AN EVALUATION OF CONVENTIONAL AND NO-TILLAGE SYSTEMS ON SOIL PHYSICAL CONDITIONS

By

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Declaration

I hereby certify that the work reported in this dissertation is my own original and unaided work except where specific acknowledgement has been made

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Abstract

The use of no-tillage (NT) system has increased in the past few years in South Africa, but its effects on soil physical conditions have not been adequately documented. This study was undertaken to ascertain these effects, as compared to Conventional tillage (CT) system. Several sites were selected in the Bergville and Winterton areas of the midlands of KwaZulu-Natal, and at the Cedara Agricultural Research Station.

NT generally increased bulk density in the topsoil and this altered total porosity and pore-size distribution. Water retention, organic C and aggregate stability were increased under NT, partly due to the maintenance of the mulch cover on the surface soil. Organic C and aggregate stability were positively correlated with each other. Differences in bulk density between tillage systems with soil depth did not clearly indicate where soil compaction had occurred. Significant differences in soil compaction between treatments were, however, illustrated by changes in soil penetration resistance (SPR), especially at the 150 mm depth. In addition, depending on the soil type, SPR was greater in the topsoil under NT than CT. It was suggested that conversion from CT to NT was carried out when the topsoil of the CT-fields was structurally poor, due to a previous history of continuous CT.

Tractor traffic under CT and repeated tillage when the soil was wet had, in some cases, resulted in the formation of a compacted layer at the depth of cultivation. In clay soils, this has resulted in subsoil compaction. The formation of compacted layers caused major changes to pore size distribution and continuity and this resulted in substantially reduced hydraulic conductivity, infiltration rate, air-filled porosity and air permeability. It was concluded that compacted subsoil layers need to be broken up prior to conversion from CT to NT, and that compaction in the surface soil under NT has occurred and, in some cases, this will be a limitation to crop production. The use of minimum tillage systems should be considered and researched in these cases.

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List of symbols and abbreviations

α = contact angle of soil water

γ = surface tension of water (N m^{-1})

φ_g = gravimetric potential (k Pa)

φ_m = matric potential)- kPa)

φ_o = osmotic potential (kPa)

φ_p = pressure potential (kPa)

φ_t = total potential (kPa)

θ_m = mass water content (kg kg^{-1})

θ_{sat} = saturated water content (m^3 m^{-3})

θ_v = volumetric water content (m^3 m^{-3})

ρ_b = bulk density (kg m^{-3})

ρ_s = particle density (kg m^{-3})

ρ_w = density of water (kg m^{-3})

AFP = air-filled porosity

ANOVA = Analysis of variance

CARS = Cedara Agricultural Research Station

CIR = compacted interrow

CT = conventional tillage

d.f. = degree of freedom

DRI = double ring infiltrometer

DLM = dryland maize

DLS = dryland soybean

FC = field capacity

FIR = final infiltration rate

IM = irrigated maize

IS = irrigated soybean

K_a = air permeability. The SI units are m^2, but for easier interpretation the results are presented as µm^2

K_s = saturated hydraulic conductivity (mm h^{-1})

LIR = loose interrow

$LSD_{0.05}$ = least significant difference at 5 %

NT = no tillage

MWD = mean weight diameter (mm)

$P_{0.05}$ = probability level at 5 %

PAW = plant available water (% or m^3 m^{-3})

SPR = Soil penetration resistance. The SI units are kPa, but for easier interpretation the results are presented as MPa

RAW = readily available water (% or m^3 m^{-3})

S.E. = standard error

SOC = soil organic carbon (%)

WRC = water retention curve

Chapter 1

Introduction

No-tillage (NT) is defined as any tillage system with no seedbed preparation. The system involves opening a narrow slit in the soil by means of a non-powered coulter, narrow chisel or angled disc running ahead of a planter unit disc. Chemical weed control substitutes for cultivation (Mannering and Fenster, 1983). Conventional tillage (CT) is defined as mouldboard ploughing or plough tillage with a primary deep tillage operation which inverts the furrow slice, followed by a secondary tillage operation involving disking and harrowing for final seedbed preparation and weed control. No plant residues are left on the soil surface (Miller and Donahue, 1995).

Studies in many countries, especially in the United States, Australia, the United Kingdom, Canada and India have recognized NT as a preferred cropping system compared to CT. Economically, NT has been recognized as a more profitable and less risky tillage system than the CT system, through a reduction in soil erosion and in the cost of labour, fuel and machinery input (Brown *et al.*, 1989; Hill and Lake, 1992; Lawrance *et al.*, 1999; Lawrance, 2000). According to McGarry *et al.* (2000), NT is a particularly attractive system for clay soils, in terms of minimising soil compaction and inducing natural structure formation.

