaluate the drainage coefficient necessary or the number of field work days permissible from the compaction view point, (c) make decisions in application of machinery pressure, and time for operations.

Raghavan et al., (1976b) established a mathematical relationship to predict dry density 'γ_b' from contact pressure, 'np' (kPa) and moisture content, mc (%).

$$\gamma_b = \frac{An}{Am} + \frac{Bn}{Bm} \ln (np) + \frac{Cn}{Cm} \ln(mc) \text{--------} (2.4)$$

They showed how to use experiments and laboratory data to estimate constants An, Am, Bn, Bm; Cn, Cm from a multiple regression stepwise procedure. Later on Raghavan and McKyes (1978) extended equation (2.4), considering more variables such as depth 'd', distance 'Da' away from the wheel centre line and slip 's'. The model was developed for clay soil as follows with a statistical 'R' value of 0,79.

$$\gamma_b = 1,31 + 0,0075 (d) - 0,00005 (Da) + 0,0009 (s)$$
$$+ 0,039 (\ln (np)) - 0,128 (\ln(mc)) \text{---------} (2.5)$$

Furthermore, they developed models for sandy loam and loamy sand. Finally they concluded that the dry density increased with increases in contact pressure and moisture content as well as slip less than 30 percent. The higher density was found under the centre of the tire. Dry density away from the tire decreased linearly up to 40cm from the centre of the tire path.

(b) Soil Aeration

Soil aeration is one of the important soil physical properties which has been given considerable recognition in soil compaction studies. When soil is compacted, a reduction of pore volume is exhibited. In other words, "non capillary porosity", which is responsible in conducting gases, is reduced to smaller pores, which may reduce aeration considerably. Reduced aeration may cause the accumulation of toxic substances, thus affecting root growth.

There are two principles of gaseous flow in the soils widely used for studying aeration, (1) the principle of mass flow, and (2) the principle of diffusive flow.

Mass flow is defined as the movement of air through soil by processes such as expansion and concentration of gases as a result of changes in temperature or barometric pressure, and air removal from rainfall or irrigation (Robinson, 1964).

Diffusion is the main mechanism by which molecules of gas are exchanged between soil and atmosphere. This movement takes place in response to concentration gradients. In diffusion, the flow path is not linear, but is made tortuous by the shape of voids and the way in which voids are connected. Marshall (1959) introduced the equation (2.6) to predict the ratio of diffusion in soil 'D' to diffusion in air 'D_O' from air-filled porosity 'N' as follows.

$$D/D_0 = N^{3/2} \qquad \text{-----------------(2.6)}$$

Grable (1966) gave an extensive review of soil aeration studies. Vomocil and Flocker (1961) indicated that in the ideal root bed, when the soil is drained after irrigation or rainfall to reach its field capacity, the soil at that point must contain 50 percent solids, 25 percent water and 25 percent air. Different soils behave differently in relation to soil-water properties. Fine textured soil has a high bubbling pressure property, and therefore, there is low air and water permeability (Grable, 1966) Coarser textured soils have 50 percent porosity and more than one half of the total porosity will drain free of water before drainage ceases (Vomocil and Flocker, 1961).

With respect to the effect of compaction on soil aeration, Phillips and Kirkham (1962) found that the air permeability decreased as the level of compaction increased. Rosenberg and Willits (1962) showed a decrease in non capillary pores at 0-60 mbar suction as a result of compaction on three types of soil studied. Raghavan <u>et al.</u>, (1978c) examined the effect of contact pressure on air porosity. Air porosity decreased as the vehicle contact pressure increased. There was a very small difference of 10 percent air-filled porosity at corresponding depths when two years of studies were compared.

Different levels of density represent differences in air space percentage at virtual completion of drainage following irrigation or rainfall. Weaver and Jamison (1951) calculated air spaces of about 12 percent at a density of 1,8 grams per cubic centimeter in Davidson loam soil. Flocker et al., (1958) found a 14 percent air filled porosity at a bulk density of 1,56 grams per cubic centimeter in Yolo loam soil.

Grable and Siemer (1968) studied the different combination of aggregate sizes, bulk densities and soil suction to see the effects on air porosity, diffusivity, oxygen concentration and redox potential. They found the air porosity decreased with severe density. A soil with a bulk density of 1,23 grams per cubic centimeter had a very low air porosity, even at high suction values. It was even less if the aggregate size was less than 0,5mm. Bulk density and aggregate sizes had very little influence on the diffusion of oxygen and oxygen concentrations at shallow depths, while they had greater effects at greater depths. Boone et al., (1978) determined that aeration was slightly affected by compaction. In severe compaction, the oxygen concentration was found to be about 15 percent at 5 cm below the depth of deeper roots.

Swanson and Jacobson (1956) pointed out that the extent of soil crusts increased with a higher intensity of rain, and that may prevent air from entering into the soil. It appears that decreased soil aeration by different actions may create an undesirable soil environment for plant growth and crop yields. The effect of soil aeration on plant growth and yield will be reviewed under the heading "Soil aeration effects".

(c) Soil Water

Another obviously important physical property of soil is the degree of wetness, or water retention characteristics. Associated with these properties are the processes of water movement, infiltration and availability of water.

Soil is a reservoir that holds water for living organisms. The amount of water a soil can hold is determined by its physical properties. It may be available in limited amounts to plants, or it may be present in excess, both situations can occur for the same soil in different seasons.

Water moves in response to a soil-water potential gradient from the soil voids to the plant roots and through the plant to evaporate from the leaf surface into the atmosphere. This whole system of water movement is known as the Soil-plant atmosphere continuum (SPA).

i) Water movement

Water movement occurs in soil in response to a difference in water content, temperature etc. One of the mechanisms that governs the movement of water in the soil is unsaturated flow. As the moisture content of soil decreases from the maximum value at 100 percent saturation of the pore space, the air phase invades the larger pores. Most of the water movement in top soil occurs when both water and air are present in the pores. In this process the hydraulic conductivity 'K' is not constant, but decreases as the water content decreases because the larger pores are emptied first. Poiseuillés equation shows that the volume flow rate varies directly as the fourth power of the pore radius. Therefore, halving the pore size decreases the volume of flow by a factor of 16.

Compaction may alter the pores. Porosity 'n' is defined as the ratio of volume of voids or pore space 'V_v', to the total volume 'V_t'.

$$n = \frac{V_v}{V_t} \qquad \text{-----------------(2.7)}$$

The bulk density 'γ_b' is related to the following equation.

$$\gamma_b = (1-n)\ \gamma_p \qquad \text{----------------(2.8)}$$

where 'γ_p' is the particle density. The change in density will be accompanied by the change of porosity and thus water transporting properties. Warkentin (1971) discussed the effect of compaction on water transmissibility by altering the void size distribution of soils. He discussed the forces of water retention and change in bulk density in relation to soil-suction, temperature and solute gradient in homogeneous as well as layered soils. He concluded that compaction may increase or decrease the amount of water retained at higher suction levels. Slaytor and Taylor (1960) have defined soil water suction to be the affinity of the soil matrix for water. It is therefore the soil-water and geometry of the soil, which contribute to soil suction.

Soil geometry is related to pore size distribution (Box and Taylor, 1962). Taylor and Box (1961) showed that there is a change of suction due to compaction when the moisture content is held constant. They proposed that bulk density should be used in place of the geometry factor, because a geometry factor neglects surface and ionic influences, whereas bulk density is very easy to obtain. When the bulk density increased from 1,1 to 1,5 grams per cubic centimeter, the suction decreased, but it increased as the bulk density reached 1,6 grams per cubic centimeter.

Soil type also has a great influence on water retention characteristics at different bulk densities. Hill and Sumner (1967) investigated the moisture contents of different soils in the range of total available moisture. In sandy soils, the moisture retention increased as the bulk density increased, but the magnitude of this became smaller as the suction increased. In clay and clay loam soils, moisture retention increased as the bulk density increased, but the magnitude became higher as the suction increased. In sandy loam and sandy clay loam, the moisture retention decreased as the bulk density increased at low suction, whereas retention increased at high suction. This influence of grain size distribution on moisture content at 30,6cm of H_2O suction is shown in Fig. 2 4.

Eagleman and Jamison (1962) examined the effect of texture on water transmissibility in laboratory experiments. They prepared different combinations of soils varying in particle size distribution with and without compaction. They indicated that the water movement from larger pores to smaller pores is unrestricted at the contact if the volume of both is about the same, while the water movement becomes slower from the smaller pores to the larger pores in the unsaturated state because the larger pores emptied soon. The remaining water in the small pores of sand is discontinuous in nature at the contact with a larger number of smaller pores in silt. The water cannot move from smaller pores to the larger pores until same suction is attained. As the suction increases, the water film around the solid particles becomes thin and decreases rapidly.

Boone et al., (1978) have shown that compaction produced finer pores at a certain volume, and moisture content increased at every suction up to saturation. Further compaction decreased the moisture content by loss of water. Fig. 2.5 shows the optimum curve of the phenomenon. Raghavan et al., (1978c) obtained higher moisture contents retained by three clay soils at different locations with the application of higher compaction efforts.

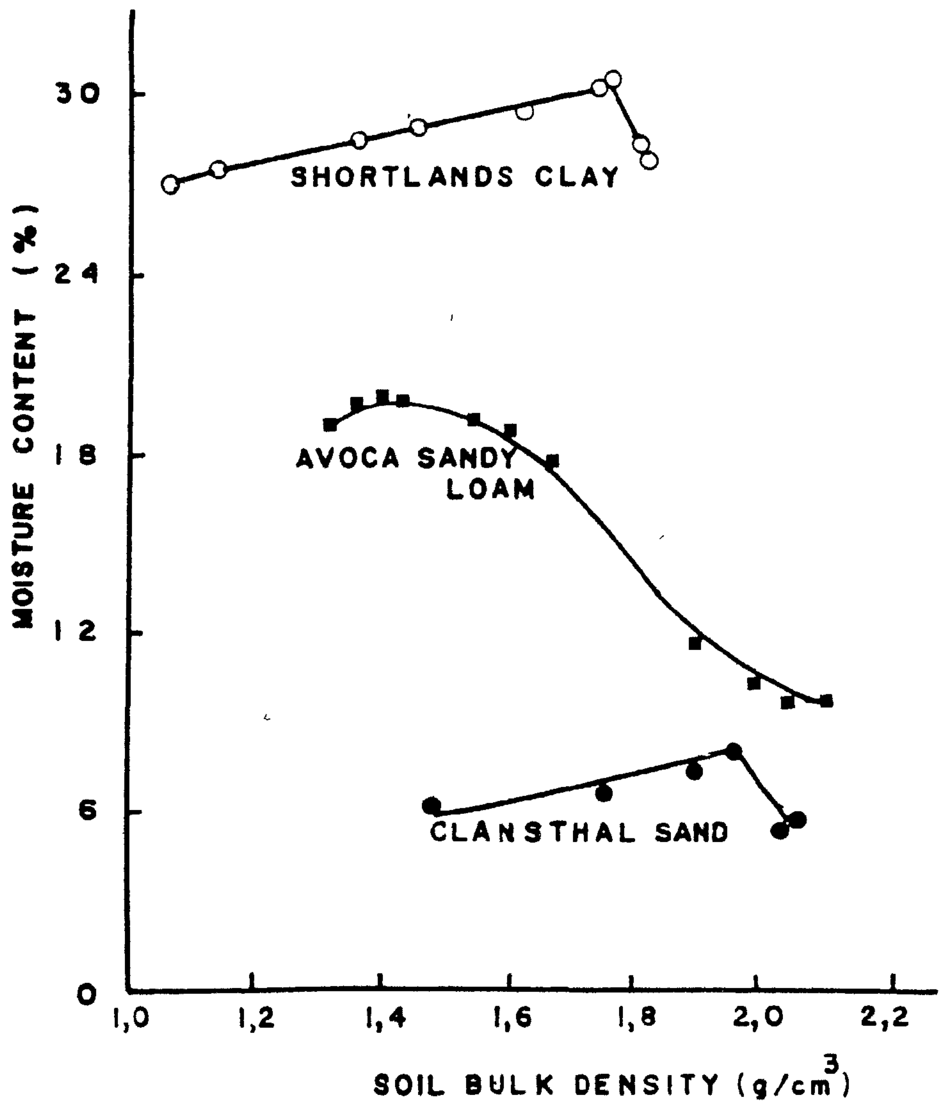


Figure 2.4 Influence of soil bulk density on water content of three Natal soils at a matric suction of 0,3 bar or 30,6 cm of suction (redrawn from Hill and Sumner, 1967).

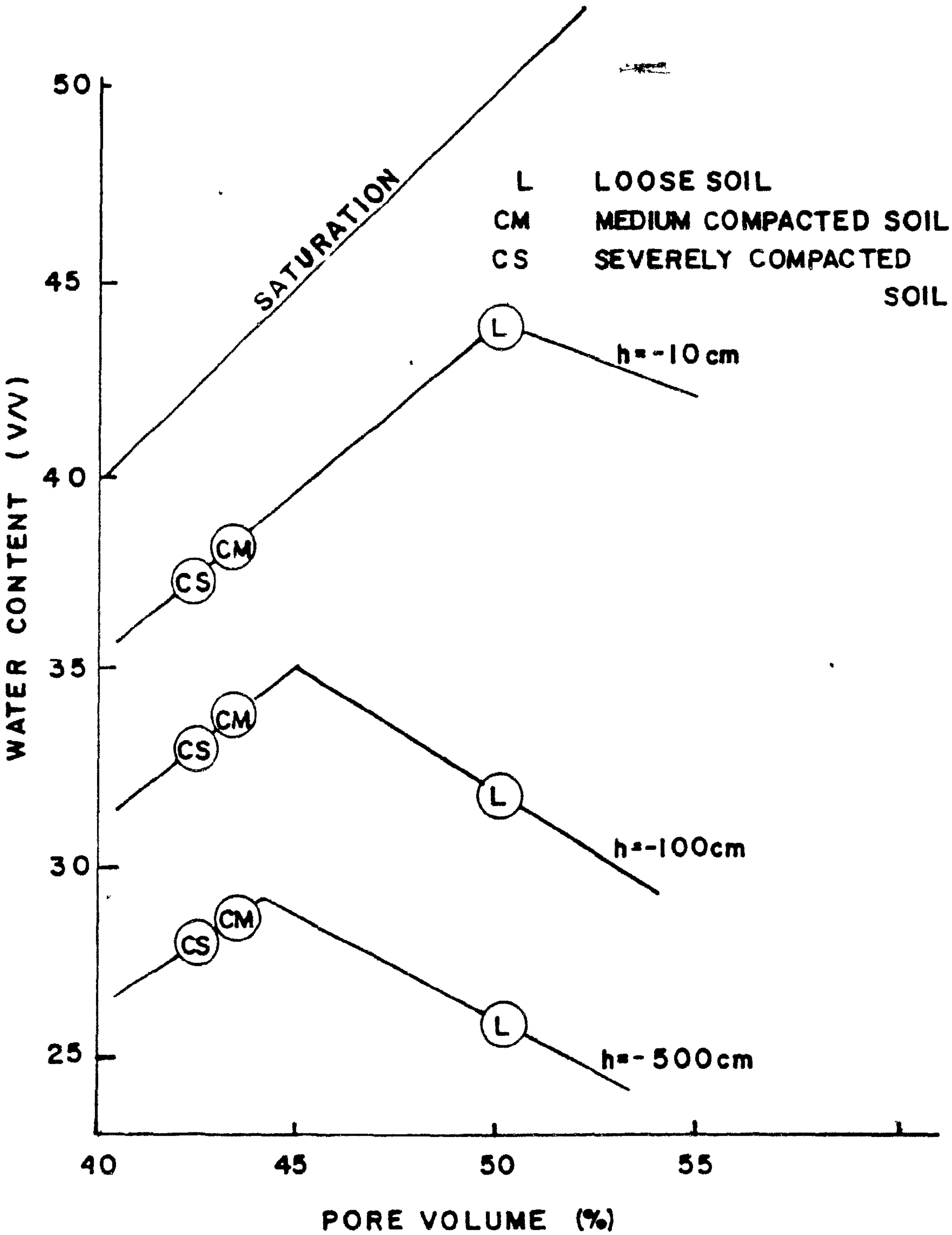


Figure 2.5 Relationships between pore volume and water content at different potentials (h) for various treatments (redrawn from Boone et al., 1978).

ii) Availability of water

Compaction has a marked effect on availability of water. The amount of available water is that held between the field capacity and the permanent wilting point (usually defined as 15 bars or 153m of H_2O suction). Field capacity is defined as the amount of water remaining in a well drained soil when the velocity of downward flow in unsaturated soil has become small (Warkentin, 1970). Water availability is measured by water retention characteristics of the soil. The water holding capacity may be increased depending upon the level of compaction. However, it does not necessarily follow that this water will be readily available for plant growth, for water availability does not depend directly on the permeability of the soil (Jamison, 1956). When the soil is compacted, the permeability of the soil decreases and water will be lost by evaporation or runoff. This condition may not allow enough water to infiltrate into the soil. Gupta (1933) measured the amount of water passing through soil samples compressed at bulk density of 1,37 and 1,27 grams per cubic centimeter with varying pore spaces at a given time. The results are shown in Table 2.1. The results clearly show the resistance to flow due to compaction of the soil. The effect will be more significant if the losses due to transpiration, evaporation and runoff are considered. This situation may create a great danger of reaching the permanent wilting point in the soil.

Flocker et al., (1958) showed that the total amount of water which passed into a non compacted soil plot in 3 hrs was 21,1cm, while in a severely compacted plot it was 0,27cm for Yolo fine sandy loam. Smith et al., (1955) found an increase in available water in loose soil but, a decrease in strongly compacted subsoil and topsoil. Whereas Raghavan et al., (1978c) showed more available water in compacted clay soil than in non compacted clay soil at higher suctions. There was more water available in the middle range of dry density than in higher

TABLE 2.1 - Rate of flow of water in 30 minutes

COMPRESSED		INTERMEDIATE		LOOSE	
Height cm	Amount of water in cm^3	Height cm	Amount of water in cm^3	Height cm	Amount of water in cm^3
6,8	15,54	7,4	44,91	8,3	192,72
6,8	13,67	7,4	40,97	8,3	187,17
6,8	11,14	7,4	36,26	8,3	184,91
6,8	11,09	7,2	35,09	8,3	180,62
6,8	10,67	7,3	34,80	8,3	168,12
6,8	10,56	7,4	32,03	8,3	160,18
6,7	10,53	7,4	32,01	8,3	157,00
6,7	8,97	7,4	31,37	8,2	154,62
6,8	8,95	7,0	25,61	8,2	152,17
6,8	7,59	7,4	24,67	8,2	150,14
6,6	7,10	7,4	24,00	8,3	145,57
6,7	6,76	7,1	23,93	8,1	128,42
6,8	6,19	7,2	23,30	8,2	118,59
6,7	5,72	7,4	22,30	8,2	109,65
6,7	4,94	7,4	21,05	8,2	102,47
6,6	4,20	7,0	20,25	8,3	100,37
6,5	4,15	7,4	20,07	8,2	98,18
6,4	3,25	7,2	16,09	8,2	91,67
Mean 6,7	8,38	7,3	28,26	8,25	143,47
Range 6,4-6,8	3,25-15,54	7,0-7,4	16,09-44,91	8,1-8,3	91,67-192,72
Height of 1cm of vol. 11,34 cm^3	1,25		3,87		17,3

or lower densities.

Water can be available also from a water table by capillary rise Boone et al., (1978) observed the decrease in potential for capillary rise in topsoil by severe compaction, but moderate compaction increased the potential

Many studies on soil compaction have indicated the interrelationship of porosity, pore size distribution and rate of water infiltration, hydraulic conductivity and water retention characteristics (Schmidt 1963, Douglas and McKyes, 1978, Flocker et al., 1958, Vomocil et al., 1958). They all used these parameters as the indicators of compaction. Most of the studies on soil water movement require the knowledge of hydraulic properties of soil in order to understand the soil structure. Measurement of soil water and matric suction provide the relationships between soil water content and suction and hydraulic conductivity.

iii) Theory

Mostly water movement is described using Darcy's equation. This equation can be written for flow in one direction in unsaturated soil as follows

$$v = K(\theta)\frac{\partial H}{\partial z} \qquad \text{------------(2.9)}$$

where v = soil water flux

$K(\theta)$ = hydraulic conductivity

H = hydraulic head

and z = depth

Combining equation (2.9) with the equation of continuity, which states that the flow of water into or out of a unit of soil equals the rate of change in water content,

$$\frac{\partial \theta}{\partial t} = \frac{\partial v}{\partial z} \qquad \text{--------------------(2.10)}$$

the flow equation will result as follows

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{\partial H}{\partial z}\right) \text{ ----------------(2.11)}$$

In order to obtain the hydraulic conductivity 'k' at a depth 'L', integrate equation (2.11) with respect to depth, z = o (the soil surface) to z = -L

$$\int_0^{-L} \frac{\partial \theta}{\partial t} dz = K \frac{\partial H}{\partial z}\bigg|_{z=-L} - K \frac{\partial H}{\partial z}\bigg|_{z=0} \text{ ------- -(2.12)}$$

In infiltration tests, the soil surface is covered with a plastic cover and there is no flow across the surface, the second term on the right hand side of equation (2.12) is zero (Nielsen et al., 1973)

Hydraulic head H for downward flow is always the sum of suction head 'h' and gravitational head 'z'

$$H = h + z \text{ ----------------(2.13)}$$

Therefore equation (2.12) can be written as

$$\int_0^{-L} \frac{\partial \theta}{\partial t} dz = K\left[\frac{\partial h}{\partial z} + 1\right]_{z=-L} \text{ ------(2.14)}$$

Assuming that the suction is a function of water content only and there is no hysteresis effect, then equation (2.14) can be written as follows:

$$\int_0^{-L} \frac{\partial \theta}{\partial t} dz = K\left[\frac{\partial h}{\partial \theta} \cdot \frac{\partial \theta}{\partial z} + 1\right]_{z=-L} \text{ ------(2.15)}$$

Measuring the volumetric moisture content at different depths as a function of time and matric suction variation with time can yield the calculation of hydraulic conductivity values as a function of soil moisture content

There are many experimental methods which have been developed to evaluate hydraulic conductivity 'K(θ)'. These methods involve pore geometry systems (Marshall, 1958, Millington and Quirk, 1959, Green and Corey, 1971, Schmidt, 1963), steady state columns (Klute, 1965) and field studies (Richards et al., 1956; Nielsen et al., 1961, Rose et al., 1965, LaRue et al., 1968 and Davidson et al., 1969)

Very little is known about predicting the hydraulic properties of soils. Schmidt (1963) measured the hydraulic conductivity as an indicator of compacted soil by using the Marshall method. He prepared compacted samples of Yolo clay loam and Greenfield sandy loam. The hydraulic conductivities obtained agreed well with calculated hydraulic conductivities

Douglas and McKyes (1978) found an equation to predict unsaturated hydraulic conductivity as a function of compaction of St Rosalie clay soil. The values of porosities were obtained from laboratory compacted soil samples and the values of hydraulic conductivity were corrected due to changes in effective porosity under increasing pressure gradients. They obtained linear relationships between porosity and the logarithm of hydraulic conductivity at the 95 percent confidence level

2-6 Soil Strength

Soil strength is defined as "the ability or capacity of a particular soil in a particular condition to resist or endure an applied force" (Brewer, 1964). Soil compaction involves the volumetric as well as the linear deformation of the soil. The strength of soil is a measure of resistance to both volumetric and linear deformations of soil structure. Soil fabric is also responsible for changing the soil strength. Besides this, the other factors which affect the soil strength are discussed by Taylor (1971). The factors that influence soil strength are water content, soil bulk density, changes in type and amount of saturation, cations, the number of particle-to-particle contacts and the amount and type of organic material. The results of Chesness et al., (1972) showed an increase in soil strength as the silt and clay content of a soil increased, soil moisture decreased, depth and bulk density increased.

During the past few years most workers have investigated the effects of high strength soil layers on the rooting habits and yield of crops. Most studies have employed a penetrometer to characterize the strength of soil material. The penetrometer is useful for cohesive soils because the mode of failure is defined (Soane, 1975). It is not as useful for soils which show an appreciable angle of friction, since the penetrometer involves a complex function of the properties. Yet, it provides an empirical indication of soil strength which can be useful and informative.

Many relationships have been established between penetrometer resistance and dry bulk density (Taylor and Bruce, 1968, Camp and Lund, 1968, Taylor et al., 1966, Mazurak and Pohlman, 1968). All authors showed relationships between penetrometer resistance and bulk density at a given soil water content or suction. For example at a given soil suction (1/3 bar or 340,23cm H_2O suction) and bulk density (1,5 or 1,6 g/cm^3) penetrometer resistance varied for different soils. This could be due to the variation in distribution of particle size and shape which on compaction behave differently (Soane, 1975). Chancellor (1971) discussed the relationship of penetrometer resistance with density. He pointed out that the penetrometer resistance declines very steadily as the moisture content increases, whereas compacted density increases to a peak then decreases as the moisture content increases.

Lyles and Woodruff (1963) determined a linear relationship between penetrometer density and core sample density (A penetrometer force of 2,23 x 10^{-2} kN was associated with a dry bulk density of 1,35 g/cm^3 at 6,5 percent moisture). Further, they observed that the penetrometer measured density was very sensitive to moisture content. Gooderham and Fisher (1975) predicted penetrometer resistance 'PEN' from bulk density 'γ_b' and percentage of soil moisture 'mc' with an 'R' value of 0,944, in silt loam soil

$$PEN = 3\ 466\ (\gamma_b) + 62,6(mc) - 124,5\ (mc)\ (\gamma_b) + 1,588\ (mc)^2 - 2\ 683 \quad \text{------} \quad (2\ 16)$$

Chesness et al., (1972) tried a non-linear exponential equation to predict cone index 'CI' in the laboratory, correlating depth 'd', bulk density 'γ_b' and moisture content 'mc'. They obtained the following empirical equation with an 'R' value 0,98

$$CI = 1,305\ (d)^{0,79} (\gamma_b)^{13,18} (mc)^{2,17} \quad \text{--------} (2\ 17)$$

The equation was used on field data but the field soil did not exhibit the same strength as laboratory samples.

Terry and Wilson (1953) have shown that about 20 percent moisture content is suitable for accurate measurement of soil bulk density with a soil penetrometer. Phillips and Kirkham (1962) obtained a linear relationship between the needle penetrometer reading and bulk density at 100cm soil suction in Colo clay soil. Eavis (1972) and Rosenberg and Willits (1962) showed that the penetrometer resistance increased as the bulk density and suction increased.

Soil strength is expected to increase as porosity decreases at constant moisture content. Adams et al., (1960) have shown that the penetrometer resistance increased as the bulk density increased and porosity decreased at 60cm suction in a two year experiment on a silty clay loam.

Taylor and Burnett (1964) determined the soil strength with a penetrometer and vane shear device. The vane shear strength was calculated with the assumptions that (1) the soil sheared along the surface of a cylinder which had the same diameter and height as that of the vane (2) the distribution of shear stress was uniform across the bottom of the cylinder. They found a linear relationship between the vane shear strength and penetrometer strength with an "R" value of 0,97. Payne and Fountaine (1952) demonstrated several advantages of the direct measurement of shear strength in the field. For example, the vane shear strength test is suitable at different depths and it gives satisfactory results in purely cohesive soils

2-7 Plant Performance Related to Soil Compaction

Soil compaction in excess is believed to cause damage to soil structure and crop production. Crop growth is affected by increased mechanical impedance, reduced aeration, altered moisture availability and soil temperature which follow from increased density and reduced pore space. Any of the factors or combinations of all of them affect plant growth, depending upon the soil type, the climatic conditions, the plant species and the stage of development of the plant.

Raghavan et al., (1978d) presented the data on varying levels of tire contact pressure and traffic intensity and their effect on yields of silage corn on clay soil. The range of contact pressure varied from 31,4, 41,2 and 61,8 kPa with 1, 5, 10 and 15 passes of wheel. The operations for compaction were done before and after seeding. The results indicated a potential 50 percent reduction in yield of corn with severe contact pressures. The effect of compaction was more before seeding than after seeding.

a) Soil Density Effects

Soil density affects the plant yield as has been related by many workers (e.g. Raghavan et al., 1978b; Trouse and Humbert, 1961) The maximum and minimum yields in 1977 were 12,5 Mg/ha and 9,7 Mg/ha, and in 1976 they were 16,0 Mg/ha and 9,8 Mg/ha respectively, (Raghavan et al., 1978c). Minimum and maximum yields in 1977 and 1976 were obtained at density 1,27 g/cm^3, 1,11 g/cm^3 and 1,29 g/cm^3 and 0,90 g/cm^3 respectively. The difference in yield obtained in both years shows that there are other factors operating beside soil density. Therefore, it can be said that soil density is not the only factor that affects plant yield, but moisture stress or soil aeration could be the limiting factor. However, the year 1977 was drier than the year 1976 (Raghavan et al., 1978c).

Yet, soil density is a useful parameter which is known to alter other physical properties of soil and can be used in relation to plant yield. Trouse and Humbert (1961) reported the reduction of sugarcane yield in Hawaii in soils with increasing density. Potato yield decreased about 50 percent on severe compaction of topsoil compared to loose soil (loamy sand) at first harvest (vanLoon and Bouma, 1978) Adams et al., (1960) showed the reduction of potato yield was 54 percent, sugar beets 30 percent, wheat 13 percent and corn 7,5 percent by surface packing of soil. The surface soil density rose from 1,07 g/cm^3 to 1,19 g/cm^3. Both surface and subsurface compaction reduced corn yield by 14,5 percent. More details regarding yield reduction of major crops like corn, tomatoes, potatoes, sugar beets and cotton is given in the review done by Rosenberg, (1964).

Rosenberg (1964) discussed the Vomocil equation which expressed the parabolic relationship:

$$Ymr - Y = C'(\gamma_{bo} - \overline{\gamma_b})^2 \qquad \text{----------(2.18)}$$

where Y = Plant yield

Ymr = Maximum relative yield of a given crop from a given soil under given weather conditions (including irrigation)

γ_{bo} = Optimal 4-16 inch (10-40cm) average profile bulk density

C' = Sensitivity constant

$\overline{\gamma_b}$ = Actual average density

Amir and Broughton (1975) calculated yield reductions and values of "C" from the literature. Table 2.2 shows optimum dry density for different crop yield. Rosenberg and Willits (1962) reported increased yield of barley by 50 percent with the increase in bulk density from 1,3 to 1,6 g/cm^3 on Glastown sand. A 37 percent barley yield decreased with increased bulk density from 1,3 to 1,65 g/cm^3 on Freehold loamy soil. Raghavan et al., (1978e) related dry bulk density 'γ_b' with plant yield 'Y'

$$Y = -2\,16\,270 + 438{,}8(\gamma_b) - 0{,}2107\,(\gamma_b)^2 \qquad \text{---------(2.19)}$$

TABLE 2.2 - Showing the optimum density for maximum yield.

SOURCE	SOIL	DENSITY g/cm^3	DEPTH	CROP	YIELD kg/ha.
Raghavan et al., (1978c)	clay	1,03 1,1	5-20cm 20 cm	Corn	12219,000
Flocker et al., (1958)	Yolo fine sandy loam	1,39 1,42	0-3cm 3-6cm	Weeds	2370,304
				Austrian Peas	1060,642
				Barley	4749,830
				Rye	5865,810
				Bromgrass	2868,344
		1,58 1,54	0-3cm 3-6cm	Horse Beans	1392,669
		1,22 1,29	0-3cm 3-6cm	Volunteer Weeds	2370,304
				Rye Grass	3504,729
				Purple Vetch	1577,128
				Vetch & Barley	4842,060
				Mililotus Indica	1457,230
				Oats	5386,215
Wittsel and Hobbs (1965)	Grearylike silt loam	1,2	2.5-10cm	Sorghum	6048,425
		1,3	17.5-25cm	Tomato	1,418 kg/plant

b) Soil Water Effects

Soil is a storage place for plant nutrients, a habitat for bacteria, an anchorage for plants and a reservoir that holds the water needed for plant growth. The mechanism by which the water moves to the plants in the SPA System will be given a brief review to allow an understanding of the soil-water-plant interactions.

i) Uptake of water

Generally, two processes are involved to regulate the water uptake in SPA System namely (1) passive water movement (2) active water movement. In passive water movement, water moves in response to a potential gradient, i.e., from higher to lower potential energy, as it moves through the soil into the plant root, and through the plants to the leaves. The potential energy continuouslsy decreases until the water reaches the point in the leaves at which evaporation is occurring. At this point an amount of energy must be supplied equal to the heat of vaporization, the necessary energy being supplied through solar radiation, convection and conduction of heat through the atmosphere and the plant.

In active water uptake the plant uses metabolic energy to absorb water from the soil. The water potential must be lower in the plant than in the soil, and lower in the atmosphere than in the plant for water to move in this path. When the potential of the water in the soil decreases to the lowest value of potential which the plant can maintain, water ceases to move to the plant. The plant then wilts if water movement continues from the leaf into the atmosphere.

Those studies in which only the root system is considered have shown that increased water suction is accompanied by reduced rate of growth. The growth is related to both soil, water stress and water content.

Wadleigh (1946) assumed that the plant root system would remove water from the soil in such a way as to maintain the total soil moisture stress constant throughout the root zone.

The difference in water potential between plant root and soil and the hydraulic conductivity in the soil determine the rate at which water moves to the root. Philip (1957) and Gardner (1960) assumed a cylindrical root at a fixed location and applied the following equation in cylindrical coordinates. It was also assumed that the water content was spatially dependent only on the radial coordinate and the effect of gravity was negligible.

$$\frac{\partial \theta}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \, D_{\omega} (\theta) \frac{\partial \theta}{\partial r} \right) \text{ -------------(2.20)}$$

where
θ = water content
r = distance from root axis
t = time
D_{ω} = soil water diffusivity

Molz and Remson (1970) developed a mathematical model for moisture removal of the plant and induced moisture movement from the soil.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(D \frac{\partial \theta}{\partial z} \right) - \frac{\partial k}{\partial z} - S \text{ --------------(2.21)}$$

Where z is vertical coordinate positive downward, D is the diffusivity, equal to $K \frac{\partial \Psi}{\partial \theta}$ and S is negative source term or extraction term and is related by the following equation. Under steady state conditions, the following relation between soil moisture flux "S_f (Z)", flux in the plant root "S(Z)" and transpiration rate "T" exists:

$$S_f \ (Z) + \int S(Z) \ dZ = T \text{ ----------------(2.22)}$$

ii) Water availability

Richards(1928) defined water availability as follows: "availability involves both the ability of the plant to absorb water with which it is in contact, and the readiness with which water moves in to replace that used by the plant." The soil water available to the plant in sufficient quantity depends upon the soil suction and hydraulic conductivity These quantities are altered by soil compaction. Compaction produces small voids which can retain water at high suction (Warkentin,1971), but the plant growth will not necessarily increase due to the other factors such as impedance to root growth, low aeration, poor structure and so on (Eavis,1972).

Relative distribution of roots with depth and the water retaining properties of soil determine the main features of the water uptake pattern. The more dense the root system, the greater the water uptake (Gardner,1960). Compaction, which increases the strength of soil, impedes root development resulting in less extraction from greater depths. Consequently, the growth reduction caused by compaction is more likely to occur in drier soil conditions where the total moisture absorbed by the plant is not sufficient to meet the physiological requirement of the plant. Compacted soil usually has slower water movement and more of the rain water is lost by surface runoff. Consequently, the plant will not receive the required amount of water it needs, and will ultimately die or suffer poor growth due to water stress.

Trouse (1971) indicated that the plant can obtain adequate moisture from the drier soil if there are enough roots functioning in a large enough volume of soil. Following his study he reported that the moisture aspects of compacted soils will have an indirect effect on plant development. The following situations in a compacted soil can affect the root absorption:

1) Slow permeability of the compacted soil reduces infiltration if the soil is sloped.
2) Ponding in basin areas restricts aeration and may injure the root, resulting in reduction of root activity.

Besides soil compaction there are other factors which affect the availability of water to the plants. In general, these factors are divided into three broad classes, (1) soil factors, (2 plant factors and (3) climatic factors. These factors are discussed by Richards and Wadleigh (1952), Kelley (1954), Hagan (1962), Jamison (1956), Slatyer (1960), Kramer (1969), John and Neil (1976) and Boyer and Pherson (1975). The reviews of the authors indicated that it is very difficult to say that one or the other factor is responsible for the availability of water to the plant. This depends upon soil type, climatic conditions and plant species.

Some plants can withstand drought conditions for longer times. Kelley et al., (1945) have shown that guayule will withstand a long period of drought and renew growth. Likewise, sorghum can be subjected to considerable moisture stress and will subsequently renew growth. On the other hand, celery, potatoes and lettuce are very sensitive to drought. Yield of wheat is very sensitive to lack of available water in its final growth stages, but much less in its early growth (Warkentin ,1970).

The decrease of soil moisture is a function of evapotranspiration and percolation. As the water content decreases, the moisture availability to the plant decreases, thus affecting the growth of the plant. The results of Richards and Wadleigh (1952) on the rate of stem elongation of sunflowers as a function of water content showed that the growth rate decreased as the water content decreased from field capacity to the permanent wilting percentage. From these results, they suggested that all the water between the upper and lower limits is not equally available to plants. Some results on this concept are summarized by Kelley (1954).

c) Soil Aeration Effects

Plant roots and living organisms in soil take up oxygen and respire mainly carbon dioxide. The growth of plants will be restricted if the concentration of carbon dioxide is too high or oxygen concentration too low. Therefore, it is very important that there should be a sufficient amount of aeration present in the root zone of the soil; not only that, but there must be rapid exchange of gases

It has long been believed that improved soil structure promotes plant growth through better soil aeration. Russel (1949) expressed his opinion in these words. "The most promising approach to the evaluation of soil structure, particularly as this affects plant growth, lies not in the elaboration of the physical architecture of the soil but in the description of the air, water, temperature and compaction conditions that greatly influence root activity and plant growth If such measurements are to be significant, much additional quantitative information is needed on the relation of these factors to plant growth".

It was observed through experiments that soil aeration depends upon the type of soil and kind of crop grown. Kopecky, quoted by Grable (1966), proposed optimum porosities for certain crops. Optimum air porosity for Sudan grass ranges from 6-10 percent, 10-15 percent for wheat and oats and 15-20 percent for barley and sugar beets.

Compaction affects the air porosity and is reviewed in the compaction section. Trouse and Humbert (1961) showed a decrease of air porosity to less than 10 percent when the density reached the critical level for sugarcane roots. The critical air porosity for plant growth is usually considered to be 10 percent (Vomocil and Flocker, 1961). Gill and Miller (1956) found the growth of corn seedlings to be decreased under high impedance when the oxygen content was below 10 percent. Meredith and Patrick (1961) presented the relationship between air porosity and root penetration for three soils. Root penetration stopped when air porosity decreased to 2 percent.

Eavis and Payne (1968) found restrictions to root elongation occurred at 30 percent gas space and below in loose soil (1,1 g/cm^3), below 22 percent in a medium compacted soil (1,4 g/cm^3) and below 10 percent in a highly compacted soil (1,6 g/cm^3). The dry weight of the roots decreased with the decrease in oxygen concentration.

d) Mechanical Impedance

It has been observed that the soils with high strength could hardly allow the root to penetrate because of insufficient force to overcome such resistance (Taylor and Gardner 1963 and Phillips and Kirkham,1962) Mechanical impedance is the resistance of soil encountered by a root trying to penetrate.

The force exerted by the root must be larger to push the soil particles aside to form an opening for root elongation and thickening Root proliferation depends on the bulk density of individual soil units, pore size, water content and soil type.

Pfeffer studied the root growth pressure by use of a small penetrometer (Gill and Bolt,1955). He found the pressure exerted by roots in coarse soil was less than the pressure measured by the penetrometer, whereas in a fine grained homogeneous medium, the relationship between penetrometer and root pressure appeared to be quite good. He considered that in nature a plant would deviate from its path in coarse-grained soils to go around solid resistance; thus the pressure exerted by root would be less than pressures measured with a penetrometer.

Eavis and Payne (1968) indicated that the several levels of stress were four to eight times smaller than equivalent stresses on the penetrometer probe using a plaster of paris medium. It appears that the forces exerted by the root are smaller than those encountered by a probe similar to the root shape.

Greacen et al., (1968) considered a model of the spherical expansion of a cavity at the point of the probe. They assumed two main zones where the compression of soil occurs, namely, the zone of plastic failure compression surrounding the probe, and elastic compression outside this zone. They indicated that the roots penetrate the soil by cylindrical compression to avoid soil-root friction. Further, they found that the maximum pressure which the root can exert is approximately 700 kPa. Barley et al., (1965) determined the maximum available pressure which the root can exert is approximately 800 kPa.

When the soil is subjected to a load which tends to change its total volume, this in turn decreases the proportion of large pore spaces in the adjacent soil. Wiersum (1957) indicated that mechanical resistance to root penetration is governed by the rigidity of pore structure. It means that the plant roots grown into a rigid system are only able to penetrate a pore which has a diameter exceeding that of the root-tip, while Henry and McKibben (1967) showed that it is not necessary to have sufficient pore sizes for roots to penetrate since roots can easily penetrate if the soil is plastic or moist. On the other hand, Taylor and Gardner (1960) conducted an experiment using wax substrates. They showed that roots have easily grown into and through 2 or 3cm of wax substrates. Taylor and Burnett (1964) reported that soil compaction reduces cotton root penetration by increasing the strength of the soil in which pores are located, rather than by reducing the size of the pores below some critical diameter. However, the ability of plant root penetration depends upon the wax rigidity, the type of plant and the density of the soil above rigidity. Henry and McKibben (1967) showed that soil productivity decreases as the soil strength increases.

Taylor and Burnett (1964) presented the data of a one year experiment on five sandy loam soils. The results indicated that the lint yield of cotton was reduced to less than half when the soil was at field capacity moisture content with a bulk density of 1,8 grams per cubic centimeter, air porosity 15 percent and a strength less than 800 kPa at field capacity. Taylor et al. (1964) have examined the effect of soil strength on cotton and sorghum yields in sandy loam soil. The yields were reduced by half as the soil strength increased to 2500 kPa.

Many workers (Trouse and Humbert, 1961 and Veihmeyer and Hendrickson 1946, 1948) reported that one critical bulk density exists for the soil at which no root penetration occurs. Taylor and Gardner (1963) rejected this concept by showing the evidence that the resistance of Amarillo fine sandy loam depends upon the soil moisture content. They indicated the effects of soil suction on bulk density and root penetration. Only 80 percent of roots penetrated at 2cm of H_2O suction with 1,65 grams per cubic centimeters bulk density, and there was 20 percent of the root penetration at 6,8cm of H_2O suction with bulk density of 1,65 grams per cubic centimeter. The difference was 60 percent when the moisture content by weight was 2,5 percent with the same bulk density at 2 to 6,8cm of H_2O suction. At the same moisture content by weight, a bulk density of 1,75 grams per cubic centimeter caused a change in root penetration from 60 to 0 percent. Root penetration was lower in high soil suction at a given bulk density than in a lower soil suction. Barley et al., (1965), showed the effects of bulk density and suction on pea emergence. All pea seedlings emerged after 3 days from a core with a bulk density of 1,5 to 1,6 grams per cubic centimeter at 3,1cm of H_2O suction, and 60 percent emerged from the confined 1,7 grams per cubic centimeter cores. At 1,7 grams per cubic centimeter and 7,1cm of H_2O suction, 30 percent still had not emerged even at 5 days For wheat, only 80 percent emerged from the strongest core. The data indicated that the root reduction was due to an increase of soil strength at higher suction and bulk density. Taylor and Ratliff (1969) used higher suction values than those used by the above workers. They concluded that soil suction between 1,7 and 71,4 cm of H_2O suction for peanuts did not affect the relation between root elongation rate and penetrometer resistance. Taylor and Bruce (1968) measured the root elongation rate of pregerminated cotton seed on loamy sand soil. The root elongation rates for the penetrometer resistance 250, 500 and 750 kPa were 51, 14 and 5 percent, respectively of that in loose soil Gooderham and Fisher (1975) determined that the rate of seedling root elongation was negatively correlated with penetrometer resistance considered over a range of bulk densities and soil moisture contents.

Mechanical impedance, aeration and moisture stress on pea seedlings in sandy loam soil is well summarized by Eavis (1972) The Fig. 2.6 shows that at low suction and low bulk density the root elongation was affected by only aeration, while at medium suction and high bulk density, root elongation was affected by aeration and mechanical impedance At medium suction there was only mechanical impedance in all levels of bulk density, but at high suction and low bulk density the root elongation was affected by moisture stress. For medium density, moisture stress and mechanical impedance affected root elongation but at high bulk density level there was only mechanical impedance. Fiskell et al., (1968) examined the effect of plow pans in a coarse textured soil. Under droughty conditions, soil strength increased with the increase of moisture tension. The plow pan then acted as an effective barrier to the supply of subsoil moisture and nutrients for crop utilization.

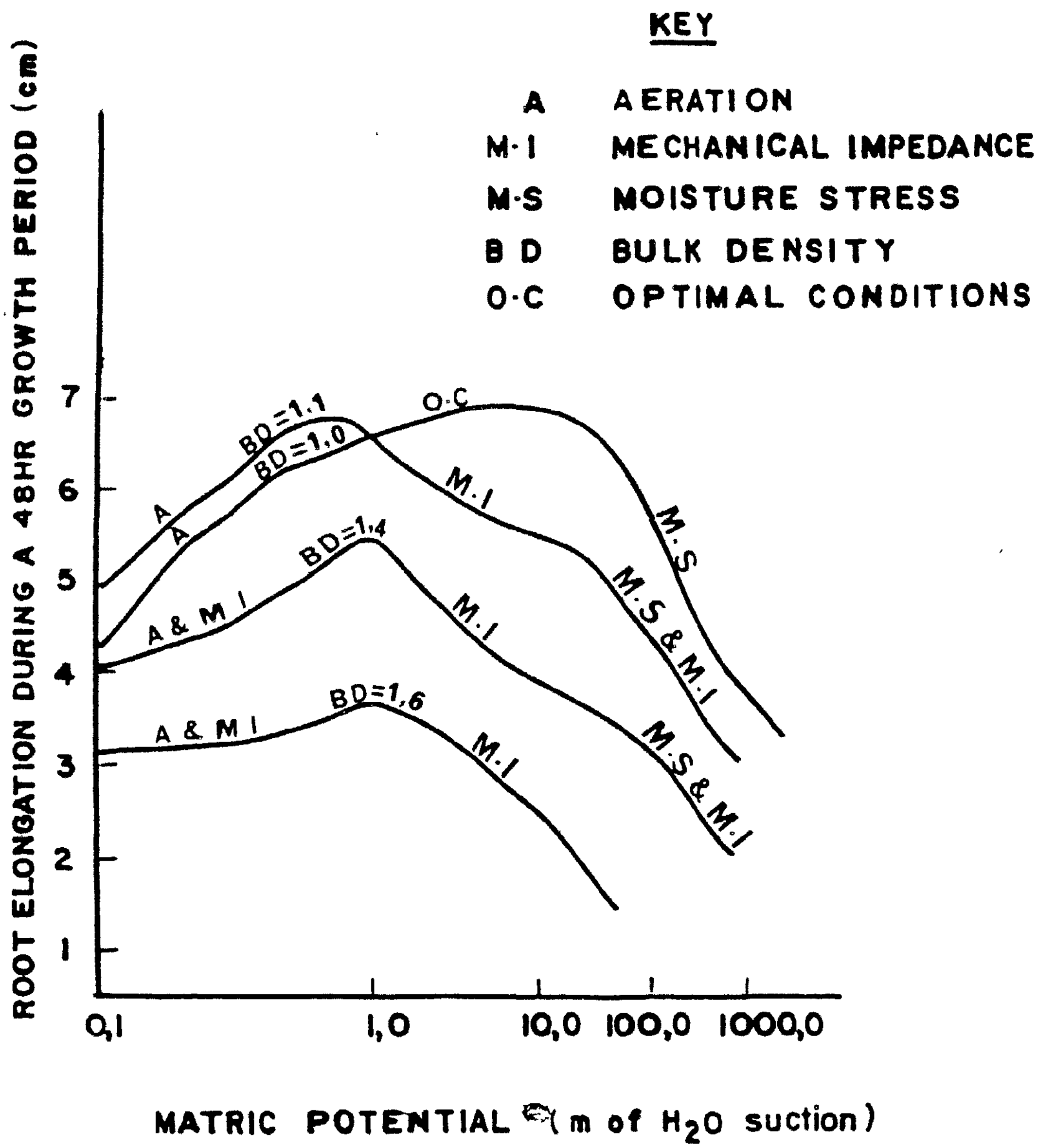


Figure 2.6 Summary of effects of mechanical impedance, aeration and moisture stress on pea seedling root elongation in a sandy loam held at different matric potentials and bulk densities (redrawn from Eavis, 1972).

2-8 Tillage

The use of tillage tools on agricultural soils is extremely important when one finds a compacted layer or zone in the soil. This compacted zone must be loosened in order to provide a healthy environment for roots to grow. Taylor and Burnett (1964) reported that if the compaction of soil is not loosened by subsequent tillage, then a reduction of root weight occurs.

The development of tillage tools has made possible the selection of which one can change the soil conditions as desired. The necessary operations on the field can be minimized if the proper selection of tillage tool is made, and this will aid in evaluation cost and benefits of changing the soil conditions.

The objectives of tillage are to increase the supply of air, water, nitrogen and minerals to plants, as well as weed control (Cooper, 1971). This will then influence water intake and storage and the extraction of water from the soil by the plant root in addition to microbial activity. In other words, tillage changes soil physical properties in such a way that optimum conditions for plant growth can be obtained. The effect of soil physical properties on plant growth has already been discussed in previous sections. Here the performance of two tillage implements such as the moldboard and chisel plows will be assessed from the viewpoint of previous studies.

Chiselling is usually done to break through and shatter compact soil. Papendick and Miller (1977) demonstrated the benefits of chisel plowing. Chisel plowing is done where soil is commonly frozen. It is not used on soils when dry because the weak aggregates flow back into the chisel track. Chiselling produces large stable clods in medium to fine-textured soils which facilitate water intake through fractures and the chisel channels. It also reduces runoff under wet and frozen conditions several centimeters deep. Chiselling is normally done to a depth of 20 - 30cm with narrow shanks spaced 30 or 60 cm apart. Chiselling greater than 30 centimeters depth becomes a subsoiler operation.

A moldboard plow is particularly power demanding (Soane and Pidgeon 1975). The draft of a chisel plow is about half that of the moldboard plow per 20cm of width of soil tilth at comparable depths as observed by Soane and Pidgeon (1975). Therefore, chiselling is faster and more economical than the moldboard, and it takes less skill. A chisel plow operates at the same depth or slightly more than moldboard (Amemiya,1977).

A chisel plow does not invert the soil as the moldboard does, but it results in a density intermediate between that of the moldboard and zero plowing in the top 18cm (Soane and Pidgeon 1975). Mannering et al., (1975) showed that chiselling gave a slightly lower density than moldboard plowing and no-till on Pewano silty clay loam. They compared several plows as shown in Fig. 2.7. McKyes et al., (1979) showed that the chisel plow reduced dry density and produced finer peds not greater than 6 or 8cm and retained more water than other types of tillage operations. Negi et al., (1979) compared several plows on compacted soil. Chisel and moldboard plows reduced the density of compacted soil up to a 15cm depth. They obtained highest corn yields with a chisel plow on sandy loam soil, while the moldboard and chisel plow produced highest yields in clay soil compared to the compacted and no-till treatments. Patterson et al., (1980) found chisel plow more versatile than a moldboard in their six years of study at two locations in England.

It is obvious that dense or compacted soil tends to restrict root growth and water movement. Grissom et al., (1955), observed that the soil

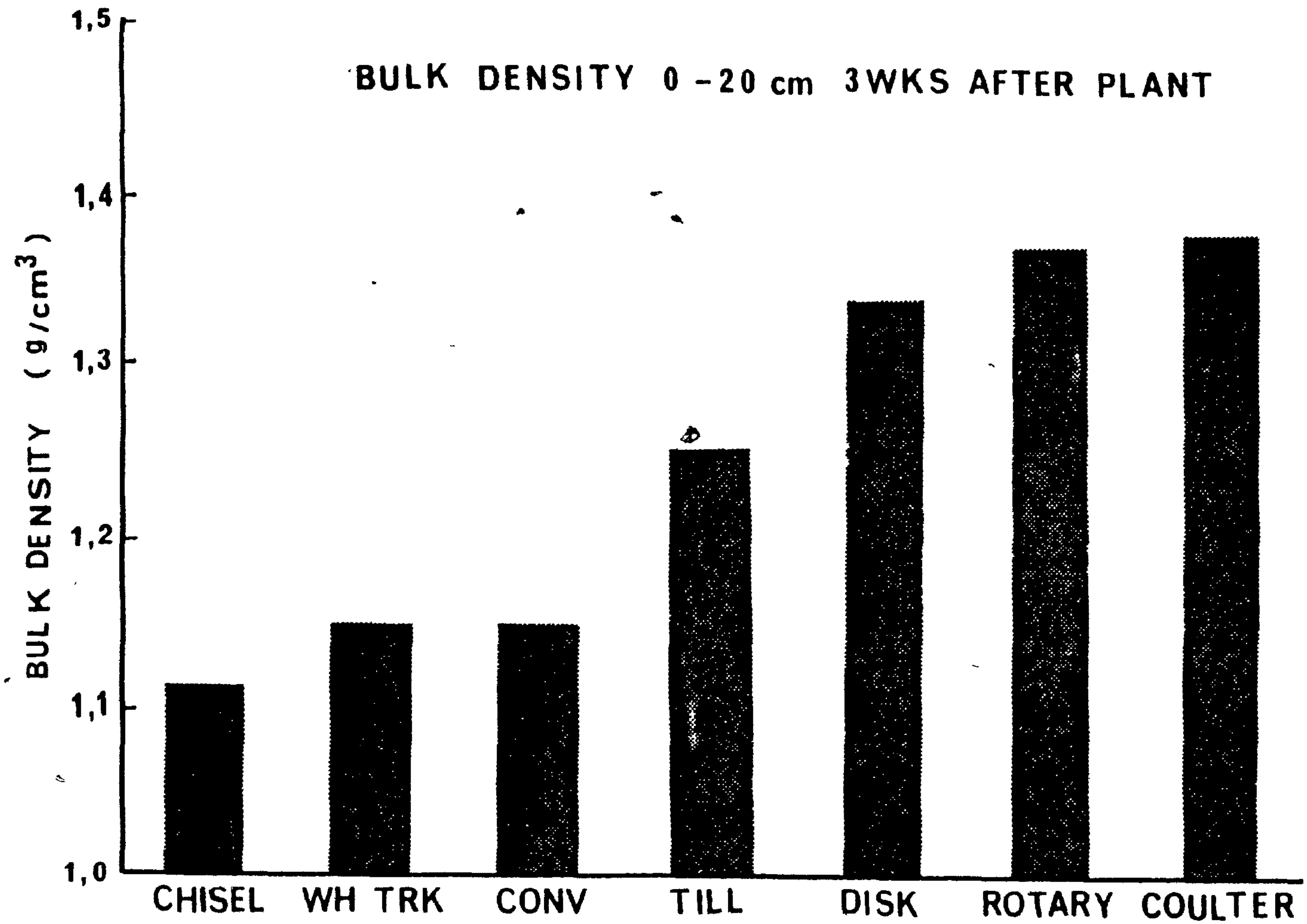


Figure 2.7 Change of bulk density due to different tillage treatments (redrawn from Mannering et al., 1975).

strength was the only factor which most commonly limited the root growth of cotton. Since one reason for plowing soil is to improve porosity, after deep plowing or chiselling cotton yield increased. Cassel et al., (1978) measured the soil penetration resistance at seven positions, spaced 15cm apart on a transect normal to the third row of soybeans in each plot four times in a season. Chisel plowing reduced the cone index more than did normal tillage at all seven positions Doty et al., (1975) examined the rooting depth, oxygen levels and water availability following tillage operations. All the above properties increased in chiselled plots during the wet season. During the dry season, roots proliferated to a greater depth and extracted sufficient water Chiselled plots permitted greater water infiltration and allowed upward water movement. Chiselling also produced significantly more dry matter and larger crop yields

Hobbs et al., (1961) reported that the chisel plow reduced the density and increased the permeability of the soil and this situation lasted for 18 months. Papendick and Miller (1977) showed the effect of chiselling on silt clay loam soil after a wheat harvest Chiselling increased internal water transmission from 4 to 15 times compared with no-tillage. The results of Mannering et al., (1975) showed an increase of infiltration and reduced runoff by chisel plowing. The chisel plow affected both the soil water desorption curve and hydraulic conductivity in the upper 30cm depth (Allmaras et al., 1977).

The soil can be made productive if the desired porosity could be obtained at the shallow water depth. Water can thus be extracted by the plant roots with the movement of water from the capillary fringe. Reicosky et al., (1976) found that a chisel plow treatment improved corn roots in a Varina sandy soil, and enabled the utilization of water from the capillary fringe above the water table.

The corn ear yield increased as a result of this action.

A moldboard plow on uncompacted soil produces unfractured clods which may persist. The surface produced is generally rough and free of plant material. Therefore, it is important to break down the furrow slice, otherwise there will be a rapid loss of moisture (Johnson and Taylor, 1960) due to increased surface area exposed to the atmosphere (Hakimi and Kachru, 1976). Hakimi and Kachru (1976) compared the moldboard plow with other plows. They found a field cultivator followed by disking resulted in the best yields over other tillage treatments in their study. They further suggested that the moldboard plow can be replaced by other types of tillage tools for satisfactory seed bed preparation. Voorhees et al., (1978) showed that the moldboard plow was more effective in reducing the soil bulk density and penetrometer resistance. Disking and chiselling gave about 5 and 40 percent higher values, respectively, compared to the moldboard plow. Hanna and Masry (1962) studied a moldboard plow with respect to other plows. The results showed no significant difference in yield, but there was an increase of compaction in the subsoil layer, ranging from 15-20cm depth. The moldboard plow action at 25cm depth showed a remarkable decrease of compaction from 15-20cm depth, to a layer below 30cm depth, thus creating a favourable environment for root growth.

Laws (1953) reported that the yield of crops such as cotton, corn and oats was reduced by 40 to 50 percent during 50 to 60 years of cropping. The factor which most affected the reduction of yield was compaction, which was probably created by the cropping system if the climate was not materially changed in the area. This zone of compaction was formed due to mechanical equipment during tillage operations by repeated trips along the bottom of the furrow. The study was carried out to find a mechanical method of preventing the formation of a compacted soil layer. The results indicated that the moldboard plow produced higher yields because it produced a granular and mellow structure at 20cm depth on Houston black clay soils, whereas chisel-type tillage cracked down structure by the stress of the chisel plow. Finally he concluded that the chisel plow proved ineffective on Houston black clay soils composed of montmorillonite clays

Cook et al., (1953) compared different plows on Hilldale sandy loam cropped with oats, beans and corn, Brookston loam cropped with beets, oats beans and corn, Fox sandy loam cropped with oats and corn, and Brookston clay loam cropped with beets, oats, beans and corn. The results indicated that the moldboard plow gave significantly greater yields than other types of plows.

Crop responses to tillage systems vary with time, location and weed control. In a three year experiment, Bolton and Aylesworth (1959) observed that a moldboard plow produced greater yields in two out of three years compared to other types of tillage on Brookston clay soil. The study of Cook and Peikert (1950) presented data of a three year experiment on Brookston clay loam, Brookston loam and Hilldale sandy loam soil using different types of tillage equipment. The results indicated an increase in yields of beets, oats, beans and corn in moldboard plow treatments. The increase was due to fewer weeds in moldboard plots than other methods.

The interaction of soil, crop and climatic conditions make it complex to attempt to predict the desirable type of tillage with respect to crop response. Precise recommendations for tillage have not been available, such as have fertilizer recommendations. However, Soane and Pidgeon (1975) generalized the need for tillage for different crops and soils. For cereal crops on well drained soils, tillage can be reduced if other measures of weed control are adopted. Poorly drained or compacted soils need cultivation to improve soil conditions. Vegetable crops or large rooted crops require a large number of pores and therefore tillage is necessary Potato crops require high porosity, therefore, one or two cultivations give highest yields (Blake and Aldrich,1955). On the other hand, excessive cultivation can result in lower air space and aggregation and higher bulk density. Therefore, any cultivation on the field should be justified by the initial soil condition and the crop to be grown.

2-9 Summary

The literature reported demonstrates that there can be a considerable effect of compaction and loosening on most of the soil physical properties and on plant performance. There exist discrepancies among the reported results in the critical density and soil strength related to optimum root growth and plant yields. It is established that both soil suction and bulk density affect root growth, depending upon the soil texture and plant species. There is considerable variation in the response of different plants to soil aeration at various levels of bulk density and soil suction.

Availability of water for plant growth depends upon the soil type. The coarse-grained soil held most of the available water at low suction levels, but in fine-grained soil it is present over the whole range up to the permanent wilting point. Availability of soil water in a clay soil is higher probably due to high moisture contents at higher suction levels compared with coarse-grained soil. Hydraulic conductivity is a function of soil suction, or moisture content. Increasing soil suction decreases hydraulic conductivity and also results in decrease in moisture content of the soil. Amount of soil water decreases appreciably if the transpirational demand of the plant is high, which in turn increases soil suction and decreases the hydraulic conductivity.

Many of the studies have tested the effects of tillage practices on yields over a wide range of soil texture. The principal physical significance of tillage is the change in soil properties, which should be used as the criteria in defining tillage-plant interactions. The study of the soil-air-water-plant system in compacted and subsequent tilled soils has started only recently, and there is still much to learn. Therefore, it is necessary to consider the subject in its broadest terms to study as many individual properties as possible if a full understanding of the soil responses to the use of machinery is to be gained. It was therefore decided to study the change of soil properties, mainly, soil density, soil strength, air-filled porosity and hydrology of the soil, due to compaction and subsequent tillage by two specific tools. This change in soil properties could then be related to plant performance for a selected crop grown on the experimental plots.

CHAPTER III

OBJECTIVES AND SCOPE

The specific objectives of this study were as follows:

1. To design a field experiment to have three field traffic treatments (5, 10 and 15 passes of a tractor), one control (no traffic) treatment and two tillage treatments in four replicates. The tillage treatments will be performed on plots already compacted by 5 and 15 passes of a tractor exerting a ground contact pressure of 41 kPa.
2. To determine the initial status of the soil with reference to physical properties in each plot.
3. To conduct laboratory tests to establish the soil texture, compaction and mechanical properties of the soil.
4. To measure the soil density, penetrometer and vane resistance in all plots after compaction and tillage treatments, and to determine statistically any difference due to changes in soil physical properties resulting from compaction and tillage treatments.
5. To grow a buckwheat crop on the plots.
6. To monitor rainfall and water table depth throughout the growing season.
7. To observe the time required for the buckwheat seedlings to emerge.
8. To determine the plant heights up to the maturation of the crop.
9. To determine the weight of root mass, dry matter and grain yields on harvesting of the crop.
10. To describe the influence of soil physical properties on plant performance as a result of compaction and tillage treatments.
11. To compare the results of 1978 and 1979 and to determine the influence of environmental variations.

12. To investigate the effects of the variation of soil density, penetrometer and vane resistance on aeration, water retention characteristics, unsaturated hydraulic conductivity and availability of water and relate these properties to crop growth.

13. To present the suggestions and recommendations for further research in the light of this study.

The study would be conducted on one soil type, a Bearbrook clay in two growing seasons of 1978 and 1979. The plots already compacted by a MF-165D tractor in 5 and 15 passes would be subjected to moldboard and chisel plow treatments. Three sets of soil density, penetrometer resistance, vane shear resistance and soil moisture profiles would be taken, one before compaction or tillage treatments, one after the completion of treatments and one during the period of growth.

Soil suction and gravimetric moisture content, along with bulk density measurements, would serve to calculate hydraulic retention properties of the soil for one irrigation cycle during the growing season.

The resulting soil conditions due to the various treatments would be related to plant growth in order to quantify the effects and to justify machinery management decisions.

CHAPTER IV

MATERIALS AND METHODS

With these objectives in mind, the experiment was conducted on Bearbrook clay soil at the Macdonald College Research Station, St. Anne de Bellevue for two consecutive summers, 1978 and 1979, by growing a buckwheat crop.

4-1 Experiment 1978

The test site was uncultivated for the last three years and many weeds were standing in the field. The problem of weeds was more severe during the growing period in 1978, even though the field was sprayed with Roundup herbicide at the rate of 5,6 ℓ per hectare in 350 ℓ of water. The field schedule is shown in Table 4 1.

The experiment was layed out in collaboration with E. Perraton, a fellow graduate student studying different field treatments. The idea for a combined experiment was to keep the common treatments together in one statistical design for obtaining more statistical information about the treatment effects. Table 4.2 shows the distribution of treatments for the years 1978 and 1979.

After applying the herbicide at the recommended rate, the field was left for 15 days to recover fully from toxic effects. Then it was disked, followed by a rotary tiller in order to get a more uniform profile up to 0,20m depth.

The layout for this experiment consisted of 48, 10 x 2m plots staked out to give required treatments as shown in Fig. 4.1. The completely randomized block design with 12 treatments, replicated 4 times each were used

TABLE 4.1 - Schedule of field operations for the years 1978 and 1979.

FIELD OPERATIONS	YEAR 1978	YEAR 1979
Herbicide application	June 15	
Disc harrowing	June 30	June 16
Rotary tilling	June 30	June 20
Plot layout	July 1	June 20
Compaction treatments	July 4, 5, 6	June 21, 22
Tillage treatments	July 7, 8	July 25
Seeding and fertilizer incorporation	July 11	June 27
Insecticide spraying	Aug. 2	
Soil measurement		
Soil density	July 4,5,6,7,8,14 Aug. 15, 16	June 21,22,23,25
Penetrometer resistance	July 4,5,6,7,8,14	June 21,22,23,25
Vane shear resistance	July 4,5,6,7,8,14	June 21,22,23,25
Moisture content	July 4,5,6,7,8,14 Aug. 15,16	June 21,22,23,25
Soil water measurement		
Soil suction and vol. moisture content	Aug. 11,13,16,22 & Sept. 6	
Water table	July 12,15,20,24,25 26,28,21 Aug. 2,3,5,6,9,17, 18,20,21,22,25,29 Sept.1,7,1[illegible],23,30	July 1,5,6,10,14,18 23,28,31 Aug. 9,14,17,21,25 Sept. 1,5,10,15,20, 25
Plant measurement		
Plant germination	July 21,24,25,28,31 Aug. 1,2,3	July 5,6,10,14 18,23,28,31
Plant height	Aug. 4,10,14,18	Aug. 9,15,21,28
Harvesting	Sept. 23	Sept. 22
Root digging	Sept. 31	

TABLE 4.2 - Showing the distribution of treatments for layout in the years 1978 and 1979.

YEAR	PASSES	REPLICATE	CONTACT PRESSURE Y, kPa	NAME OF TREATMENT	NO. OF PLOTS	TILLAGE PERFORMED	TREATMENTS BELONGS TO
1978							
	5	4	41,0	5YO*	4	-	Common
	10	4	41,0	10YO	4	-	Common
	15	4	41,0	15YO	4	-	Common
	0	4	-	000	4	No tillage	Common
	5	4	41,0	5YM	4	Moldboard & disking	This study
	5	4	41,0	5YC	4	Chisel plow	"
	15	4	41,0	15YM**	4	Moldboard & disking	"
	15	4	41,0	15YC	4	Chisel plow	"
	5	4	41,0	5YS	4	Sub soiler	E.Perraton
	5	4	41,0	5YR	4	Rotovator	E.Perraton
	15	4	41,0	15YS	4	Sub soiler	E.Perraton
	15	4	41,0	15YR	4	Rotovator	E.Perraton
			Total plots -		48		
1979							
	15	3	41,0	15YO	3	-	Common
	0	3	-	000	3	No tillage	Common
	15	3	41,0	15YM	3	Moldboard & disking	This study
	15	3	41,0	15YS	3	Subsoiler	E. Perraton
			Total plots -		12		

* 5YO = 5 stands for passes of tractor; Y = ground contact pressure and 0 stands for no tillage.

**15YM = 15 passes; Y = contact pressure(41,0 kPa); M = Moldboard plow and C for chisel plow

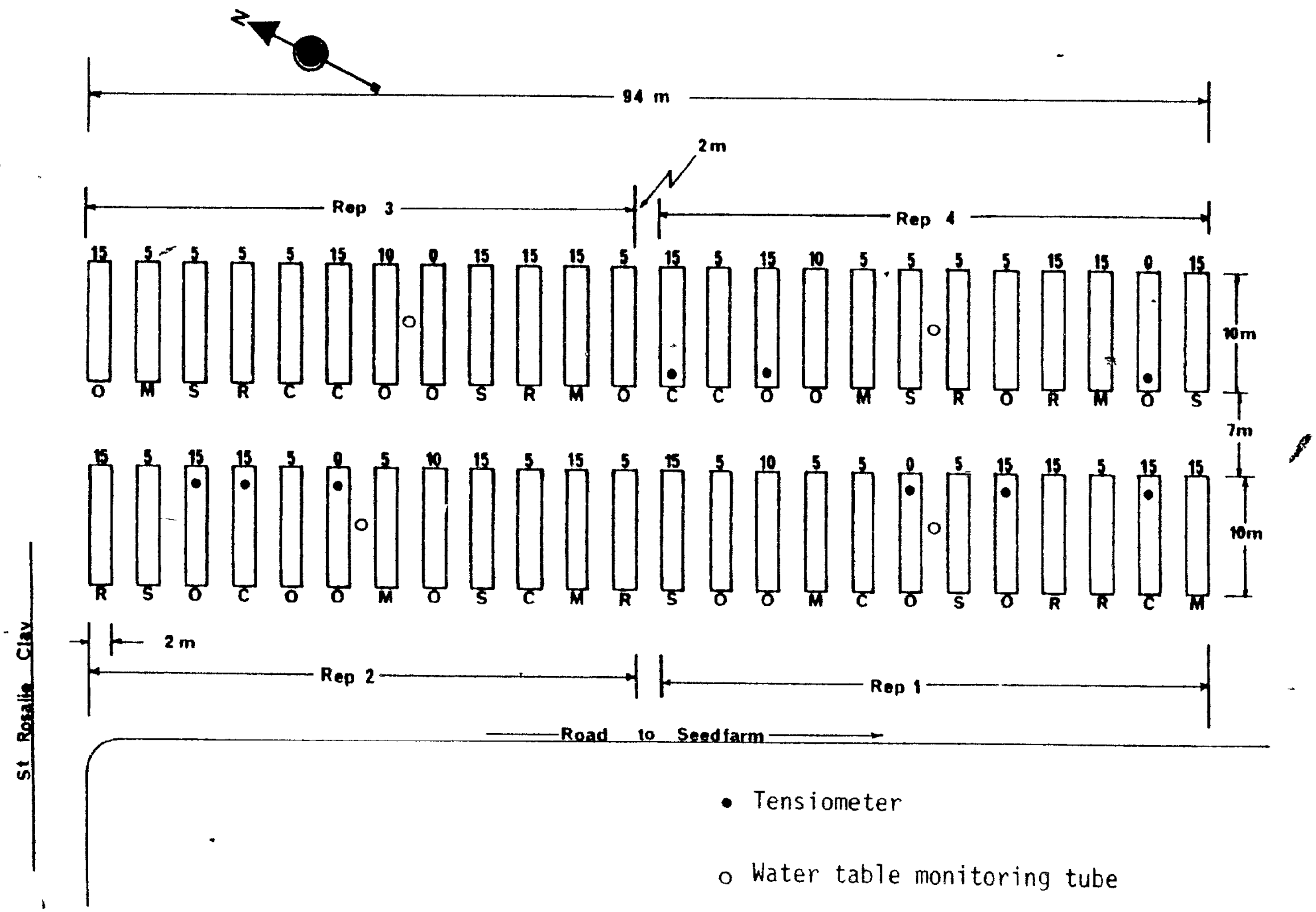


Figure 4.1 Layout of field experiment at Macdonald College seed farm in 1978.

in this experiment (this study consisted of only 8 treatments, see Table 4.2). Right after staking, initial soil conditions were recorded by measuring soil dry density, penetrometer resistance, vane shear resistance and moisture content at various depths. The depths of each soil parameter measurement throughout the growing season are shown in Table 4.3.

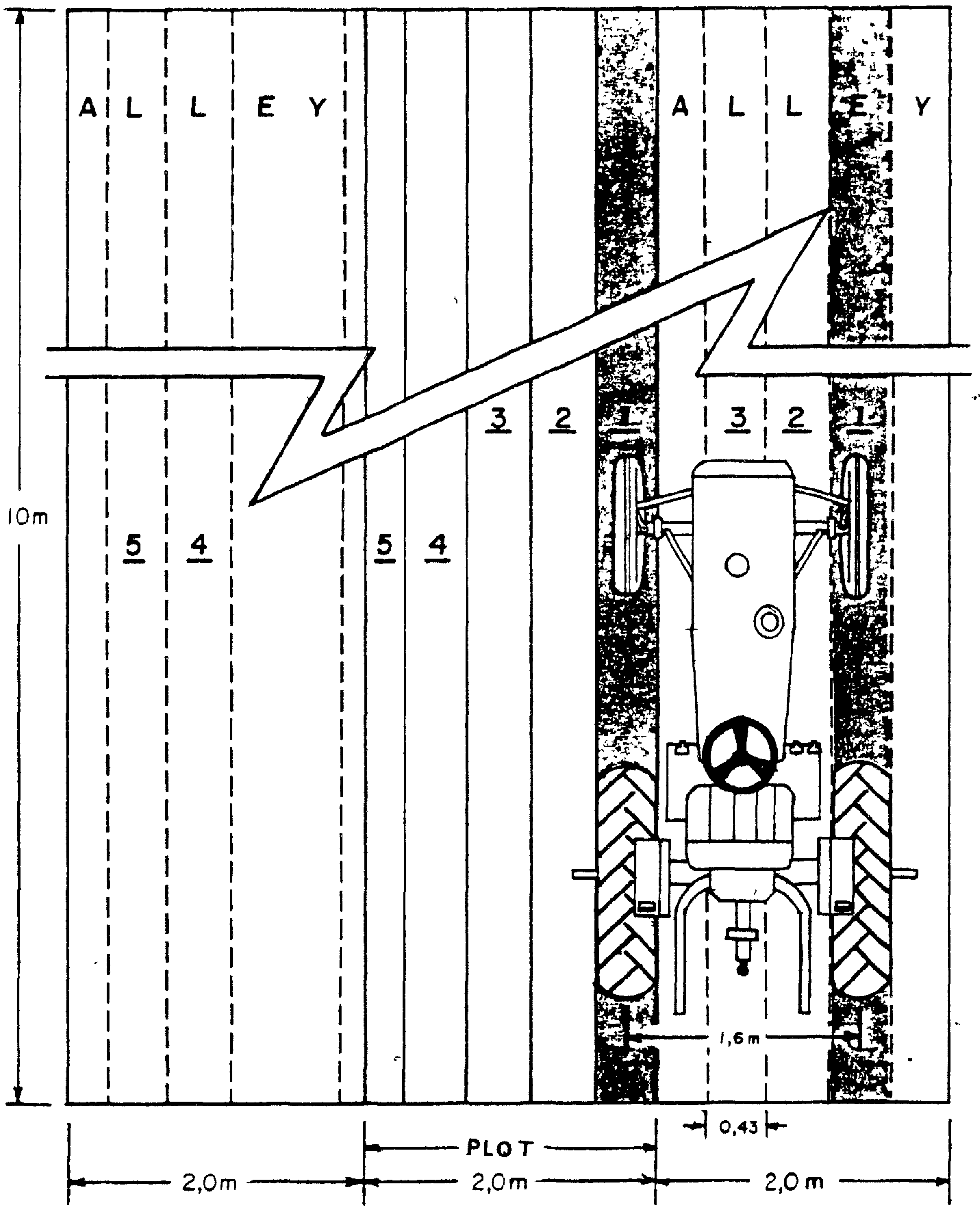
Compaction treatments were carried out with a MF 165D tractor, having an average rear tire contact pressure of 41 kPa, assigned with letter "Y", run on the plot to give 5, 10 and 15 passes. The required amount of passes was given in such a way that wheel traffic should be distributed equally throughout the plot. The path followed by the tractor was considered by its wheel width and tire size, which helped in calculating the dimension of the plot and alley to have had equally distributed paths of wheel over the entire plot (Fig. 4.2). The control plot "000" was used for comparison without any traffic on it. In fact this plot was rototilled during the initial preparations of the field.

After having been compacted with the required number of passes, the change of soil condition due to compaction was observed by measuring soil dry density, penetrometer resistance and moisture content at various depths.

Following the compaction, specific tillage treatments were carried out on the compacted plots with 5 and 15 passes of the tractor, by a moldboard and chisel plow. The moldboard plow "M" and chisel plow "C" were used to till the specific compacted plots. A moldboard plow with two bottoms was used in this study. This plow consisted of two single shares spaced 40cm apart with a plain rolling coulter mounted directly above the share point used to cut the furrow slice. Three passes of the implement were used to cover the entire area of each plot, operating at 20cm depth, followed by one pass of disking. Plates 4.1a and b are photographs of the moldboard plow used, and

TABLE 4.3 - Depths at which soil measurements were made.

SOIL MEASUREMENTS	YEAR 1978	YEAR 1979
	Depth (m)	Depth (m)
Soil density	0,05 0,10 0,15 0,20 0,25	0,05 0,10 0,15 0,20 0,25 0,30
Penetrometer resistance	0,05 0,10 0,15 0,20 0,25	0,05 0,15 0,30
Vane shear resistance	Surface 0,10 0,20	Surface 0,15 0,30
Moisture content	Surface 0,125, 0,25	Surface 0,15 0,30
Soil suction	0,25	-
Volumetric moisture content	0 - 0,15 and 0 - 0,25	-



Fiqure 4.2 The path followed by MF-165D tractor for compacting the soil uniformily.

Plate 4.1a - Photograph showing the two bottom moldboard plow used for tillage treatment

Plate 4.1b - The condition of plot after plowing with moldboard plow

the soil condition after plowing.

The tillage implement used for this study consisted of a 5-shank chisel plow with narrow spear-pointed shovels spaced 30cm apart, operating at 15 to 25cm depths (Plates 4.2a and b). Following the tillage treatment, the change of soil conditions due to tillage was recorded by measuring soil dry density, penetrometer resistance, vane shear resistance and moisture content at various depths.

Buckwheat (variety Tokyo, which is commercially available in the area) was seeded at 5cm depth with an International 510 semi-mounted grain drill at the rate of 56 kg/ha. The seed drill had 13 rows, 17,7cm apart and a fertilizer hopper attached adjacent to the seed hopper. During seeding, two seed openings were closed to give 11 rows approximately equal to the size of the plot. Fertilizer with formula 3-4-12 (N-P-K) was incorporated at the rate of 120 kg/ha during the seeding operation with the same drill (Plate 4.3).

The instruments used for the soil measurements, such as soil density, penetrometer resistance, vane shear resistance and moisture content (gravimetric) were a Troxler gamma-ray density meter, soil test vane shear, standard penetrometer and T-sampler. The Troxler model 3401 density meter (Plate 4.4) was used to measure dry density up to 0,30m depth in the soil from the base of the machine. The procedure and working formula is given in Appendix A.

The penetrometer used is shown in Plate 4.5. It is a hand operated measuring device consisting of a proving ring, dial guage and 30° circular cone with base diameter of 9,4mm and 17,4mm height. The instrument was calibrated against the different forces applied on the proving ring and the corresponding change in dial guage reading was recorded. The applied force divided by the area of the cone base gave the penetration resistance, expressed in MPa.

Plate 4.2a - Photograph showing the chisel plow used for tillage treatments

Plate 4.2b - Photograph showing the condition of plot after chiselling

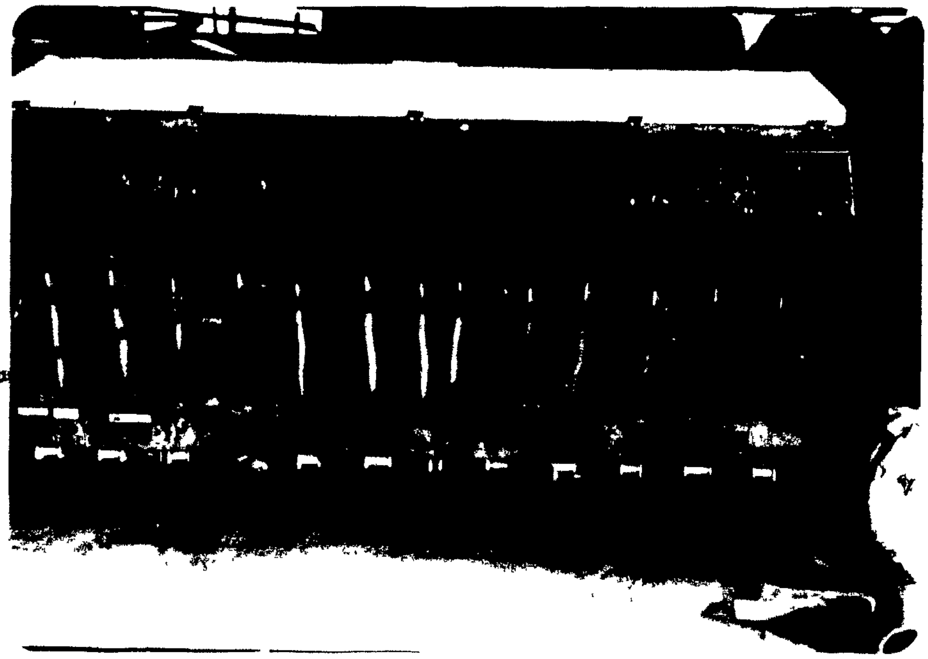


Plate 4 3 - International 510 - semi-mounted graindrill used for seeding

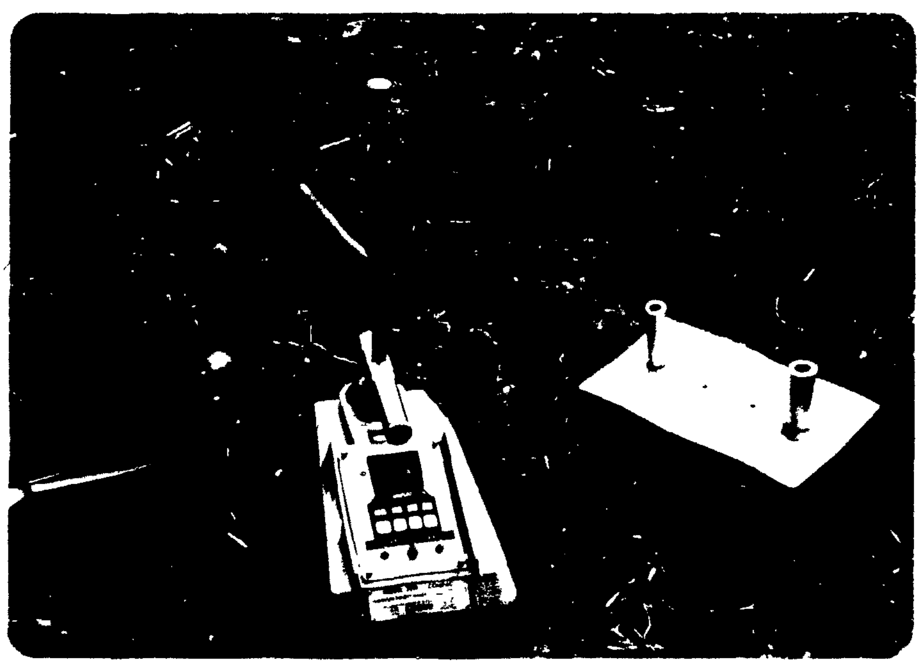


Plate 4 4 - Troxler 3401 gamma ray density meter

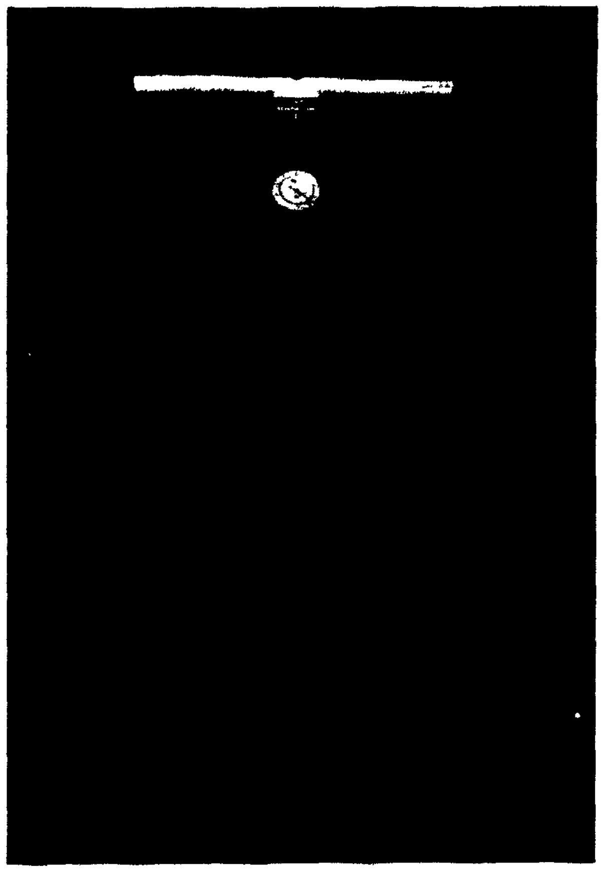


Plate 4.5 - Standard Penetrometer used for measuring penetrometer resistance

The vane shear model PILCON DR 673 used is shown in Plate 4.6 with two different sizes of vanes. The device simply consists of four blades set at right angles on one end of the shaft and the mechanism on the other end by which the torque required to rotate the vane blades in the soil can be measured. Soane (1975) indicated that the vane shear is satisfactory in purely cohesive soils at different depths.

The soil samples for the standard gravimetric moisture content were collected from the field at various depths (Table 4.3) using a T-sampler (Oakfield Apparatus Company, Wisconsin), stored in cans and brought into the laboratory. These samples were weighed and dried at 105^{o}C in an oven for 24 hours and reweighed. The loss in moisture due to drying divided by the weight of the dry soil equals the moisture content on dry basis.

a) Soil Water Measurements

To determine the retention characteristics of the soil, soil water movement and soil water availability, tensiometers were installed in the specific 3 treatments, each replicated 3 times at 25cm depth, and are shown in the layout of Fig. 4.1.

The tensiometers used in the experiment were "jet-fill" tensiometers, with a body made of clear acrylic plastic, a replaceable screw-on one bar porous ceramic tip and a vacuum gauge with a 5cm dial gauge, graduated from 0-100 centibars. Before installation in the field, the tensiometers were calibrated in centimeters of water with a vacuum pump and a mercury manometer in the laboratory.

The soil around each installed tensiometer was covered with a black polyethylene sheet, which covered one by one meter of area after heavy rainfall. The black polyethylene sheet was used to prevent vegetation growth and evaporation (Hillel <u>et al.</u>, 1972). Some soil was placed on top of the black

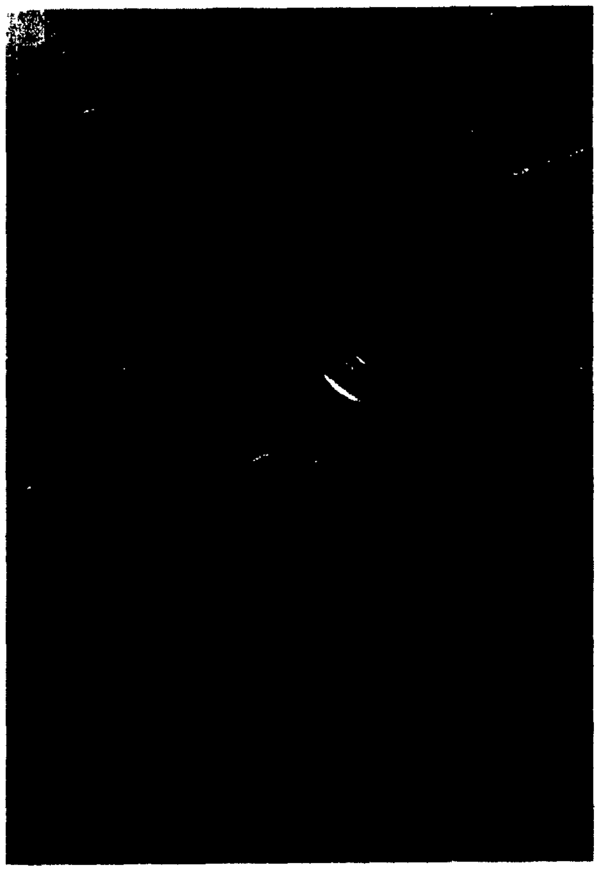


Plate 4.6 - Soil test vane shear used for measuring vane shear resistance

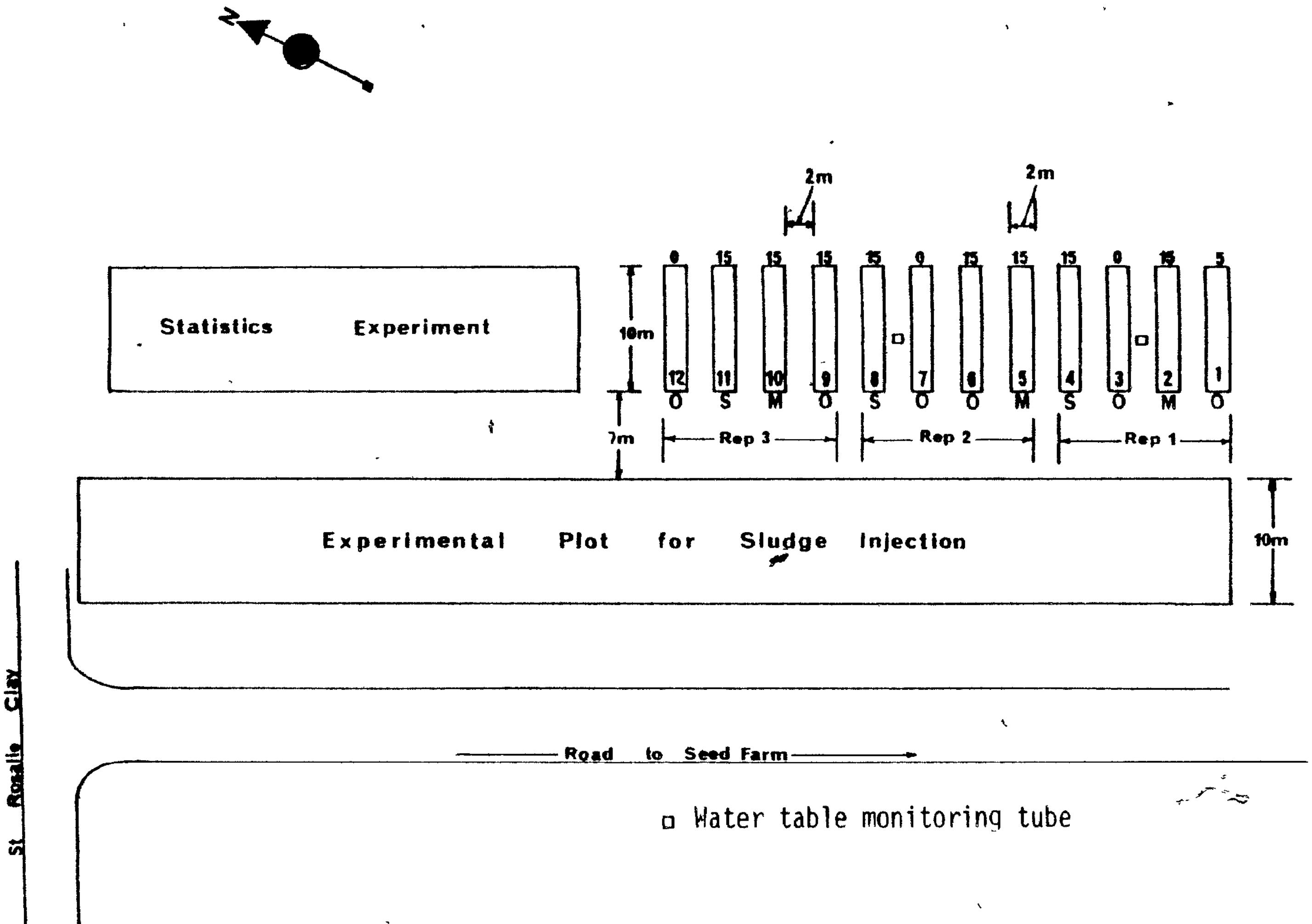


Figure 4.3 Layout of experimental field at Macdonald College seed farm in 1979

polyethylene sheet in order to avoid high temperatures from sun rays.

The soil suction measurements were done for one infiltration cycle between one and twenty-six days after recession of surface water.

Soil water content on a volume basis was calculated by standard gravimetric moisture content (dry basis) at 0,05m, 0,15m and 0,25m depth and the corresponding dry density measurement was carried out by using the Troxler model 3401 density meter.

b) Plant Measurements

Plant growth measurements were recorded at regular intervals throughout the growing season in the 5 rows in the centre out of the 11 rows. Six rows, three on each side,were eliminated in order to avoid boundary effects.

To begin with, the number of days required for plant emergence was recorded for each plot when 80 percent of the plants in the plot had emerged. These observations were taken by two persons separately in order to have an exact value.

Plant height was measured throughout the growing season. Five plants from each row were randomly selected for the measurement of plant height. The measurement of plant height was considered from the ground to the top of the plant.

During the growing season, the crop was attacked by aphids. Therefore, the insecticide, melathine, at the rate of 2,8 ℓ per hectare per 35 litres of water, was applied with a sprayer.

When the crop was just at its maturing stage, the frost started and killed the premature seeds. The reason for killed seeds at the immature stage may be due to a delayed emergence attributed to the lack of moisture in contact with the seed in the top 5cm of surface soil during the emergence period. Therefore, the dry matter yield was the only substitute to consider for comparing the treatment effects. At maturity, the five middle rows, leaving the one meter on both sides due to border effects, were harvested by hand. After all the plots were harvested, samples of 500 grams were dried for 3 days at 75°C in a forced air dryer and the dry weights of the samples were known on a hectare basis for each treatment. The working formula is given in Appendix B.

c) Dry Weight Root Measurement

Root growth is usually an indicator of compaction, therefore, dry weights of the roots also were recorded. The technique used to obtain roots from the soil was to dig out a one meter diameter monolith about 0,6m in length in each plot of only one block with a shovel. This monolith was then broken in such a way that the plant roots would not receive any injury. These roots with soil lumps were then brought into the laboratory and six root samples from each plot were washed carefully, dried at 75°C and weighed.

4-2 Experiment 1979

In the summer of 1979 the study was conducted on the same soil and the same crop. The design considered for the layout was the same as that in 1978. Four treatments with three replications each were used in the layout (Fig. 4.3) (this study consisted of only 3 treatments, see Table 4.2). The reason for 4 treatments with 3 replications was due to the small space provided this year; part of field was being engaged with other experiments as shown in Fig. 4.3.

The field operations were carried out according to the schedule shown in Table 4.1.

The compaction treatments were carried out with a MF 165D tractor, having a contact pressure of 41 kPa. The tractor was run over the plot 15 times on each track over the entire plot. This way all the 12 plots were compacted.

Plots under tillage treatments were plowed with specific implements, following compaction. Three passes of the moldboard plow (M) at 20 cm depth were followed by a disk.

Soil measurements conducted in 1979 were extended to 0,30m depth in order to observe the effects of treatments at greater depths (Table 4.3).