In South Africa, the NT system has been researched and recommended for many years (Berry and Mallett, 1988). The benefits in terms of water and soil conservation, as well as increased yield in dry seasons, have been clearly demonstrated (Berry and Mallett, 1988;

Lawrance *et al.*, 1999; Lawrance, 2000). However, technical difficulties of planting, weed control and diseases have prevented the system from being adopted by farmers on a large scale. With the improvement in design of no-till planters and more suitable cultivars of maize, wheat and soybeans being available, the system has become far more attractive to farmers. Another major factor that has driven farmers to change their system from CT to NT has been the dramatic increase in the cost of fuel and mechanical equipment. In fact, the NT system leads to great savings in this regard (Berry and Mallett, 1988; Lawrance *et al.*, 1999; Lawrance, 2000). As a result, the use of NT has increased in popularity over the past decade in South Africa, and there is currently a strong move to convert from CT ("rip" to approximately 250 mm followed by disking) to NT (planting into a 50 mm deep groove). More than 10,000 hectares of cultivated land is currently under NT management in the KwaZulu–Natal province, using rotations of maize-wheat-soybean crops (Johnston, 2001, personnal communication).

In recent times, problems associated with the use of NT have begun to emerge in South Africa. In particular, the formation of a dense, compacted surface (100 – 150 mm) layer has been observed. In a number of cases, this has been suspected to be limiting crop root proliferation and, in wet years, resulting in waterlogging with poor seedling emergence and uneven crop growth. However, to date, little research in South Africa has addressed this aspect of NT and most examples quoted are anecdotal in nature. There is a need for some objective data on the soil physical conditions that have developed under NT.

Conventional tillage has been the dominant practice in South Africa for many years, and some of the lands have been under production more than 100 years (Johnston, 2001, personnal communication). CT has been shown to have negative impacts on the soil physical properties, such as the development of a plough-pan that impedes root penetration and increases bulk density and soil strength (Gómez *et al.*, 1999; Rasmussen, 1999). This can lead to poorly aerated conditions and plant root growth problems, owing to the great reduction of macro-porosity (Ball *et al.*, 1988; Holt *et al.*, 1993; Brady and Weil, 1996). In addition, a substantial amount of soil erosion can occur. Water erosion results in sediments entering waterways and dams and it reduces their water storage capacity.

In order to conduct a valid comparison of the soil physical changes, as affected by both NT and CT, this project was conducted on seven paired-sites (a NT-plot arranged next to a CT-plot). These sites were chosen on different farms in the Winterton, Bergville and Cedara areas. To assess the changes in soil physical properties due to both tillage systems, three important criteria were considered in the selection of sites:

- The fields should be close and arranged as a pair of plots subjected to conventional and no tillage systems;
- To ensure the assessment of soil physical changes due to the long-term tillage system, no tillage had to have been applied for > 7 years;
- Although several soil types occur at the selected site (farm), the sampling area was selected on the dominant soil type, and this had to be as close as possible in both plots (CT and NT plots).

The aim of this study was to identify and quantify any positive or negative effects that NT might have on soil physical properties, as compared to CT. Specifically, the project aims to determine:

- The effects of NT on soil water retention characteristics and pore-size distribution, as compared to CT;
- The effects of tillage (NT and CT) on soil aeration and air permeability;
- The effects of tillage systems on soil transport properties (soil infiltration and hydraulic conductivity), as influenced by soil porosity and pore-size distribution;
- The effects of tillage systems on penetrometer soil strength and the relative impacts on soil aeration and water movement;
- The effects of NT and CT on soil aggregate stability, as affected by the distribution of organic carbon.

In Chapter 2 literature concerning the effects of tillage systems on soil physical conditions is reviewed. Soil physical changes are described, based on NT and CT management and the ecological study area.

Chapter 3 describes the study-sites and their cropping history. The choice of sites was very selective, especially in terms of looking for a long-term experiment site. Details on the description of the climate and soils at each study-site are given in this chapter.

Chapter 4 investigates and discusses the effects of tillage system on soil aggregate stability, as affected by the distribution of soil organic carbon.

Chapter 5 deals with the effects of tillage system on soil water retention characteristics. Bulk density and pore-size distribution, as derived from water retention data, are presented herein, and discussed as factors affecting the water retention curve. The principles and concepts related to water retention curves and their derivations, are also presented herein, and constitute the necessary background information to describe the soil water retention characteristics. In addition, the tillage effects on soil aeration and the influence of tillage on plant available water (PAW) and readily available water (RAW) are presented in this chapter.