Plant growth measurements consisted of plant emergence, plant height and yield. Plant heights were recorded during the entire growing season as in 1978.

At maturation, the five middle rows of each plot were harvested in the same way as in 1978. The harvested plants were put in bags and labeled with the particular plot number. These bags were then kept in the air dryer for one week to get ready for the threshing machine. The grains obtained were weighed and thus the yield in grain acquired on a hectare basis for each treatment was obtained.

4-3 <u>Laboratory Measurements</u>

Laboratory measurements were done on the soil samples brought from the field to conduct the following tests.

a) Grain size analysis

b) Compaction test

c) Liquid limit and plastic limit tests

a) Grain Size Analysis

Soil samples were collected randomly from the entire experimental field to conduct the experiment by the hydrometer method for classifying the type of soil, following the method of Lambe (1951). The method employs the calculations of the "effective diameter" and "percentage finer" by the equations derived from Stoke's equation for the velocity of freely falling spheres in water.

b) Compaction Test

This test is also known as the standard Proctor compaction test and is discussed by Lambe (1951). The purpose of a compaction test is to determine the degree of denseness at various moisture contents after a fixed amount of compactive energy has been applied. To accomplish this purpose, one would determine the optimum moisture content at which high density occurs in the field.

c) Liquid Limit and Plastic Limit

These tests are also called Atterberg limit tests and are described by Lambe (1951). The liquid limit test is defined as "the water content at which the soil has such a small shear strength that it flows to close a groove of standard width when jarred in a specific manner". The plastic limit is the "water content at which the soil begins to crumble when rolled into threads of specified size". The field soil samples were used to determine the moisture content at which the soil behaved in a manner as described in the definitions of liquid limit and plastic limit.

4-4 Rainfall and Water Table Measurements

Perforated plastic tubes surrounded by a filter envelope were installed 1,8m deep into the soil, leaving 0,2m as an allowance above the surface of the ground, in order to avoid trash or other foreign material, over the entire field (Figs. 4.1 and 4.3).

Water table measurements were recorded periodically to observe the fluctuations of the water table throughout the growing seasons of 1978 and 1979. A graduated hollow aluminium pipe about 3m long, having one end attached to a rubber hose was used to monitor the water table. The technique consisted of lowering the aluminium pipe into the perforated plastic tube very slowly whilst continuously blowing through the rubber hose until a bubbling sound was heard (Plate 4.7). This process was repeated three times in order to obtain the exact height of the water table. A correction was made to account for the height of the perforated pipe above the ground surface. In addition, rainfall data was also obtained for the 1978 and 1979 seasons from the Macdonald College weather station, located near the experimental field.

Plate 4.7 - Water table monitoring tube

CHAPTER V

RESULTS

5-1 General

Soil compaction affects the soil profile which can be hazardous for plant growth as it is observed from the review of literature. To provide a healthy environment for plant growth, the only way is to till the soil with an appropriate tool in order to improve the seed bed for proper development of the plant roots in the soil profile. The decision of implement selection requires the knowledge of soil physical properties and geometry of the tool. The complexity of this problem is large and has yet to be solved rationally.

However, to begin to achieve this goal, the study was conducted to observe the effects of two tillage tools on compacted soil. The soil profile up to 0,30m was considered with reference to the soil physical properties of dry bulk density, penetrometer resistance, vane shear resistance, air-filled porosity and soil water movement.

The measurements of the above properties along with crop growth were recorded in the field throughout the growing seasons of 1978 and 1979. The data thus collected were analysed and the results obtained are presented as follows

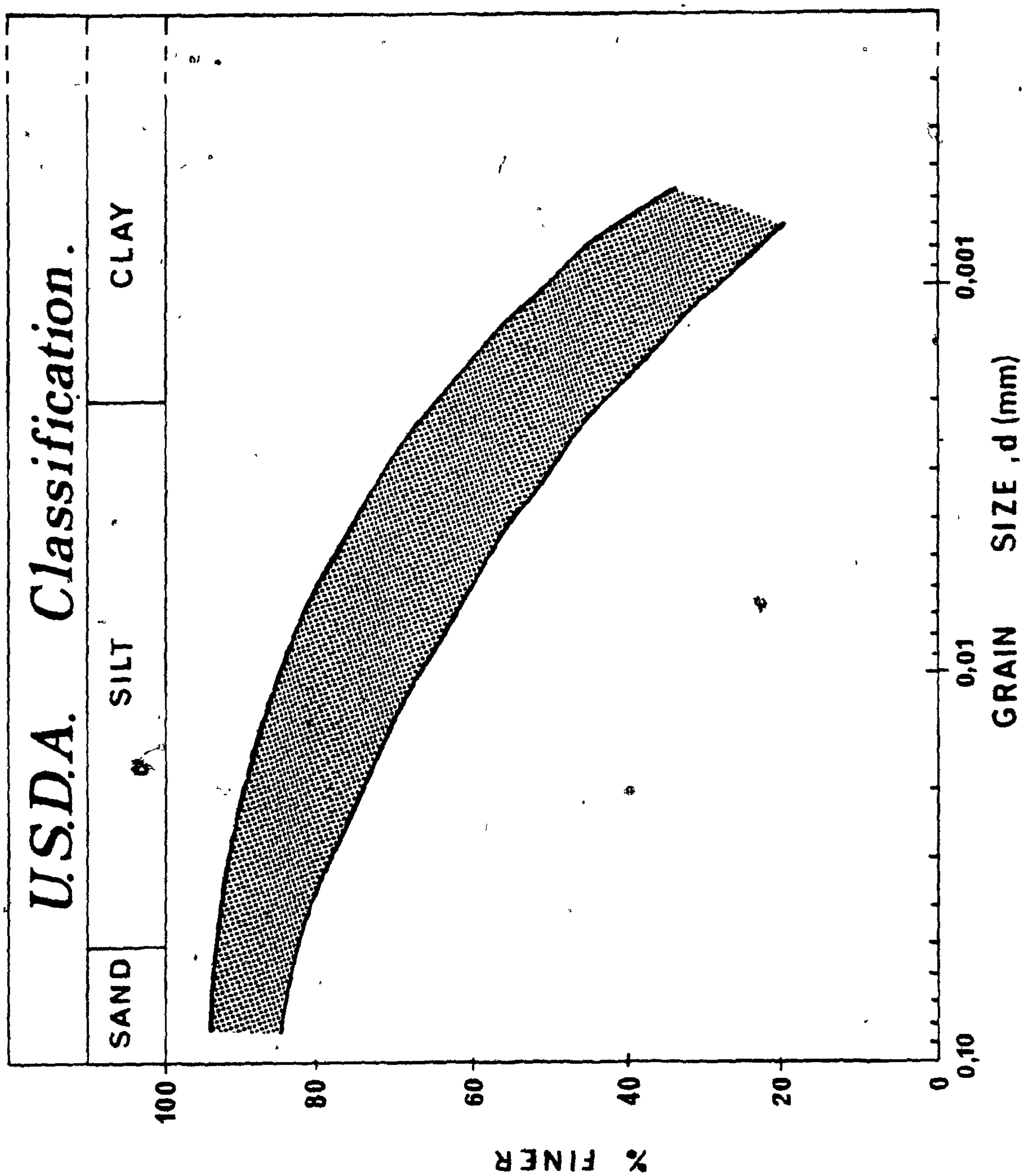
5-2 Laboratory Tests

Several tests were conducted on soil samples taken from the field and the results obtained are as follows:

a) Grain Size Analysis

The results of grain size analysis in Fig. 5.1 show that clay size particles comprise from 42 to 67% of the soil by weight, and the soil

Figure 5.1 An envelope showing the grain size distribution of experimental soil.



U.S.D.A. Classification.
SAND
SILT
CLAY
100
80
60
40
20
0
% FINER
0,10
0,01
0,001
GRAIN SIZE ,d (mm)

is uniformily classified as clay.

b) Plastic Limit and Liquid Limit

The liquid limit test results are shown in Fig. 5.2. It is seen for this clay soil that the liquid limit ranged from 55 to 60%, while the plastic limit was in the range of 41 to 42%. The average moisture percentages for the plastic limit and liquid limit were 42,1 and 57,6 respectively.

c) Compaction Test

The results of Proctor compaction test on field samples (Fig. 5.3) show the optimum moisture content is around 27%. The calculated 80% saturation curve indicates that the soil can be compacted to an air voids content of 10% or less when the moisture content is greater than 35%.

5-3 Dry Bulk Density

To observe the effects of various compaction and tillage treatments on the properties of the soil profile, the dry bulk density was used as one of the soil physical properties. In order to determine the compaction effect, it is necessary to observe the initial condition of the soil profile, so that the change in state of compaction could be detected throughout the soil profile due to induced artificial treatments.

Initial dry bulk densities at various depths were observed in the field for all treatments after uniform rototilling, but prior to any passage of wheel or subsequent tillage tool. These initial conditions of the soil are presented in Fig. 5.4 and Fig. 5.5 as the 000 density curves following initial rototilling. The results of 1978 (Fig. 5.4) and 1979 (Fig. 5.5) show the final dry bulk density after compaction (5, 10 and 15YO) and the increase in dry bulk density for these compacted no-tillage treatments. The increase

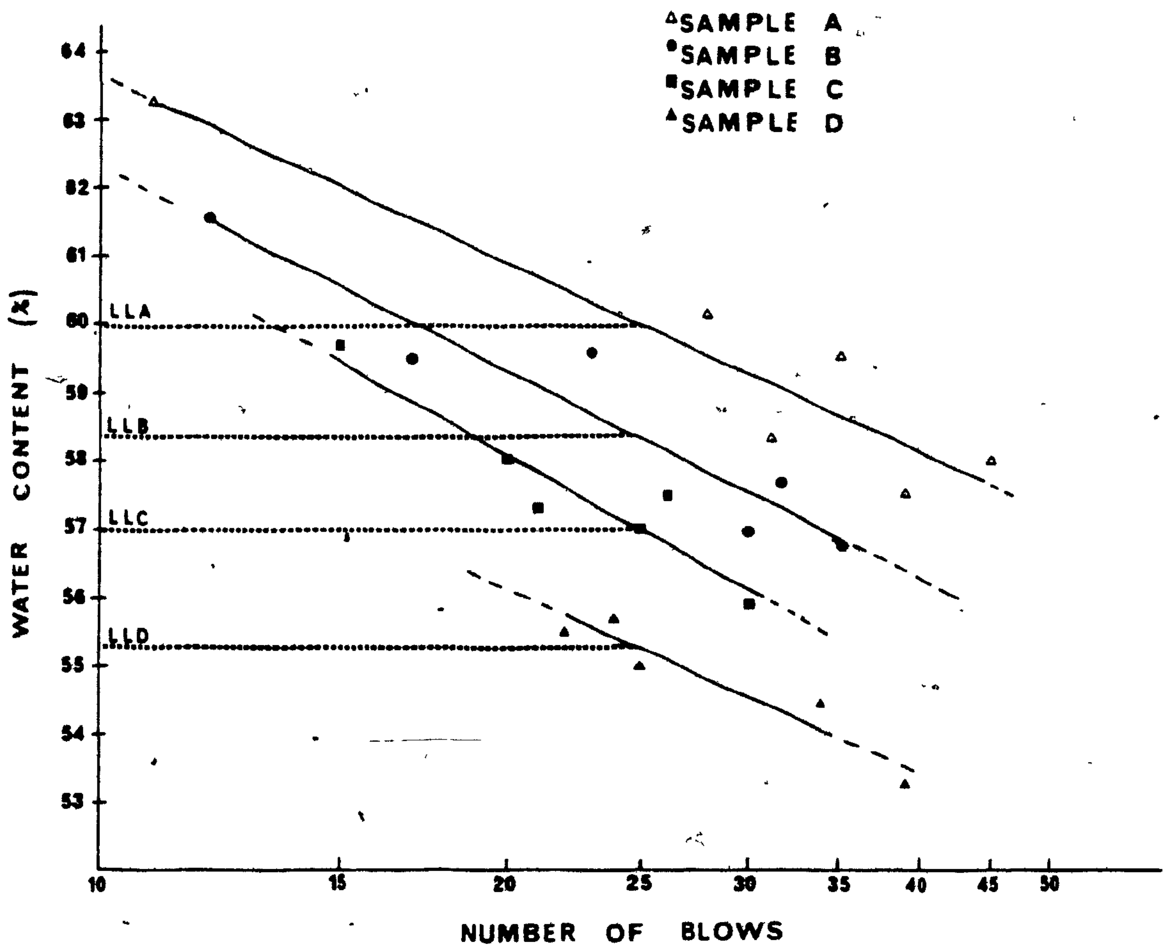


Figure 5.2 Observed critical moistures for liquid limit (LL) test.

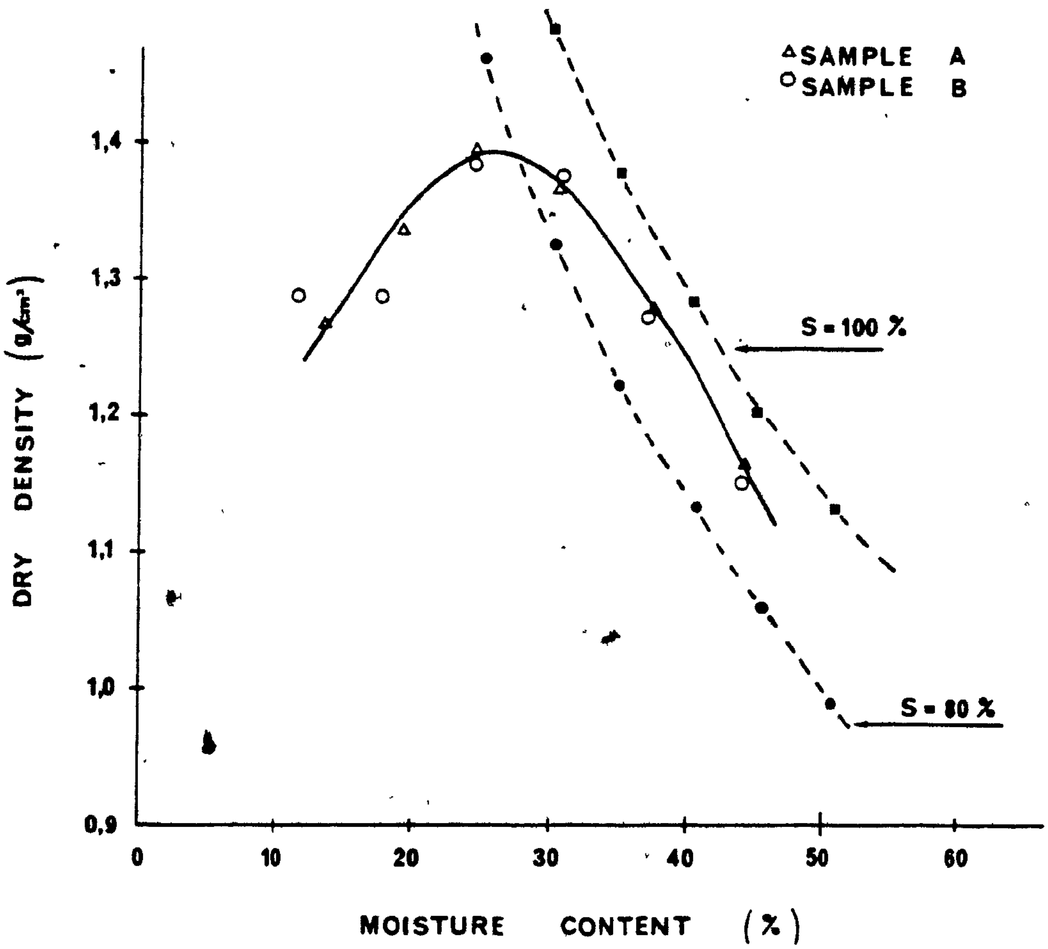


Figure 5.3 Observed compaction curve of the clay soil by the standard Proctor test.

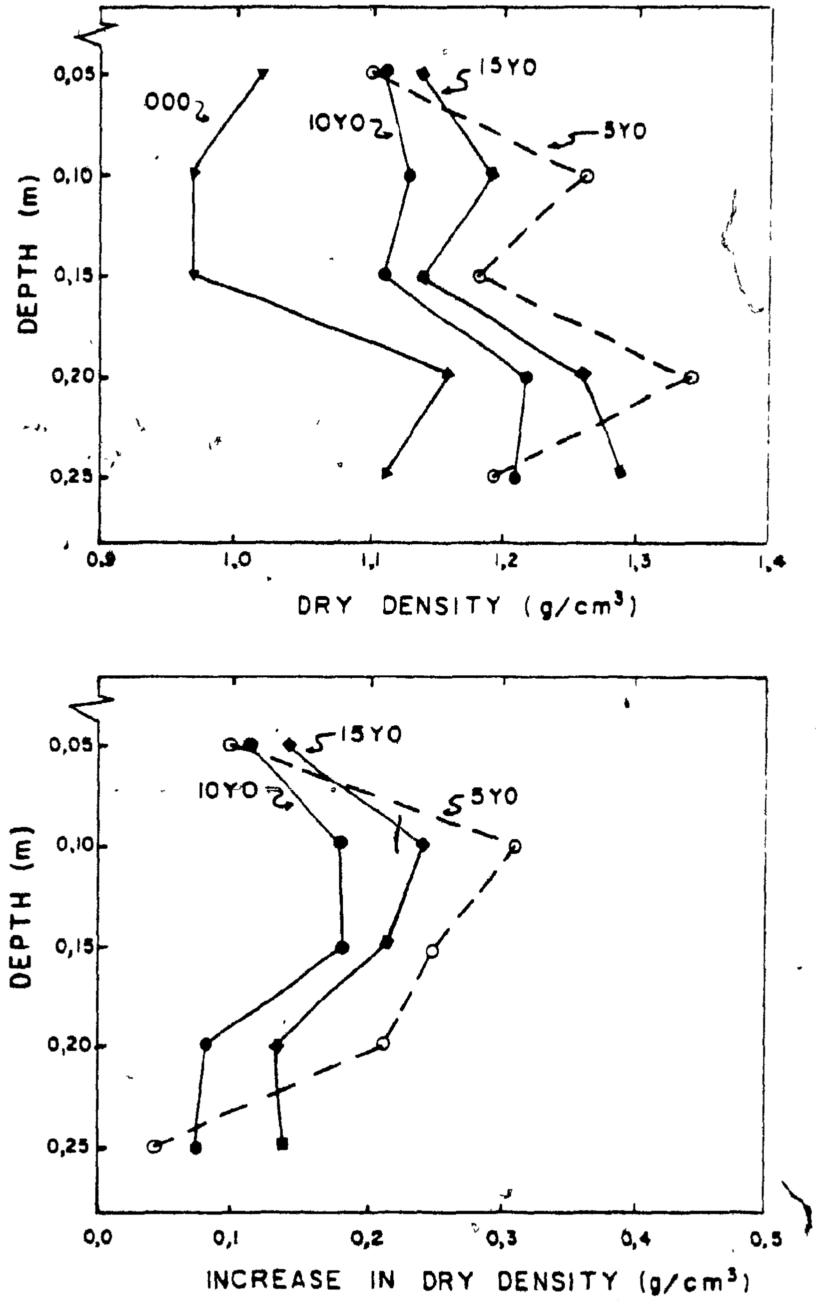


Figure 5.4 Observed changes in dry density profiles due to traffic treatments.

Note: Dry density in g/cm^3 is the same as in Mg/m^3.

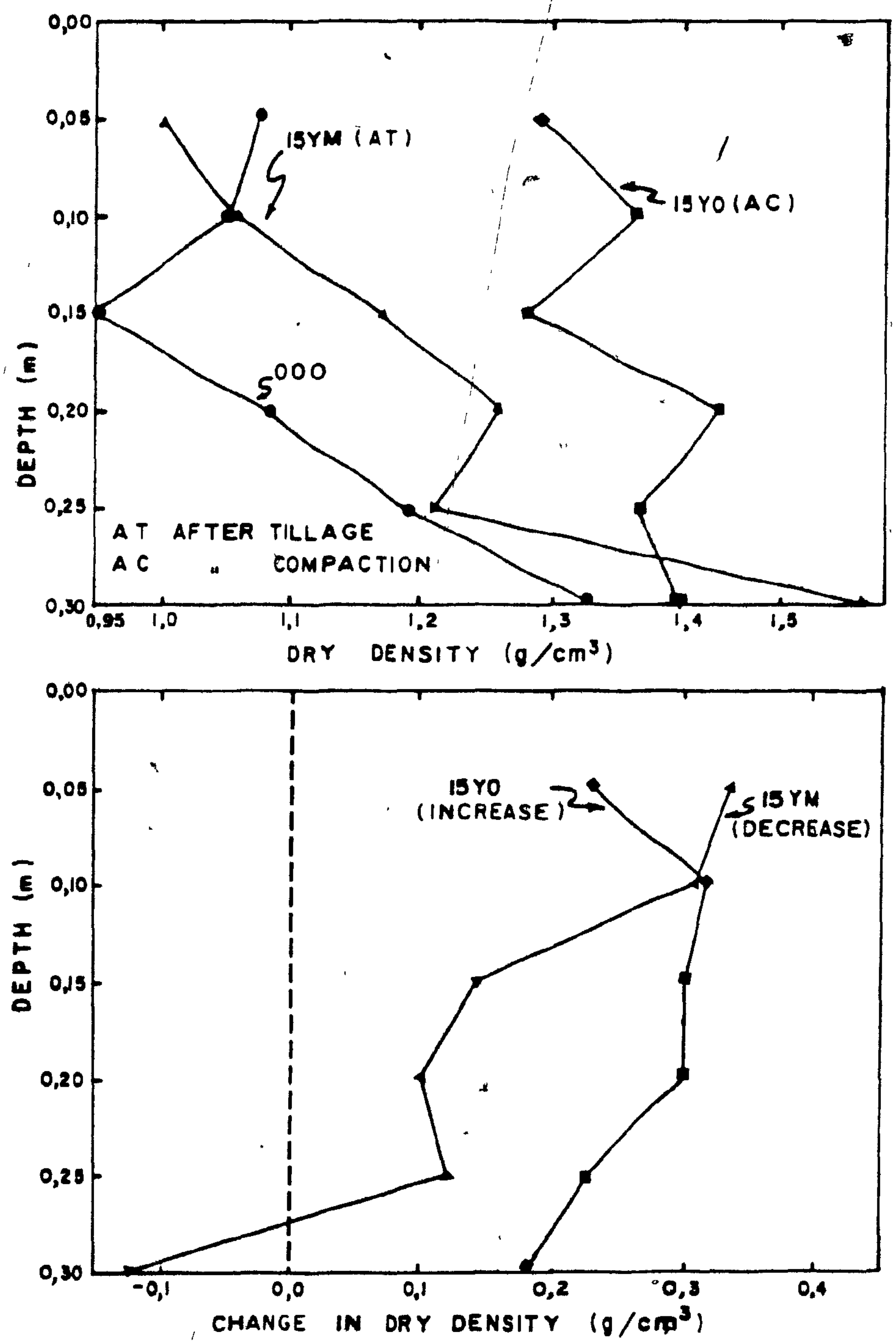


Figure 5.5 Observed changes in dry density profiles due to tillage and traffic treatments.

Note: The compacted density of the 15YM treatment prior to plowing was not exactly the same as that in the 15YO treatment. (See Appendix C).

in dry bulk density values were calculated from the initial state of corresponding treatments before compaction (Appendix C, Table C.6 - C.7). It can be seen in Fig. 5.4 that the dry bulk density increased throughout the soil profile for compacted-no tillage treatments, as compared to the no compaction treatment (000). The maximum increase in dry bulk density was found at 0,10m depth. As the depth increased, the compaction had less effect. The figure also illustrates that the lightly compacted (5Y0) curve shows higher dry bulk density than the moderately or heavily compacted curves (10 and 15Y0). It is not known why 5 passes caused more compaction than 10 and 15 passes, otherwise trend of increase in dry bulk density was found as the number of passes of the tractor increased. These results are in agreement with Raghavan et al., (1977b), who observed that repeated passes of the tractor increased the dry bulk density of clay soil. The results of an analysis of variance (Table D.1, Appendix D) show that the treatments are significantly different up to 0,15m depth. When mean density values of all compacted treatments were compared with the means of no-tillage treatment, it was found that the severely and moderately compacted-no tillage treatments (10 and 15Y0) had significantly higher values of dry bulk density up to 0,10m depth. Duncan's new multiple range test was performed at the 10 percent probability level (Table 5.1).

In 1979, Fig. 5.5 shows the increase in dry bulk density for only the severely compacted-no tillage treatment (15Y0). In this year a maximum increase in dry bulk density of 0,32 g/cm^3 was found at 0,10m depth. The results of Duncan's new multiple range test at the 10 percent probability level show that all mean values of the severely compacted-no tillage treatment (15Y0) were significantly higher compared to the no-tillage treatment up to 0,20m depth (Table 5.2). The results of analysis of variance are shown in Table D.2,

TABLE 5.1 - Average values for dry density in different depth ranges for the various tillage and traffic treatments.

YEAR 1978

TREATMENT	MEAN VALUES FOR DRY DENSITY (g/cm³)		
	0,05 (m)	0,10 (m)	0,15 (m)
000	1,018 cd	0,966 d	0,966 b
5YO	1,100 abc	1,260 a	1,176 a
5YM	1,022 bcd	1,134 abc	1,050 ab
5YC	0,990 d	1,012 cd	1,043 ab
10YO	1,111 ab	1,134 abc	1,111 ab
15YO	1,143 a	1,185 ab	1,138 ab
15YM	1,069 abcd	0,994 cd	1,042 ab
15YC	1,039 bcd	1,155 abc	1,112 ab
	0,20 (m)	0,25 (m)	
000	1,155 bc	1,105 a	
5YO	1,344 ab	1,185 a	
5YM	1,243 abc	1,097 a	
5YC	1,229 abc	1,166 a	
10YO	1,215 abc	1,212 a	
15YO	1,263 abc	1,285 a	
15YM	1,080 c	1,173 a	
15YC	1,249 abc	1,312 a	

a - d Letters denote significance at 10 percent level using Duncan's new multiple range test. Means with the same letter are not significantly different.

TABLE 5.2 - Average values for dry density in different depth ranges for the various tillage and traffic treatments.

YEAR 1979

TREATMENT	MEAN VALUES FOR DRY DENSITY (g/cm^3)		
	0,05 (m)	0,10 (m)	0,15 (m)
000	1,074 a	1,053 a	0,946 a
15YO	1,292 b	1,367 b	1,276 b
15YM	1,001 a	1,056 a	1,174 b
TREATMENT	MEAN VALUES FOR DRY DENSITY (g/cm^3)		
	0,20 (m)	0,25 (m)	0,30 (m)
000	1,082 a	1,192 a	1,328 a
15YO	1,427 b	1,371 a	1,398 a
15YM	1,260 ab	1,214 a	1,548 b

a - b Letters denote significance at 10 percent level using Duncan's new multiple range test. Means with the same letter are not significantly different.

Appendix D.

The comparison of dry bulk density values between 1978 and 1979 for the severely compacted-no tillage treatment (15Y0) needs further discussion. The increase in dry bulk density for the severely compacted-no tillage treatment (15Y0) in 1979 was more throughout the soil profile than that in 1978. This could probably be attributed to a difference in soil moisture content at the time of compaction treatments. The average soil moisture content in 1979 was 20% below the optimum range most favourable for compaction, whereas in 1978, the soil moisture content was 31% above the optimum range at the time of compaction treatments (Fig.5.6). The optimum moisture content for maximum dry bulk density was found by the Proctor test to be 27% (Fig. 5.2).

The effect of tillage method on ameliorating soil compaction can be seen in Fig. 5.7 and Fig. 5.5. The results of 1978 are presented in Fig.5.7, which shows that the moldboard and chisel plows have markedly decreased dry bulk density from the compacted state (Appendix C, Table C.7 - C.8) by up to 0,18 g/cm^3 to a 0,25m depth. The analysis of variance for dry bulk density due to tillage treatment is shown in Table D.3, Appendix D. Duncan's new multiple range test is shown in Table 5.1 and represents the mean values of each treatment. The moldboard plow (15YM) has significantly lowered dry bulk density values at 0,10m depth, whereas with the chisel plow, soil density (15YC) was significantly different at 0,05m depth when compared with the compacted-no tillage treatment (15Y0). When both chisel and moldboard plows density results were compared, no significant difference was found for subsoil layers at the 10% probability level.

Fig. 5.5 illustrates the results of 1979. The moldboard plow produced a lowering of dry bulk density values from the compacted state (Appendix C, Table C.11) up to 0,25m depth, while at a 0,30m depth it created higher dry bulk density values. This is an indication of the formation of a plow pan at the lower depth. The plow pan formed by the moldboard plow below the operating

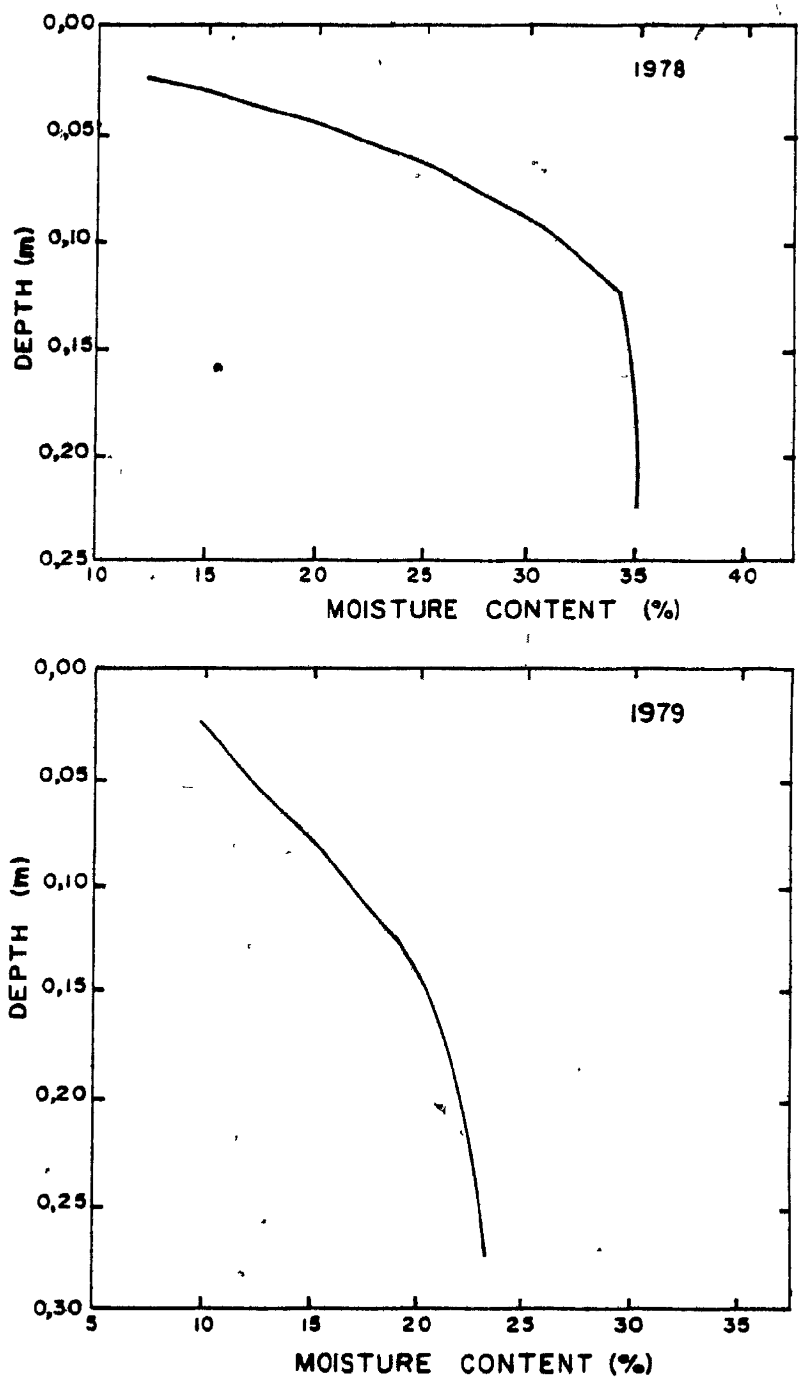


Figure 5.6 Initial soil moisture status of the soil.

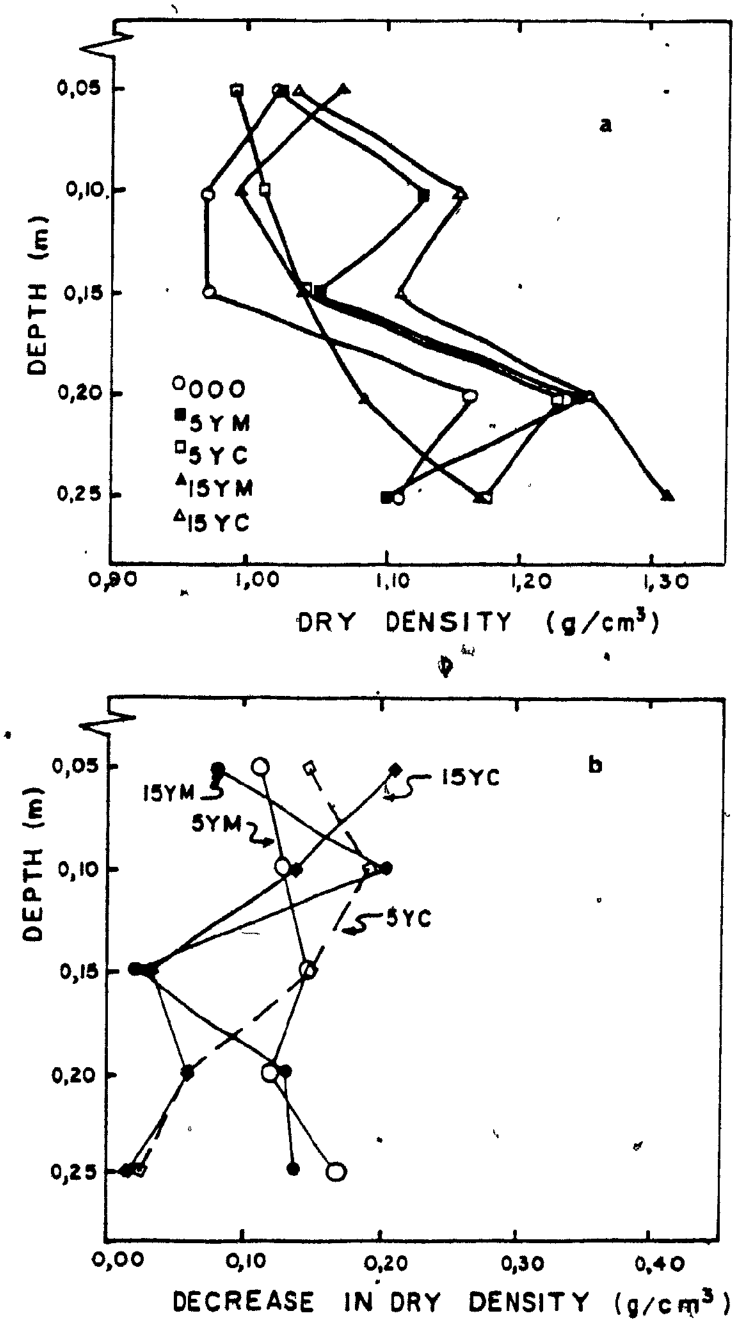


Figure 5.7 Observed changes in dry density profiles due to tillage treatments.

Note: The compacted density of the 15YM, 15YC, 5YM and 5YC treatments prior to plowing was not exactly the same as that in the 15YO and 5YO treatments. (See Appendix C).

depth has been reported, for example by Taylor et al., (1978), in clay soils. The statistical analysis is given in Table D. 4, Appendix D, which shows significant differences in dry bulk density values at 0,05, 0,10 and 0,30m depths. Duncan's new multiple range test for these results is given in Table 5.2. When mean dry density values of the moldboard treatment (15YM) were compared with those of the compacted-no tillage treatment (15YO), it was found that the 15YM treatment had a significantly lower dry bulk density up to a 0,10m depth, and significantly higher values at a 0,30m depth. These results are in agreement with those of Hanna and Masry (1978), who also found a significant increase in compaction under the plow sole when compared with no-tillage plots.

5-4 Penetrometer Resistance

The penetrometer resistance profiles for different compaction treatments in 1978 have been averaged and the results are shown in Fig. 5.8a and b (average of 12 observations). The Fig. 5.8a shows the final penetrometer resistance for all compacted-no tillage treatments (5, 10 and 15YO), whereas Fig. 5.8b demonstrates the increase in penetrometer resistance from initial status of soil (Appendix C, Table C.15 - C.16). All compacted-no tillage treatments had dramatically increased penetrometer resistance.

The most increase was found at a 0,05m depth. The maximum increase in penetrometer resistance of 4,60 MPa was found in severely compacted-no tillage plots (15YO). This increase was more pronounced with the repeated passes of the tractor. The other depths were found variable. This could be associated with moisture content affecting the penetrometer readings. Results of an analysis of variance (Table D.5, Appendix D) show that the treatments are highly significant at 0,05, 0,10 and 0,20m depths. Duncan's new multiple range test done on the data (Table 5.3) shows that the severely compacted-no tillage treatment (15YO) had higher penetrometer resistance values at all depths compared to the no-tillage or no compaction

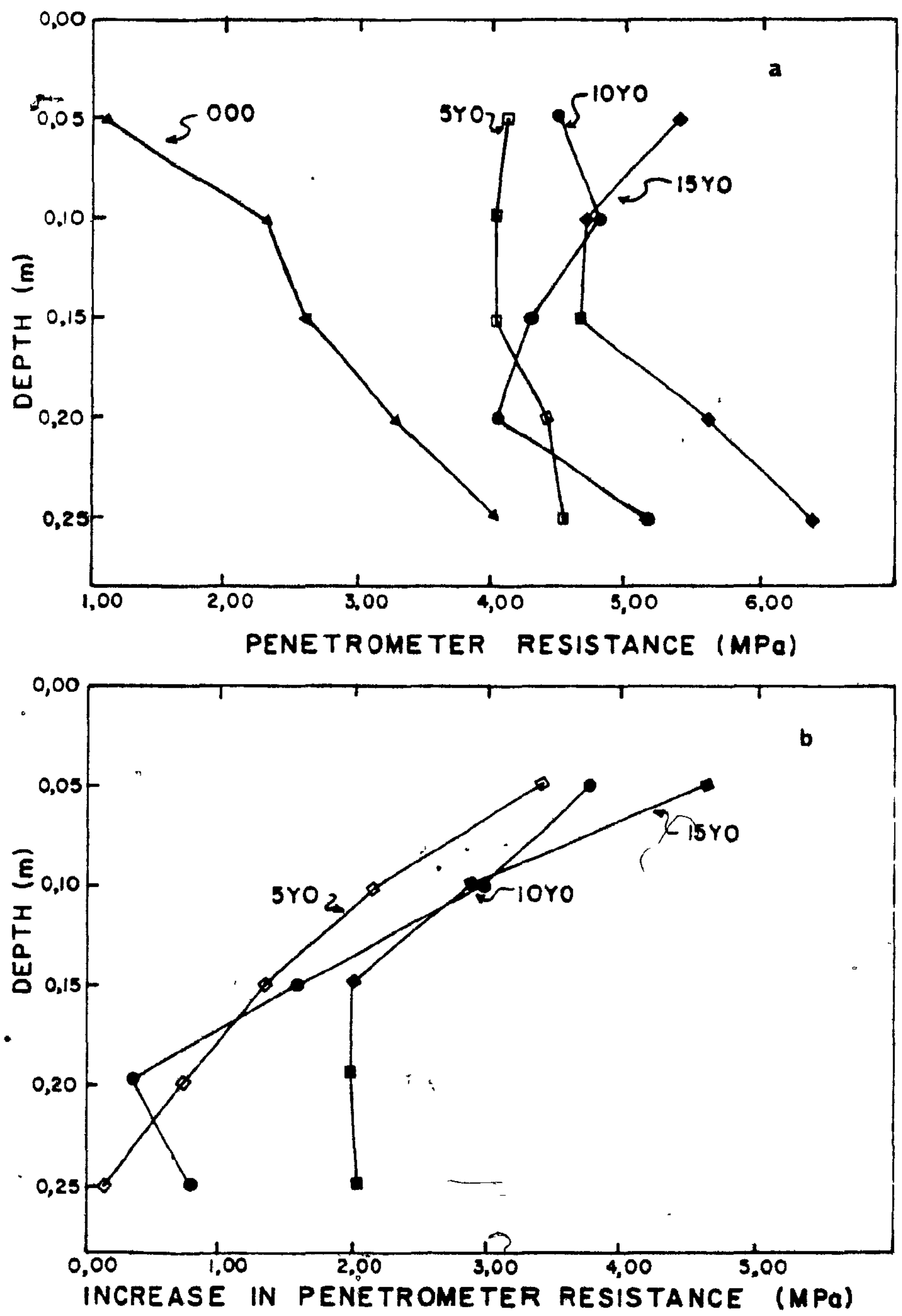


Figure 5.8 Observed changes in penetrometer resistance profiles due to traffic treatments.

TABLE 5.3 - Average values for penetrometer resistance in different depth ranges for the various tillage and traffic treatments.

YEAR 1978

TREATMENT	MEAN VALUES FOR PENETROMETER RESISTANCE (MPa)		
	0,05 (m)	0,10 (m)	0,15 (m)
000	1,070 e	2,323 c	2,626 e
5YO	4,095 abc	4,033 ab	4,025 abc
5YM	2,613 cde	3,220 bc	3,848 abcd
5YC	2,615 cde	2,628 c	2,770 de
10YO	4,478 ab	4,801 a	4,278 ab
15YO	5,360 a	4,678 a	4,641 a
15YM	2,075 de	3,073 c	3,791 abcd
15YC	2,681 cde	2,855 c	3,730 abcde

TREATMENT	0,20 (m)	0,25 (m)
000	3,278 c	4,048 de
5YO	4,403 abc	4,531 cde
5YM	4,975 ab	4,975 bcd
5YC	4,145 bc	5,553 abc
10YO	4,045 bc	5,180 bc
15YO	5,638 a	6,400 a
15YM	4,992 ab	5,490 abc
15YC	3,893 bc	5,408 abc

a - e Letters denote significance at 1 percent level using Duncan's new multiple range test. Means with the same letter are not significantly different.

treatment (000) at a 1 percent probability level.

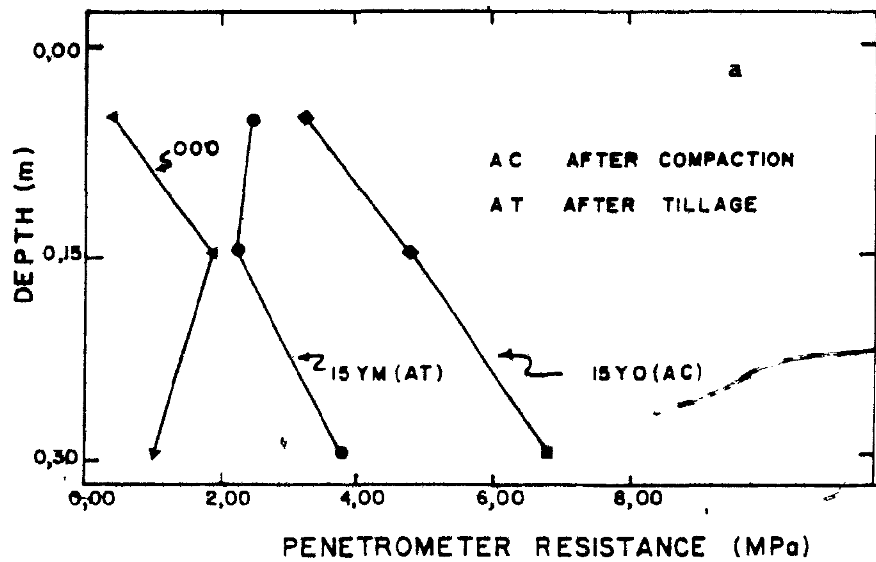
The moderately compacted-no tillage (10Y0) and lightly compacted (5Y0) results were not significantly different at 0,20m and 0,25m depths. When all compacted-no tillage treatments (5, 10 and 15Y0) were compared with each other at various depths, no significant difference was found at any depth except that the severely compacted-no tillage treatment (15Y0) plots had significantly higher values than lightly compacted-no tillage plots (5Y0) at a 0,25m depth.

The results of penetrometer resistance for compacted-no tillage treatments in 1979 are plotted in Fig. 5.9a and b. It can be seen that the most increase in penetrometer resistance from initial status of the soil (Appendix C. Table C.18) was found at lower depths. This increase was more erratic at greater depths. The maximum penetrometer resistance of 5,40 MPa was found at 0,30m depth. This increase was probably due to pushing of the probe continuously from 0,15m depth to a 0,30m depth which raised the readings by continuous friction of the soil particles.

The statistical analysis in Table D.6, Appendix D shows that the treatments are significantly different at all depths except at a 0,15m depth. The mean values of penetrometer resistance in severely compacted-no tillage treatment (15Y0) were significantly higher at 0,05 and 0,30m depths compared to the no-tillage treatment (000) at a 1 percent probability level.

In the 1978 summer, the increase in penetrometer resistance at a 0,05m depth was 150 percent more than in 1979. This could be possibly due to the reorientation of soil particles which might have been changed due to cultivation in the 1978 summer, or the different degrees of compaction because of soil moisture content inequalities between years.

The effect of tillage on penetrometer resistance is demonstrated in Fig. 5.10a and b for the 1978 summer. The Fig. 5.10a presents the final



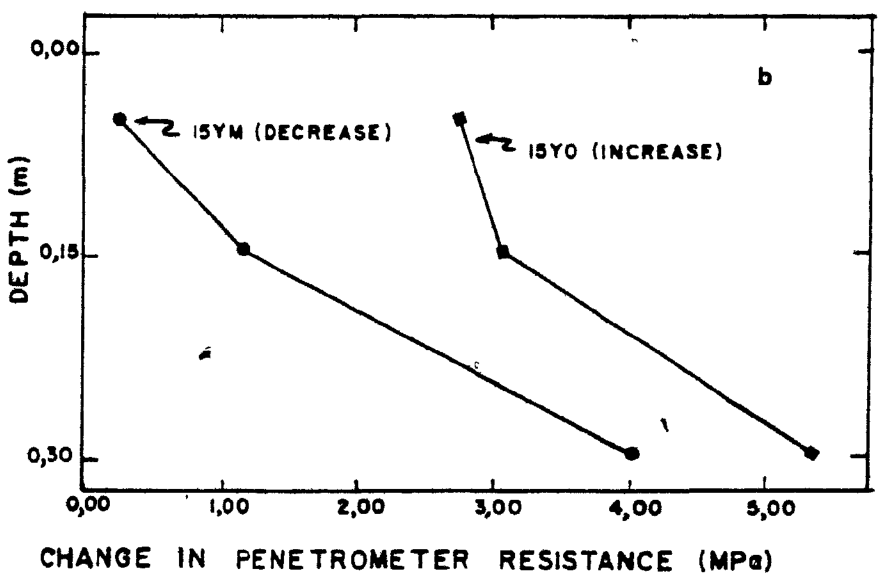


Figure 5.9 Observed changes in penetrometer resistance profiles due to traffic and tillage treatments.

Note: The compacted penetrometer resistance of the 15YM treatment prior to plowing was not exactly the same as that in the 15YO treatment. (See Appendix C).

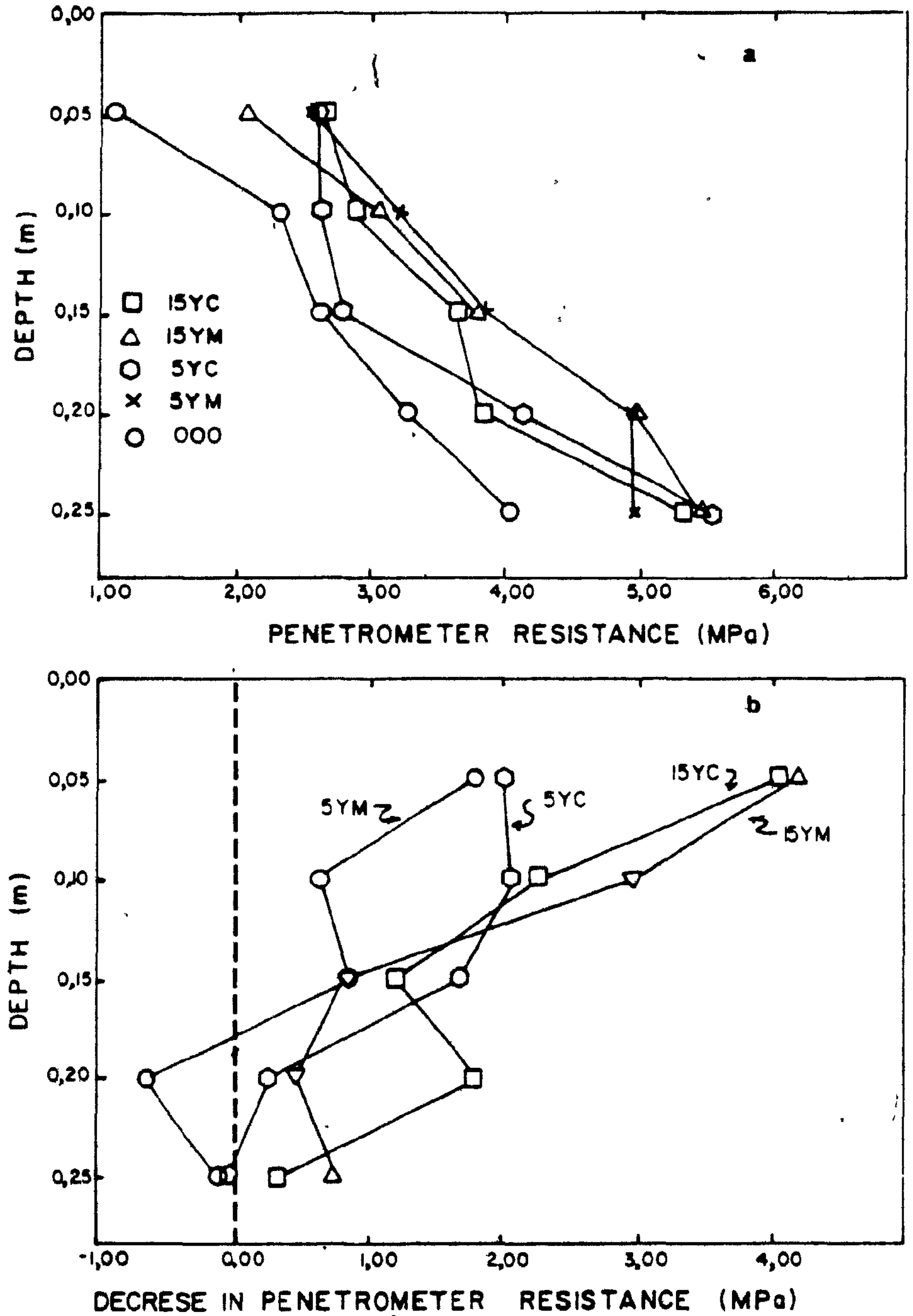


Figure 5.10 Observed changes in penetrometer resistance profiles due to tillage treatments.

Note: The compacted penetrometer resistance of the 15YM, 15YC, 5YM and 5YC treatments prior to plowing was not exactly the same as that in the 15YO and 5YO treatments. (See Appendix C).

values of penetrometer resistance upon the compaction and subsequently tilled throughout the soil profile. The Fig. 5.10b illustrates the effectiveness of tillage tools in decreasing the penetrometer resistance from compacted state (Appendix C, Table C.16 - C.17) at each depth. In severely compacted tillage plots (15YM and 15YC), the moldboard plow had effectively decreased the penetrometer resistance up to 0,15m depth and the chisel plow decreased it up to a 0,25m depth. Below 0,15m depth the plowed plot increased in penetrometer resistance. This increase was more pronounced at a 0,20m depth rather than at a 0,25m depth. If dry bulk density (Fig. 5.7) and penetrometer resistance (Fig. 5.10) are compared at the depth below 0,15m, it is clear that the penetrometer showed a more prominent difference in the soil profile. It appears that the penetrometer is more sensitive in showing the structural consistency of the soil profile effectively. Voorhees et al., (1978) stated a similar conclusion, which showed that the penetrometer resistance increased 400% more than the dry bulk density, and therefore the penetrometer was a more sensitive indicator of soil compaction than was dry bulk density. In lightly compacted tillage treatments (5YM, 5YC), the moldboard plow has decreased penetrometer resistance up to a 0,25m depth, whereas the chisel plow decreased it up to a 0,20m depth. There was a slight increase of resistance at a 0,25m depth in chiselled plots. It can also be noted that, when chiselling was done on lightly compacted plots (5YC), it reduced the penetrometer resistance up to a 0,15m depth more than did the moldboard plow (5YM). This could probably be due to the fact that the chisel plow on a lightly compacted plot shatters the soil, which produces small aggregate sizes with low strength, whereas the moldboard plow produces larger lumps of soil aggregate with high strength. These aggregates in moldboard plowed plots, when exposed to the atmosphere, dried very quickly and presented high strength at the top of the soil profile.

The results of an analysis of variance Table D.7, Appendix D, show the significant differences in treatments at 0,05, 0,10 and 0,20m depths (at various significance levels). When mean values of penetrometer resistance of the plots subjected to tillage treatments (15YM, 15YC) were compared with the severely compacted-no tillage treatment (15YO), these were found significantly different up to a 0,10m depth (Table 5.3). The moldboard plow (5YM) resistance was not significantly different for all depths, whereas the chisel plow (5YC) result was significantly different at 0,10 and 0,15m depths when compared with lightly compacted plots (5YO). When the results of all tillage treatments (15YM, 15YC, 5YM and 5YC) were compared with each other, no significant difference was found throughout the soil profile by the use of Duncan's new multiple range test.

The Figs. 5.9a and b present the results of the 1979 summer for the severely compacted tillage treatment (15YM). Fig. 5.9a shows the penetrometer resistance after the tillage operation and Fig. 5.9b illustrates the decrease in penetrometer resistance from compacted state (Appendix C, Table C.18) due to the moldboard plow action throughout the soil profile. The Duncan's new multiple range test (Table 5.4) shows that the moldboard plow has significantly decreased the penetrometer resistance at 0,05 and 0,30m depths, compared to that in the severely compacted-no tillage plot (15YO). It is interesting to note that the penetrometer could not show the increase in resistance below the operating depth of the plow. It is possible that the soil at that depth could be soft due to moisture and would not have offered a high resistance because of low strength.

TABLE 5.4 - Average values for penetrometer resistance in different depth ranges for the various tillage and traffic treatments

YEAR 1979

TREATMENT	MEAN VALUES FOR PENETROMETER RESISTANCE (MPa)		
	0,05 (m)	0,15 (m)	0,30 (m)
000	0,444 a	1,875 a	1,033 a
15YO	3,254 b	4,797 a	6,777 b
15YM	2,452 b	2,227 a	3,770 a

a - b Letters denote significance at 1 percent level using Duncan's new multiple range test. Means with the same letter are not significantly different.

5-5 Vane Shear Resistance

The vane shear resistances of the soil in each compaction and tillage treatment at each depth were averaged and are plotted in Figs. 5.11a and b, 5.12a and b and 5.13a and b. Fig. 5.11a demonstrates the results of vane shear resistance in 1978 for compacted-no tillage treatments (5, 10 and 15YO). The vane shear resistance showed the same trend as the penetrometer resistance. The vane shear resistance increased as the number of passes increased. Fig. 5.11b shows the increase in vane shear resistance from initial status of the soil due to compaction (Appendix C, Table C.19 - C.20). The maximum increase was found at 0,10m depth in the severely compacted plots (15YO), considerably more than in moderately and lightly compacted-no tillage plots (10YO and 5YO). As the depth increased below 0,10m, the increase in shear resistance was almost constant. The results of an analysis of variance in Table D. 9, Appendix D, show the significant differences in treatments up to 0,10m depth. Duncan's new multiple range test was also performed to compare the mean values of vane shear resistance of compacted-no tillage treatments with the no-tillage treatment (000) and the results are shown in Table 5.5. It can be seen that the severely compacted-no tillage plots (15YO) had higher values up to 0,10m depth than the no-tillage plots (000). When compacted-no tillage treatments (5, 10 and 15YO) were compared with each other, the severely compacted-no tillage treatment (15YO) had significantly higher values of vane shear resistance than that of the lightly compacted-no tillage (5YO) treatment in the top 0,025m. There was no significant difference between severely and moderately compacted plots at any depth. This test was performed at 1 percent probability level.

Fig. 5.12a and b show the results of the 1979 summer. Fig. 5.13a

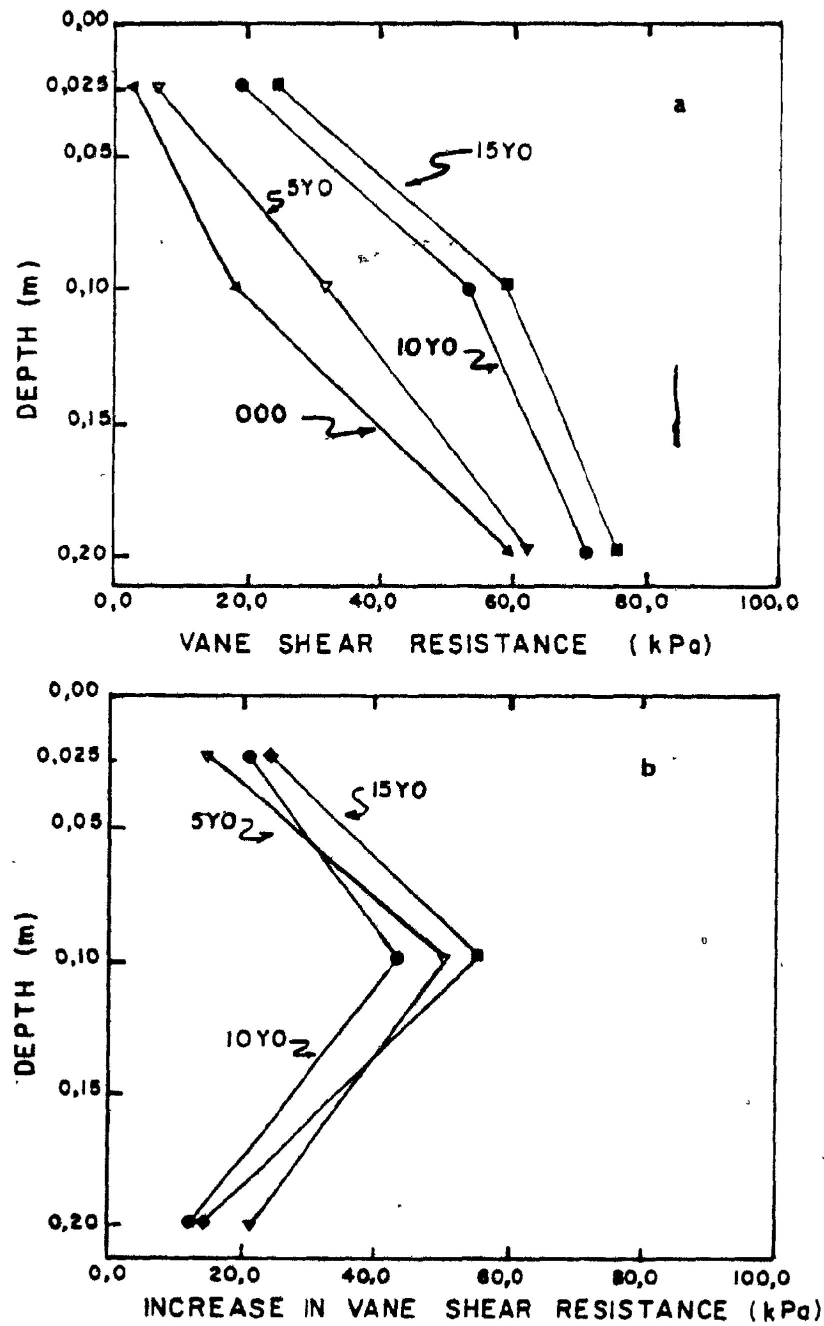


Figure 5.11 Observed changes in vane shear resistance profiles due to traffic treatments.

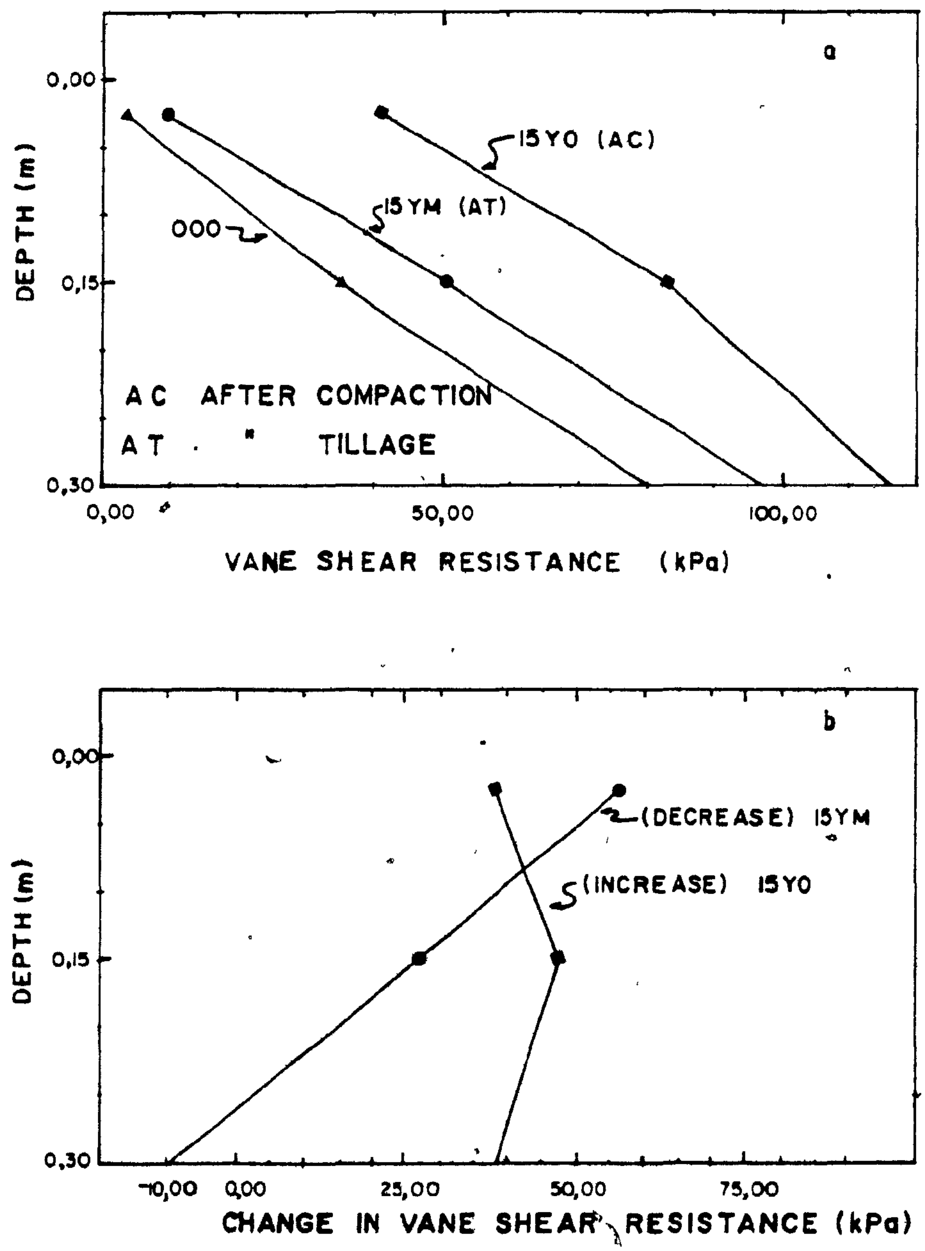


Figure 5.12 Observed changes in vane shear resistance profiles due to traffic and tillage treatments.

Note: The compacted vane shear resistance of 15YM treatment prior to plowing was not exactly the same as that in the 15YO treatment. (See Appendix C).

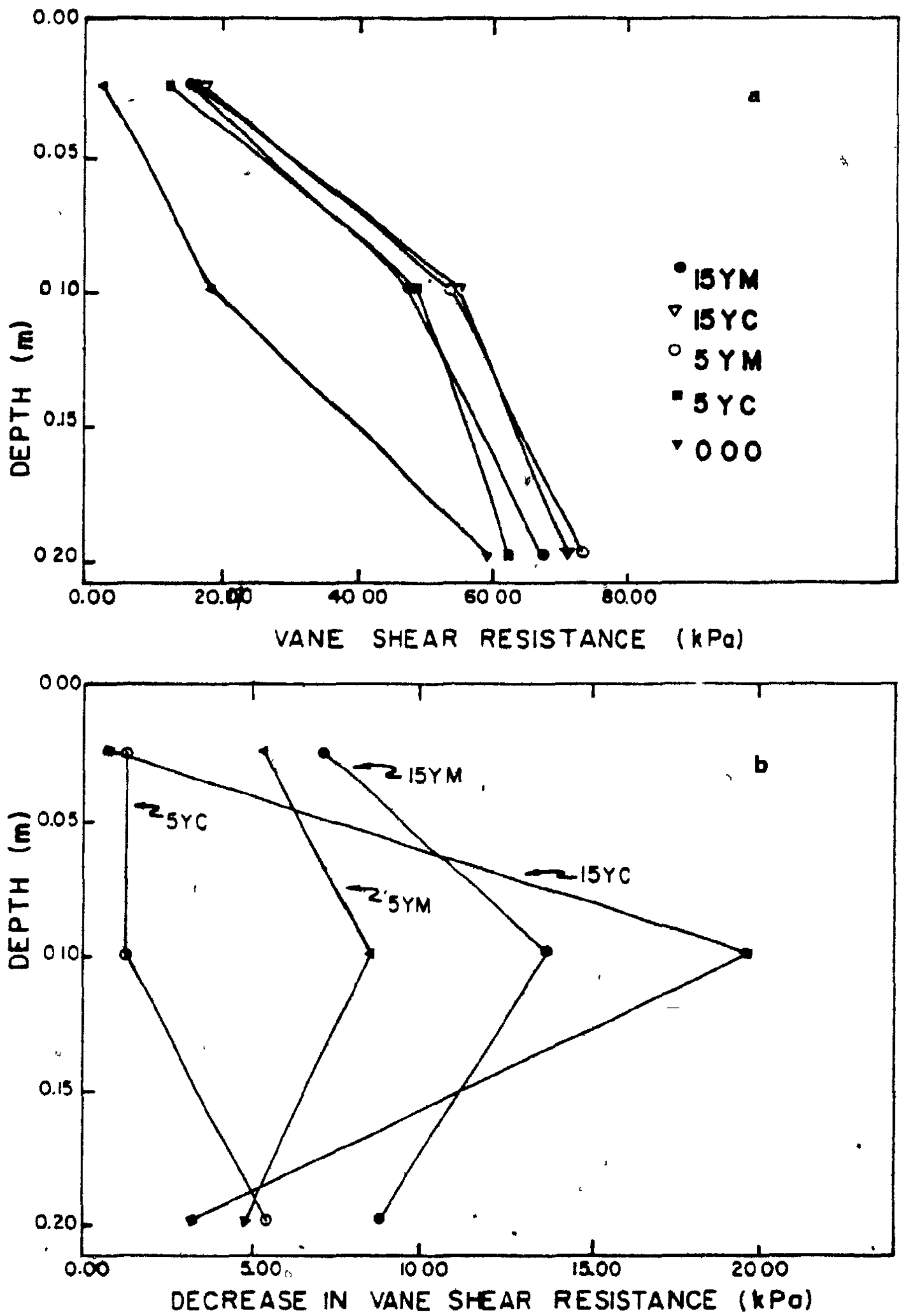


Figure 5.13 Observed changes in vane shear resistance profiles due to tillage treatments.

Note: The compacted vane shear resistance of the 15YM, 15YC, 5YM and 5YC treatments prior to plowing was not exactly the same as that in the 15YO and 5YO treatments. (See Appendix C).

TABLE 5.5 - Average values for vane shear resistance in different depth ranges for various tillage and traffic treatments.

YEAR 1978

TREATMENT	MEAN VALUES FOR VANE SHEAR RESISTANCE (kPa)		
	0,025 (m)	0,10 (m)	0,30 (m)
000	2,452 c	18,194 b	59,613 a
5YO	5,747 bc	31,361 ab	62,243 a
5YM	15,921 abc	55,046 a	73,136 a
5YC	12,448 abc	53,867 a	62,843 a
10YO	18,075 ab	52,548 ab	70,623 a
15YO	24,778 a	58,059 a	75,411 a
15YM	15,921 abc	47,994 ab	67,391 a
15YC	16,639 abc	55,733 a	71,103 a

a - c Letters denote significance at 1 percent level using Duncan's new multiple range test. Means with the same letter are not significantly different.

and b show the results of the 1978 summer. Fig. 5.12a gives the overall mean values of vane shear resistance in the severely compacted-no tillage treatment (15YO). The increase in vane shear resistance calculated from initial status of the soil of particular treatment (Appendix C, Table C.22) is shown in Fig. 5.12b. The maximum increase of vane shear resistance was found at a 0,15m depth. The increase at the surface and below 0,15m was approximately the same. It appears that the maximum shear strength occurred in the range of 0,10 to 0,15m depth.

The results of a statistical analysis are given in Table D.10, Appendix D, which shows that treatments are significantly different at all depths. Table 5.6 presents Duncan's new multiple range test at a 0,01 probability level used for comparing the mean values of vane shear resistance of all treatments at each depth. The severely compacted plots (15YO) had significantly higher resistances at all depths when compared with no tillage plots (000).

Fig. 5.13a demonstrates the vane shear resistance due to tillage action in the compacted plots (5 - 15 passes). The values were higher for all tillage plots (15YM, 15YC, 5YM and 5YC) as compared to the no-tillage or compaction plots (000). Tillage treatments were found effective in decreasing vane shear resistance from compacted state (Appendix C, Table C.20 - C.21) throughout the soil profile as is shown in Fig. 5.13b. The maximum decrease was found to be more in the chiselled plots (15YC) than in the moldboard plowed plots (15YM) at a 0,10m depth. From the surface to a 0,025m depth, the chisel plow did not decrease the vane shear resistance as much as in moldboard plowed plots. At a 0,20m depth, only the moldboard plow (15YM) decreased the vane shear resistance appreciably, compared to the other tillage treatments (15YC, 5YM and 5YC).

TABLE 5.6 - Average values for vane shear resistance in different depth ranges for the various traffic and tillage treatments.

YEAR 1979

TREATMENT	MEAN VALUES FOR VANE SHEAR RESISTANCE (kPa)		
	0,025 (m)	0,15(m)	0,30 (m)
000	3,697 a	34,952 a	80,599 a
15YO	41,761 b	82,725 b	115,710 b
15YM	9,255 a	50,805 a	97,355 ab

a - b Letters denote significance at 1 percent level using Duncan's new multiple range test. Means with the same letter are not significantly different.

The results of an analysis of variance, Table D.11, Appendix D, show significant differences in treatments up to a 0,10m depth. Further investigation to identify treatment differences was based on Duncan's new multiple range test and is shown in Table 5.5. The test did not show any significant differences at a 1 percent probability level. when mean resistance values of each tillage treatment were compared with each other.

The results of decrease in vane shear resistance from compacted state (Appendix C, Table C.22) for the 1979 summer are presented in Fig. 5.12b. It can be seen that the severely compacted-tillage treatment (15YM) markedly decreased shear resistance at the surface by about 55 kPa. The decrease was less as the depth increased. At a 0,30m depth, shear resistance increased in plowed plots (15YM).

A statistical analysis of the vane shear resistance results is shown in Table D.12, Appendix D. The results indicate that there was a significant difference in treatments at 0,025 and 0,15m depths, but not at a 0,30m depth. In addition, Duncan's new multiple range test was used to compare each treatment in order to provide evidence of possible differences. This test is shown in Table 5.6, which shows that the 15YM treatment decreased vane shear resistance at 0,025 and 0,15m depths significantly, but there was no significant difference at a 0,30m depth when compared with severely compacted-no tillage plots (15YO). This test was performed at 1 percent probability level.

5-6 Air-filled Porosity

Air-filled porosity is influenced by changes in both dry bulk density and moisture content. The values of air-filled porosity were calculated from the relationship given in Appendix B. The values thus obtained for all the compacted and tilled plots at various depths are plotted in Figs. 5.14a and b, 5.15a and b and 5.16 from the measurements taken within a few days after the treatments were completed.

The results of air-filled porosity in 1978 are reported in Figs. 5.14a and b, and 5.15a and b. Fig. 5.14a presents the results for compacted treatments (5, 10 and 15YO), which show very high values in the top 0,05m depth from the surface, and low values below 0,15m depth compared to no-tillage plots (000). If the optimum value of 10 percent air-filled porosity is taken as a criterion for this condition (Vomicil and Flocker, 1961), then the air-filled porosity values obtained for all compacted plots were found to be below 10 percent at 0,20m - 0,25m depths.

Tillage has considerably increased the air-filled porosity up to 0,15m depth from the surface but the effect was less as the depth increased (Fig. 5.14b). Below 0,20m depth the values of air-filled porosity were less than 10 percent in severely compacted-tilled plots (15YC, 15YM), and lightly compacted-tilled plots (5YC) as compared to the no-tillage or compaction plots (000). This is consistent with the development of a plowpan in these treatments. It is also interesting to note that either lightly compacted or subsequently tilled plots (5YO, 5YM, 5YC) has lower air-filled porosity values than heavily compacted or subsequently tilled plots (15YO, 15YM, 15YC). It is probably due to higher moisture contents observed in these treatments than those of other treatments.

The air-filled porosity in the soil varies continuously with time and soil depth. One month after seeding, dry bulk density and soil moisture content values were obtained again from the field and

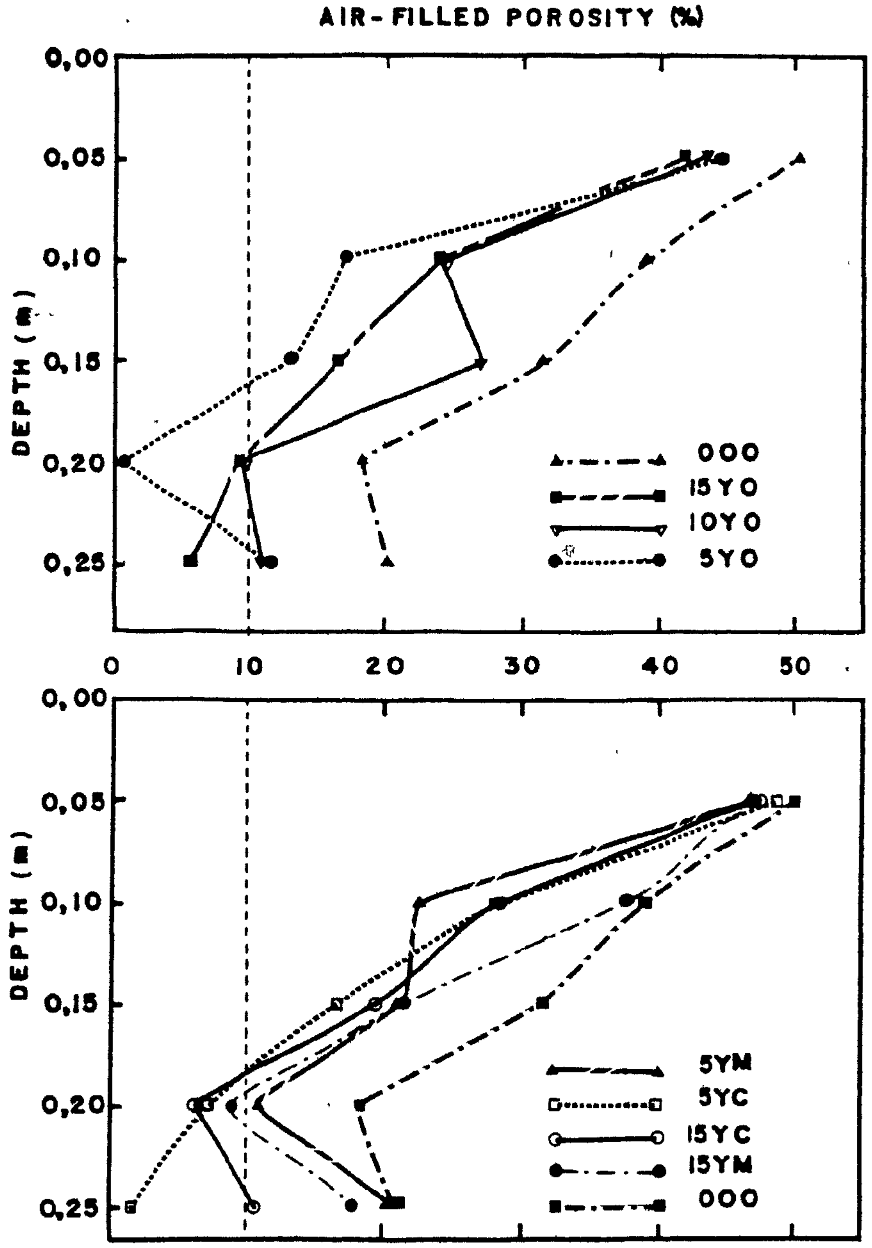


Figure 5.14 Effect of compaction and tillage treatments on air-filled porosity of the soil.

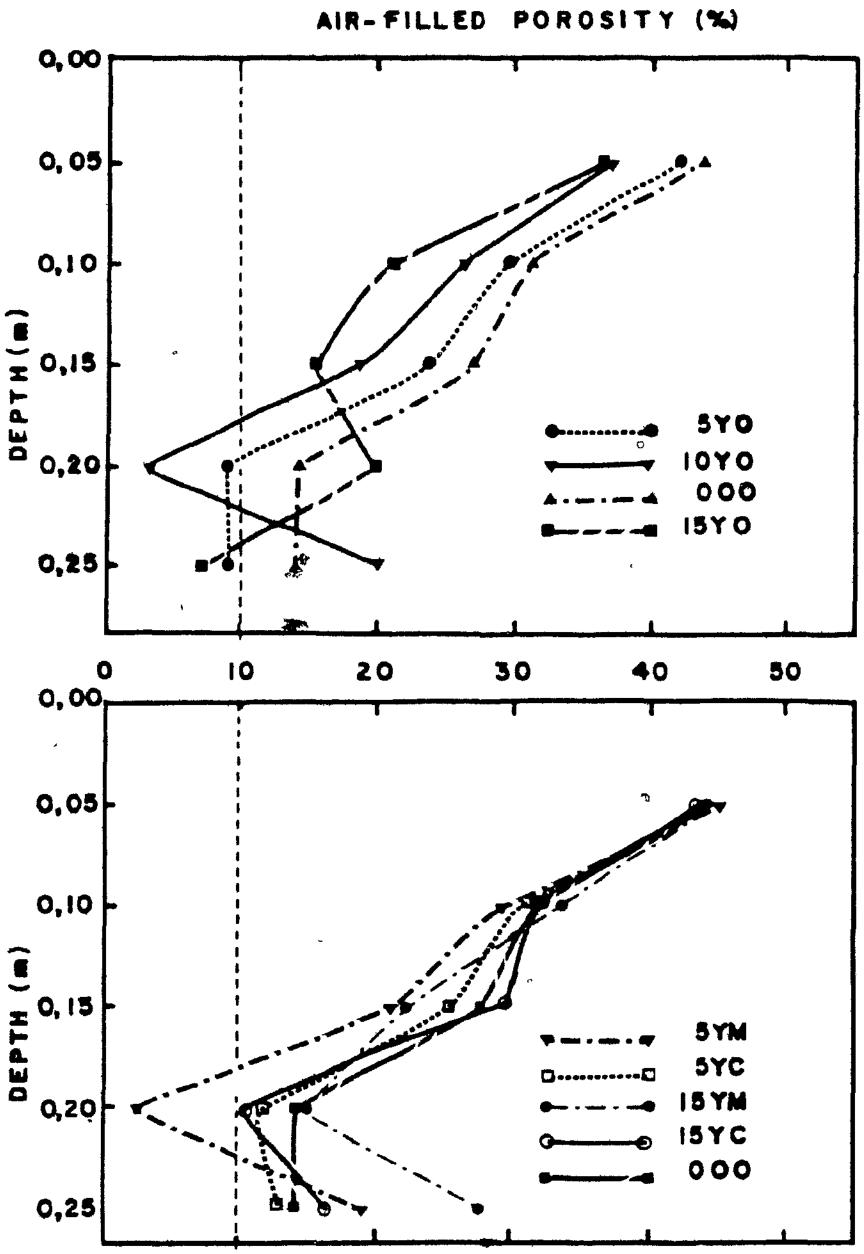


Figure 5.15 Effect of compaction and tillage treatments on air-filled porosity of the soil during the crop stand.

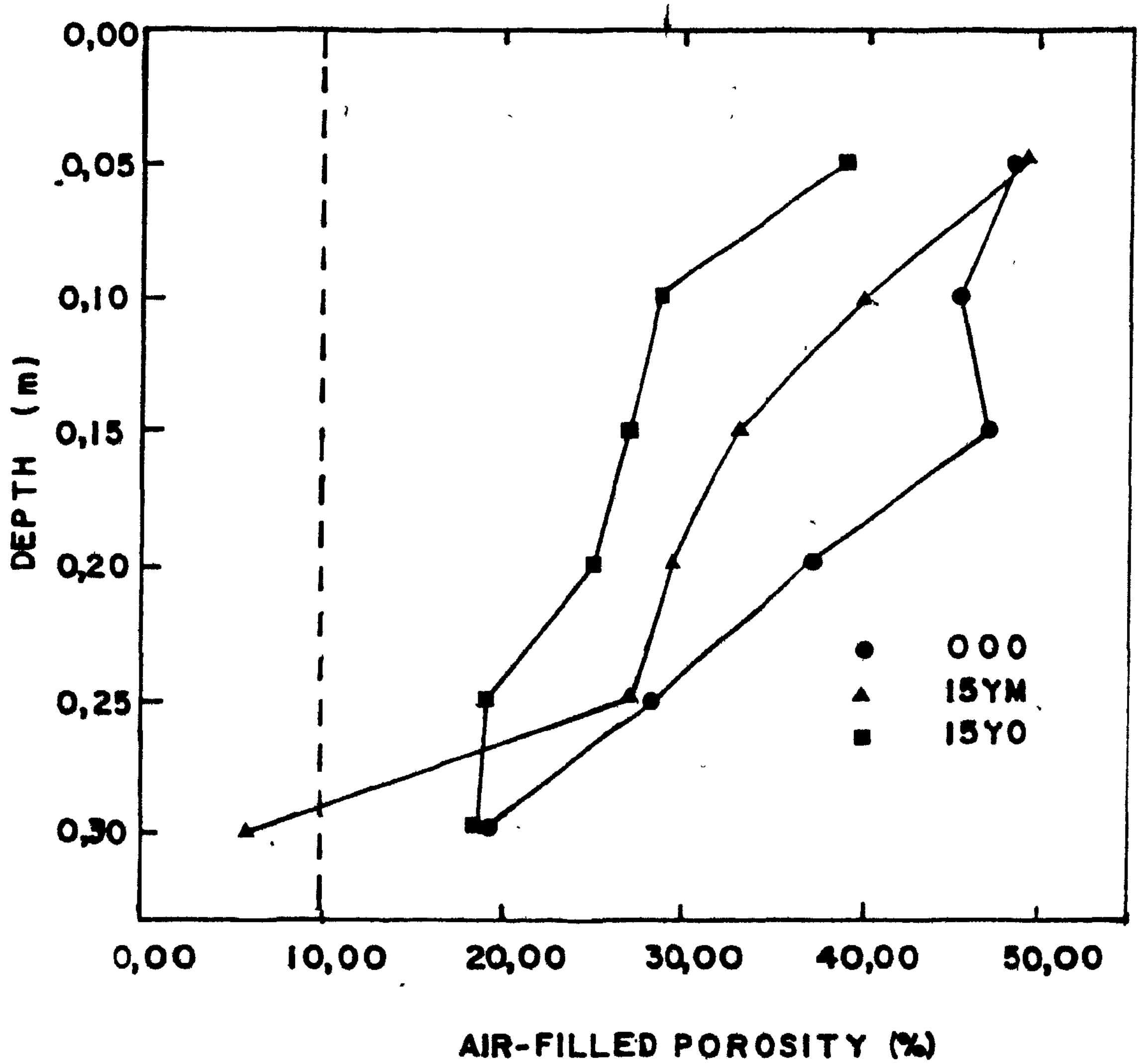


Figure 5.16 Effect of compaction and tillage treatments on air-filled porosity of the soil.

values of air-filled porosity were calculated and are reported in Fig. 5.15a and b. It appears from Fig. 5.15a that the air-filled porosity during this time decreased by more than 5% at each depth for all compacted treatments. Inversely, the values of air-filled porosity were increased appreciably beyond the critical value of 10% at a 0,20m depth for the tillage treatments 15YC, 5YC and 15YM, except 5YM (Fig. 5.15b). The values for the tillage treatment (5YM) decreased appreciably below 10 percent. This is attributable to the increase in dry bulk density values found in this treatment at the same depth.

The results of the 1979 summer are given in Fig. 5.16. It can be seen that 15 passes of the tractor have lowered the values of air-filled porosity when compared with the no-tillage or compaction treatment throughout the profile. When these compacted plots were tilled with the moldboard plow, the increase in air-filled porosity was found up to a 0,25m depth. Below this depth the values of air-filled porosity decreased appreciably beyond the 10% critical value. This is attributable to the higher dry bulk density values obtained at this depth due to the formation of a compacted pan.

5-7 Soil Water

To calculate the unsaturated hydraulic conductivity of a clay soil at a 0,25m depth, equation (2.15) was used. This equation requires a knowledge of soil water flux, the change of soil suction with respect to soil moisture content and soil moisture content with respect to depth. To obtain soil water flux values, the variation of soil water as a function of time was assumed by an equation given by Ogata and Richards (1957),

$$\theta = at^{b} \quad \text{-----------------(5.1)}$$

Where θ is the volumetric moisture content, t is the time and b is a constant exponent. The experimental data on volumetric moisture contents at 0,15 and 0,25m depths during one 26-day infiltration cycle were used to perform statistical analyses on the computer. A maximum R^2 improvement method of stepwise regression was used to search for the best model producing the highest R^2 coefficient of correlation (Barr et al., 1980).

This statistical analysis relating to the model is shown in Table D.13, Appendix D. The variation of the volumetric moisture content with time was calculated from the model for each depth and Figs. 5.17 and 5.18 were then plotted for each treatment. Fig. 5.17 demonstrates the moisture content variation with time. After 20 days, all the treatments showed nearly constant values except for the no-tillage plot (000). In Fig. 5.18, the no-tillage treatment at a depth of 0,25m had still not attained as steady a value as the other treatments. It can also be seen that for this treatment, the profile is draining faster than for the other treatments. This seems to be due to the open structure provided by a rotary tiller which enhances rapid infiltration and a larger volumetric moisture content at the beginning of the observation.

To obtain soil water flux, the slope $(\frac{d\theta}{dt})$ was measured from Figs. 5.17 and 5.18 at particular points in time by integrating the moisture-time curve with respect to depth. The results of soil water flux measurements leaving the 0,25m depth are plotted in Fig. 5.19. Higher values for the 26-day infiltration cycle were obtained in the severely compacted-tillage treatment (15YC), followed by the no-tillage (000) and the severely compacted-no tillage treatment (15YO).

Water retention characteristics of the clay soil for the 0,25m depth were obtained from field measurements of soil suction and volumetric

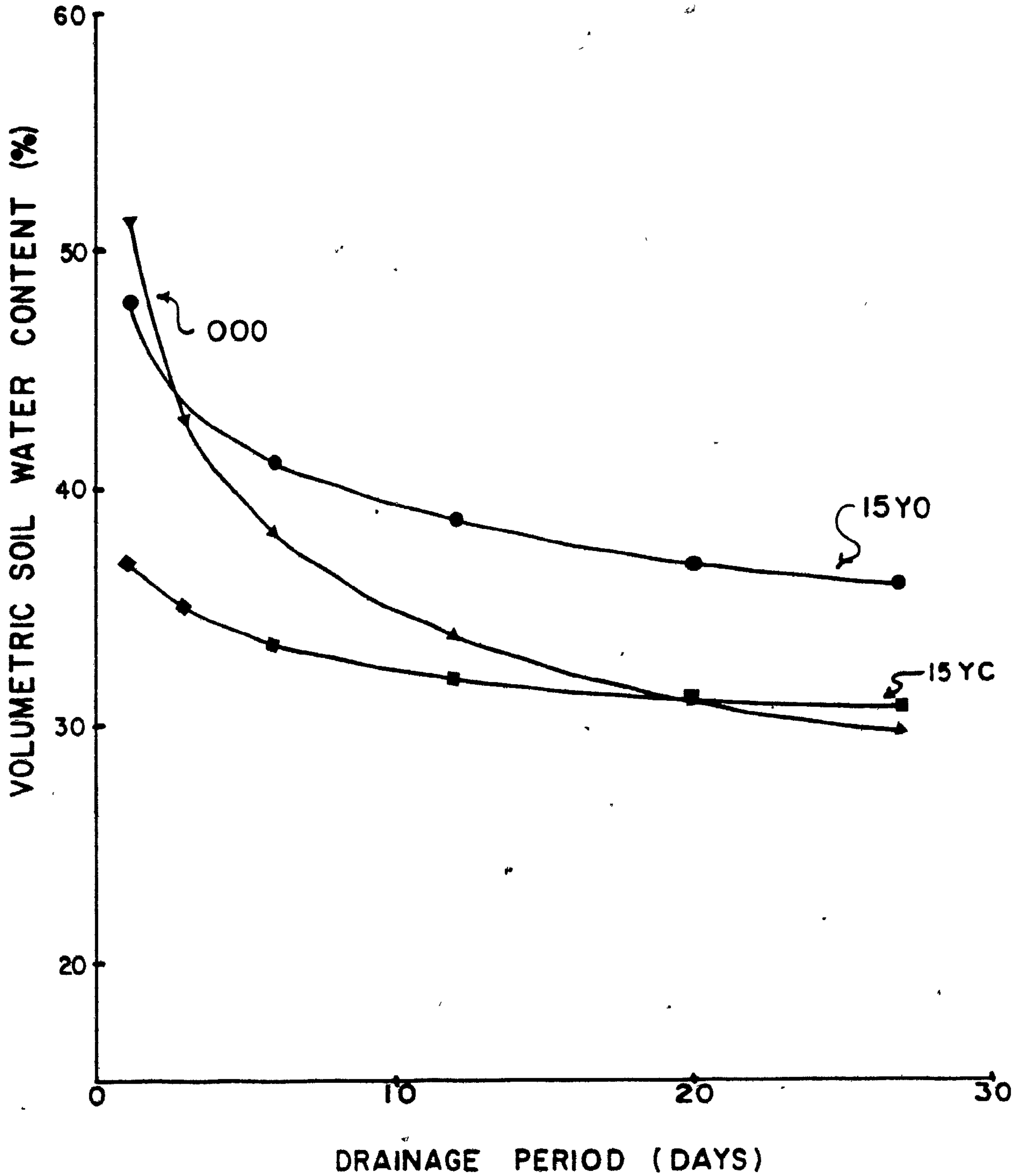


Figure 5.17 Volumetric moisture content versus drainage period at 0,15m depth.

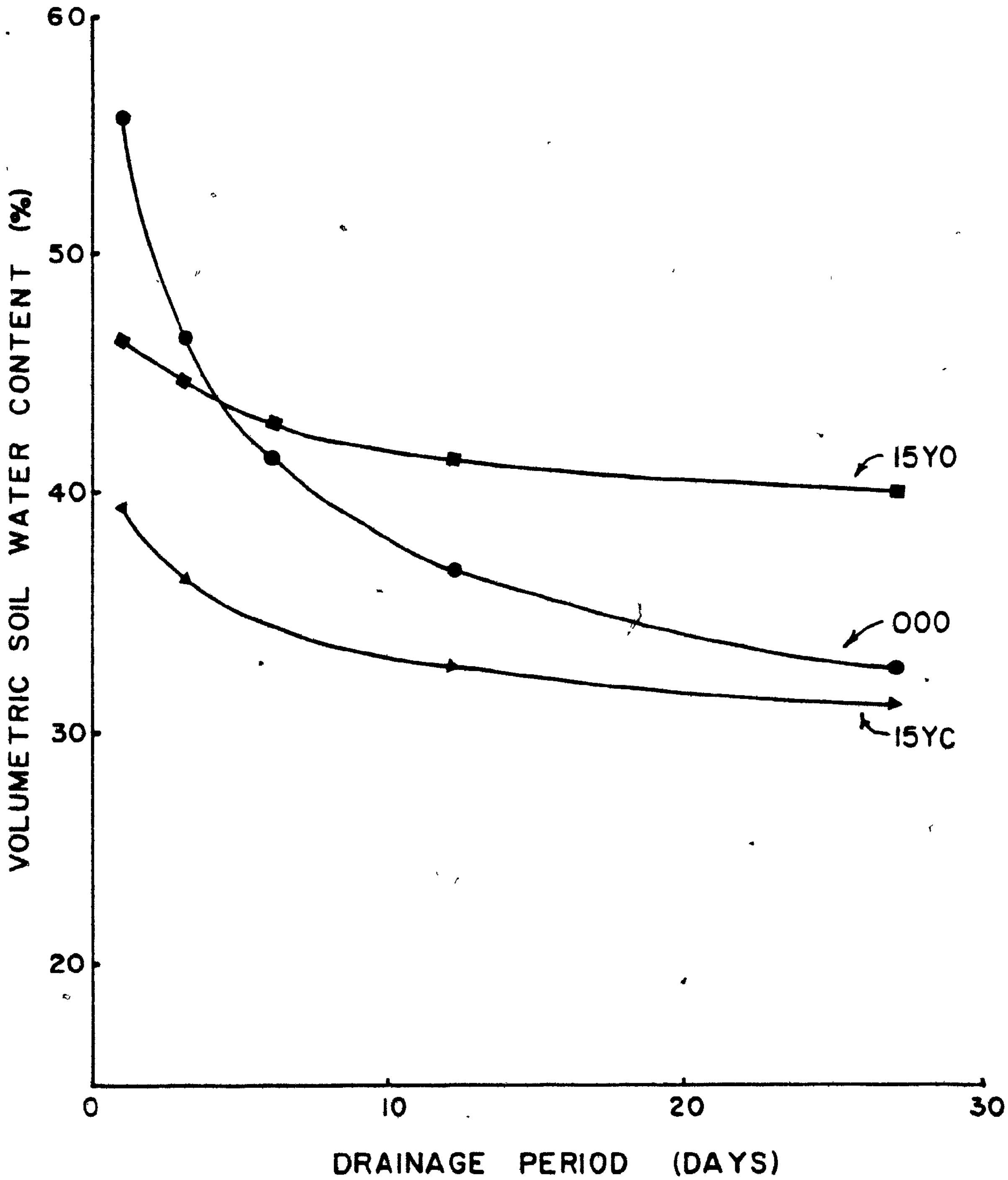


Figure 5.18 Volumetric moisture content versus drainage period at 0,25m depth.