Chapter 6 is concerned with the effects of tillage system on soil infiltration and hydraulic conductivity. Soil infiltration was measured by a field approach, whilst saturated hydraulic conductivity was determined on undisturbed soil cores, taken for water retention measurements.

Chapter 7 describes the penetrometer soil resistance, as affected by tillage system. A general conclusion of this study, showing the main points from each chapter and recommendations, is given in Chapter 8.

It is relevant to emphasize that this study does not provide a detailed quantification of soil physical changes due to the NT system, as compared to the CT system. To observe subtle differences in soil physical characteristics as affected by tillage regime, a long-term NT trial needs to be established. In addition, as discussed by many other workers (Cassel and Nelson, 1985; Heard *et al.*, 1988; Cassel *et al.*, 1995), much more data are needed on the spatial and temporal variations in soil physical properties, as affected by tillage system.

Chapter 2

Literature review on the influence of tillage system on soil physical properties and organic carbon

2.1 Introduction

Tillage systems can modify soil physical properties in a number of ways depending on the cropping history, soil type, climatic conditions, and previous tillage systems used (Mahboubi *et al.*, 1993; Chagas *et al.*, 1994). In addition, the frequency and the depth of the tillage operation also affect soil physical properties, and thereby, crop response. Crop response to changes in physical properties will, in turn, depend on factors such as the length of the growing season, the amount of rainfall, and the native soil properties (Ferreras *et al.*, 2000). Thus, changes in the soil physical properties due to tillage can differ greatly for regions, localities within a region, and often for soils on a farm, when these soils differ appreciably in drainage, texture, depth, and topographic characteristics (Sprague and Triplett, 1986).

From a practical viewpoint, most studies have shown that soil bulk density was higher in the topsoil under NT than CT (Edwards *et al.*, 1988; Heard *et al.,* 1988; Benjamin, 1993; Azooz *et al.*, 1996). Some other workers such as Blevins *et al.* (1983) found no differences in bulk densities between tillage systems. Heard *et al.* (1988), Raghavan *et al.* (1992) and Smith *et al.* (1997) reported that the extent of the increased bulk density under NT depends greatly upon the soil texture and soil moisture content.

Soil water retention is strongly influenced by the pore-size distribution and total porosity (Azooz *et al.*, 1996; Arshad *et al.*, 1999; Ferreras *et al.*, 2000; Smith *et al.*, 2001). A decrease in total porosity due to soil consolidation is shown by the decrease in saturated soil water content, and an increase in bulk density (Azooz *et al.*, 1996). The collapse of large pores is further shown by the lower volumetric water content held between a certain range of matric potentials (Smith *et al.*, 2001). Owing to its different pore-size distribution, soil under NT has been shown by some workers to have a greater ability to store water at field capacity than under CT (Smith *et al.*, 1997; Singh *et al*, 1998).

Usually, infiltration rates under NT are found to be higher than under CT (Edwards, 1982; Shipitalo *et al.*, 2000), but in some cases, they are lower (Lindstrom *et al.*, 1981; Heard *et al*, 1988). Other authors have found no differences in infiltration rates between NT and CT (Ankeny *et al.*, 1990). The development of a surface crust (Zuzel *et al.*, 1990), a plough-pan layer (Bennie and Krynauw, 1985; Gómez *et al.*, 1999, Rasmussen, 1999), and tillage-induced macroporosity under CT (Meek *et al.*, 1990) may help to explain these differences. In addition, it is difficult to predict soil responses to changes in tillage methods without the help of long-term experimentation (Gómez *et al.,* 1999).

Some studies of water flow have shown that hydraulic conductivity in NT soils is greater than under CT, because of the effect of continuous earthworm channels (Chan and Mead, 1989) and termite galleries that increase the volume fraction of macropores (Ehlers, 1976; Holt *et al.*, 1993). By contrast, despite the greater volume of macropores found under NT, Gantzer and Blake (1978) measured higher hydraulic conductivity in CT soils. Similarly, Heard *et al.* (1988) measured lower saturated hydraulic conductivity (K_S) under NT compared with CT, and attributed this to the higher bulk density in the surface soil measured under the NT system. However, they indicated that other relevant soil properties (soil texture, organic carbon content, etc) had greater effects on K_S than did tillage system.

Air permeability (K_a) is usually found to be greater under CT than NT, owing to greater total porosity and volume of macroporosity, resulting in greater air-filled porosity (AFP) (Roserberg and McCoy, 1992). However, large differences in K_a and AFP between different horizons through the soil profile can suggest the presence of an impeding layer within the soil profile, resulting in the deterioration of soil pore structure (Groenevelt *et al.*, 1984; Heard *et al.,* 1988).