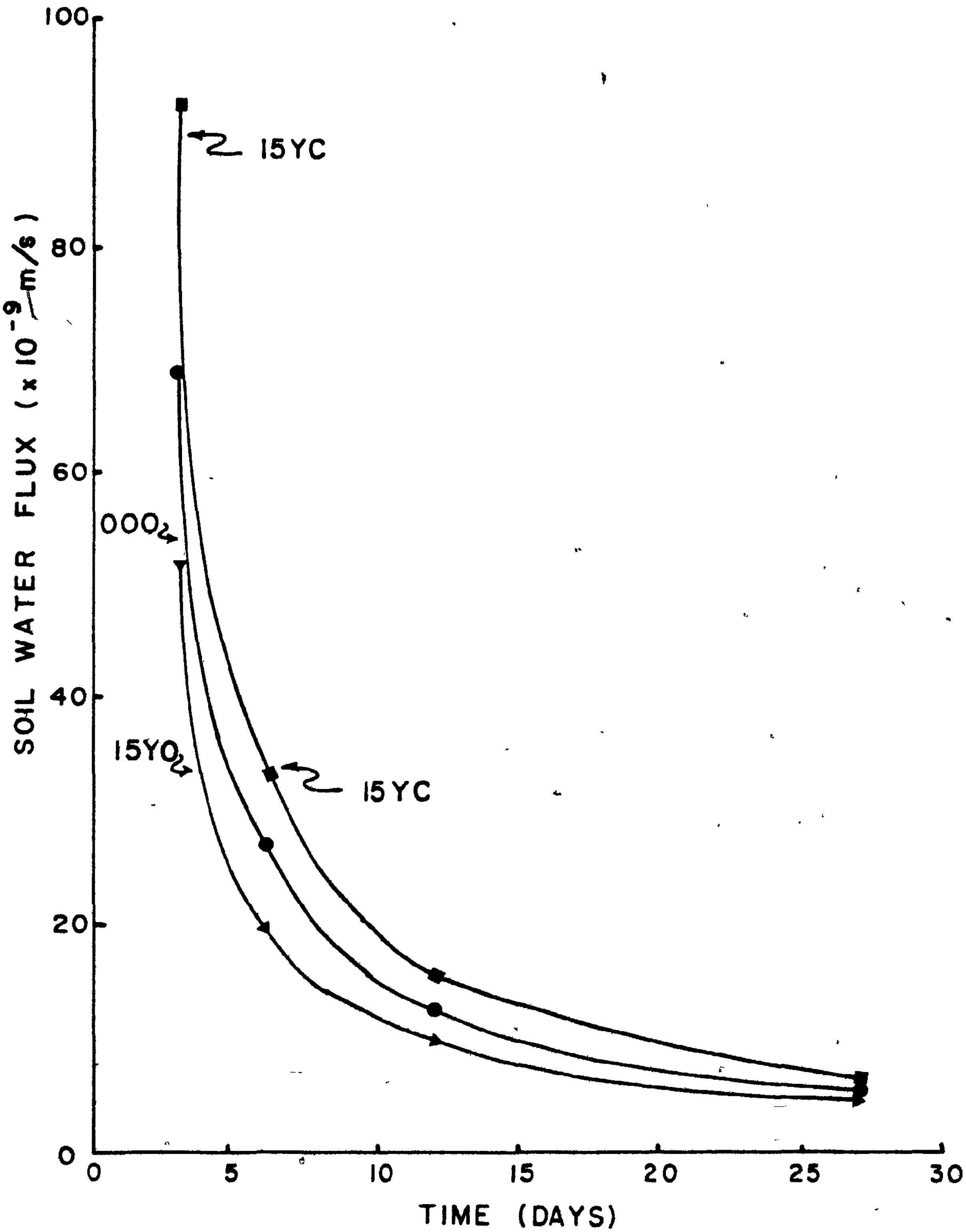


Figure 5.19 Soil water flux leaving 0,25m profile.

moisture content within tensiometer range. The values above this range were obtained from the relationship given by Campbell (1974),

$$\phi = \phi_e \ (\theta/\theta_s)^{-b_1} \qquad \text{-------------------(5.2)}$$

where ϕ_e is the soil suction at the air entry value, θ_s is the saturated water content and b_1 is the slope. The regression analysis relating to this model is given in Table D.14, Appendix D. The experimental values of volumetric moisture content corresponding to the soil suction in the tensiometer range at a 0,25m depth were smoothed by means of a cubic spline technique (Appendix E). The values obtained were then averaged for the three replicates of tillage and compaction treatments, and the curves are plotted in Fig. 5.20. It can be seen that at lower suction levels, the difference in volumetric moisture content is hardly noticeable but as the suction increased, obvious differences appeared in water retention for each treatment. At higher soil suction levels, the severely compacted-no tillage treatment (15YO) retained the most water, followed by no-tillage and then severely compacted tillage (15YC) treatments.

The only unknown for calculating hydraulic conductivity from equation (2.15) was calculated from the water retention characteristics curve as described by Nielsen et al., (1964). The hydraulic conductivity as a function of volumetric moisture content for each tillage and compacted treatment is plotted on a semilog graph. The straight lines shown in Fig. 5.21 for all treatments, were fitted to the data by regression analyses. The coefficients of correlation 'R^2' for the severely compacted-no tillage (15YO), the severely compacted tillage (15YC) and no-tillage (000) treatments were 0,89, 0,80 and 0,98, respectively. The Student's 't' test was also performed and showed an 80 percent confidence belt where this correlation

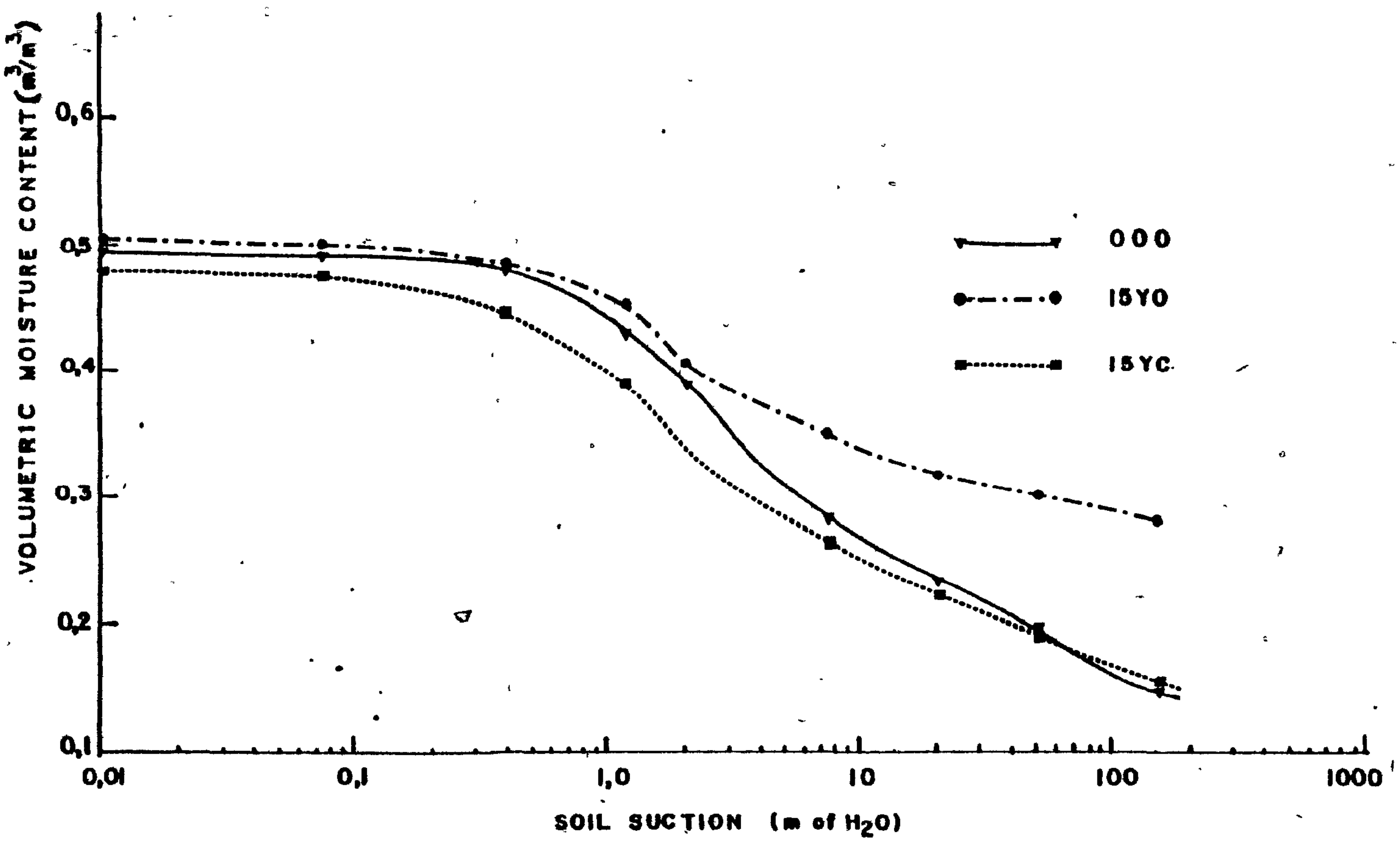


Figure 5.20 Soil moisture retention characteristics at 0,25m depth.

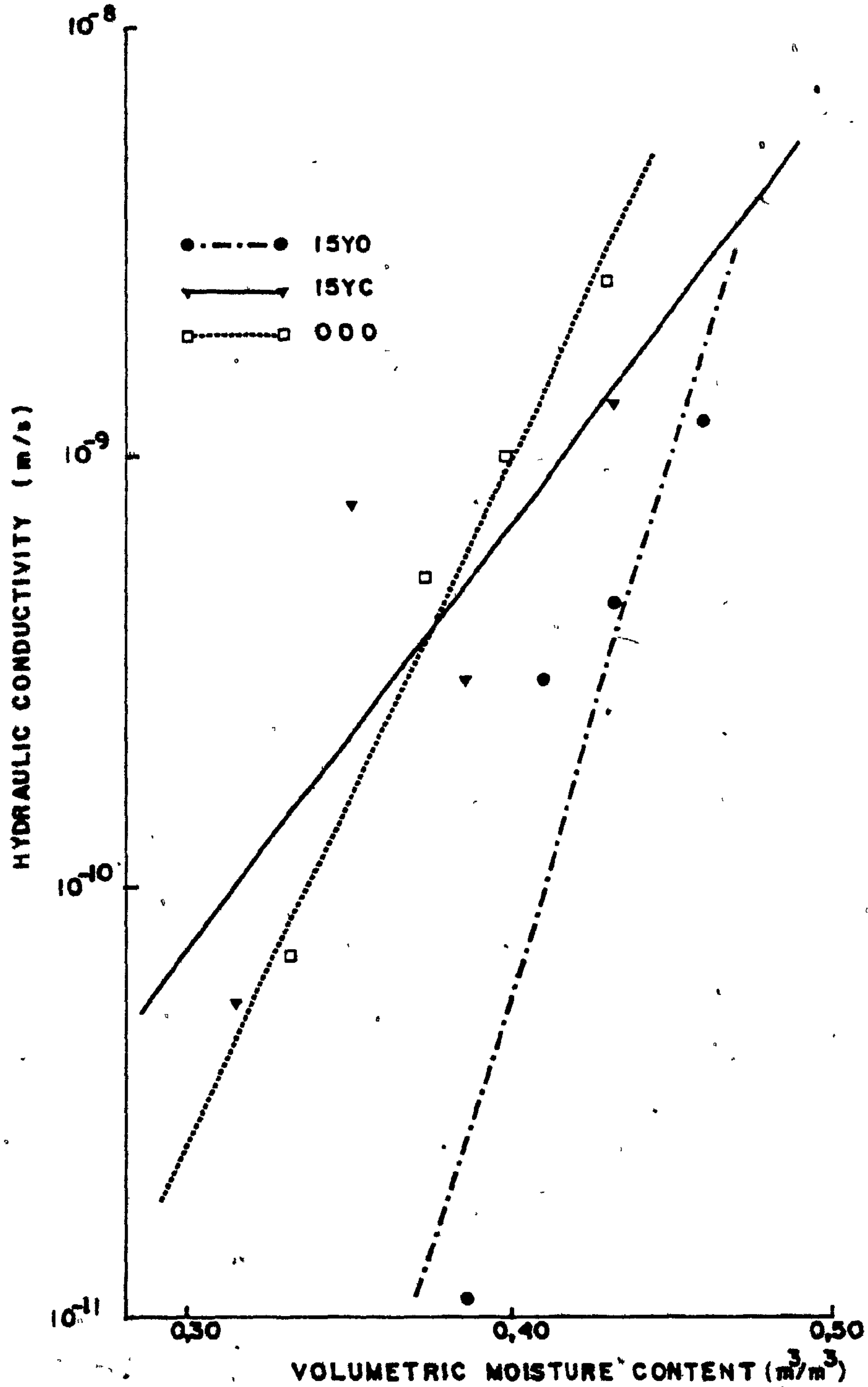


Figure 5.21 Effect of compaction and tillage treatments on unsaturated hydraulic conductivity of the soil at 0,25m depth.

exists for severely compacted-no tillage and severely compacted-tillage treatments. The no-tillage treatment (000) had a 95% confidence interval.

It was found that the severely compacted-no tillage treatment (15YO) had the lowest values of hydraulic conductivity for all values of volumetric moisture content. The highest values of hydraulic conductivity were found in no-tillage treatment, followed by the severely compacted-tillage treatment.

Availability of soil water is defined as the amount of water held from field capacity to the permanent wilting point. Field capacity (FC) for clay soil is assumed to be at 344cm of H_2O suction (Ahuja, 1973), and permanent wilting point (PWP) is generally taken as 150m of H_2O suction. The following relation holds for calculating availability of soil water,

$$AW = (FC - PWP)\ Z \qquad \text{------------------(5.3)}$$

where AW is the available water and Z is the depth range of interest. The values thus calculated are plotted against dry plant yield for each tillage and compaction treatment. The straight line shown in Fig. 5.22 for all treatments was fitted to the data by a regression analysis. It can be seen that severely compacted-no tillage plots had low dry plant yields due to a smaller amount of water being available to the plants. As the availability of water increased, the dry plant yield also increased. There was more soil water available in no-tillage (000) plots followed by severely compacted-tillage (15YC) and then severely compacted-no tillage (15YO) plots.

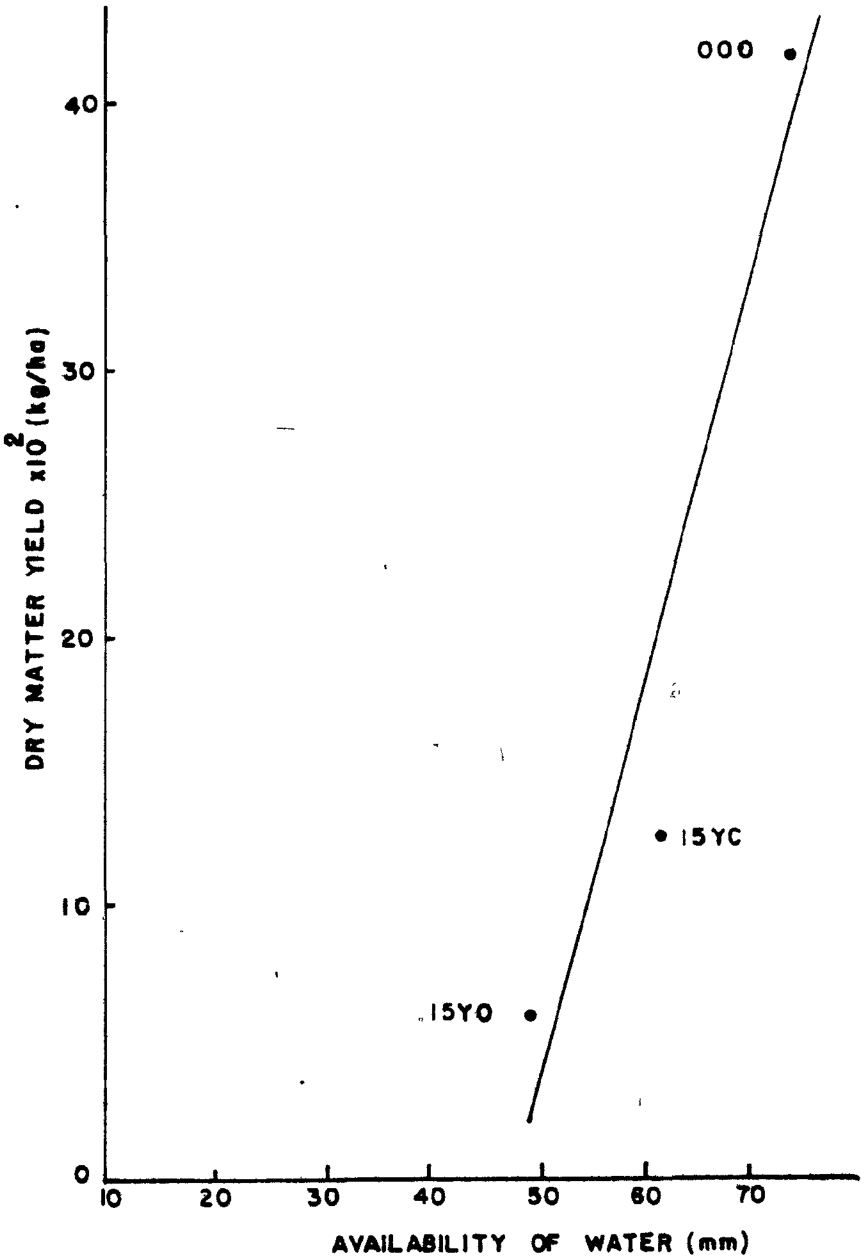


Figure 5.22 Relationship between availability of water and dry matter yield of compaction and tillage treatments.

5-8 Plant Performance

The effects of soil compaction and tillage treatments on emergence of seeds, plant heights and yields of dry plant matter, grain and dry root mass were observed throughout the growing seasons of 1978 and 1979 and the results are reported as follows:

a) Plant Emergence

The emergence of the buckwheat crop was observed for various compacted and tillage treatments in 1978 and 1979, as previously described, and the results are presented in Figs. 5.23 and 5.24. Fig. 5.23 shows the results of 1978, which indicate that the treatments had a definite effect on seed emergence. The number of days required to emerge 80% of each plant population was very much affected in compacted-no tillage treatments (5, 10 and 15YO). As a result, the emergence in these treatments took a longer time than with other treatments. It can be seen that the chiselled plots (5 and 15YC) were not as effective in altering seedling emergence time as the moldboard (5 and 15YM) and no-tillage (000) plots, and comparatively took more time for plant emergence than the latter. The delayed emergence in compacted plots seems to be related to the mechanical impedance of the soil which resulted in the seedling emerging from a compacted layer. Stout et al., (1961) reported similar results for a corn crop; also Talha et al., (1978) had the same conclusion for wheat and cotton crops.

The results of the 1979 experiment are given in Fig. 5.24, which indicates a similar trend, except that the emergence of seedlings was twice as early as that of 1978. This large difference may be attributed to the deficiency of water content during the seedling emergence in 1978.

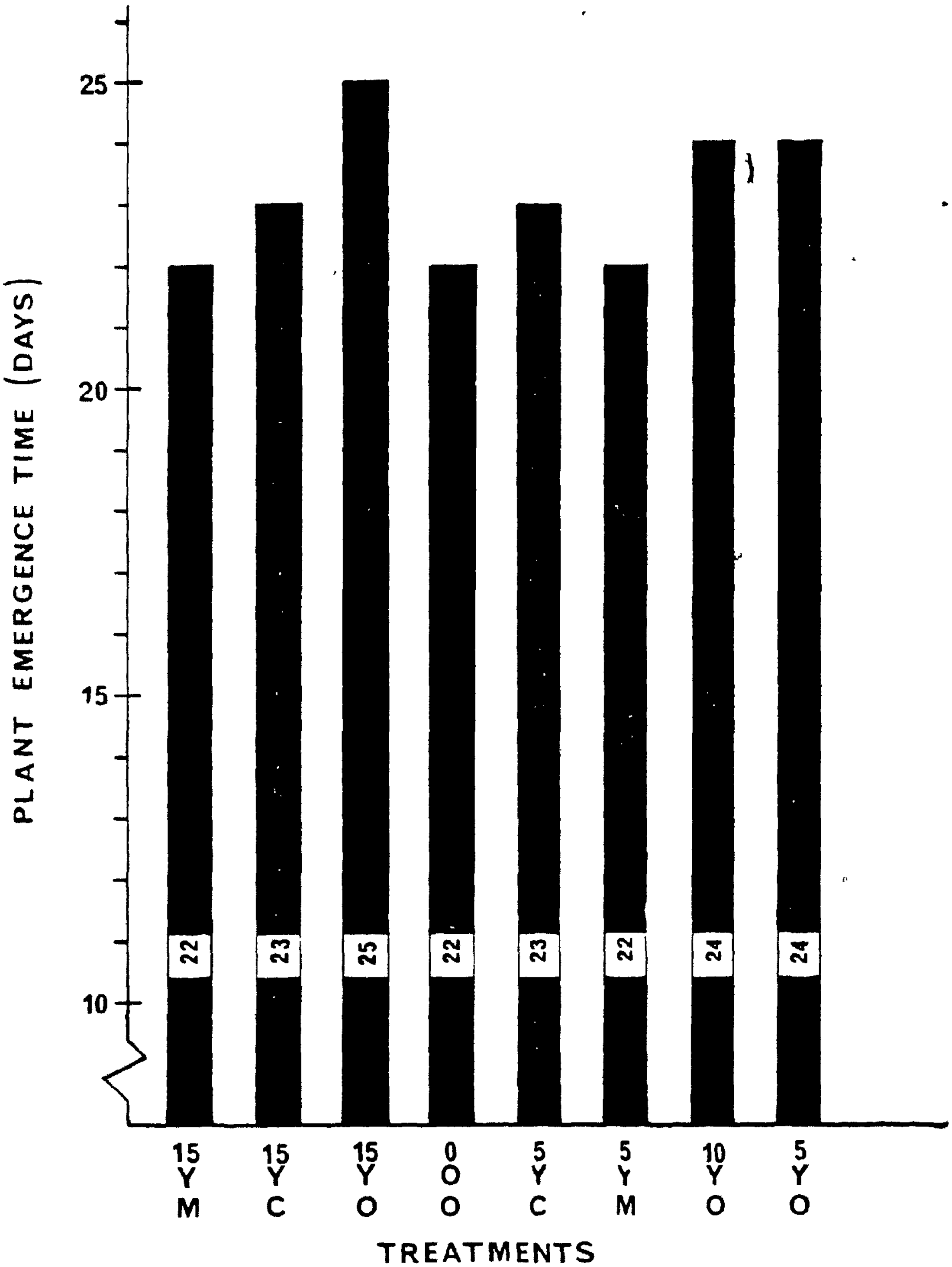


Figure 5.23 Effect of various compaction and tillage treatments on plant emergence time.

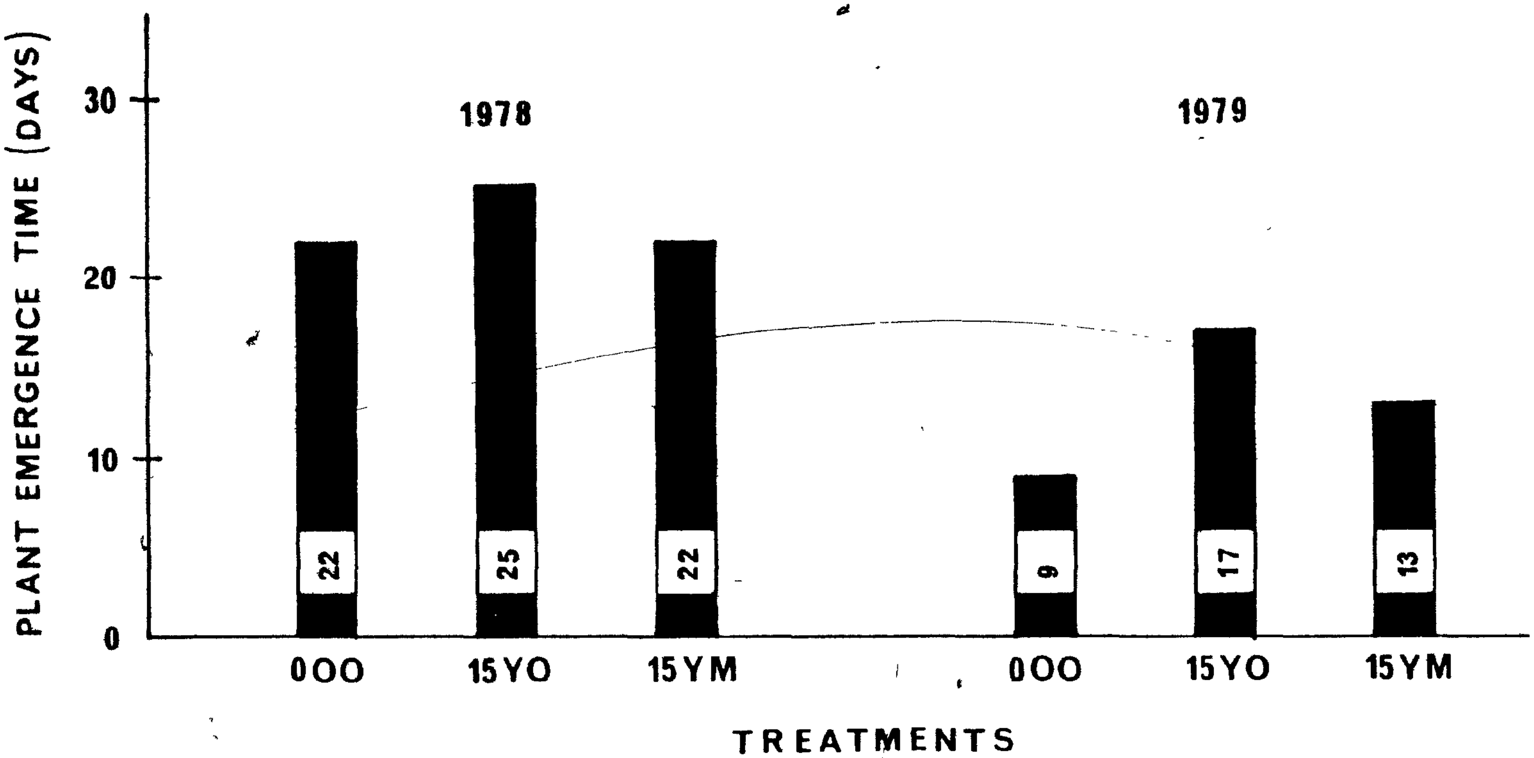


Figure 5.24 Comparison of days to emerge between two growing seasons due to the effect of compaction and tillage treatments.

b) Plant Height

Plant height was measured routinely with a view to identifying differences in treatment at various times during the seasons of 1978 and 1979. Plant height was adversely affected as observed in the compacted plots. The effect was more severe in the severely compacted-no tillage treatment (15YO) than in any other treatment, Figs. 5.25(1978) and 5.26(1979). The maximum heights of the plants in 1978 at 24 days after seeding were 5, 6, 7 and 17 cm for the 15YO, 10YO, 5YO and 000 treatments, respectively, and 22 and 27cm in 1979 for the 15YO and 000 treatments, respectively. The higher plant heights in 1979 at 24 days after seeding were due to earlier emergence than in 1978. A difference was found at 45 days after seeding in 1978, when the 10YO treatment plants surpassed those on the 5YO treatment at about 2cm high, but this difference was gradually decreased by a slowing down of the growth rate in the 5YO treatment when the next observation was taken 5 days later. The last observation was taken at 60 days after seeding, and the maximum plant heights were 48, 52, 55 and 87 cm for the 15YO, 10YO, 5YO and 000 treatments, respectively. The maximum plant heights in 1979 at 63 days after seeding were 92 and 99 cm for the 15YO and 000 treatments, respectively.

When moderately compacted plots (5 passes) were subsequently tilled by moldboard and chisel plow in the 1978 summer, a definite difference was found in improving the soil environment for better growth of plants (Fig. 5.27). During early growth periods, the moldboard plow treatment did not show as good a performance as the

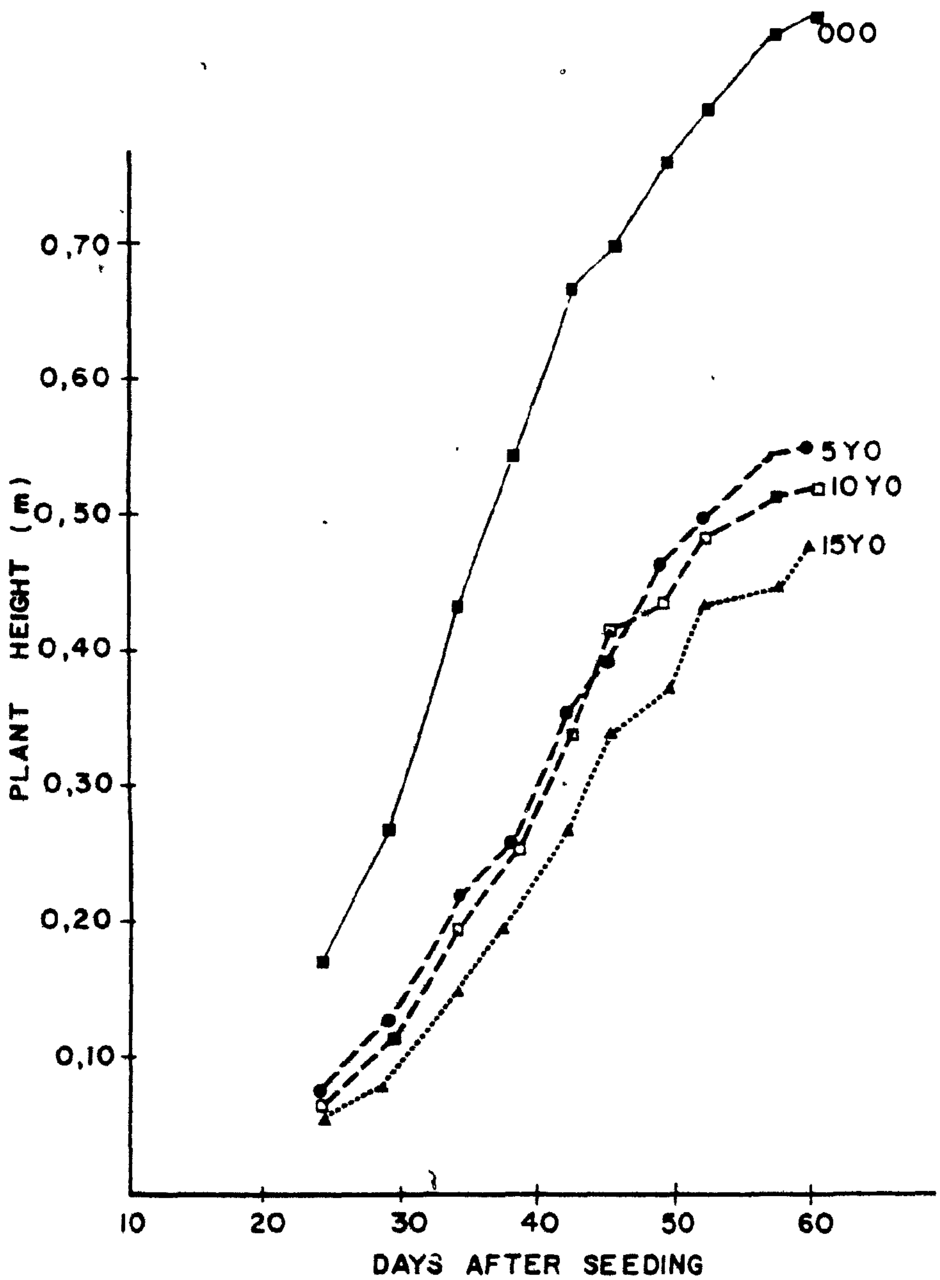


Figure 5.25 Rate of plant growth as affected by various compaction treatments during the growing season.

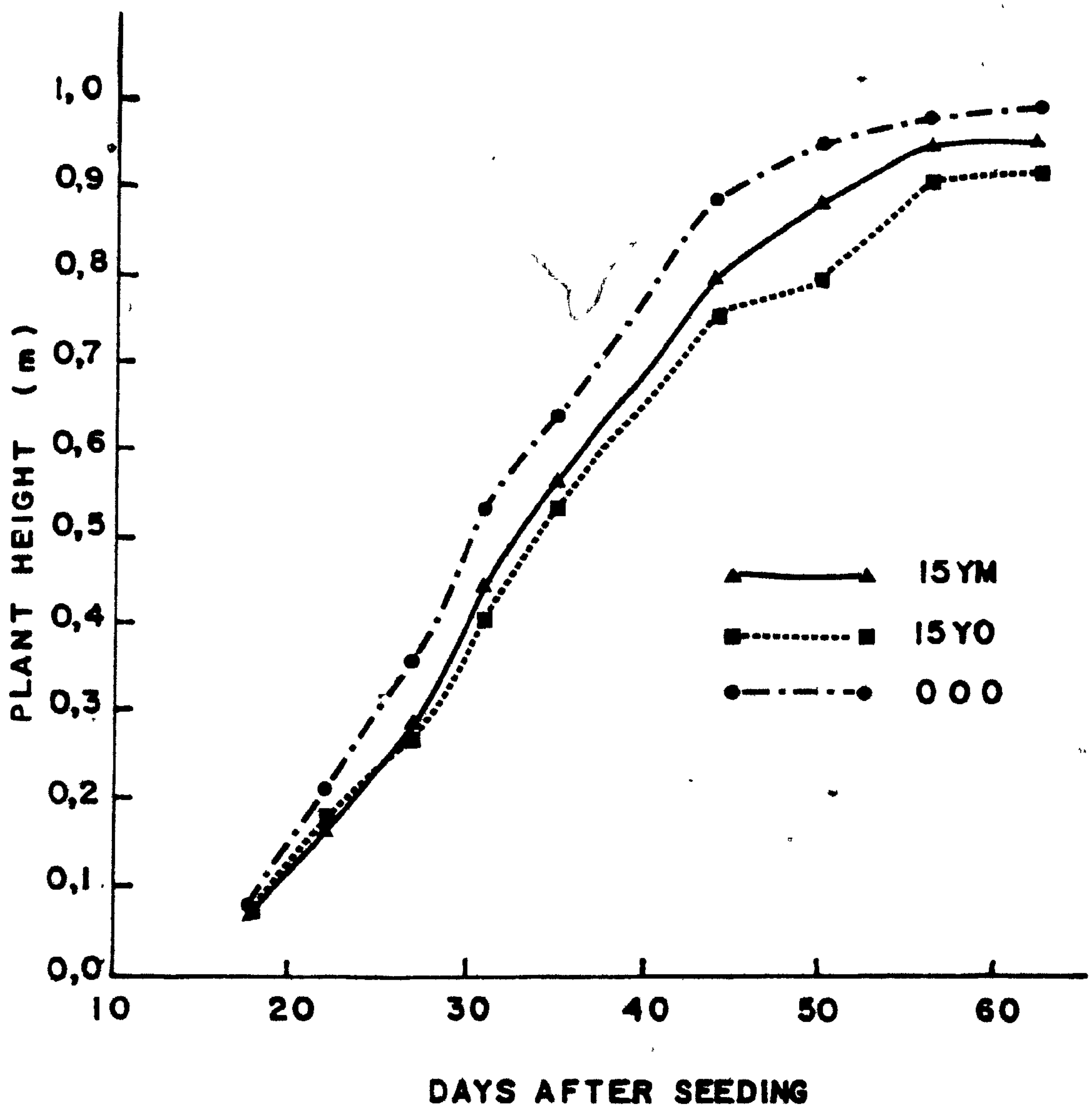


Figure 5.26 Rate of plant growth as affected by compaction and tillage treatments during crop growth.

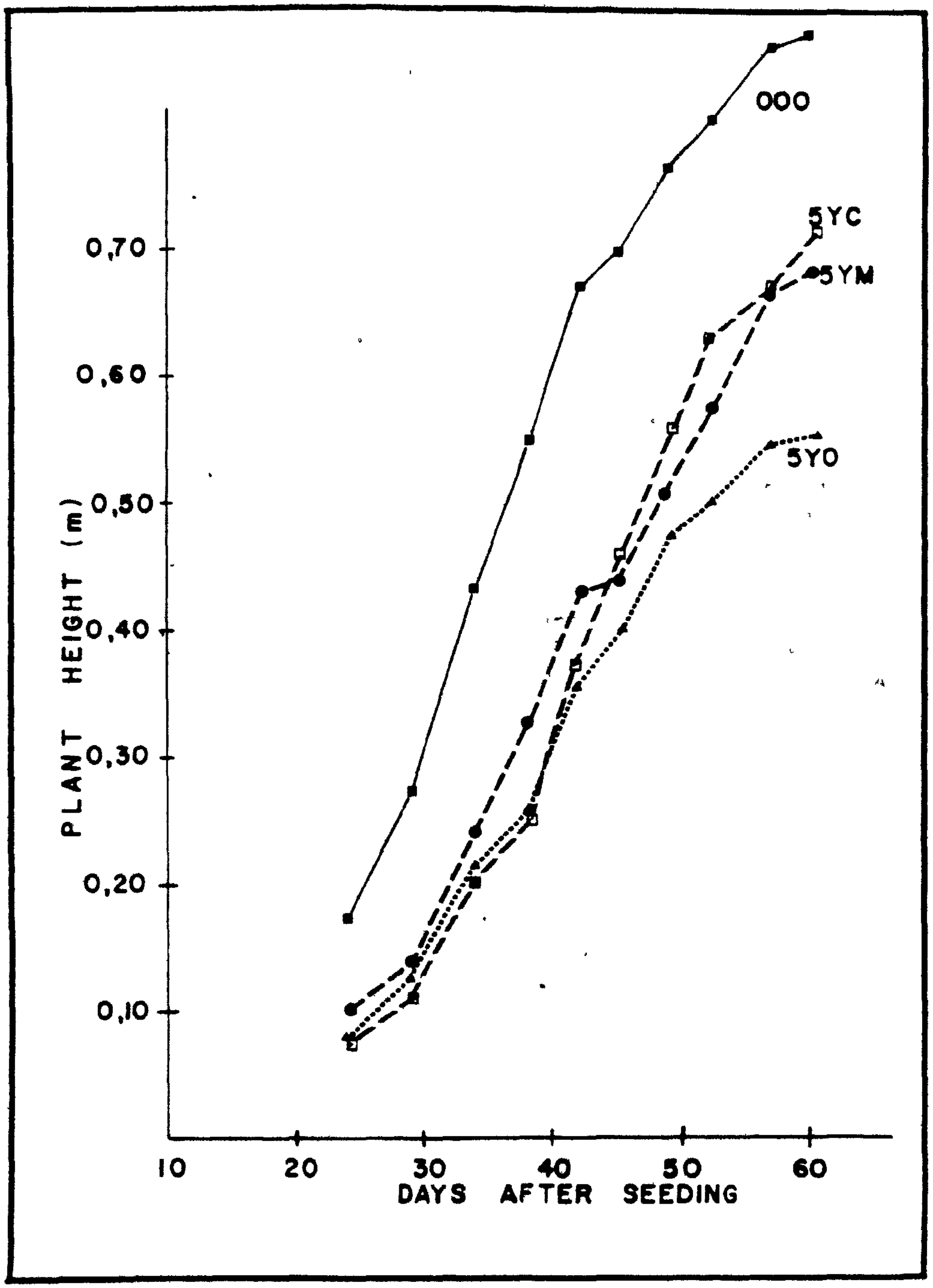


Figure 5.27 Rate of plant growth as affected by various compaction and tillage treatments during the growing season.

chisel plow treatment when compared to the 5YO (moderately compacted-no tillage) treatment. However, 42 days after seeding, plants in the moldboard plots showed rapid rates of growth, passing the 5YO treatment. The most interesting point to note is that this rate of growth in the plowed treatment also surpassed the 5YC treatment when observed at 45, 49 and 52 days after seeding, but slowed down when observed on the last observation, i.e. 60 days after seeding, representing the maximum plant height of 68cm. The maximum plant height of 70 cm was found in the 5YC treatment, and the lowest plant height of 55cm was found in the 5YO treatment.

The effect of moldboard and chisel plow action on severely compacted plots (15 passes) is shown in Figs. 5.28 (1978) and 5.26 (1979). It can be seen that the tillage has remarkably improved soil conditions which provide a healthy environment for plant growth. In the early stages of growth for the summer of 1978, the difference between chisel (15YC) and severely compacted plots (15YO) was hardly noticeable but moldboard plots showed the greatest height at the beginning of the observations and at 34 days after seeding, as compared to severely compacted-no tillage (15YO) and severely compacted tillage (15YC) plots. Thereafter, this disparity gradually decreased and was finally reversed, so that at maturation (60 days after seeding) chisel plots (15YC) attained the greatest plant heights, followed by the moldboard (15YM) plots, when compared with the severely compacted-no tillage plots (15YO).

In the 1979 summer (Fig. 5.26), the growth pattern was

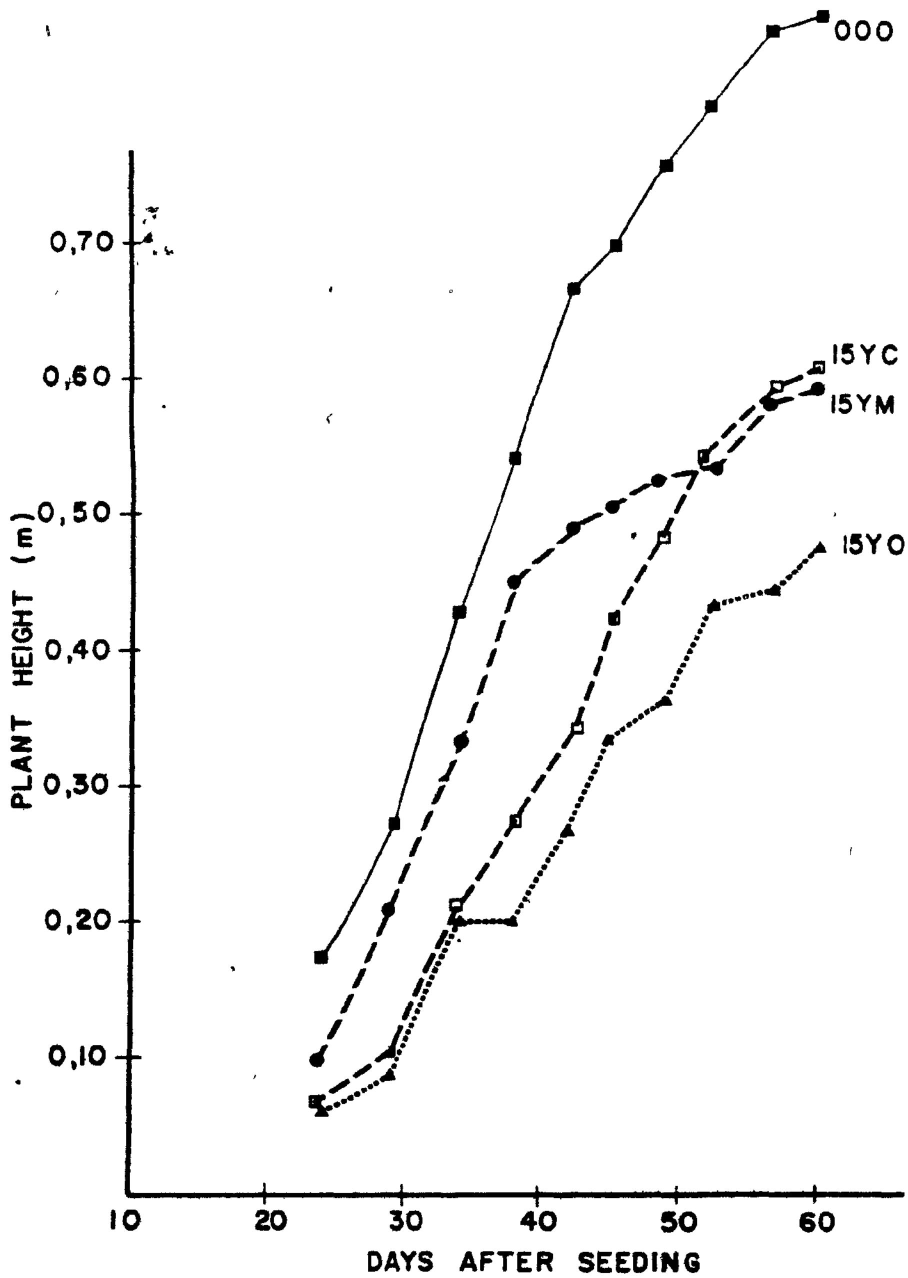


Figure 5.28 Rate of plant growth as affected by various compaction and tillage treatments during the growing season.

similar for tillage plots compared with severely compacted-no tillage plots (15YO), but the only difference was the greater height at the time of maturation observed in 1979. This difference was about 38% and 92% for moldboard (15YM) and severely compacted (15YO) plots, respectively, as compared to the 1978 growing season. This could have been due to the relatively droughty conditions during the growth period of 1978.

Overall plant heights observed in 1978 and 1979 for each compacted and tillage treatment at the time of harvest can be arranged in descending order as follows: 87, 70, 68, 61, 59, 55, 52 and 48 cm for 000, 5YC, 5YM, 15YC, 15YM, 5YO, 10YO and 15YO, treatments respectively in 1978, whereas in 1979 the plant heights were 99, 95 and 92 cm for the 000, 15YM and 15YO treatments, respectively.

c) Yield

In order to quantify the effects of compaction and tillage treatments, the dry weight of the plant (kg/ha) and average dry mass of the roots (mg) were used as the basis for assessing the treatment differences over the course of whole season of 1978. Fig. 5.29 demonstrates the dry weight of the plant response to various treatments. The dry plant yield under compacted treatments (5, 10 and 15YO) was found to be very low as compared to that of the no tillage treatment (000). This difference was about 85% in both 10 and 15YO and 72% in 5YO treatments. Although the moldboard and chisel plows on compacted plots had lower yields than that of the no tillage treatment (000), they certainly increased the yield in comparison with respective compaction plots. When

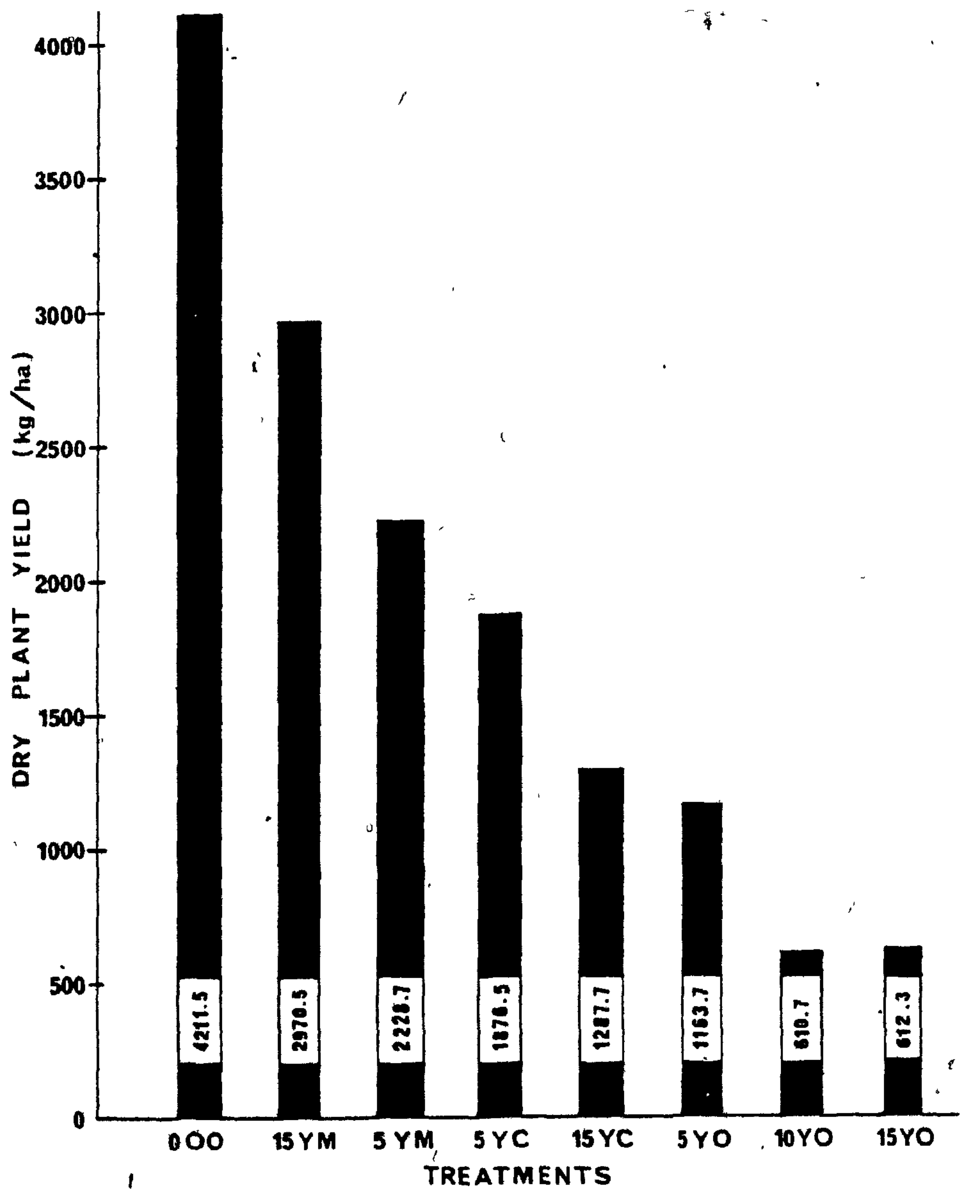


Figure 5.29 Effect of compaction and tillage treatments on dry plant yield of buckwheat.

severely (15 passes) and lightly (5 passes) compacted plots were tilled with the moldboard plow, the dry plant yield was increased by about 5 and 2 times respectively. The chisel plow also had the same effect in increasing the yield by 110% in 15YC and 61% in 5YC, when compared to severely compacted-no tillage (15YO) and lightly compacted-no tillage (5YO) treatments, respectively. The order of treatments in terms of yield performance can be given as follows:- OOO, 15YM, 5YC, 15YC, 5YO, 10YO and 15YO.

In the same year the average dry mass of the root/plant was also observed and is presented in Fig. 5.30. It seems that the compacted plots restricted the root development, which consequently resulted in less average dry mass. Lightly compacted plots (5 passes) subsequently tilled with a moldboard plow gave the highest average dry mass of the root/plant of any treatment. No tillage (OOO) was the second highest in this case, and the severely compacted-no tillage treatment (15YO) had the least average dry mass of the root/plant. Comparing the performance of moldboard and chisel plows on both compaction levels (5 and 15 passes), it was found that the moldboard plow treatment had approximately 98% and 27% higher yields than chisel plow treatments in the case of lightly compacted (5 passes) and severely compacted (15 passes) treatments.

In the 1979 summer, grain yield (kg/ha) was used in order to provide evidence of possible differences in treatments. The results are shown in Fig. 5.31. It can be seen that the severely compacted-no tillage treatment (15YO) produced 27% less yield than that of the no-tillage treatment (OOO). It can also be noted that

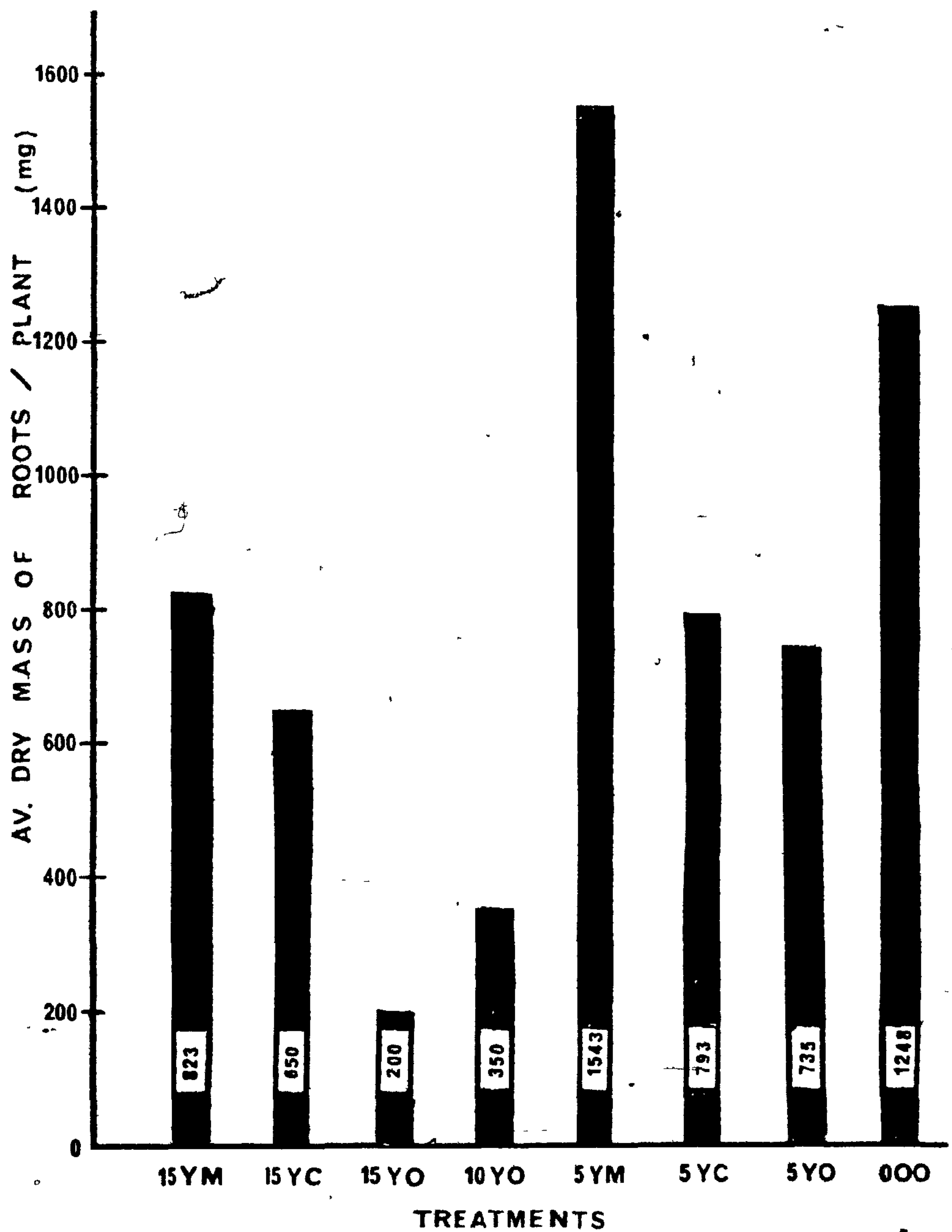


Figure 5.30 Effect of compaction and tillage treatments on dry mass of the root of buckwheat.

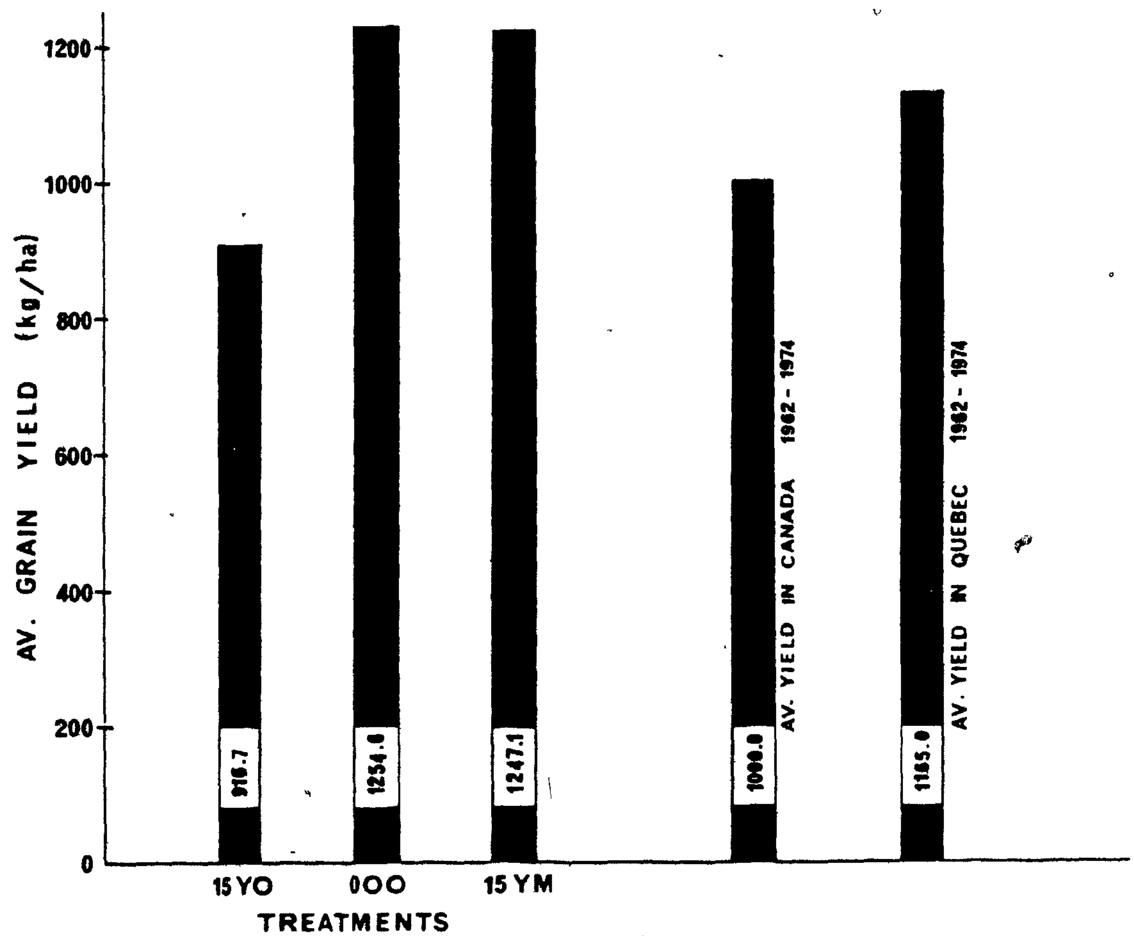


Figure 5.31 Effect of compaction and tillage treatments on grain yield of buckwheat.

the plowed plots (15YM) gave about the same yield as the no tillage treatment, but increased by about 36% as compared with severely compacted-no tillage treatment (15YO).

CHAPTER VI

DISCUSSION

The basic objective of this study was to find the effects of compaction, and the effectiveness of the tillage tools on compacted soils, with respect to soil physical properties and the response of crop production.

Compaction, which can occur during standard crop growing practices, when machines drive several times over the field, can deteriorate soil structure, depending on many variables which include the characteristics of the load applied, the number of passes and the condition of soil at that time. As a simple case 5, 10 and 15 passes of a tractor (MF-165D) with a contact pressure of 41 kPa were done on a clay soil and their damage to soil physical properties was examined. These plots were then subsequently tilled by a moldboard and chisel plow to see the effectiveness of these plows in minimizing the damage of the soil caused by compaction.

Experiments were conducted at the Macdonald College seed farm to measure certain physical properties of the soil in relation to induced artificial treatments throughout the growing seasons of 1978 and 1979. The results obtained from the field are discussed below.

6-1 Traffic and Physical Properties

It is concluded from the study that the deterioration of soil looseness under the effect of compaction was very distinct. Determinations of soil density suggest that this deterioration occurred throughout the soil profile, especially when the traffic over the same path increased in intensity. The density pattern due to compaction, as influenced by soil moisture content and varying number of passes, will be considered first. In 1978, the soil moisture content in the top 0,05 and 0,10m was in the range of 10 to 18 percent and 23 to 29 percent, respectively. It is obvious that at 0,10m depth, one can expect a higher resultant soil density due to an "optimum" level of moisture content for maximum compaction. It should be remembered that "optimum" moisture content for maximum soil density of this clay soil was found to be 27 percent by weight by the standard Proctor test. Below the depth of 0,10m, there was little or no effect of compaction, which could be due to moisture content ranging from 30 to 48 percent by weight, above the "optimum" range for maximum compaction. In 1979, the average moisture content was found to be 15 and 24 percent for 0 - 0,15 and 0,15 - 0,30m depths, respectively. Upon driving the tractor once, greater compaction occurred at lower depths due to moisture content most favourable for maximum compaction found at these depths; the effect was additive to the upper layers as the passes of the tractor increased. The significantly higher values of soil density compared to the no-compaction treatment (000) up to a 0,20m depth were noteworthy. Also, soil density values obtained by 15 passes of the tractor in 1979 were greater than in 1978. It appears that the soil, during the initial measurements, was considerably looser, and its moisture content was at its "optimum" level for maximum compaction; these conditions are extremely favourable for a decrease in volume of soil, even with lighter loads.

Along with the bulk density increase is an increase in the mechanical strength of the soil mass. Resistance of soil to penetrometer and vane shear proved this situation.

Field results indicated that the penetrometer resistance was more sensitive to moisture content variations than was the change in density. For example, on one occasion, the density values in the moderately compacted treatment were not significantly different from those in the no compaction treatment, even at a 10 percent probability level in the top 0,05m of soil. On the other hand, there was a significant difference at the 1 percent probability level for penetrometer resistance values. This is because of the low moisture content in the top 0,05m, which increased the resistance of the soil to the penetrometer. It can also be noted that the soil density in the top 0,05m was less than at the 0,10m depth, whereas, the resistance of the soil to the penetrometer was more. This was due to a higher moisture suction at the 0,05m depth than at the 0,10m depth. Although the penetrometer was influenced by moisture content, it clearly defined the soil profile with respect to compaction levels. It is concluded that the resistance of soil to a penetrometer increased with the increase of compaction effort.

In interpreting the vane shear resistance results, it appears that the shear strength of the soil increased as the bulk density increased. At lower depths, vane shear resistance did not show any significant differences between treatments, because at the higher moisture contents the vane shear resistance is about the same (Freitag, 1971). The moisture contents observed at lower depths in both years were higher than those in the surface layers.

Upon compaction, the pore geometry of a soil is altered in such a way that changes in the magnitude of aeration and moisture holding capacity result. The aeration status of a soil is represented in terms of air-filled porosity. The calculated results of air-filled porosity in both years suggest that the increase in density and moisture content in compacted plots decreased the aeration status of the soil appreciably, especially at lower depths. These low values were noticed in the 0,20 - 0,25m depth range in 1978, below the critical value of 10%. These conditions at lower depths may provide anaerobic conditions for plant growth and hamper root elongation into sub-layers. If the soil contains iron and manganese, the reduction of oxygen will frequently result in a toxic formation which can affect root growth and complicate the direct effect.

The reduction of volume due to compaction caused a decrease in size of individual pores of the soil media which affected the capacity of soil appreciably in terms of water retention and transmission characteristics. The low moisture content in severely compacted plots at the beginning of the observation, suggests that the rate of infiltration was very slow and required more time than that of other treatments. The longer time required for the advancement of water into the soil increased the evaporation losses from the soil surface during the infiltration period, ultimately decreasing the moisture intake into the soil profile. The effect of compaction may be explained in terms of void geometry. Upon compaction the larger voids are decreased and produce more smaller voids which retain water at higher suction levels. In other words, the magnitude of moisture content becomes greater as the suction increases. In clay soils, increasing the bulk density increases the capacity of the soil to retain water (Hill and Sumner, 1976). The results of severely compacted (15 passes) treatments substantiated these findings. Water transport in the soil is very sensitive to soil compaction because the infiltration characteristics are affected. The unsaturated hydraulic conductivity rate is closely related to bulk density and water content. As the bulk density increases, there is a rapid decline in hydraulic conductivity as observed by Koshi and Fryrear (1973) and Negi *et al.*, (1977). This is because the increase in bulk density decreases the effective size of voids, resulting in lower hydraulic conductivity. Similar results were obtained in severely compacted (15 passes) soil which produced high soil bulk density by reducing the voids, and decreased hydraulic conductivity by 25 times at 38% volumetric moisture content when compared to the no-compaction (000) soil.

6-2 Tillage and Physical Properties

The basic purpose of tillage is to provide a good seed bed for the development of root and shoot growth. Spoor (1975), cited by Soane and Pidgeon (1975), suggests that the tillage effect should be defined by the resulting soil condition, not by the implement used. Tillage of compacted soils provides a complexity of soil property alterations. For example, the moldboard plowing of compacted soil does not achieve a high degree of loosening, but some unfractured clods persist (Soane and Pidgeon, 1975), whereas chisel plowing results in less inversion and more shattering of compacted soil (Cooper, 1971). The effect of both plows in altering the soil properties indicated a considerable difference on different compaction levels. However, the changes in physical properties measured in the field reveal that the tillage has markedly lowered dry bulk density, resistance of soil to a penetrometer and vane shear, and has increased air-filled porosity, availability of water and hydraulic conductivity. The moldboard and chisel plows had significantly lowered dry bulk density values in the top 0,10m and 0,05m depths as compared to the severely compacted plots. There were no significant differences in bulk density values in the moldboard and chisel plow plots, but their magnitude and consistency warrant some discussion.

The results of this study suggest that the chisel plow was more effective in decreasing dry bulk density at the surface than at lower depths, whereas the moldboard had the opposite effect. The effect of the moldboard plow was more in reducing dry bulk density by up to 0,18 g/cm^3 compared to compacted-no-tilled soil. Higher dry bulk density profiles were observed in chisel plots than in moldboard plots. These results are in agreement with those of Soane and Pidgeon (1975). The results are more interesting when density profiles of plowed plots of both years are compared. When severely compacted soil (15 passes) was subsequently tilled by the moldboard plow in 1979, the average dry bulk density of the 0 - 0,25m soil layer was lowered more than twice as much as in 1978. This is because the moisture content in 1979 was more suitable for tillage operations. The average moisture content of the 0 - 0,25m depth was about 20 percent and, from the 0,25 - 0,30m depth, was 24%. The suitable moisture for plowing shown by Davies et al., (1972) is 2 percent lower than the "optimum" moisture content on the Proctor compaction curve. The values of moisture content for the 0 - 0,25m soil layer were 4 - 5 percent below the "optimum" moisture content. The plow was operated below its normal depth and has created a plow sole which has increased the dry bulk density of the 0,25 - 0,30m soil layer from the original soil by about 0,15 g/cm^3.

It was expected that lowering the dry bulk density would reduce the soil strength. It appears from the results that the penetrometer resistance did not depend so much on bulk density but rather on the traffic and tillage effect (Negi et al.,1979). The results of penetrometer resistance were affected by different tillage treatments at various compaction levels, and variation of moisture content. Nevertheless, tillage has reduced the resistance of soil to the penetrometer effectively up to a 0,20m depth, and values have nearly approached those of the no tilled (000) soil. The most decrease was found in the top 0,10m. A comparison of the results of both years indicate that the soil penetrometer resistance in severely compacted plots, subsequently tilled by the moldboard plow, was higher in the top 0,15m in 1979 than in 1978. As the depth increased, the decrease in resistance was more pronounced. This is because the average gravimetric moisture content of the 0 - 0,15m soil layer in 1979 was 9% less than that in 1978. Voorhees et al., (1978) also showed that high penetrometer resistances were associated with a 4% decrease in gravimetric moisture content on silty clay loam soil.

The vane shear resistance in 1979 was considerably decreased in severely compacted soil subsequently tilled by the moldboard plow in the top 0 - 0,15m, but increased at a 0,30m depth by up to 10 kPa

These results are consistent with the low and high bulk density values obtained at the top 0 - 0,15m and at 0,30m depths, respectively, in the same treatment. In fact the results were significant up to a 0,15m depth. The results of vane shear resistance profiles of both plowed and chiselled plots in 1978 showed no significant difference when compared to each other. However, each plow had some effect at different compaction levels. Severely compacted plots (15 passes), when subjected to chisel and moldboard treatments, showed some differences in vane shear resistance with soil depths. The chisel plow had decreased the vane shear resistance at a 0,10m depth appreciably more than at 0,025 and 0,20m depths, whereas the moldboard had decreased the values throughout the profile, especially at a 0,10m depth. In the case of lightly compacted plots (5 passes) the chisel and moldboard plow treatments had considerably decreased vane shear resistances at a 0,20m depth, and the magnitude of resistance was the same in both treatments. The effect of the moldboard plow in decreasing soil strength was more in the top 0,10m depth than in the case of the chisel plow. These results suggest that the chisel-type tillage implement can effectively shatter the soil structure, depending on the degree of compaction. It was seen during tillage operations in the field that the chisel plow was not able to break the large masses of soil into small aggregates on severely compacted soil, and it formed cracks into which surface soil was falling. The higher vane shear resistance in the top 0,025m was likely to be the reconsolidation of surface soil, whereas the moldboard plow provided a granular structure due to shearing and inversion action, resulting in lower vane shear resistance values for the whole profile.

The aeration status and hydrology of the soil are influenced by the pore geometry, and this is altered by tillage operations. Decreasing the soil density increases the porosity at a constant moisture content, resulting in an increase of air-filled pores. In the field an increase in air-filled porosity can be achieved by decreasing soil density with the help of tillage tools. Larson (1964),gave an example showing how tillage affects the air-filled porosity and storage of water at the normal plow depth of 18cm at field capacity, which he termed as "plow layer storage". When an 18cm thick layer initially having 8,4cm of water at a bulk density of 1,4 g/cm^3 is loosened by plowing to a bulk density of 1,0 g/cm^3,the total porosity is increased from 47 to 62% and the thickness of the layer increased from 18cm to 25cm. As a result, the amount of water increased by up to 15,5cm. Suppose the field capacity is 25% by weight, and the plow layer storage is 2,3cm initially, then the subsequent plowed soil will have about 9,4cm of storage. It is therefore expected that the tillage, which has decreased the bulk density, would have naturally increased the air-filled porosity and thus moisture storage. The results of the field experiments suggest that the moldboard and chisel plows have effectively increased the air-filled porosity up to a 0,15m depth, and, in some instances, rendered the soil equivalent to the no-till plots. At deeper depths the moldboard plow has decreased air-filled porosity values in both years, which is simply due to the higher bulk density and moisture content observed in these treatments. It was expected, during the growth period of 1978, that the soil-plant root system and time may change the air-filled porosity values, but only a 5% increase in air-filled porosity was found one month after seeding. Hence, in 1979, no observation of porosity was repeated during the growth period. The above results obtained are consistent with the bulk density and moisture content variations described previously in each treatment.

The theoretical treatment of water movement predicts that the physical properties of a soil affect the rates at which water moves in response to suction gradients. The reduced rates of movement through a porous body are due to the cross-sectional area of individual pores, which are the main contributors to the passage of water, and it is also due to increased path lengths imposed by the geometrical arrangement of pores. Therefore, a decrease in density due to tillage affected the geometry of the soil, and resulted in higher downward movement (Fig. 5.18) and higher hydraulic conductivity values observed in the chisel plots. The lower volumetric moisture content values in chisel plots at the beginning of the observation were due to the fact that the plants have covered the area where the tensiometers were installed and most of the rain was intercepted by the plants, resulting in less water received around the tensiometer gauge area.

6-3 Physical Properties and Crop Response

It is seen, from the physical properties of soil, that compaction has increased the dry bulk density, penetrometer resistance and vane shear resistance values significantly up to 0,15, 0,25 and 0,10m depths. Whereas the moldboard plow was more efficient than the chisel plow, and lowered the values significantly up to 0,15m depth. However, both conditions in the field could result in decreased or increased plant growth.

A consideration of the emergence of seedlings suggests that a delayed emergence in 1978 was not only due to the compaction levels, but also to the moisture stress at the beginning of the 1978 growing season. The rainfall data in Figs. 6.1 and 6.2 shows that there was no rainfall for about one week after seeding in 1978, but in 1979 there was rainfall immediately after seeding. Therefore, it is evident that less moisture contact during emergence in 1978 caused a delayed emergence of seedlings. The promising effect of tillage on emergence is clear from the results of the 1979 experiment. Emergence was delayed, on an average, by 4 days in compacted soil compared to the moldboard tilled soil. The moldboard seemed to be more effective in disrupting the compaction layers and resulted in earlier emergence and the same grain yield as that of no compaction plots. This yield, when compared to average yields of Canada* and the province of Quebec*, averaged 25 and 8 percent more, respectively (Fig. 5.31).

*Bulletin trimestriel de la statistique agricole. Ministère de l'Industrie et du Commerce, Bureau des Statistiques. S.A. 241-J:51. Janvier-Mars, 1969, 1975; Province de Québec.

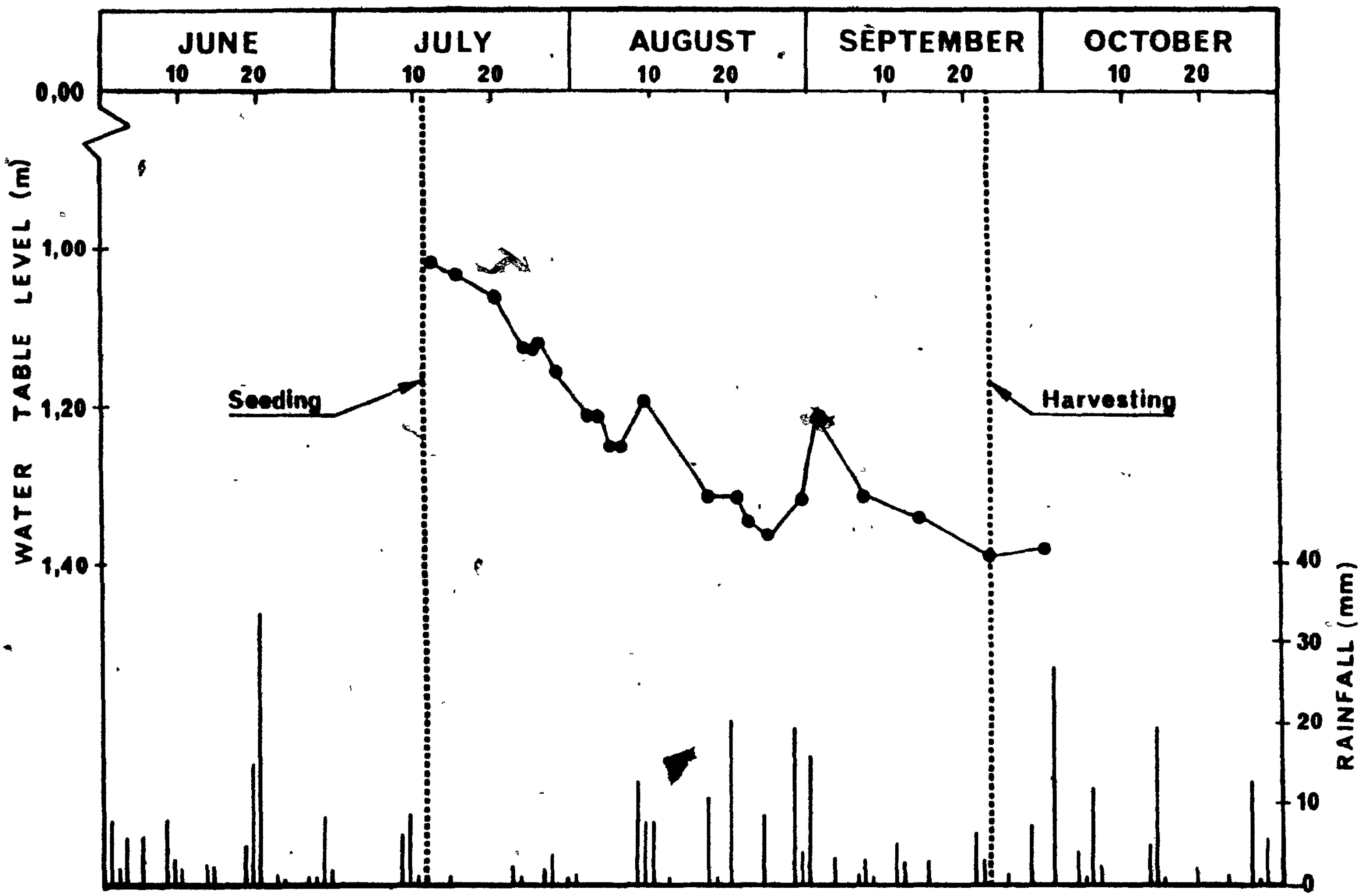


Figure 6.1 Water table fluctuations and rainfall during the growing season of 1978.

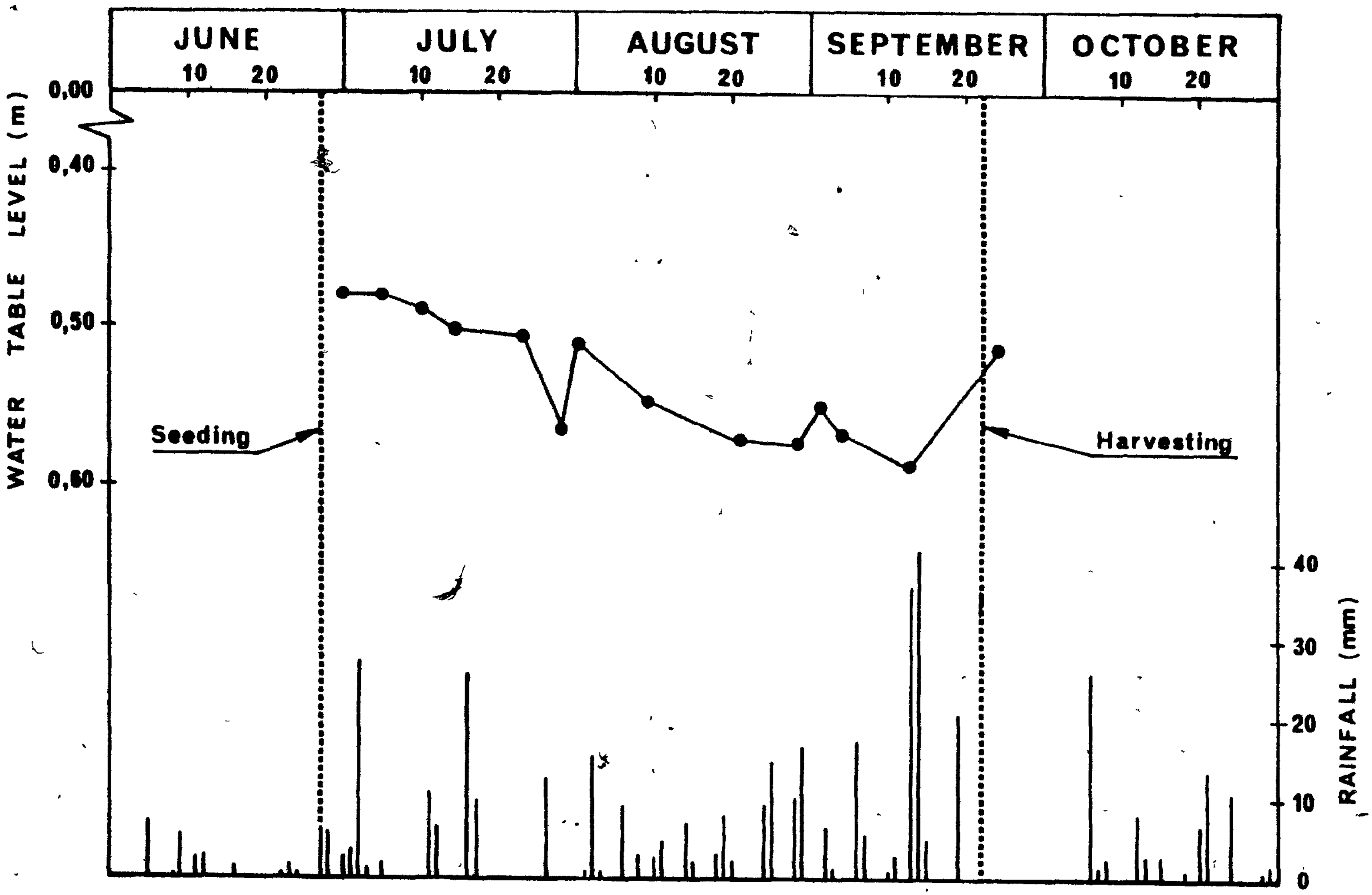


Figure 6.2 Water table fluctuations and rainfall during growing season of 1979.

In using the plant emergence as an indicator of crop yield, one might gain a false impression,even if the time allowed for maturation was equal in both years. The difference in plant heights at a given day after seeding can be attributed to plant emergence, but the development of the plant system is dependent on environmental conditions of the subsoil as well as climate. However, in 1978, the buckwheat was grown late in June, which was about one month later than that of 1979, and late sowing could have affected plant growth. The results of both years suggest that the poor environmental conditions provided by compaction have resulted in smaller plant heights, whereas subsequent tillage improved soil conditions and allowed greater plant heights. The climatic factors, such as temperature and rainfall variation, play an important role in plant growth. The most important factor observed during the growing season of 1978 was a less than average rainfall, which provided dry conditions for the needs of rapidly transpiring plants. The average rainfall from July to September was 55 and 116mm for 1978 and 1979 growing seasons, repsectively. Evidently the water table in 1978 was lower than that found in 1979 (Figs. 6.1 and 6.2).

Compaction decreased the air-filled porosity, only at lower depths in severely compacted and plowed plots, and could not have affected the growth of roots because only few roots might have penetrated to this depth. Actually, the root length of buckwheat was observed to be approximately 0,20m. Therefore, the average bulk density and penetrometer resistance of the 0 - 0,20m soil layer were calculated for various compaction and tillage treatments and related to plant parameters, as summarized in Tables 6.1 and 6.2.

TABLE 6.1 - Average dry bulk density, penetrometer resistance and vane shear resistance of 0 - 0,20m soil layer for various treatments and their effect on plant growth, for the growing season of 1978.

TREATMENTS	DRY BULK DENSITY (g/cm^3)	PENETRO-METER RESISTANCE (MPa)	VANE SHEAR RESISTANCE (kPa)	DRY PLANT YIELD (kg/ha)	ROOT MASS (mg)	PLANT HEIGHT (cm)	DAYS TO EMERGE (days)
5YO	1,220	4,05	33,12	1163,7	735	55	24
10YO	1,143	4,40	47,08	610,7	350	52	24
15YO	1,182	5,08	52,75	612,3	200	48	25
15YC	1,139	3,29	47,83	1287,7	650	61	23
15YM	1,046	3,48	43,77	2970,5	823	59	22
5YC	1,069	3,04	43,05	1876,5	793	70	23
5YM	1,112	3,66	48,03	2228,7	1543	68	22
000	1,026	3,32	26,75	4211,5	1248	87	22

TABLE 6.2 - Average dry bulk density, penetrometer resistance and vane shear resistance for various treatments and their effect on plant growth for the growing season of 1979.

TREATMENTS	DRY BULK DENSITY ** (g/cm^3)	PENETROMETER * RESISTANCE (MPa)	VANE SHEAR * RESISTANCE (kPa)	DAYS TO EMERGE (days)	PLANT HEIGHT (cm)	GRAIN YIELD (kg/ha)
000	1,039	1,16	19,32	9	99	1254,6
15YO	1,341	4,03	62,24	17	92	916,7
15YM	1,123	2,34	30,03	13	95	1247,1

* 0 - 0,15m soil layer

** 0 - 0,20m soil layer

It is most probable that the growth of roots might have been affected by the mechanical impedance. The penetrometer does not measure exactly the forces encountered by the growing roots, but provides only an index of soil resistance. Roots penetrate into the soil more easily than the penetrometer probe by following paths offering less than average resistance (Camp and Lund, 1968). Nevertheless, the dry weight of the root indicates that the vertical proliferation of the root system was impeded as the penetrometer resistance increased and thus resulted in less dry plant weight.

Roots are the main source supplying water and nutrients from the soil to the entire growing plants. Therefore, it is necessary for the roots to exploit large volumes of soil for easy access to supply. If the supply is scarce, the growth will be retarded or poor growth results. The factors which affect the plant growth, also affect the availability of soil water to a greater or lesser extent. For example, the increase in soil density decreases the permeability of the soil and therefore the recharge of the soil could be greatly affected and result in less availability of water to the plant. The effect will be greater in a dry year than in a wet year. Availability of soil water, as observed in the 1978 growing season, was closely correlated with the dry plant yield. Compaction decreased the availability of soil water and decreased the dry matter yield by about 85%, while subsequent tilling with a chisel plow increased the availability of water and increased the dry plant yield by about 110%. The results suggest that, besides mechanical impedance, the availability of water was also affected by soil compaction due to lower transmission through the compacted layers, and influenced the plant growth. The lower hydraulic conductivity (the rate at which water is supplied to the plants) with lower dry mass of the root (may be shallower or less root density) in compacted soil may have been the limiting factors for the supply and uptake of the required amount of water to the transpiring plants.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Field studies to determine the effects of compaction (5, 10 and 15 passes) and tillage with moldboard and chisel-type implements on soils with two compaction levels (5 and 15 passes) were set up in the Macdonald College seed farm for the two seasons of 1978 and 1979.

The grain size analysis classified the soil in the tests as clay. The compaction tests indicated the optimum moisture content for maximum density after a fixed amount of loading. Plastic and liquid limit tests showed the critical moisture levels at which soil tends to crumble and shear.

Tillage and compaction effects were measured in terms of soil bulk density, penetrometer resistance, vane shear resistance, unsaturated hydraulic conductivity, and crop response. A buckwheat variety served as the test crop.

The soil density, vane and penetrometer resistance profiles for various compaction levels were compared with no compaction soil plots. A compacted soil subsequently tilled by moldboard and chisel plows was compared with respective compacted soils.

Upon compaction, the maximum increase in density, vane shear and penetrometer resistance occurred from 0,10 to 0,15m depths, depending on compaction levels. Subsequently tilled soils indicated lower values up to a 0,25m depth. Below this depth the moldboard plow produced a plow pan. Otherwise there was no significant difference between moldboard and chisel plow plots.

Air-filled porosity values, which were calculated from the measurements of dry bulk density and moisture content at each soil depth, indicated lower values in compacted soils and higher values under tilled soil conditions. Moldboard and chisel plow plots tended to lower air-filled porosity values below the plowing depth.

Water retention characteristic curves for various compaction and tillage treatments at 0,25m depth were obtained from the smoothed values of moisture contents against the field values of soil suction in the range of the tensiometers. The values above this range were obtained from the relationship of Campbell (1974), in order to calculate the availability of water. The consequences of compaction and tillage effects on water retention characteristics and availability of soil water determinations are illustrated. Soil bulk density changes due to compaction and tillage have been shown to have a marked effect on water retention characteristics of the soil and moisture availability.

The unsaturated hydraulic conductivity of the soil under different compaction and tillage treatments was calculated as a function of moisture content $[K(\theta)]$. Calculated unsaturated hydraulic conductivity showed a strong relation to soil compaction and moisture content.

Soil compaction showed a definite effect on plant growth characteristics. The time for seedling emergence increased, while growth rate, dry weight of the root mass, dry weight of the plant and grain yield were decreased as the compaction level increased. When the compaction was alleviated by tillage, all growth parameters were increased; the moldboard plow was especially effective in loosening the soil, resulting in better plant performance.

In separating the effects of soil physical properties, air-filled porosity could not have been the limiting factor affecting plant growth because the measurements of roots indicated a root length less than 0,20m. Mechanical impedance and moisture availability are probably the important factors responsible for the reduced plant growth.

The conclusions of this study can be stated as follows:

(1) The repeated passes of the tractor caused increases in soil density. The maximum soil density was found 0,10m below the surface of the soil in both years. A comparison of both years showed that soil dry density is strongly dependent on moisture content and initial status of the soil.

(2) Penetrometer resistance was more sensitive than soil dry density measurements in showing the structural consistency of the soil profile effectively as a result of the increase of compaction efforts.

(3) Vane shear resistance, unlike the penetrometer, did not show a definite difference among treatments at lower depths, but was dependent on the dry bulk density of the soil.

(4) Unsaturated hydraulic conductivity and air-filled porosity showed a strong dependence on the dry bulk density and moisture content of the soil. Increasing densities reduced the void sizes and decreased the unsaturated hydraulic conductivity by about twenty-five fold at a constant volumetric moisture content.

(5) Plowing was more effective than chiselling in decreasing soil dry bulk density and vane shear resistance from 0 - 0,15m depths, but penetrometer resistance showed a decrease up to 0,25m depth in soils subjected to plowing and chiselling.

(6) The results of 1979 suggested that the tillage would be more effective in providing appropriate soil structure for plant growth if the soil, at that time, is under suitable conditions for tillage operations.

(7) Tillage of compacted soil by a chisel plow improved the physical condition of compacted layers and increased the conduction properties of soil, accompanied by increased rates of water entry or a larger volume of water available for plants. While compacted soil had retained more water at higher suctions due to smaller voids, this water was not readily available for plants due to higher suction levels.

(8) Compaction produced a lower hydraulic conductivity and the soil could not supply water according to the transpirational demand of the plants. However, the compacted soils subjected to chisel plow action had increased hydraulic conductivities which augmented plant growth and increased yields.

(9) Despite the compaction and tillage effect, the dry and wet seasons also had a great influence on plant growth. The 1978 season was relatively drier than the 1979 season and plant growth was correspondingly less.

(10) Compaction has resulted in poor emergence together with lower plant heights, dry root mass and dry matter yields. The magnitude of reduction was greater from light to severe compaction.

(11) Severe and moderate compaction of soils have reduced dry matter yield by about 85 %, whereas lightly compacted soil has reduced it by about 72 percent. Plowing by moldboard and chisel tools of compacted soils has increased dry matter yield by about 385 and 110 percent, respectively.

(12) Compacted soils, subsequently tilled by a moldboard plow, produced the highest dry root mass.

(13) In the 1979 growing season, the grain yield of buckwheat was reduced by 27% in severely compacted soil. When this soil was tilled by a moldboard plow, the yield was increased by about 36%. The superiority of the moldboard plow can be demonstrated by the fact that grain yields of 25 and 7 percent more than the average yields of Canada and Quebec province, respectively, were measured.

(14) The rate of emergence, plant height, dry weight of root mass, dry matter yield and grain yield were markedly higher in no compaction or tilled soil than in other treatments for both years.

(15) A very narrow dry bulk density range of 1,026 to 1,046 g/cm^3 produced the highest yields in 1978, whereas a higher dry bulk density range of 1,039 to 1,123 g/cm^3 was the best for yields in 1979.

Suggestions and Recommendations for Further Research

An investigation of soil physical property changes due to compaction and subsequent tillage indicates that the compaction by tractor traffic has adversely affected the soil properties and reduced the plant growth. On the other hand, a compacted soil subjected to tillage has markedly improved the physical constraints of the soil and increased the crop yield. A narrow range of soil density in a dry season and higher range in a wet season indicate that the seasonal variations have a great influence on machinery management effects. In a wet season, even soil with high density did give better results in plant performance, because of the adequate moisture supply to the rapidly growing plants. It is therefore advisable to avoid as much traffic as possible in the dry season. If the traffic is reduced then there might be no need for tillage.

The moldboard plow proved to be better for this crop in the particular climatic conditions, but it may diminish the yields for other crops. The development of a plow pan under the normal depth of plow could restrict the growth of longer roots due to impedance and low root aeration. The plow pan does not seem to be formed by the plow, but by the tractor tire riding in the furrow bottom. The out-of-furrow plow could be utilized and compaction can be minimized by reducing the amount of field traffic.

This study gives some knowledge of soil physical properties altered by compaction and subsequent tillage, but still more comprehensive knowledge could be gained by studying a dynamic system, the so-called "SPA" (soil-plant-atmoshpere). Field experiments on compaction and machinery use could well be conducted with the additional measurements of the interaction of soil physical conditions with climatic factors. For example, the hydrology of the soil depends on the atmospheric conditions as well as on induced changes by compaction and loosening of the soil, which may be of greater importance to the growing plants, than the changes in bulk density or strength. However, uptake of water by plant roots should be considered in studying the water status in the soil. The absorption of water by plant roots depends on the plant properties (e.g. rooting density, depth and rate of extension), soil properties (e.g. stroage, conductivity, suction inter-relations) and micrometeorological conditions (evaporation). These properties should be studied to consider the subject in its broadest terms if the full understanding of the soil in relation to machinery management is to be gained. The study should be conducted with different soils and crops under various climatic conditions, which may help in developing a mathematical model. Once the model is developed, it will be easier to make the recommendations for efficient machinery management on a variety of soils, crops and climate.

BIBLIOGRAPHY

Adams, E.P., Blake, G.R., Martin, W.P., and Boelter, D.H. 1960. Influence of soil compaction on corn growth and development. 6th Int. Congr. of soil sci. 26: 607-614.

Ahuja, L.R. 1973. A numerical and similarity analysis of infiltration into crusted soils. Water Resour. Res. 9(4): 987-994.

Allmaras, R.R., Rickman, R.W., Ekin, L.G., and Kimball, B.A. 1977. Chiselling influences on soil hydraulic properties. Soil Sci. Soc. Amer. Proc. 41: 796-803.

Amemiya, M. 1977. Conservation tillage in the western corn belt. In Conservation Soc. Amer. Special Pub. 20, pp. 29-36.

Amir, I., and Broughton, R.S. 1975. Principles of an operational model for evaluating suitability of wet soil for plowing, planting and haulage. CSAE Paper No. 75-413.

Amir, I., Raghavan, G.S.V., McKyes, E., and Broughton, R.S. 1976. Soil compaction as a function of contact pressure and soil moisture. Can. Agric. Eng. 18: 54-57.

Arndt, W., and Rose, C.W. 1966. Traffic compaction of soil and tillage requirements. J. Agric. Eng. Res. 3: 170-187.

ASAE-SSSA. 1958. Joint Soil Compaction Committee Report. Soil compaction research, TRANSACTIONS of the ASAE 1: 56-64.

ASAE-SSSA. 1958. Joint Soil Compaction Committee Report. Concepts, terms, definitions and methods of measurement for soil compaction. AGRICULTURAL ENGINEERING 39: 173-176.

ASAE-Monograph. 1971. Compaction of agricultural soils. Amer. Soc. Agric. Eng. St. Joseph, MI 49085.

Barley, K.P., Farrell, D.A., and Greacen, E.L. 1965. The influence of soil strength on the penetration of a loam by plant roots. Aust. J. soil Res. 3: 69-79.

Barr, A.J., Goodnight, J.H., Sall, J.P., and Helwig, J.T. 1980. SAS Institute Inc., P.O. Box 10066, Raleigh, N.C. 27605.

Bateman, H.P., Naik, M.P., and Yoerger, R.R. 1965. Energy required to pulverize soil at different degrees of compaction. J. Agric. Eng. Res. 10(2): 132-141.

Baver, L.D. 1938. Soil permeability in relation to non-capillary porosity. Soil Sci. Soc. Amer. Proc. 3: 52-56.

Bertramson, B.R., and Rhoades, H.F. 1938. The effects of cropping and manure applications on some physical properties of a heavy soil in eastern Nebraska. Soil Sci. Soc. Amer. Proc. 3: 32-36.

Blake, G.R., and Aldrich, R.J. 1955. Effect of cultivation on some soil physical properties and on potato and corn yields. Soil Sci. Soc. Amer. Proc. 19: 400-403.

Bolton, E.F., and Aylesworth, J.W. 1959. Effect of tillage traffic on certain physical properties and crop yield on a Brookston clay soil. Can. J. Soil Sci. 39: 98-102.

Boone, F.R., Bouma, J., and de Smet, L.A.H. 1978. A case study on the effect of soil compaction on potato growth in a loamy sand soil. 1. Physical measurements and rooting patterns. Neth. J. Agric. Sci. 26: 405-420.

Box, J.E., and Taylor, S.A. 1962. Influence of soil bulk density on matrix potential. Soil Sci. Soc. Amer. Proc. 26: 119-122.

Brewer, R. 1964. Fabric and mineral analysis of soils. John Wiley & Sons, New York.

Boyer, J.S., and Pherson, M.C. 1975. Physiology of water deficits in cereal crops. Adv. in Agron. 27: 1-23.

Camp, C.R. Jr., and Lund, Z.F. 1968. Effect of mechanical impedance on cotton root growth. TRANSACTIONS of the ASAE. 11(2): 188-190.

Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci. 117: 311-314.

Cassel, D.D., Bowen, H.D., and Nelson, L.A., 1978. An evaluation of mechanical impedance for three tillage treatments on Norfolk sandy loam. Soil Sci. Soc. Amer. Proc. 42: 116-120.

Chancellor, W.J. 1971. Effect of compaction on soil strength. pp. 190-212. In K.K. Barnes et al.(ed). Soil compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

Chancellor, W.J., Schmidt, R.H., and Soehne, W.H. 1962. Laboratory measurements of soil compaction and plastic flow. TRANSACTIONS of the ASAE. 5(2): 235-239.

Chassé, M., Raghavan, G.S.V., Mérineau, F., and McKyes, E. 1975. Compaction of Orchard soils in Southern Quebec. CSAE. Paper No. 75- 316.

Chesness, J.L., Ruiz, E.E., and Cobb, C.J. 1972. Quantitative description of soil compaction in peach orchards utilizing a portable penetrometer. TRANSACTIONS of the ASAE. 15(2): 217-219.

Cohron, G.T. 1971. Forces causing soil compaction. pp. 106-119. In K.K. Barnes et al.(ed). Soil compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

Coleman, G.E., and Perumpral, J.V. 1974. The finite element analysis of soil compaction. TRANSACTIONS of the ASAE. (17): 856-860.

Cook, R.L., and Peikert, F.W. 1950. A comparison of tillage implements AGRICULTURAL ENGINEERING 31 (5): 211-214.

Cook, R.L., Turk, L.M., and McColly, H.F. 1953. Tillage methods influence crop yields. Proc. Soil Sci. Soc., 17: 410-414.

Cooper, A.W. 1971. Effects of tillage on soil compaction. pp. 315-364. In K.K. Barnes et al.(ed). Soil compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

Davidson, J.M., Stone, L.R., Nielsen, D.R., and LaRue, M.E. 1969. Field measurement and use of soil-water properties. Water Resour. Res. 5(6): 1312-1321.

Davies, D.B., Eagle, D.J., and Finney, J.B. 1972. Soil management. Farming Press Ltd., Suffolk, U.K.

Doty, C.W., Campbell, R.B., and Reicosky, D.C. 1975. Crop response to chiselling and irrigation in soils with a compack AZ horizon. TRANSACTIONS of the ASAE. 18(4): 668-672.

Douglas, E., and McKyes, E. 1978. Compaction effects on the hydraulic conductivity of a clay soil. Soil Sci. 125: 278-282.

Eagleman, J.R., and Jamison, V.C. 1962. Soil layering and compaction effects on unsaturated moisture movement. Soil Sci. Soc. Amer. Proc. 26: 519-522.

Earl, J.R. 1965. Methods of soil analysis, Part - 1. Agronomy series No. 9, Amer. Soc. of Agron. Madison, Wisconsin. pp. 400-412.

Eavis, B.W. 1972. Soil physical conditions affecting seedling root growth. III. Comparisons between root growth in poorly aerated soil and at different oxygen partial pressures. Plant and soil 37: 151-158.

Eavis, B.W., and Payne, D. 1968. Soil physical conditions and root growth. Proc. 15th Easter School in Agric. Sci. 315-338.

Eden, T., and Maskell, E.J. 1928. The influence of soil heterogeneity on the growth and yield of successive crops. J. Agric. Sci. 18: 163-185.

Elder, W.R. 1958. Soil compaction zones as affected by conservation system. Soil Sci. Soc. Amer. Proc. 22: 79-82.

Fiskell, J.G.A., Carlisle, V.W., Kashirad, R., and Hutton, E.E. 1968. Effect of soil strength on root penetration in coarse-textured soils. 9th Int. Congr. Soil Sci. Trans. 793-801.

Flocker, W.J., Vomocil, J.A., and Vittum, M.T. 1958. Response of winter crops to soil compaction. Soil Sci. Soc. Amer. Proc. 22: 181-184.

Freitag, D.R. 1971. Methods of measuring soil compaction. pp. 47-100. In K.K. Barnes et al.(ed). Soil compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

Gardner, W.R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89: 63-73.

Gill, W.R. 1959. Soil compaction by traffic. AGRICULTURAL ENGINEERING 40: 392-394, 400, 402.

Gill, W.R. 1961. Mechanical impedance of plants by compact soils. TRANSACTIONS of the ASAE: 4(2) 238-242.

Gill, W.R., and Bolt, G.H. 1955. Pfeffer's studies of the root growth pressures exerted by plants. Agron. J. 47: 166-168.

Gill, W.R., and Miller, R.D. 1956. A method for study of the influence of mechanical impedance and aeration on the growth of seedling roots. Soil Sci. Soc. Amer. Proc. 21: 154-157.

Gill, W.R., and Vandenberg, G.E. 1967. Soil dynamics in tillage and tractions. U.S.D.A., Hand Book No. 316.

Grable, A.R. 1966. Soil aeration and plant growth. Adv. in Agron. 18:57-106.

Grable, A.R., and Siemer, E.G. 1968. Effect of bulk density, aggregate size and soil water suction on oxygen diffusion, redox potential, and elongation of corn roots. Soil Sci. Soc. Amer. Proc. 32: 180-186.

Greacen, E.L., Farrel, D.A., and Crockroft, B. 1968. Soil resistance to metal probes and plant roots. Trans. 9th Int. Congr. Soil Sci. (Adelaide) 1: 769-779.

Green, R.E., and Corey, J.C. 1971. Calculation of hydraulic conductivity: A further evaluation of some predictive methods. Soil Sci. Soc. Amer. Proc. 35: 3-8.

Grissom, P., Williamson, E.B., Wooten, O.B., Fulgham, F.E., and Raney, W.E. 1955. Cotton yields doubled by deep tillage in 1954 tests on hard pan soils in Delta. Miss. Farm Res. 18: 1, 2.

Gooderham, P.T., and Fisher, N.M. 1975. Experiments to determine the effect of induced soil compaction on soil physical conditions, seedling root growth and crop yield. MAFF., Tech. Bull. 29, Hanso, London.

Gupta, P.S. 1933. Reaction of plants to the density of soil. J. Ecol. 21: 452-474.

Hagan, R.M. 1962. Plant growth under mediterranean climatic conditions as influenced by water supplies. Proceedings of the 7th Congress of the International Potash Institute. pp. 191-218.

Hakimi, A.H., and Kachru, R.P. 1976. Response of barley crop to different tillage treatments on calcareous soil. J. Agric. Eng. Res. 21: 399-403.

Hanna, G.B., and Masry, L.E. 1962. Effect of different kinds of plows on soil compaction. Soil Sci. UAR. 2: 79-101.

Harris, W.L. 1971. The soil compaction process. pp. 9-46. In K.K. Barnes et al.(ed). Soil compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

Henry, J.E., and McKibben, J.S. 1967. Effect of soil strength on corn root penetration. TRANSACTIONS of the ASAE. 10: 281-283, 288.

Hill, J.N.S., and Sumner, M.E. 1967. Effect of bulk density on moisture characteristics of soils. Soil Sci. 103: 234-238.

Hillel, D., Krentos, V.D., and Styllanou, Y. 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in Situ. Soil Sci. 114: 395-400.

Hobbs, J.A., Herring, R.B., Peaslee, D.E., Harris, W.W., and Fairbanks, G.E. 1961. Deep tillage effects on soils and crops. Agron. J. 53: 313-316.

Jamison, V.C. 1956. Pertinent factors governing the availability of soil moisture to plants. Soil Sci. 81: 459-471.

Jamison, V.S., Weaver, H.A., and Reed, I.F. 1950. The distribution of tractor tire compaction effects in Cecil clay. Soil Sci. Soc. Amer. Proc. 15: 34-37.

John, E.B., and Neil, C.T. 1976. Crop water deficits. Adv. in Agron. 28: 161-217.

Johnson, W.H., and Taylor, G.S. 1960. Tillage treatment for corn on clay soils. TRANSACTIONS of the ASAE. 3: 4-7, 10.

Kelley, O.J. 1954. Requirement and availability of water. Adv. in Agron. 6: 67-94. .

Kelley, O.J., Hunter, A.S., and Hobbs, C.H. 1945. The effect of moisture stress on nursery-grown guayule with respect to the amount and type of growth and growth response on transplanting. J. Amer. Soc. Agron. 37: 194-216.

Klute, A. 1965. Laboratory measurement of hydraulic conductivity of saturated soil. In C.A. Black, Editor-in-Chief, Methods of soil analysis, Agronomy Monograph 9: 253-261.

Koshi, P.T., and Fryrear, D.W. 1973. Effect of tractor traffic, surface mulch, and seedbed configuration on soil properties. Soil Sci. Soc. Amer. Proc. 37: 758-762.

Kramer, P.J. 1969. Plant and soil water relationship a modern synthesis McGraw Hill Book Co., New York.

Kumar, L., and Weber, J.A. 1974. Compaction of unsaturated soil by different stress paths. TRANSACTIONS of the ASAE 17: 1064-1069, 1072.

Lambe, T.W. 1951. Soil testing for Engineers. John Wiley and Sons, Inc., New York.

Larson, W.E. 1964. Soil parameters for evaluating tillage needs and operations. Soil Sci. Soc. Amer. Proc. 28: 118-122.

LaRue, M.E., Nielsen, D.R., and Hagan, R.M. 1968. Soil-water flux below a ryegrass root zone. Agron. J. 60: 625-629.

Laws, W.B. 1953. Tillage tests on Texas Black lands. Soil Sci. 75: 131-136.

Lyles, L., and Woodruff, N.P. 1963. Effects of moisture and soil packers on consolidation and cloddiness of soil. TRANSACTIONS of the ASAE. 6: 273-275.

Mannering, J.V., Griffith, D.R., and Richey, C.B. 1975. Tillage for moisture conservation. ASAE Paper No. 75-2523.

Marshall, T.J. 1958. A relation between permeability and size distribution of pores. J. Soil Sci. 9: 1-18.

Marshall, T.J. 1959. The diffusion of gases through porous media. J. Soil Sci. 10: 79-82.

Mazurak, A.P., and Pholman, K. 1968. Growth of corn and soybean seedlings as related to soil compaction and matric suction. 9th Int. Congr. Soil Sci. Trans. 813-821.

McKibben, E.G. 1971. Compaction of agricultural soils. pp. 1-6. In K.K. Barnes et al.(ed). Soil compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

McKyes, E., Chassé, M., Raghavan, G.S.V., and Mérineau, F. 1977. Soil compaction in an orchard of Southern Quebec. J. Terramechanics 14(1): 23-29.

McKyes, E., Negi, S., Douglas, E., Taylor, F., and Raghavan, G.S.V. 1979. The effect of machinery traffic and tillage operations on the physical properties of clay and on yield of silage corn. J. Agric. Eng. Res. 24: 143-148.

McKyes, E., Raghavan, G.S.V., Chassé, M., and Broughton, R.S. 1975. Traction and compaction in humid eastern Canadian soils. CSAE., Paper No. 75-315.

Meredith, H.L., and Patrick, W.H. Jr. 1961. Effects of soil compaction on subsoil root penetration and physical properties of three soils in Louisiana. Agron. J. 53: 163-167.

Millington, R.J., and Quirk, J.P. 1959. Permeability of porous media. Nature. 183: 387-388.

Molz, F.J., and Remson, I. 1970. Extraction term models of soil moisture used by transpiring plants. Water Resour. Res. 6(5): 1346-1356.

Negi, S., Douglas, E., McKyes, E., and Raghavan, V. 1977. Effect of machinery traffic and tillage operations on soil physical properties and plant yields. Eng. Res. Serv. Report, Quebec Ministry of Agriculture. pp. 43.

Negi, S., Douglas, E., Taylor, F., McKyes, E., and Raghavan, V. 1979. Effects of machinery traffic and tillage operations on soil physical properties and plant yields. Eng. Res. Serv. Report, Quebec Ministry of Agriculture. pp. 83.

Nichols, M.L. 1957. Soil compaction by farm machinery. Soil Cons. 23(5): 95-98.

Nielsen, D.R., Biggar, J.W., and Erh, K.T. 1973. Spatial variability of soil-water properties. Hilgardia 42(7): 215-259.

Nielsen, D.R., Davidson, J.M., Biggar, J.W., and Miller, R.J. 1964. Water movement through Panoche clay loam soil. Hilgardia 35: 491-506.

Ogata, G., and Richards, L.A. 1957. Water content changes following irrigation of bare field soil that is protected from evaporation. Soil Sci. Soc. Amer. Proc. 21: 355-356.

Papendick, R.I., and Miller, D.E. 1977. Conservation tillage in the Pacific Northwest. Soil Cons. Soc. Amer. Special Pub. No. 20: 49-56.

Patterson, D.E., Chamen, W.C.T., and Richardson, C.D. 1980. Long-term experiments with tillage systems to improve the economy of cultivation for cereals. J. Agric. Eng. Res. 25: 1-35.

Payne, P.C.J., and Fountaine, E.R. 1952. A field method of measuring the shear strength of soil. J. Soil Sci. 3: 136-144.

Philip, J.R. 1957. The physical principles of soil water movement during the irrigation cycle. Int. Irrig. Drainage Proc. 3rd Congr., Quest. 8, 125-154.

Phillips, R.E., and Kirkham, D. 1962. Soil compaction in the field and corn growth. Agron. J. 54: 29-34.

Raghavan, G.S.V., and McKyes, E. 1978. Statistical models for predicting compaction generated by off-road vehicular traffic in different soil types. J. Terramechanics 15(1): 1-14.

Raghavan, G.S.V., McKyes, E., Beaulieu, B., Mérineau, F., and Amir, I. 1976b. Study of traction and compaction problems on eastern Canadian agricultural soils. II. Canada Eng. Res. Services Report, Ottawa. pp. 79.

Raghavan, G.S.V., McKyes, E., and Beaulieu, B. 1978a. Claysoil compaction due to wheel slip. TRANSACTIONS of the ASAE. 21 (4): 646-649, 653.

Raghavan, G.S.V., McKyes, E., and Chassé, M. 1977a. Effect of wheel slip on soil compaction. J. Agric. Eng. Res. 22: 79-83.

Raghavan, G.S.V., McKyes, E., Chassé, M., and Mérineau, F. 1976a. Development of compaction patterns due to machinery operation in an orchard soil. Can. J. Plant Sci. 56: 505-509.

Raghavan, G.S.V., McKyes, E., Gendron, G., Borglum, D.K., and Le, H.H. 1978d. Effects of tire contact pressure on corn yield. Can. Agric. Eng. 20: 34-37.

Raghavan, G.S.V., McKyes, E., Gendron, G., Borglum, D.K., and Le, H.H. 1978b. Effects of soil compaction on development and yield of corn (Maize). Can. J. Plant Sci. 58: 435-443.

Raghavan, G.S.V., McKyes, E., Stemshorn, E., Gray, A., and Beaulieu, B. 1977b. Vehicle compaction patterns in clay soil. TRANSACTIONS of the ASAE. 20(2): 218-220, 225.

Raghavan, G.S.V., McKyes, E., Taylor, F., Richard, P., Douglas, E., and Negi, S. 1978e. Corn yield affected by wheel compaction in a dry year. CSAE., Paper No. 78-305.

Raghavan, G.S.V., McKyes, E., Taylor, F., Richard, P., Watson, A. 1979. The relationship between machinery traffic and corn yield reductions in successive years. TRANSACTIONS of the ASAE. 22: 1256-1259.

Raghavan, G.S.V., Taylor, F., McKyes, E., and Douglas, E. 1978c. Machinery traffic effects on the production capability of agricultural soils. Canada Eng. Res. Services Report, Ottawa. pp.52, 59.

Raney, W.A., and Edminister, T.W. 1961. Approaches to Soil Compaction Research. TRANSACTIONS of the ASAE. 4: 246-248.

Reicosky, D.C., Campbell, R.B., and Doty, C.W. 1976. Corn plant water stress as influenced by chiselling, irrigation and water table depth. Agron. J. 68: 499-503.

Richards, L.A. 1928. The usefulness of capillary potential to soil moisture and plant investigators. J. Agric. Res. 37: 719-742.

Richards, L.A., Gardner, W.R., and Glen, O. 1956. Physical processes determining water loss from soil. Soil Sci. Soc. Amer. Proc. 20: 310-314.

Richards, L.A., and Wadleigh, C.N. 1952. Soil water and plant growth. Agronomy II, Soil physical conditions and plant growth, ed. by B.T. Shaw. Academic Press, Inc., New York. pp. 73-252.

Robinson, F.E. 1964. Required percent airspace for normal growth of sugar cane. Soil Sci. 98: 206-207.

Rose, C.W., Stern, W.R., and Drummond, J.E. 1965. Determination of hydraulic conductivity as a function of depth and water content for soil in Situ. Aust. J. Soil Res. 3: 1-9.

Rosenberg, N.J. 1964. Response of plant growth to the physical effects of soil compaction. Adv. in Agron. 16: 181-196.

Rosenberg, N.J., and Willits, N.A. 1962. Yield and physiological response of barley and beans grown in artificially compacted soils. Soil Sci. Soc. Amer. Proc. 26: 78-82.

Russel, M.B. 1949. Methods for measuring soil structure and aeration. Soil Sci. 68: 25-35.

Schmidt, R.H. 1963. Calculated hydraulic conductivity as a measure of soil compaction. TRANSACTIONS of the ASAE. 6(3): 177-181, 185.

Slatyer, R.O. 1960. Absorption of water by plants. Bot. Rev. 26: 331-392.

Slatyer, R.O., and Taylor, S.A. 1960. Terminology in plant and soil-water relations. Nature 187: 922-924.

Smith, R.M., Robinson, F., and Thompson, D.O. 1955. Soil compaction can be cured. Crops and Soils 7: 12-13, 28.

Soane, B.D. 1970. The effects of traffic and implements on soil compaction. J. Proc. Inst. Agric. Eng. 25: 115-126.

Soane, B.D. 1975. Studies on some soil physical properties in relation to cultivations and traffic. MAFF tech. Bull. 29, 160-182.

Soane, B.D., and Pidgeon, J.D. 1975. Tillage requirements in relation to soil physical properties. Soil Sci. 119: 376-385.

Soehne, W. 1958. Pressure distribution and soil compaction under tractor tires. J. Agric. Eng. 39: 276-290.

Stout, B.A., Buchele, W.F., and Synder, F.W. 196[illegible]. Effect of soil compaction on seedling emergence under stimulated field conditions. AGRICULTURAL ENGINEERING 42 68-7[illegible], 87.

Swanson, C.L.W. 1954. Some physical facts about Connecticut soils. J. Soil and Water Cons. 9: 132.

Swanson, C.L.W., and Jacobson, H.G.M. 1956. Effects of soil hardness and compaction on corn growth. Soil Sci. Soc. Amer. Proc. 20: 161-166.

Talha, M., Metwally, S.Y., and Abu-Gabal, E. 1978. Effect of soil compaction on germination and growth of cotton and wheat grown in alluvial and calcareous soils. Egypt. J. Soil. Sci. 18: 39-50.

Taylor, F., Douglas, E., Negi, S., McKyes, E., and Raghavan, V. 1978. Effects of machinery traffic and tillage operations on soil physical properties and plant yields. Report to the Quebec Ministry of Agriculture, Quebec. pp. 57.

Taylor, H.M. 1971. Effects of soil strength on seedling emergence, root growth and crop yield. pp. 292-305. In K.K. Barnes et al.(ed). Soil Compaction. Amer. Soc. Agric. Eng. St. Joseph, ~~Mich.,~~ MI 49085.

Taylor, S.A., and Box, J.E. 1961. The influence of confining pressure and bulk density on soil water matric potential. Soil Sci. 91: 6-10.

Taylor, H.M., and Bruce, R.R. 1968. Effect of soil strength on root growth and crop yield in Southern United States. Trans. 9th Int. Congr. Soil Sci. 1: 803-811.

Taylor, H.M., and Burnett, E. 1964. Influence of soil strength on root growth habits of plants. Soil Sci. 98: 174-180.

Taylor, H.M., and Gardner, H.R. 1960. Use of wax substrates in root penetration studies. Soil Sci. Soc. Amer. Proc. 24: 79-81.

Taylor, H.M., and Gardner, H.R. 1963. Penetration of cotton seedling taproots as influenced by bulk density, moisture content and strength of soil. Soil Sci. 96: 153-156.

Taylor, H.M., Locke, L.F., and Box, J.E. 1964. Pans in Southern Great Plains soils. III. Their effects on yield of cotton and grain sorghum. Agron. J. 56: 542-545.

Taylor, H.M., and Ratliff, L.F. 1969. Root growth pressures of cotton, peas, and peanuts. Agron. J. 61: 398-402.

Taylor, H.M., Robertson, G.M., and Parker, J.J. Jr. 1966. Soil strength-root penetration relations for medium to coarse textured soil materials. Soil Sci. 102: 18-22.

Terry, C.W., and Wilson, H.M. 1953. The soil penetrometer in soil compaction studies. AGRICULTURAL ENGINEERING 34: 831-834.

Trouse, A.C. Jr. 1971. Soil conditions as they affect plant establishment, root development and yield. A. Present knowledge and need for research. pp. 225-240. In K.K. Barnes et al.(ed). Soil Compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

Trouse, A.C. Jr., and Humbert, R.P. 1961. Some effects of soil compaction on the development of sugar cane roots. Soil Sci. 91: 208-217.

Vandenberg, G.E. 1966. Triaxial measurement of shearing strain to compaction in unsaturated soils. TRANSACTIONS of the ASAE. 9 (4): 460-463, 467.

van Loon, C.C., and Bouma, J. 1978. A case study on the effect of soil compaction on potato growth in a loamy sand soil. 2. Potato plant responses. Neth. J. Agric. Sci. 26: 421-429.

Veihmeyer, F.J., and Hendrickson, A.H. 1946. Soil density as a factor in determining the permanent wilting percentage. Soil Sci. 62: 451-457.

Veihmeyer, F.J., and Hendrickson, A.H. 1948. Soil density and root penetration. Soil Sci. 65: 487-495.

Vomocil, J.A., and Flocker, W.J. 1961. Effects of soil compaction on storage and movement of soil air and water. TRANSACTIONS of the ASAE 4(2): 242-245.

Vomocil, J.A., Fountaine, E.R., and Raginato, R.J. 1958. The influence of speed and draw-bar load on the compacting effect of wheeled tractors. Soil Sci. Soc. Amer. Proc. 22: 178-180.

Voorhees, W.B. 1977. Soil compaction: Our newest natural resource. Crops and soils 29(5): 13-15.

Voorhees, W.B., Senst, C.G., and Nelson, W.W. 1978. Soil and water management and conservation. Soil. Sci. Soc. Amer. Proc. 42: 344-349.

Wadleigh, C.H. 1946. The integrated soil moisture stress upon a root system in a large container of saline soil. Soil Sci. 61: 225-238.

Warkentin, B.P. 1970. Soil physical properties. Lecture notes for soil physics. Department of Renewable Resources, Macdonald College, McGill University.

Warkentin, B.P. 1971. Effects of compaction on content and transmission of water in soils. pp. 165-177. In K.K. Barnes et al.(ed). Soil compaction. Amer. Soc. Agric. Eng. St. Joseph, Mich., MI 49085.

Weaver, H.A., and Jamison, V.C. 1951. Effects of moisture on tractor tire compaction of soil. Soil Sci. 71: 15-23.

Wiersum, L.K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil IX (1): 75-85.

Wittsel, L.E., and Hobbs, J.A. 1965. Soil compaction effects on field plant growth. Agron. J. 57: 534-537.

APPENDICES

APPENDIX A

DENSITY-MOISTURE METER AND METHOD OF CALCULATION

APPENDIX A

Density-Moisture Meter

A gamma ray probe, Troxler Model 3401 surface moisture-density gauge was used to determine soil densities in the field tests. This instrument has a 0,30m probe with a cesium 137/ americium 241/ beryllium radioactive source and a geiger counter resting on the surface to measure average bulk density from the tip of the probe to the surface of the soil. Since the machine was not able to measure moisture content profiles with depth, the samples were taken for gravimetric moisture content determinations at various depths as described in Chapter IV.

The procedure of measurements consisted of taking the first standard density counts, Cs, at the start of the day in order to give allowance for temperature, humidity and decay of the source. Secondly, the density counts, C, were taken to a depth of 0,30m at 0,05m interval. The average total bulk density (γ_T) values at each depth were calculated by the following formulas:

<u>At 0,05m depth</u>

$$\gamma_T = 62{,}38 \times \ln\left(\frac{8{,}2608 \times Cs}{C + (0{,}0506 \times Cs)}\right) \quad \text{---------} \quad (A.1)$$

<u>At 0,10m depth</u>

$$\gamma_T = 54{,}14 \times \ln\left(\frac{11{,}2025 \times Cs}{C + (0{,}0503 \times Cs)}\right) \quad \text{---------} \quad (A.2)$$

<u>At 0,15m depth</u>

$$\gamma_T = 47{,}55 \times \ln\left(\frac{12{,}008 \times Cs}{C + (0{,}0371 \times Cs)}\right) \quad \text{---------} \quad (A.3)$$

<u>At 0,20m depth</u>

$$\gamma_T = 38{,}87 \times \ln\left(\frac{13{,}7313 \times Cs}{C - (0{,}0009 \times Cs)}\right) \quad \text{--------} \quad (A.4)$$

At 0,25m depth

$$\gamma_T = 33{,}58 \times \ln\left(\frac{12{,}9216 \times Cs}{C - (0{,}0105 \times Cs)}\right) \quad \text{(A.5)}$$

At 0,30m depth

$$\gamma_T = 28{,}42 \times \ln\left(\frac{13{,}4438 \times Cs}{C - (0{,}0169 \times Cs)}\right) \quad \text{(A.6)}$$

Average dry bulk density was calculated using the appropriate gravimetric moisture content by the following relation:

$$\gamma_b = \frac{\gamma_T}{1 + w} \quad \text{(A.7)}$$

where γ_b = average dry bulk density, g/cm^3
γ_T = average total bulk density, g/cm^3
w = weight of the moisture/dry weight of the soil sample.

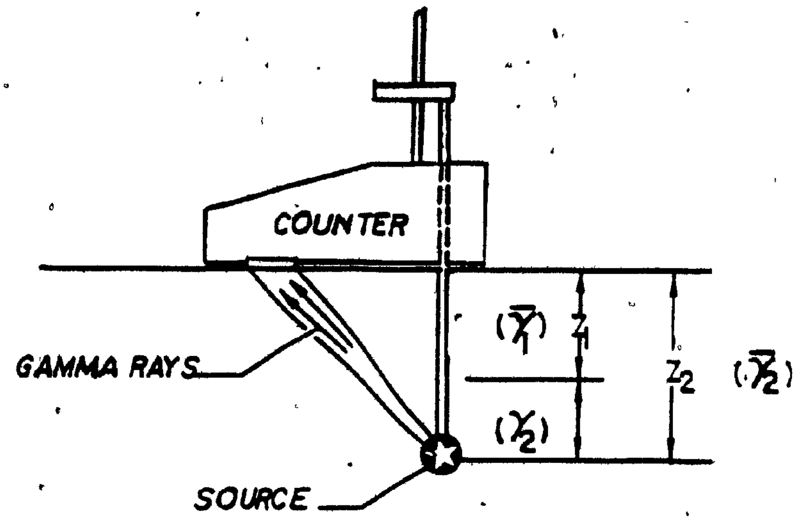
In order to observe a change in dry bulk density of each soil layer of 0,05m, the average dry bulk density values were converted into more localized density values by the following formula:

$$\frac{\bar{\gamma}_2 Z_2 - \bar{\gamma}_1 Z_1}{Z_2 - Z_1} \quad \text{(A.8)}$$

where $\bar{\gamma}_1$ = average dry bulk density of the layer Z_1
γ_2 = dry bulk density of the layer between Z_1 and Z_2
$\bar{\gamma}_2$ = dry bulk density measurement at Z_2, which is the average over Z_2 and equals to

$$\frac{\bar{\gamma}_1 Z_1 + \gamma_2 (Z_2 - Z_1)}{Z_2} \quad \text{(A.9)}$$

Fig. A-1 shows the schematic diagram of the surface moisture-density gauge and summarizes these relationships.



AVERAGE DENSITY OF LAYER TO $Z_1 = \bar{\gamma}_1$

DENSITY OF LAYER BETWEEN Z_1 AND $Z_2 = \gamma_2$

DENSITY MEASUREMENT AT Z_2 = AVERAGE OVER $Z_2 = \bar{\gamma}_2$

$$= \frac{\bar{\gamma}_1 z_1 + \gamma_2 (z_2 - z_1)}{z_2}$$

Thus

$$\gamma_2 = \frac{\bar{\gamma}_2 z_2 - \bar{\gamma}_1 z_1}{z_2 - z_1}$$

Figure A-1 Methods of calculating dry bulk density at each depth.

APPENDIX B

RELATIONSHIPS OF VARIOUS PARAMETERS STUDIED

APPENDIX B

Relationships

1. Gravimetric moisture content, %

   Mc, % = (Weight of water/Weight of dry soil)x100

2. Volumetric moisture content

   θ = (Dry density X Gravimetric moisture content)/100

3. Air-filled porosity

   AFP = (Porosity - Volumetric moisture content) X 100

4. Porosity

   Por = 1 - Dry density / Specific gravity of soil*

   *2,7 for the soil under study

5. Plant yield, kg/ha.

$$Y = \frac{1000\ \overline{W}wp}{(\overline{M}Cp + 100)\ A}$$

$$\overline{M}Cp = \frac{(Wwc - Wdc)}{Wdc - Wc} \times 100$$

APPENDIX C

TABULATED DATA FROM THE FIELD EXPERIMENT

Table C.1 - C.24 Tabulated field data of average gravimetric moisture content, % (Table C.1 - C.5), local dry density, g/cm^3 (Table C.6 - C.11), average dry density, g/cm^3 (Table C.12 - C.14), penetrometer resistance, MPa (Table C.15 - C.18), vane shear resistance, kPa (Table C.19 - C.22), average plant heights, cm (Table C.23 - C.24) for different compaction and tillage treatments.

TABLE C.1 - Average gravimetric moisture content (%) for various compaction and tillage treatments at each depth.

YEAR 1978

Before Compaction and Tillage Treatments

BLOCKS	DEPTH m	TREATMENTS							
		15YM	15YC	15YO	10YO	5YC	5YM	5YO	000
	0,05	13,13	8,39	12,87	12,76	11,64	10,35	14,65	12,17
	0,10	28,17	13,42	29,26	29,60	27,61	23,80	32,66	28,00
1	0,15	33,69	19,24	37,62	37,63	35,34	31,25	43,55	36.04
	0,20	29,92	24,87	37,87	36,85	34,83	32,68	47,34	36,29
	0,25	26,15	32,49	38,11	36,07	34,33	34,11	51,43	36,55
	0,05	14,45	7,91	11,92	10,09	11,68	11,49	10,88	10,11
	0,10	31,96	16,74	27,95	23,22	25,95	27,96	24,27	23,48
2	0,15	40,30	23,70	35,66	30,63	34,07	36,58	31,86	31,00
	0,20	39,49	28,81	35,05	32,04	36,02	37,35	33,64	32,67
	0,25	38,67	33,92	34,43	33,45	37,98	38,13	35,42	34,35
	0,05	14,90	14,69	16,28	12,51	12,12	14,57	18,72	12,80
	0,10	27,56	28,23	37,54	27,14	28,21	32,04	34,71	28,21
3	0,15	33,24	34,82	45,27	34,59	36,52	40,10	41,93	35,82
	0,20	31,93	34,47	39,46	34,86	37,07	38,73	40,36	35,63
	0,25	30,63	34,11	33,66	35,14	37,61	37,37	38,79	35,44
	0,05	12,44	12,16	13,52	10,85	12,86	12,25	13,77	10,83
	0,10	26,37	27,13	29,18	23,12	29,47	27,14	28,48	22,41
4	0,15	33,25	35,85	36,65	29,18	37,58	34,89	36,16	28,68
	0,20	33,08	36,22	35,92	29,03	37,19	35,50	35,66	29,64
	0,25	32,91	36,59	35,19	28,89	36,81	36,11	35,16	30,60

TABLE C.2 - Average gravimetric moisture content (%) for various compaction and tillage treatments at each depth.

YEAR 1978

After Compaction Treatments

BLOCKS	DEPTH m	TREATMENTS						
		15YM	15YC	15YO	10YO	5YC	5YM	5YO
1	0,05	14,05	12,92	13.96	12,90	11,22	10,24	17,94
	0,10	27.49	28,57	28,89	29,49	26,05	23,33	35,19
	0,15	33.51	35,84	36,15	38,08	31,76	30,44	42,25
	0,20	32.51	34,71	35,74	38,65	28,35	31,57	39,10
	0,25	30.59	33,59	35,32	39,22	24,95	32,67	35,95
2	0,05	14.77	11,78	13,64	16,48	16,07	11,97	13,92
	0,10	34,99	26,33	27,12	36,03	37,18	27,46	27,93
	0,15	43.66	33,50	34,76	43,42	47,94	34,63	35,17
	0,20	41,01	33,29	36,55	38,67	48,37	33,46	35,63
	0,25	38,37	33,08	38,35	33.91	48,97	32,30	36,09
3	0,05	11,54	11,75	14,47	12,09	13,93	15,35	13,82
	0,10	26,11	28,07	32,26	26,22	27,77	31,85	32,04
	0,15	33,91	36,61	40,26	33,75	35,73	39,56	41,50
	0,20	34,93	37.37	38,47	34,68	37,80	38,47	42,19
	0,25	35.95	38,13	36,68	35,62	39,87	37,39	42,89
4	0,05	10,81	11,24	12,14	13,59	13,33	12,64	12,00
	0,10	24,17	25,63	25,62	29,58	30,06	28,91	26,34
	0,15	33,62	34,01	32,98	37,33	37,13	34,99	33,44
	0,20	34,19	36,41	34,21	36,84	34,56	30,90	33,29
	0,25	35,17	38,80	35,44	36,35	31,98	26,80	33.14

TABLE C.3 - Average gravimetric moisture content (%) for various tillage treatments at each depth.
YEAR 1978

BLOCKS	DEPTH m	TREATMENTS			
		15YM	15YC	5YC	5YM
1	0,05	13,21	14,03	14,47	14,21
	0,10	24,42	26,89	32,04	27,61
	0,15	29,59	33,19	40,86	34,91
	0,20	28,74	32,92	40,93	35,94
	0,25	27,88	32.65	41,01	36,96
2	0,05	15,07	15.86	14,34	17,29
	0,10	27,65	32,57	29,09	31,82
	0,15	34,03	41,30	36,44	39,18
	0,20	34,22	42,07	36,38	39,37
	0,25	34,40	42,84	36,32	39.55
3	0,05	8,89	11,44	13,22	14.12
	0,10	17,66	26,13	31,05	31,09
	0,15	23,14	34,56	40,02	39.59
	0,20	25,31	36,73	40,31	39.64
	0,25	27,48	38,91	40,54	39.69
4	0,05	12,47	8,82	15,72	13,49
	0,10	26,04	27,09	34,10	29,84
	0,15	32,84	35,19	42,49	37,17
	0,20	32,88	32,16	40,90	35,46
	0,25	32,92	33,12	39,31	33,76

TABLE C.4 - Average gravimetric moisture content (%) for various compaction and tillage treatments at each depth.

YEAR 1978

One Month After Seeding

BLOCKS	DEPTH m	TREATMENTS							
		15YM	15YC	15YO	10YO	5YC	5YM	5YO	000
1	0,05	12,43	16,66	14,24	15,18	16,37	12,51	14,77	15,67
	0,10	21,72	26,01	26,61	29,65	32,34	27,94	26,12	29,29
	0,15	26,63	30,52	33,27	37,67	40,41	36,47	32,74	36,59
	0,20	26,18	30,19	34,23	39,24	40,58	38,11	34,65	37,57
	0,25	27,72	29,87	35,19	40,82	40,76	39,75	36,55	38,55
2	0,05	12,76	11,79	16,84	12,12	13,79	11,99	12,08	12,29
	0,10	25,34	25,60	25,76	23,64	30,58	19,88	21,69	23,41
	0,15	33,15	30,94	31,61	30,62	37,89	24,79	26,04	29,09
	0,20	36,18	36,81	34,40	33,07	35,70	26,73	25,15	39,32
	0,25	39,21	39,69	37,18	35,51	33,51	28,67	24,25	29,56
3	0,05	14,82	25,46	13,93	14,64	14,53	15,45	14,37	13,81
	0,10	26,45	34,94	26,39	25,25	24,83	30,55	26,01	25,48
	0,15	32,62	37,23	29,42	32,47	31,76	38,06	32,83	33,46
	0,20	33,33	32,33	23,03	36,30	35,33	37,97	34,82	37,73
	0,25	34,04	27,43	16,64	40,14	38,89	37,89	36,82	42,01
4	0,05	11,49	14,74	15,10	13,08	14,71	12,24	12,20	11,60
	0,10	17,95	25,81	25,43	23,25	29,32	21,89	22,47	20,89
	0,15	24,96	33,36	31,67	30,24	37,63	26,48	29,70	26,36
	0,20	32,51	37,41	33,80	34,03	39,63	26,01	33,89	28,03
	0,25	40,05	41,45	35,94	37,83	41,63	25,53	38,09	29,69

TABLE C.5 - Average gravimetric moisture content (%) for various compaction and tillage treatments at each depth. YEAR 1979

BLOCKS	DEPTH m	B.C.T. TREATMENTS 15YO	B.C.T. TREATMENTS 15YM	B.C.T. TREATMENTS 000	A.C. TREATMENTS 15YO	A.C. TREATMENTS 15YM	A.T. TREATMENTS 15YM
1	0,05	7,63	8,98	15,68	9,91	12,15	10,70
	0,10	13,12	12,44	17,40	14,77	15,48	14,11
	0,15	18,61	15,89	19,12	19,62	19,81	17,51
	0,20	21,54	18,63	20,69	21,97	22,68	19,53
	0,25	21,91	20,65	22,11	24,82	23,09	21,08
	0,30	22,82	22,67	23,53	23,67	23,59	22,33
2	0,05	9,85	8,91	9,63	10,20	14,50	14,47
	0,10	14,76	14,03	15,15	15,38	16,25	16,71
	0,15	19,66	19,15	20,67	20,56	20,00	18,95
	0,20	21,75	22,16	23,46	22,83	22,55	20,63
	0,25	21,04	23,07	23,52	25,20	22,92	21,74
	0,30	20,33	23,92	23,58	23,57	23,29	22,86
3	0,05	9,41	11,68	7,69	9,77	12,70	15,43
	0,10	13,96	16,75	11,93	1458	15,81	19,58
	0,15	18,51	21,82	16,17	19,39	23,92	23,73
	0,20	21,85	24,35	19,70	21,75	26,56	25,84
	0,25	23,98	24,36	22,51	24,65	25,73	25,91
	0,30	26,10	24,37	25,33	23,57	24,90	25,97

NOTE: B.C.T. - Before Compaction and Tillage Treatments

A.C. - After Compaction Treatments

A.T. - After Tillage Treatments

TABLE C.6 - Local dry bulk density (g/cm^3) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1978

Before Compaction and Tillage Treatment

BLOCKS	DEPTH m	TREATMENTS							
		15YM	15YC	15YO	10YO	5YC	5YM	5YO	000
1	0,05	1,033	1,150	1,017	0,980	0,980	1,000	0,957	0,980
	0,10	1,167	1,197	1,013	0,887	0,850	0,927	0,953	0,860
	0,15	1,117	1,037	1,003	1,000	0,827	0,807	0,797	0,807
	0,20	1,280	1,160	1,310	1,180	1,330	1,050	1,037	1,030
	0,25	1,217	1,230	1,233	1,020	1,130	1,140	1,170	1,093
2	0,05	0,940	1,063	1,057	1,057	1,010	1,047	1,007	1,097
	0,10	0,903	0,987	0,963	1,120	1,073	0,983	0,947	1,137
	0,15	0,867	0,967	1,007	1,253	0,997	1,063	0,847	1,170
	0,20	1,067	1,303	1,120	1,220	1,227	1,237	1,097	1,227
	0,25	0,963	0,980	1,223	1,240	1,177	1,200	1,097	1,213
3	0,05	0,923	0,970	1,017	1,143	1,013	0,943	0,933	0,997
	0,10	0,860	0,897	1,157	0,790	0,963	0,977	0,897	0,900
	0,15	0,813	0,883	0,997	0,800	0,943	0,993	0,940	0,950
	0,20	0,973	1,120	1,207	1,000	1,210	1,143	1,173	1,037
	0,25	0,930	1,097	1,180	1,300	1,177	1,150	1,027	1,060
4	0,05	1,003	1,000	1,027	1,037	0,983	0,973	0,943	0,997
	0,10	0,940	0,910	0,833	0,980	0,877	1,023	0,933	0,967
	0,15	0,897	0,917	0,753	0,913	0,790	0,933	0,873	0,937
	0,20	1,110	1,160	0,953	1,090	0,833	1,217	1,013	1,327
	0,25	0,963	1,267	1,050	0,833	0,953	1,137	1,073	1,053

TABLE C.7 - Local dry density (g/cm^3) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1978

After Compaction

BLOCKS	DEPTH m	TREATMENTS						
		15YM	15YC	15YO	10YO	5YC	5YM	5YO
1	0,05	1,223	1,150	1,127	1,190	1,210	1,180	1,187
	0,10	1,487	1,277	1,253	1,187	1,320	1,227	1,163
	0,15	1,077	1,157	1,033	1,090	1,167	1,277	1,093
	0,20	0,980	1,380	1,290	1,260	1,330	1,420	1,263
	0,25	1,283	1,442	1,143	1,230	1,217	1,260	1,270
2	0,05	1,103	1,260	1,117	0,993	1,060	1,187	1,037
	0,10	1,027	1,407	1,103	0,870	1,040	1,263	1,307
	0,15	1,067	1,067	1,057	0,880	1,217	1,153	1,207
	0,20	1,240	1,290	1,210	1,140	0,892	1,217	1,457
	0,25	1,243	1,210	1,213	1,100	0,877	1,330	1,210
3	0,05	1,147	1,340	1,170	1,193	1,203	1,087	1,123
	0,10	1,110	1,267	1,200	1,340	1,223	1,247	1,267
	0,15	0,973	1,133	1,207	1,210	1,143	1,133	1,200
	0,20	1,307	1,250	1,277	1,260	1,230	1,263	1,443
	0,25	1,373	1,287	1,443	1,293	1,350	1,340	1,047
4	0,05	1,140	1,240	1,157	1,067	1,073	1,073	1,053
	0,10	1,137	1,240	1,183	1,140	1,237	1,303	1,303
	0,15	1,123	1,217	1,253	1,263	1,230	1,223	1,203
	0,20	1,327	1,300	1,273	1,200	1,343	1,567	1,213
	0,25	1,353	1,297	1,340	1,223	1,313	1,147	1,213

TABLE C.8 - Local dry density (g/cm^3) for various tillage treatments (average of 3 samples) at each depth.

YEAR 1978

After Tillage

BLOCKS	DEPTH m	TREATMENTS			
		15YM	15YC	5YC	5YM
1	0,05	1,107	1,037	0,997	0,937
	0,10	1,000	1,027	1,053	0,943
	0,15	1,210	1,100	1,110	0,753
	0,20	0,593*	1,243	1,177	1,120
	0,25	1,077	1,243	1,223	1,200
2	0,05	1,013	0,880	0,977	1,003
	0,10	0,930	1,170	0,967	1,327
	0,15	0,947	1,033	0,933	1,100
	0,20	1,327	1,193	1,293	1,290
	0,25	1,283	1,403	1,123	0,593
3	0,05	1,073	1,197	0,960	1,047
	0,10	0,993	1,353	1,080	1,253
	0,15	0,927	1,207	1,213	1,113
	0,20	1,103	1,353	1,267	1,170
	0,25	1,110	1,327	1,167	1,313
4	0,05	1,083	1,043	1,027	1,100
	0,10	1,053	1,070	0,947	1,013
	0,15	1,083	1,107	0,917	1,233
	0,20	1,297	1,207	1,180	1,393
	0,25	1,223	1,273	1,150	1,280

*Possible existance of a cavity after plowing.

TABLE C.9 - Local dry density (g/cm^3) for various compaction and tillage treatments (average 3 samples) at each depth.

YEAR 1978

BLOCKS	DEPTH m	TREATMENTS							
		15YM	15YC	15YO	10YO	5YC	5YM	5YO	000
1	0,05	1,057	1,057	1,333	1,143	1,017	1,067	1,057	1,173
	0,10	1,000	1,067	1,353	1,087	1,033	1,173	1,117	1,170
	0,15	1,370	0,970	1,183	1,120	1,120	1,113	1,140	1,107
	0,20	1,503	1,173	1,020	1,157	1,387	1,310	1,143	1,230
	0,25	1,307	1,313	1,620	1,427	1,193	1,220	1,063	1,253
2	0,05	1,127	1,100	1,303	1,380	1,107	1,043	1,227	1,163
	0,10	1,180	1,040	1,253	1,387	1,027	1,147	0,980	1,127
	0,15	1,040	0,993	1,123	1,267	0,793	1,150	1,067	1,110
	0,20	1,107	1,363	1,243	1,343	1,013	1,400	1,400	1,243
	0,25	1,183	1,317	1,273	1,350	1,383	1,393	1,433	1,176
3	0,05	1,213	0,987	1,080	1,167	1,117	1,093	1,130	1,037
	0,10	1,183	1,103	1,217	1,317	1,173	1,223	1,333	1,070
	0,15	1,127	1,050	1,180	1,287	1,223	1,213	1,163	1,040
	0,20	1,253	1,330	1,450	1,353	1,247	1,413	1,367	1,317
	0,25	0,930	1,117	1,477	1,050	1,077	0,623	1,323	1,240
4	0,05	1,053	1,030	1,113	1,273	1,037	1,100	1,130	1,057
	0,10	1,093	0,992	1,173	0,920	0,907	1,023	1,157	1,090
	0,15	1,053	0,973	1,480	0,973	0,857	1,113	1,157	0,980
	0,20	1,147	1,157	0,950	1,513	1,080	1,533	1,357	1,107
	0,25	1,223	0,953	1,057	0,633	0,940	1,400	1,293	1,123

TABLE C.10 - Average dry bulk density (g/cm^3) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1978

Before Compaction and Tillage Treatments

BLOCKS	DEPTH m	TREATMENTS							
		15YM	15YC	15YO	10YO	5YC	5YM	5YO	000
1	0,05	1,033	1,150	1,017	0,974	0,980	1,000	0,957	0,980
	0,10	1,033	1,173	1,017	0,933	0,913	0,963	0,943	0,923
	0,15	1,067	1,127	1,010	0,953	0,887	0,910	0,893	0,880
	0,20	1,153	1,137	1,087	1,013	0,997	0,947	0,927	0,923
	0,25	1,163	1,153	1,117	1,010	1,023	0,983	0,977	0,957
2	0,05	0,940	1,063	1,030	1,057	1,010	1,047	1,007	1,107
	0,10	0,923	1,027	1,043	1,087	1,043	1,017	0,977	1,120
	0,15	0,907	1,003	1,057	1,140	1,027	1,030	0,930	1,137
	0,20	0,947	1,080	1,077	1,163	1,077	1,083	0,973	1,160
	0,25	0,947	1,057	1,127	1,177	1,097	1,107	1,000	1,170
3	0,05	0,923	0,970	1,017	1,143	1,013	0,943	0,933	0,997
	0,10	0,893	0,937	1,087	0,967	0,990	0,960	0,920	0,950
	0,15	0,863	0,917	1,053	0,910	0,973	0,973	0,927	0,950
	0,20	0,900	0,967	1,093	0,937	1,033	1,017	0,987	0,970
	0,25	0,907	0,993	1,110	1,010	1,140	1,040	0,993	0,990
4	0,05	1,003	1,000	1,027	1,037	0,983	0,973	0,943	0,997
	0,10	0,970	0,957	0,930	1,010	0,933	1,000	0,940	0,980
	0,15	0,947	0,943	0,873	0,973	0,833	0,977	0,917	0,963
	0,20	0,987	0,997	0,893	1,007	0,833	1,037	0,943	1,057
	0,25	0,983	1,050	0,927	0,970	0,897	1,060	0,97	1,057

TABLE C.11 - Local dry density (g/cm^3) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1979

BLOCKS	DEPTH m	B.C.T. TREATMENTS 15YO	15YM	000	A.C. TREATMENTS 15YO	15YM	A.T. 15YM
1	0,05	1,153	1,083	0,993	1,383	1,417	1,007
	0,10	1,127	1,147	1,037	1,380	1,490	1,127
	0,15	0,997	0,997	0,953	1,303	1,480	1,383
	0,20	1,113	1,137	1,050	1,497	1,353	1,473
	0,25	1,073	1,140	1,153	1,430	1,283	1,170
	0,30	1,113	1,237	1,260	1,243	1,483	1,643
2	0,05	1,077	1,063	1,103	1,177	1,213	1,090
	0,10	1,083	1,050	1,100	1,323	1,450	1,100
	0,15	0,853	1,043	0,940	1,210	1,177	1,073
	0,20	1,143	1,160	1,047	1,400	1,303	1,247
	0,25	1,217	1,050	0,970	1,257	1,300	1,237
	0,30	1,050	1,217	1,350	1,510	1,340	1,540
3	0,05	1,047	0,963	1,127	1,317	1,403	0,907
	0,10	1,013	1,010	1,023	1,397	1,293	1,090
	0,15	1,007	0,937	0,943	1,313	1,280	1,067
	0,20	1,173	1,137	1,150	1,383	1,430	1,060
	0,25	1,037	1,107	1,453	1,427	1,427	1,237
	0,30	1,140	1,203	1,373	1,440	1,423	1,460

NOTE: B.C.T. - Before Compaction and Tillage Treatments

A.C. - After Compaction Treatments

A.T. - After Tillage Treatments

TABLE C.12 - Average dry bulk density (g/cm^3) for various compaction and tillage treatments (average of 3 samples) at each depth
YEAR 1978

After Compaction Treatments

BLOCKS	DEPTH m	TREATMENTS						
		15YM	15YC	15YO	10YO	5YC	5YM	5YO
1	0,05	1,223	1,150	1,127	1,190	1,210	1,180	1,187
	0,10	1,357	1,213	1,193	1,190	1,263	1,207	1,180
	0,15	1,263	1,197	1,140	1,157	1,233	1,230	1,147
	0,20	1,193	1,243	1,173	1,183	1,257	1,277	1,180
	0,25	1,207	1,273	1,173	1,190	1,250	1,273	1,193
2	0,05	1,103	1,260	1,117	0,977	1,060	1,187	1,037
	0,10	1,100	1,333	1,113	0,923	1,053	1,227	1,173
	0,15	1,087	1,247	1,093	0,907	1,107	1,203	1,180
	0,20	1,130	1,257	1,123	0,970	1,023	1,207	1,253
	0,25	1,150	1,257	1,143	0,993	0,993	1,233	1,243
3	0,05	1,147	1,240	1,170	1,193	1,203	1,087	1,123
	0,10	1,130	1,307	1,187	1,267	1,213	1,170	1,197
	0,15	1,080	1,247	1,190	1,250	1,190	1,157	1,197
	0,20	1,120	1,250	1,213	1,250	1,200	1,183	1,260
	0,25	1,267	1,257	1,257	1,260	1,227	1,217	1,217
4	0,05	1,230	1,240	1,157	1,067	1,073	1,073	1,053
	0,10	1,267	1,243	1,170	1,107	1,157	1,187	1,180
	0,15	1,297	1,233	1,197	1,197	1,180	1,200	1,187
	0,20	1,303	1,250	1,220	1,167	1,220	1,290	1,197
	0,25	1,283	1,260	1,240	1,180	1,240	1,260	1,192

TABLE C.13 - Average dry bulk density (g/cm^3) for various tillage treatments (average of 3 samples) at each depth.

YEAR 1978

After Tillage Treatments

BLOCKS	DEPTH m	TREATMENTS			
		15YM	15YC	5YC	5YM
1	0,05	1,107	1,037	0,997	0,970
	0,10	1,053	1,030	1,027	0,940
	0,15	1,107	1,063	1,057	0,877
	0,20	0,977	1,157	1,087	0,943
	0,25	0,997	1,163	1,110	0,990
2	0,05	1,013	0,880	0,977	1,003
	0,10	0,970	1,027	0,973	1,167
	0,15	0,963	1,027	0,957	1,143
	0,20	1,057	1,070	1,043	1,180
	0,25	1,100	1,263	1,057	1,063
3	0,05	1,073	1,197	0,960	1,047
	0,10	1,033	1,277	1,023	1,153
	0,15	0,997	1,253	1,083	1,140
	0,20	1,023	1,280	1,130	1,150
	0,25	1,040	1,287	1,137	1,180
4	0,05	1,083	1,043	1,027	1,100
	0,10	1,070	1,057	0,990	1,060
	0,15	1,073	1,073	0,963	1,117
	0,20	1,130	1,107	1,020	1,183
	0,25	1,147	1,140	1,043	1,203

TABLE C.14 - Average dry density (g/cm^3) for various compaction and tillage treatments (average of 3 samples at each depth.

YEAR 1979

BLOCKS	DEPTH m	B.C.T. TREATMENTS 15YO	B.C.T. TREATMENTS 15YM	B.C.T. TREATMENTS 000	A.C. TREATMENTS 15YO	A.C. TREATMENTS 15YM	A.T. TREATMENTS 15YM
1	0,05	1,153	1,083	0,993	1,383	1,417	1,007
	0,10	1,140	1,117	1,013	1,380	1,453	1,070
	0,15	1,093	1,077	0,993	1,357	1,463	1,173
	0,20	1,097	1,093	1,010	1,387	1,430	1,250
	0,25	1,093	1,100	1,037	1,400	1,403	1,230
	0,30	1,097	1,123	1,107	1,373	1,420	1,300
2	0,05	1,077	1,063	1,103	1,160	1,213	1,090
	0,10	1,080	1,060	1,100	1,243	1,333	1,097
	0,15	1,003	1,053	1,047	1,233	1,283	1,090
	0,20	1,037	1,080	1,050	1,273	1,287	1,130
	0,25	1,073	1,073	1,033	1,287	1,287	1,150
	0,30	1,070	1,100	1,087	1,313	1,297	1,217
3	0,05	1,047	0,963	1,127	1,317	1,403	0,907
	0,10	1,033	0,983	1,073	1,357	1,347	1,083
	0,15	1,020	0,970	1,030	1,343	1,327	0,983
	0,20	1,060	1,010	1,063	1,353	1,353	1,007
	0,25	1,053	1,033	1,140	1,367	1,363	1,050
	0,30	1,070	0,973	1,177	1,377	1,377	1,120

NOTE: B.C.T. - Before Compaction and Tillage Treatments

A.C. - After Compaction Treatments

A.T. - After Tillage Treatments

TABLE C.15 - Penetrometer resistance (MPa) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1978

Before Compaction and Tillage Treatments

BLOCKS	DEPTH m	TREATMENTS							
		15YM	15YC	15YO	10YO	5YC	5YM	5YO	000
1	0,05	1,060	0,410	0,680	0,210	0,290	0,260	0,180	0,350
	0,10	2,343	2,750	3,230	0,950	1,680	0,620	0,580	1,150
	0,15	2,340	6,410	2,100	2,090	4,500	2,410	1,470	1,757
	0,20	3,890	4,973	5,100	2,230	4,120	3,880	2,120	2,190
	0,25	5,820	4,880	6,400	3,123	5,760	4,530	3,500	3,353
2	0,05	0,267	0,503	0,400	0,237	0,240	0,620	0,740	0,350
	0,10	0,967	0,760	1,530	0,970	0,590	3,153	0,760	1,970
	0,15	1,307	1,530	1,710	2,350	1,230	4,467	1,650	2,120
	0,20	2,837	2,587	3,860	3,000	2,090	4,470	3,090	4,850
	0,25	5,427	3,227	3,693	3,940	2,350	4,830	3,290	3,320
3	0,05	0,463	1,150	1,730	1,680	1,100	0,660	1,320	1,180
	0,10	1,280	1,543	3,910	2,013	2,470	2,610	1,880	1,810
	0,15	1,810	2,400	3,390	2,690	3,060	3,400	3,150	2,040
	0,20	3,250	3,710	4,190	3,923	4,070	3,820	3,730	3,350
	0,25	2,540	3,673	5,210	5,400	4,320	4,720	3,920	3,780
4	0,05	0,740	0,950	1,410	0,650	0,430	1,090	0,360	0,810
	0,10	2,230	2,120	3,510	2,570	1,823	3,020	2,320	2,570
	0,15	2,903	2,900	3,810	3.010	2,380	3,160	2,880	2,990
	0,20	3,960	3,570	4,080	4,020	3,920	3,900	3,780	4,400
	0,25	4,780	4,490	4,600	4,440	4,260	4,060	4,300	4,07

TABLE C.16 - Penetrometer resistance (MPa) for various compaction and tillage treatments (average 3 samples) at each depth.

YEAR 1978
After Compaction

BLOCKS	DEPTH m	TREATMENTS						
		15YM	15YC	15YO	10YO	5YC	5YM	5YO
1	0,05	7,480	6,030	5,380	5,690	4,850	4,230	4,180
	0,10	8,360	6,140	5,230	4,503	4,320	3,260	3,503
	0,15	4,820	6,820	5,090	3,260	4,970	5,050	2,930
	0,20	6,670	7,503	6,850	3,650	4,230	4,290	3,390
	0,25	7,700	5,790	7,280	4,300	6,700	4,800	3,750
2	0,05	6,350	7,820	6,240	3,320	5,850	6,760	5,650
	0,10	4,250	3,920	4,390	5,400	6,387	4,320	4,150
	0,15	4,090	3,500	3,550	4,210	3,957	4,890	4,250
	0,20	4,970	5,470	5,700	3,200	4,650	4,503	5,550
	0,25	5,440	5,030	5,590	5,260	4,410	4,030	4,733
3	0,05	5,490	7,060	5,300	5,520	4,270	3,710	3,920
	0,10	6,810	5,460	4,780	5,010	3,780	3,880	4,020
	0,15	4,253	4,460	4,883	4,740	4,300	4,060	4,310
	0,20	5,353	4,860	5,030	4,700	4,410	4,010	4,090
	0,25	6,09	6,020	6,170	5,720	5,340	5,280	4,710
4	0,05	5,740	6,060	4,520	3,380	3,550	3,060	2,630
	0,10	4,720	4,920	4,310	4,290	4,460	4,070	4,460
	0,15	5,320	5,020	5,040	4,900	4,620	4,900	4,610
	0,20	4,930	5,010	4,970	4,620	4,320	4,410	4,580
	0,25	5,800	6,100	6,200	5,440	5,610	5,390	4,930

TABLE C.17 - Penetrometer resistance (MPa) for various tillage treatments (average of 3 samples) at each depth.

YEAR 1978

After Tillage

BLOCKS	DEPTH m	TREATMENTS			
		15YM	15YC	5YC	5YM
1	0,05	1,850	3,410	2,060	2,030
	0,10	3,290	3,590	2,160	2,620
	0,15	3,560	4,620	2,750	4,070
	0,20	6,260	4,700	5,190	6,190
	0,25	5,320	5,350	6,303	5,380
2	0,05	3,440	3,653	3,820	3,620
	0,10	3,310	2,470	2,970	3,680
	0,15	3,970	3,150	2,100	4,170
	0,20	5,377	3,503	4,060	4,970
	0,25	5,850	5,330	5,230	4,190
3	0,05	1,580	1,620	1,860	1,660
	0,10	2,890	2,480	2,760	2,890
	0,15	3,813	3,530	2,820	3,270
	0,20	4,020	3,700	3,740	4,020
	0,25	5,470	5,150	4,920	5,240
4	0,05	1,430	2,040	2,720	3,140
	0,10	2,800	2,880	2,620	3,690
	0,15	3,820	3,620	3,410	3,880
	0,20	4,310	3,670	3,590	4,720
	0,25	5,320	5,800	5,760	5,090

TABLE C.18 - Penetrometer resistance (MPa) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1979

BLOCKS	DEPTH m	B.C.T. TREATMENTS 15YO	B.C.T. TREATMENTS 15YM	B.C.T. TREATMENTS 000	A.C. TREATMENTS 15YO	A.C. TREATMENTS 15YM	A.T. TREATMENTS 15YM
1	0,025	0,957	0,650	0,880	4,030	3,020	2,577
	0,15	2,350	1,790	2,037	4,583	2,900	1,950
	0,30	2,410	1,567	1,227	7,100	8,377	2,430
2	0,025	0,253	0,210	0,250	3,810	3,020	2,253
	0,15	1,467	1,437	2,207	3,857	2,900	2,297
	0,30	1,037	1,310	0,667	6,690	9,043	3,727
3	0,025	0,527	0,327	0,203	1,923	2,073	2,527
	0,15	1,450	0,690	1,383	5,959	4,497	2,433
	0,30	1,970	0,740	1,207	6,540	6,147	5,153

NOTE: B.C.T. - Before Compaction and Tillage Treatments
A.C. - After Compaction Treatments
A.T. - After Tillage Treatments

TABLE C.19 - Vane shear resistance (kPa) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1978

Before Compaction and Tillage Treatments

BLOCKS	DEPTH m	TREATMENTS							
		15YM	15YC	15YO	10YO	5YC	5YM	5YO	000
1	0,05	3,640	2,873	3,830	2,393	2,393	1,917	2,393	2,153
	0,10	21,547	22,503	20,107	16,280	22,980	17,717	15,800	18,193
	0,25	43,090	40,700	83,790	57,460	76,610	83,790	74,213	59,850
2	0,05	3,353	2,870	3,830	3,353	2,873	5,270	2,870	2,393
	0,10	14,363	11,970	13,407	17,240	16,757	15,320	14,363	13,407
	0,25	54,583	28,730	66,030	51,710	55,060	93,367	39,260	56,500
3	0,05	1,917	1,440	3,830	2,870	2,873	5,270	1,917	2,390
	0,10	15,800	14,840	28,730	22,023	24,420	27,290	82,503	23,460
	0,25	50,273	47,880	67,030	47,880	79,000	52,667	43,090	59,850
4	0,05	2,633	2,870	2,150	2,633	2,393	2,393	2,393	2,870
	0,10	16,280	22,023	2,010	17,717	19,150	22,503	17,240	17,717
	0,25	52,667	55,063	47,880	67,033	64,640	69,427	43,090	68,910

TABLE C.20 - Vane shear resistance (kPa) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1978

After Compaction

BLOCKS	DEPTH m	TREATMENTS						
		15YM	15YC	15YO	10YO	5YC	5YM	5YO
1	0,05	21,550	16,760	11,970	22,983	10,533	15,320	13,260
	0,15	90,970	93,367	97,000	55,063	45,487	57,457	60,427
	0,25	98,153	83,790	90,970	67,030	62,240	79,000	72,243
2	0,05	21,070	20,590	35,910	24,420	16,280	22,503	16,760
	0,15	59,850	88,580	76,610	55,063	57,457	74,213	64,503
	0,25	79,000	93,367	83,790	74,213	74,213	90,970	88,577
3	0,05	13,407	22,020	30,643	26,333	11,970	24,900	21,547
	0,15	55,060	69,427	83,790	74,213	62,240	69,427	71,820
	0,25	59,850	74,213	64,637	83,790	57,457	74,297	83,790
4	0,05	16,280	10,533	28,730	19,153	15,800	22,503	21,547
	0,15	40,700	50,273	57,457	64,637	55,060	52,670	71,820
	0,25	67,030	45,487	59,427	66,030	39,000	67,030	83,790

TABLE C.21 - Vane shear resistance (kPa) for various tillage treatments (average of 3 samples) at each depth.

YEAR 1978

After Tillage

BLOCKS	DEPTH m	TREATMENTS			
		15YM	15YC'	5YC	5YM
1	0,05	10,053	5,270	14,840	12,450
	0,15	64,140	62,243	69,430	45,487
	0,25	69,430	83,790	76,607	64,640
2	0,05	16,277	21,547	11,970	19,630
	0,15	50,273	76,900	55,063	59,063
	0,25	67,030	59,850	71,820	83,790
3	0,05	7,180	21,547	14,363	14,843
	0,15	27,290	43,093	45,487	55,060
	0,25	56,497	68,950	47,880	57,933
4	0,05	10,530	18,193	8,617	16,760
	0,15	50,273	40,697	45,487	64,573
	0,25	76,610	71,820	55,063	86,180

TABLE C.22 - Vane shear resistance (kPa) for various compaction and tillage treatments (average of 3 samples) at each depth.

YEAR 1979

		B.C.T			A.C.		A.T
BLOCKS	DEPTH m	TREATMENTS			TREATMENTS		
		15YO	15YM	000	15YO	15YM	000
1	0,025	3,430	2,393	5,030	47,080	70,200	11,970
	0,15	58,253	26,333	25,857	87,780	76,607	66,233
	0,30	85,387	79,800	78,203	122,093	77,407	78,203
2	0,025	2,633	3,750	2,710	32,717	77,407	7,820
	0,15	24,740	34,313	53,467	83,790	74,213	34,313
	0,30	90,177	85,390	89,377	118,103	70,227	102,940
3	0,025	2,713	4,243	3,350	45,487	48,677	7,977
	0,15	39,900	31,120	25,533	76,607	82,197	51,870
	0,30	83,787	52,667	74,217	106,933	114,910	110,923

NOTE: B.C.T. - Before Compaction and Tillage Treatments
A.C. - After Compaction Treatments
A.T. - After Tillage Treatments

TABLE C.23 - Average plant heights (cm) for various compaction and tillage treatments (average of 5 samples) throughout the growing season of 1978

BLOCKS	TREAT-MENTS	D A T E S									
		AUGUST							SEPTEMBER		
		4	9	14	18	22	25	29	1	6	9
1	15YM	8,20	14,30	22,20	31,80	48,90	49,50	51,10	51,10	52,20	53,20
	15YC	5,10	10,20	18,02	28,40	28,40	44,00	42,50	48,90	53,60	56,70
	15YO	4,70	7,40	12,34	21,70	27,90	33,90	28,90	42,20	42,30	47,40
	10YO	8,80	10,70	15,80	26,20	29,40	30,60	33,60	39,30	43,80	46,20
	5YC	7,00	13,20	20,00	25,20	32,00	42,04	52,00	59,80	61,20	67,50
	5YM	10,10	11,70	21,10	28,50	40,10	41,50	42,60	54,00	63,10	67,20
	5YO	10,10	15,70	22,90	29,2	36,40	45,30	45,50	48,10	56,50	56,80
	000	15,50	23,90	41,50	54,10	58,80	65,60	73,60	77,10	84,30	87,40
2	15YM	14,50	24,60	40,50	51,80	59,50	65,20	66,40	66,40	67,00	68,00
	15YC	9,00	9,90	29,90	24,90	35,00	36,40	43,40	52,90	58,60	60,60
	15YO	4,70	7,60	-	18,60	24,50	25,50	32,80	33,90	35,90	40,00
	10YO	5,60	10,10	18,40	20,60	23,50	31,10	33,90	38,60	44,00	45,10
	5YC	8,10	12,00	21,40	22,90	40,20	45,70	53,20	6,50	67,70	70,80
	5YM	13,80	22,70	39,3	28,50	56,40	58,70	66,90	67,90	72,40	72,50
	5YO	8,10	13,30	19,8	26,40	31,30	33,10	35,80	43,40	48,50	49,60
	000	21,30	31,60	53,5	59,40	72,50	75,90	80,90	86,00	86,70	86,90

TABLE C.23 (Cont'd.)

BLOCKS	TREATMENTS	DATES									
		AUGUST							SEPTEMBER		
		4	9	14	18	22	25	29	1	6	9
3	15YM	12,40	24,50	34,90	40,00	51,20	52,02	55,60	55,70	68,40	69,40
	15YC	5,70	9,10	14,40	23,10	35,80	41,80	56,50	58,20	59,00	61,50
	15YO	4,80	8,00	13,30	16,10	20,60	29,80	33,20	40,20	42,30	46,20
	10YO	5,80	11,50	19,40	28.40	41,04	49,50	52,40	60,20	61,00	61,00
	5YC	7,10	9,70	19,10	27,00	39,20	46,80	62,10	68,00	71,50	72,70
	5YM	6,40	8,20	14,40	20,10	32,80	33,50	46,60	49,70	61,30	64,80
	5YO	8,10	12,50	28,60	29,70	43,10	46,20	50,60	55,30	58,30	58,40
	000	17,40	32,80	45,90	59,50	74,50	74,90	82,70	86,40	86,50	86,80
4	15YM	4,00	-	-	-	36,00	36,20	42,00	42,50	45,60	46,60
	15YC	8,10	12,80	21,70	23,20	36,40	46,20	52,60	61,60	65,20	65,70
	15YO	7,80	10,50	20,60	24,20	33,60	44,90	51,20	57,20	57,30	59,20
	10YO	6,90	11,80	23,20	27,80	39,90	54,0	54,90	55,30	56,00	56,50
	5YC	6,90	8,60	17,30	23,70	37,40	46,50	52,60	61,10	66,80	69,00
	5YM	9,70	12,60	21,30	27,50	42,20	43,40	45,10	58,20	65,60	67,70
	5YO	4,70	9,70	15,00	18,40	30,50	32,50	39,50	47,20	54,30	55,50
	000	13,20	20,00	31,20	43,30	60,80	62,00	66,60	70,44	85,70	87,00

TABLE C.24 - Average plant heights (cm) for various compaction and tillage treatments (average of 5 samples) throughout the growing season of 1979.

BLOCKS	TREAT-MENTS	DATES								
		JULY					AUGUST			
		14	18	23	28	31	9	15	21	28
1	15YM	8,54	18,20	30,30	46,30	62,20	82,60	87,50	96,60	97,60
	15YO	8,20	16,10	26,00	40,30	49,00	70,00	72,00	88,20	88,60
	000	8,70	21,00	36,50	54,60	65,00	87,70	94,00	95,20	98,44
2	15YM	9,00	16,40	26,60	42,90	54,30	77,40	94,1	94,90	95,30
	15YO	8,80	16,20	28,1	41,50	54,90	78,30	86,20	96,10	96,60
	000	9,60	24,10	37,30	52,40	64,30	93,10	97,20	100,70	101,30
3	15YM	7,20	16,20	28,80	45,10	54,70	80,0	85,10	93,90	92,50
	15YO	8,70	16,50	29,80	45,00	58,50	80,80	82,50	90,70	90,80
	000	7,70	19,50	34,40	56,10	62,30	88,80	95,60	98,20	99,40

APPENDIX D

STATISTICAL ANALYSES AND REGRESSION MODELS

TABLE D.1 - Analysis of variance for increase in dry density at different depths.

YEAR 1978

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	14	0,20	0,014	2,79	0,0077	0,5418	46,98
Error	33	0,16	0,005		Std. Dev.		Z_1 Mean
Corr. Tot.	47	0,36			0,07		0,15

Source	DF	Anova SS	F	Pr> F
Block	3	0,0132	0,87	0,4662
Treatment	11	0,1835	3,31	0,0038

B. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	14	0,50	0,036	2,92	0,0057	0,5531	43,51
Error	33	0,40	0,012		Std. Dev.		Z_2 Mean
Corr. Tot.	47	0,90			0,11		0,25

Source	DF	Anova SS	F	Pr> F
Block	3	0,0726	1,99	0,1351
Treatment	11	0,4251	3,17	0,0050

C. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R_2	C.V.
Model	14	0,43	0,030	3,52	0,0014	0,5991	48,24
Error	33	0,28	0,008		Std. Dev.		Z_3 Mean
Corr. Tot.	47	0,71			0,09		0,19

Source	DF	Anova SS	F	Pr> F
Block	3	0,2165	8,33	0,0003
Treatment	11	0,2106	2,21	0,0387

TABLE D.1 (Cont'd)

D. 0,20 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	14	0,49	0,035	2,07	0,0426	0,4676	119,17
Error	33	0,56	0,017		Std. Dev.		Z_4 Mean
Corr. Tot.	47	1,05			0,13		0,11

Source	DF	Anova SS	F	Pr> F
Block	3	0,2373	4,66	0,0080
Treatment	11	0,2552	1,37	0,2349

E. 0,25 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	14	0,38	0,027	2,31	0,0240	0,4948	105,57
Error	33	0,39	0,012		Std. Dev.		Z_5 Mean
Corr. Tot.	47	0,77			0,11		0,10

Source	DF	Anova SS	F	Pr> F
Block	3	0,1422	4,00	0,0156
Treatment	11	0,2408	1,58	0,0853

TABLE D.2 - Analysis of variance for increase in dry density at different depths.

YEAR 1979

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	0,15	0,031	4,58	0,0455	0,7925	42,98
Error	6	0,04	0,007		Std. Dev.		V_1 Mean
Corr. Tot.	11	0,19			0,08		0,19

Source	DF	Anova SS	F	Pr> F
Block	2	0,0238	1,78	0,2476
Treatment	3	0,1299	6,46	0,0262

A. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	0,25	0,045	12,33	0,0041	0,9113	25,50
Error	6	0,02	0,004		Std. Dev.		V_2 Mean
Corr. Tot.	11	0,27			0,06		0,25

Source	DF	Anova SS	F	Pr> F
Block	2	0,0018	0,23	0,8026
Treatment	3	0,2462	20,41	0,0015

B. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	0,26	0,053	8,67	0,0102	0,8784	35,88
Error	6	0,04	0,006		Std. Dev.		V_3 Mean
Corr. Tot.	11	0,30			0,08		0,22

Source	DF	Anova SS	F	Pr> F
Block	2	0,0111	0,91	0,4511
Treatment	3	0,2528	13,84	0,0042

TABLE D.2 (Cont'd)

D. 0,20 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	0,22	0,045	17,20	0,0017	0,9348	29,04
Error	6	0,02	0,003		Std. Dev.		V_4. Mean
Corr. Tot.	11	0,24			0,05		0,18

Source	DF	Anova SS	F	Pr>F
Block	2	0,0158	3,05	0,1221
Treatment	3	0,2070	26,63	0,0007

E. 0,25 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	0,10	0,019	1,77	0,2532	0,5958	69,47
Error	6	0,06	0,011		Std. Dev.		V_5 Mean
Corr. Tot.	11	0,16			0,10		0,15

Source	DF	Anova SS	F	Pr>F
Block	2	0,0424	1,94	0,2241
Treatment	3	0,0543	1,66	0,2740

F. 0,30 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	0,07	0,013	1,12	0,4400	0,4823	55,37
Error	6	0,07	0,011		Std. Dev.		V_6 Mean
Corr. Tot.	11	0,14			0,11		0,20

Source	DF	Anova SS	F	Pr>F
Block	2	0,0095	0,40	0,6869
Treatment	3	0,0568	1,60	0,2861

TABLE D.3. - Analysis of variance for decrease in dry density at different depths.

YEAR 1978

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr > F	R^2	C.V.
Model	14	0,32	0,023	3,05	0,0041	0,5644	90,46
Error	33	0,24	0,007		Std. Dev.		Z_1 Mean
Corr. Tot.	47	0,56			0,09		0,10

Source	DF	Anova SS	F	Pr > F
Block	3	0,0217	0,98	0,4160
Treatment	11	0,2959	3,62	0,0020

B. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr > F	R^2	C.V.
Model	14	0,66	0,047	3,33	0,0022	0,5855	102,41
Error	33	0,46	0,014		Std. Dev.		Z_2 Mean
Corr. Tot.	47	1,12			0,12		0,12

Source	DF	Anova SS	F	Pr > F
Block	3	0,1516	3,60	0,0237
Treatment	11	0,5036	3,26	0,0042

C. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr > F	R^2	C.V.
Model	14	0,23	0,016	1,15	0,3548	0,3281	231,22
Error	33	0,47	0,014		Std. Dev.		Z_3 Mean
Corr. Tot.	47	0,40			0,12		0,05

Source	DF	Anova SS	F	Pr > F
Block	3	0,0695	1,61	0,2048
Treatment	11	0,1617	1,02	0,4475

TABLE D.3 (Cont'd)

D. 0,20 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	0,44	0,032	1,28	0,2700	0,3522	5021,05
Error	33	0,81	0,025		Std. Dev.		Z_4 Mean
Corr. Tot.	47	1,25			0,16		0,003

Source	DF	Anova SS	F	Pr>F
Block	3	0,1220	1,65	0,1964
Treatment	11	0,3196	1,18	0,3375

E. 0,25 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	0,49	0,035	0,82	0,6468	0,2573	257,60
Error	33	1,42	0,043		Std. Dev.		Z_5 Mean
Corr. Tot.	47	1,91			0,21		0,08

Source	DF	Anova SS	F	Pr>F
Block	3	0,1011	0,78	0,5122
Treatment	11	0,3912	0,83	0,6159

TABLE D.4 - Analysis of variance for decrease in dry density at different depths.

YEAR 1979

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr > F	R^2	C.V.
Model	5	0,27	0,053	5,16	0,0350	0,8114	75,72
Error	6	0,06	0,010		Std. Dev.		V_1 Mean
Corr. Tot.	11	0,33			0,10		0,13

Source	DF	Anova SS	F	Pr > F
Block	2	0,0160	0,78	0,5016
Treatment	3	0,2494	8,09	0,0157

B. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr > F	R^2	C.V.
Model	5	0,21	0,043	14,17	0,0029	0,9219	42,71
Error	6	0,02	0,003		Std. Dev.		V_2 Mean
Corr. Tot.	11	0,23			0,05		0,13

Source	DF	Anova SS	F	Pr > F
Block	2	0,0012	0,20	0,8218
Treatment	3	0,2125	23,48	0,0010

C. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr > F	R^2	C.V.
Model	5	0,07	0,013	6,00	0,0249	0,8334	70,23
Error	6	0,01	0,002		Std. Dev.		V_3 Mean
Corr. Tot.	11	0,08			0,05		0,07

Source	DF	Anova SS	F	Pr > F
Block	2	0,0123	2,82	0,1372
Treatment	3	0,0535	8,13	0,0155

TABLE D.4 (Cont'd)

D. 0,20 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	0,13	0,026	1,54	0,3063	0,5613	183,63
Error	6	0,10	0,017		Std. Dev.		V_4 Mean
Corr. Tot.	11	0,23			0,13		0,07

Source	DF	Anova SS	F	Pr>F
Block	2	0,0598	1,79	0,2449
Treatment	3	0,0681	1,36	0,3408

E. 0,25 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	0,08	0,015	2,02	0,2087	0,6271	133,89
Error	6	0,04	0,007		Std. Dev.		V_5 Mean
Corr. Tot.	11	0,12			0,08		0,06

Source	DF	Anova SS	F	Pr>F
Block	2	0,0254	1,68	0,2643
Treatment	3	0,0511	2,25	0,1833

F. 0,30 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	0,37	0,074	14,80	0,0025	0,9250	139,15
Error	6	0,03	0,005		Std. Dev.		V_6 Mean
Corr. Tot.	11	0,40			0,07		0,05

Source	DF	Anova SS	F	Pr>F
Block	2	0,0110	1,09	0,3947
Treatment	3	03592	23,93	0,0010

TABLE D.5 - Analysis of variance for increase in penetrometer resistance at different depths.

YEAR 1978

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	113,14	8,081	12,79	0,0001	0,8443	19,23
Error	33	20,86	0,632		Std. Dev.		Z_1 Mean
Corr. Tot.	47	134,00			0,79		4.13

Source	DF	Anova SS	F	Pr>F
Block	3	23,3403	12,31	0,0001
Treatment	11	89,8001	12,92	0,0001

B. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	62,65	4,475	3,95	0,0006	0,6260	37,96
Error	33	37,43	1,134		Std. Dev.		Z_2 Mean
Corr. Tot.	47	100,08			1,06		2,81

Source	DF	Anova SS	F	Pr>F
Block	3	20,1127	5,91	0,0024
Treatment	11	42,5399	3,41	0,0031

C. 0,20 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	30,48	2,177	4,83	0,0001	0,6723	67,45
Error	33	14,86	0,450		Std. Dev.		Z_4 Mean
Corr. Tot.	47	45,34			0,67		0,99

Source	DF	Anova SS	F	Pr>F
Block	3	5,9399	4,40	0,0104
Treatment	11	24,5372	4,95	0,0002

TABLE D.6 - Analysis of variance for increase in penetrometer resistance at different depths.

YEAR 1979

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	15,22	3,043	9,57	0,0080	0,8886	31,46
Error	6	1,91	0,318		Std. Dev.		V_1 Mean
Corr. Tot.	11	17,13			0,56		1,79

Source	DF	Anova SS	F	Pr> F
Block	2	0,9304	1,46	0,3037
Treatment	3	14,2863	14,98	0,0034

B. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	40,26	8,052	2,32	0,1670	0,6594	81,11
Error	6	20,79	3,466		Std. Dev.		V_2 Mean
Corr. Tot.	11	61,05			1,86		2,30

Source	DF	Anova SS	F	Pr> F
Block	2	13,6082	1,96	0,2208
Treatment	3	26,6521	2,56	0,1506

C. 0,30 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	98,90	19,780	19,73	0,0012	0,9427	22,61
Error	6	6,02	1,003		Std. Dev.		V_3 Mean
Corr. Tot.	11	104,92			1,00		4,43

Source	DF	Anova SS	F	Pr> F
Block	2	5,7093	2,85	0,1351
Treatment	3	93,1927	30,98	0,0005

TABLE D.7 - Analysis of variance for decrease in penetrometer resistance at different depths.

YEAR 1978

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	125,17	8,941	13,50	0,0001	0,8514	41,89
Error	33	21,85	0,662		Std. Dev.		Z_1 Mean
Corr. Tot.	47	147,02			0,81		1,94

Source	DF	Anova SS	F	Pr>F
Block	3	2,8715	1,45	0,2473
Treatment	11	122,2984	16,79	0,0001

B. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	59,00	4,214	3,87	0,0007	0,6218	78,04
Error	33	35,89	1,088		Std. Dev.		Z_2 Mean
Corr. Tot.	47	94,89			1,04		1,34

Source	DF	Anova SS	F	Pr>F
Block	3	2,7095	0,83	0,4867
Treatment	11	56,2932	4,71	0,0003

C. 0,20 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	30,24	2,160	8,32	0,0001	0,7791	161,84
Error	33	8,57	0,260		Std. Dev.		Z_4 Mean
Corr. Tot.	47	38,81			0,51		0,31

Source	DF	Anova SS	F	Pr>F
Block	3	0,3974	0,51	0,6782
Treatment	11	29,8442	10,44	0,0001

TABLE D.8 - Analysis of variance for decrease in penetrometer resistance at different depths.

YEAR 1979

A. 0,05 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	1,02	0,205	1,21	0,4062	0,5015	172,72
Error	6	1,02	0,170		Std. Dev.		V_1 Mean
Corr. Tot.	11	2,04			0,41		0,24

Source	DF	Anova SS	F	Pr>F
Block	3	0,0384	0,11	0,8949
Treatment	3	0,9870	1,94	0,2249

B. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	43,08	8,617	2,11	0,1945	0,6378	154,73
Error	6	24,46	4,077		Std. Dev.		V_2 Mean
Corr. Tot.	11	67,54			2,02		1,30

Source	DF	Anova SS	F	Pr>F
Block	2	10,8119	1,33	0,3335
Treatment	3	32,2711	2,64	0,1440

C. 0,30 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	74,32	14,865	8,09	0,0121	0,8708	58,15
Error	6	11,02	1,837		Std. Dev.		V_3 Mean
Corr. Tot.	11	85,34			1,36		2,33

Source	DF	Anova SS	F	Pr>F
Block	2	7,1196	1,94	0,2242
Treatment	3	67,2042	12,19	0,0058

TABLE D.9 - Analysis of variance for decrease in vane shear resistance at different depths.

YEAR 1978

A. 0,025 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	14	1761,03	125,788	6,67	0,0001	0,7390	27,47
Error	33	621,98	18,848		Std. Dev.		Z_1 Mean
Corr. Tot.	47	2383,01			4,34		15,80

Source	DF	Anova SS	F	Pr> F
Block	3	118,3873	2,09	0,1199
Treatment	11	1642,6403	7,92	0,0001

B. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	12221,92	872,99	6,50	0,0001	0,7338	26,87
Error	33	4434,76	134,39		Std. Dev.		Z_2 Mean
Corr. Tot.	47	16656,68			11,59		43,14

Source	DF	Anova SS	F	Pr> F
Block	3	437,40	1,08	0,3690
Treatment	11	11784,52	7,97	0,0001

C. 0,20 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	14	1943,38	138,81	1,23	0,3019	0,3427	75,42
Error	33	3727,58	112,96		Std. Dev.		Z_3 Mean
Corr. Tot.	47	5670,96			10,63		14,10

Source	DF	Anova	F	Pr> F
Block	3	207,0683	0,61	0,6126
Treatment	11	1736,3158	1,40	0,2202

TABLE D.10 - Analysis of variance for increase in vane shear resistance at different depths.

YEAR 1979

A. 0,025 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	6324,93	1264,986	12,35	0,0041	0,9114	27,87
Error	6	614,44	102,407		Std.Dev.		V_1 Mean
Corr. Tot.	11	6939,37			10,12		36,31

Source	DF	Anova SS	F	Pr>F
Block	2	231,5986	1,13	0,3831
Treatment	3	6093,3331	19,83	0,0016

B. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	4217,40	843,481	10,43	0,0064	0,8968	28,83
Error	6	485,46	80,842		Std. Dev.		V_2 Mean
Corr. Tot.	11	4702,46			8,99		31,19

Source	DF	Anova SS	F	Pr>F
Block	2	31,8937	0,20	0,8261
Treatment	3	4185,5094	17,26	0,0024

C. 0,30 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	5	2646,82	529,364	2,16	0,1881	0,6427	79,40
Error	6	1471,55	245,258		Std. Dev.		V_3 Mean
Corr. Tot.	11	4118,37			15,66		19,72

Source	DF	Anova SS	F	Pr>F
Block	2	408,9513	0,83	0,4792
Treatment	3	2237,8695	3,04	0,1143

TABLE D.11 - Analysis of variance for increase in vane shear resistance at different depths.

YEAR 1978

A. 0,025 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	1050,90	75,064	1,89	0,0651	0,4456	112,69
Error	33	1307,30	39,615		Std. Dev.		Z_1 Mean
Corr. Tot.	47	2358,20			6,29		5,59

Source	DF	Anova SS	F	Pr>F
Block	3	143,2093	1,21	0,3232
Treatment	11	907,6893	2,08	0,0511

B. 0,10 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	7810,85	557,918	1,87	0,0686	0,4428	124,47
Error	33	9828,29	297,827		Std. Dev.		Z_2 Mean
Corr. Tot.	47	17639,14			17,26		13,87

Source	DF	Anova SS	F	Pr>F
Block	3	1834,1943	2,05	0,1255
Treatment	11	5976,6533	1,82	0,0896

C. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr>F	R^2	C.V.
Model	14	3399,84	242,846	1,18	0,3319	0,3343	200,24
Error	33	6770,70	205,173		Std. Dev.		Z_3 Mean
Corr. Tot.	47	10170,54			14,32		7,15

Source	DF	Anova SS	F	Pr>F
Block	3	891,6232	1,45	0,2464
Treatment	11	2508,2205	1,11	0,3835

TABLE D.12 - Analysis of variance for decrease in vane shear resistance at different depths.

YEAR 1979

A. 0,025 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	7247,41	1449,482	11,01	0,0055	0,9018	49,15
Error	6	789,60	131,560		Std. Dev.		V_1 Mean
Corr. Tot.	11	8037,01			11,47		23,34

Source	DF	Anova SS	F	Pr>F
Block	2	169,5442	0,64	0,5579
Treatment	3	7077,8655	17,93	0,0021

B. 0,15 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	3382,37	676,477	8,01	0,0124	0,8698	56,62
Error	6	506,50	84,416		Std. Dev.		V_2 Mean
Corr. Tot.	11	3888,87			9,19		

Source	DF	Anova SS	F	Pr>F
Block	2	35,7425	0,21	0,8150
Treatment	3	3346,6308	13,21	0,0047

C. 0,30 (m)

Source	DF	Sum of Sq.	Mean Sq.	F	Pr> F	R^2	C.V.
Model	5	3830,68	766,135	4,93	0,0388	0,8042	198,18
Error	6	932,51	155,418		Std. Dev.		V_3 Mean
Corr. Tot.	11	4763,19			12,47		6,29

Source	DF	Anova SS	F	Pr>F
Block	2	339,2884	1,09	0,3942
Treatment	3	3491,3894	7,49	0,0188

TABLE D.13 - Regression model of lnθ = a + blnt for various compaction and tillage treatments at 0 - 0,15 and 0 - 0,30m depth.

A. 15YC

at 0 - 0,15m depth

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F
Regression	1	0,53956	0,53956	29,76	0,0001
Error	13	0,23573	0,01813		
Total	14	0,77528			

	B Value	Std Error	Type II SS	F	Prob > F	R
Intercept	-0,66876					
Days	-0,16741	0,03069	0,53956	29,76	0,0001	0,70

at.0 - 0,25m depth

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F
Regression	1	0,10347	0,10347	5,30	0,0001
Error	13	0,02674	0,00206		
Total	14	0,13021			

	B Value	Std Error	Type II SS	F	Prob > F	R
Intercept	-0,93094					
Days	-0.07331	0,01034	0,10347	50,30	0,0001	0,79

TABLE D.13 (Cont'd.)

B. 15YO

at 0 - 0,15m depth

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F	
Regression	1	0,14987	0,14987	19,11	0,0008	
Error	13	0,10192	0,00784			
Total	14	0,25179				
	B Value	**Std. Error**	**Type II SS**	**F**	**Prob > F**	**R**
Intercept	-0,7378					
Days	-0,08823	0,02018	0,14987	19,11	0,0008	0,60

at 0 - 0,25m depth

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F	
Regression	1	0,39735	0,03975	30,10	0,0001	
Error	13	0,01716	0,00132			
Total	14	0,05689				
	B Value	**Std Error**	**Type II SS**	**F**	**Prob > F**	**R**
Intercept	-0,76741					
Days	-0,04543	0,00828	0,03973	30,10	0,0001	0,70

TABLE D.13 (Cont'd.)

C. 000

at 0 - 0,15m depth

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F
Regression	1	0,06327	0,06327	3,43	0,0867
Error	13	0,23960	0,01843		
Total	14	0,30286			

	B Value	Std Error	Type II SS	F	Prob > F	R
Intercept	-0,99442					
Days	-0,05733	0,03094	0,06327	3,43	0,0867	0,21

at 0 - 0,25m depth

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F
Regression	1	0,51184	0,51184	78,62	0,0001
Error	13	0,08463	0,00651		
Total	14	0,59647			

	B Value	Std Error	Type II SS	F	Prob > F	R
Intercept	-0,58691					
Days	-0,16306	0,01839	0,51184	78,62	0,0001	0,89

TABLE D.14 - Regression model of $\ln\theta = a + b\ln(\theta/\theta_S)$ for various compaction and tillage treatments at 0,25m depth

A. 15YC

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F
Regression	1	4,49814	4,49814	65,48	0,0001
Error	13	0,89302	0,06869		
Total	14	5,39116			

	B Value	Std Error	Type II SS	F	Prob > F	R
Intercept	2,35433					
Theta	-5,87760	0,72634	4,49814	65,48	0,0001	0,83

B. 000

Source	DF	Sum of Sq.	Mean Sq.	F.	Prob > F
Regression	1	14,94562	14,94562	37,95	0,0001
Error	13	5,11904	0,39377		
Total	14	20,06466			

	B Value	Std Error	Type II SS	F	Prob > F	R
Intercept	3,190713					
Theta	-5,00566	0,81251	14,94562	37,95	0,0001	0,74

TABLE D.14 (Cont'd.)

C. 15YO

Source	DF	Sum of Sq.	Mean Sq.	F	Prob > F
Regression	1	4,72228	4,72228	50,38	0,0001
Error	13	1,21852	0,0937		
Total	14	5,94079			

	B Value	Std Error	TYPE II SS	F	Prob > F	R
Intercept	2,37593					
Theta	-9,11060	1,28356	4,72228	50,38	0,0001	0,79

APPENDIX E

PROGRAMME FOR CUBIC SPLINE SMOOTHING TECHNIQUE

Programme E.1 Cubic spline smoothing programme for smoothing field values of moisture content against the soil suction values.

```
C
C     *****************************************************
C     CUBIC SPLINE SMOOTHING TECHNIQUE FOR SMOOTHING FIELD DATA OF
C
C     MOISTURE CONTENT AGAINST THE SOIL SUCTION AT 0,25 M DEPTH
C
C     *****************************************************
C
      DIMENSION TIME(6)
      INTEGER NX,IC,IER,SET,SETMAX,IY,N,M,INC,IOPT,IMAG4(5151),ITITLE(14
     14),ICHAR(10),BLOCK(3),TREAT(3)
      REAL*8 W(60),Z(60,2),F(6),X(6),Y(6),C(5,3),WK(56),DF(6),SM,SD(6)
      REAL RANGE(4),SMCE(6),SWPF(6)
      DATA        ICHAR(1)/1H /,RANGE/0.0,0.0,28.0,58.0/
      READ(5,7) (ITITLE(I),I=1,144)
    7 FORMAT(72A1)
      NX=6
      SETMAX=9
    8 SET=1
      IC=5
    9 NB=1
   12 READ(5,10) BLOCK(NB),TREAT(NB),TIME(NB),SMCE(NB),SWPF(NB)
   10 FORMAT(I1,2X,A2,2X,I2,2X,F5.2,2X,F6.2)
      X(NB)=SWPF(NB)
      IF(NB.EQ.NX) GO TO 11
      NB=NB+1
      GO TO 12
   11 SQ=0
      SUM=0
      DO 14 NB=1,NX
      F(NB)=SMCE(NB)
      SUM=SUM+F(NB)
   14 SQ=SQ+F(NB)**2
      SD(SET)=((SQ-NX*(SUM/NX)**2)/(NX-1))**0.5
      DO 13 I=1,NX
   13 DF(I)=SD(SET)
      SM=0
      CALL ICSSCU (X,F,DF,NX,SM,Y,C,IC,WK,IER)
      K=1
      J=1
      W(1)=SWPF(1)
      Z(1,1)=F(1)
      Z(1,2)=Y(1)
      RINCR=(SWPF(NX)-SWPF(1))/49.0
      DO 110 J=2,60
      W(J)=RINCR+W(J-1)
      D=W(J)-SWPF(K)
      IF(W(J)-SWPF(K+1)) 107,106,105
  105 W(J)=SWPF(K+1)
  106 K=K+1
      Z(J,1)=F(K)
      Z(J,2)=Y(K)
      IF(K.EQ.NX) GO TO 111
      GO TO 110
  107 Z(J,2)=((C(K,3)*D+C(K,2))*D+C(K,1))*D+Y(K)
  110 CONTINUE
  111 INC=1
      N=J
      M=2
      IOPT=0
      IY=60
```

```
      WRITE(6,115)
115   FORMAT(10X,'SET',09X,'SMPE',2(09X,'SMCE'),10X,'Y',10X,'SM',5X,'BLO
     1CK',5X,'TREAT')
      DO 125 IB=1,J
      WRITE(6,120) SET,W(IB),(Z(IB,K),K=1,2),Y(IB),SM,BLOCK(IB),TREAT(IB
     1)
120   FORMAT(' ',11X,I2,8X,F8.3,2(8X,F6.3),10X,F6.3,20X,F4.1,6X,I1,8X,A2
     1)
125   CONTINUE
      CALL USPLTD (W,Z,IY,N,M,INC,ITITLE,RANGE,ICHAR,IOPT,IMAG4,IER)
      SET=SET+1
      IF(SET.GT.SETMAX) GO TO 40
      DO 126 I=1,J
      DO 126 L=1,2
126   Z(I,L)=0.0
      GO TO 9
 40   STOP
      END
*EOR
```