The use of NT systems generally increases the soil organic carbon (SOC) concentration near the soil surface when compared to conventionally tilled soils (Yang and Wander, 1999). Under CT, as the plough layer is often inverted each year to bury plant residues, the distribution of organic carbon content down the soil profile is fairly uniform (Douglas *et al.*, 1986). BØrresen and NjØs (1994) and Riley and Ekeberg (1998) reported that reduced ploughing depth led to an accumulation of soil organic carbon near the surface, but the total amount was unaffected. Haynes (1999) showed that the concentration of organic matter is highest near the surface and decreases steadily down the profile under NT.

Owing to greater SOC, Arshad *et al.* (1999) found greater aggregate stability in the surface soil under NT compared with CT. On long-term tillage trials, Rasmussen (1999) showed a similar trend, even on weakly structured soils. Similarly, Mahboubi and Lal

(1998) reported higher soil aggregation and the formation of large soil aggregates under NT, especially in summer and autumn.

Penetration resistance has been reported to be more sensitive than bulk density to changes in tillage system (Hammel, 1989; Ferreras *et al.*, 2000). Most studies have reported higher soil penetration resistance (SPR) under NT than CT (Chaney *et al.*, 1985; Douglas, 1986; Hill, 1990; Johnson *et al.*, 1990; Braim *et al.*, 1992; Horne *et al.*, 1992; Liebig *et al.*, 1993; Pikul *et al.*, 1993; Sharratt, 1996; Materechera and Mloza-Banda, 1997; Karunatilake *et al.*, 2000; Krzic *et al.*, 2000; Yavuzcan, 2000). Among other workers, Unger and Jones (1998), Gomez *et al.* (1999) and Rasmussen (1999) found the development of a compacted layer below the depth of soil cultivation under CT. The thickness of the compacted layer varies widely, depending on the soil type, soil quality and soil moisture status (Unger and Jones, 1998).

This review presents an overview of different studies conducted on various soil tillage systems and the effects of these systems on important soil physical properties and processes. These include water retention, as affected by soil porosity and bulk density; water movement described through soil infiltration and hydraulic conductivity; soil aggregation and structure, as affected by soil organic carbon content; and soil strength measured as a function of soil penetration resistance (SPR).

2.2 Soil water retention

2.2.1 The concept of soil water potential

Soil water retention can be described using fundamental concepts of soil water potential. Several empirical equations have been developed to describe these concepts. Some of them were developed by Brooks and Corey (1966), Visser (1966), Laliberte (1969), Gardner *et al.* (1970), White *et al.* (1970), Su and Brooks (1975), van Genuchten (1978, 1980), Marshall and Holmes (1979, 1988), and Hillel (1980a, 1980b, 1998).

Water, at any particular point in the soil, is associated with a specific energy state (Hillel, 1998). Differences in potential energy of water between two points in the soil constitute the driving force for the movement of water (Hillel, 1998). Accordingly, the force causing the soil water flow in the direction of decreasing potential, is equal to the negative potential ($-d\phi/dx$), which is the change of energy potential (ϕ) with distance (x). The negative sign indicates that the force acts in the direction of decreasing potential (Hillel, 1998).

Knowing the potential energy state of soil water can help to estimate how much of water is retained and its availability to the plant, or how far the water in the soil system is from equilibrium. Briefly, the potential energy, which is due to the position or internal condition, is of primary importance in determining the state and the movement of water in the soil.

In soil, water is subjected to a number of possible forces, each of which may cause its potential to change from that of pure, free water at a reference elevation. These forces can be related to the mutual attraction between the soil matrix and water, gravity and the concentration of solutes (Hillel, 1998).

Accordingly, the total soil water potential is expressed as the sum of these various physical factors, as follows:

$$\varphi_t = \varphi_g + \varphi_p + \varphi_o \quad \ldots\ldots\ldots\ldots \quad \textbf{Eq 2.1}$$

where φ_t is the total potential, φ_g is the gravitational potential, φ_p is the pressure potential and φ_o is the osmotic potential.

The gravitational potential of the soil water at a particular point is determined by the elevation of the point relative to a reference level. The pressure potential is obtained from the difference in pressure between that of the soil water and atmospheric pressure. The pressure potential will be considered positive when the pressure of water is greater than atmospheric, as happens beneath a water table (saturated soils). On the other hand, in unsaturated soils, the pressure potential is negative due to capillary forces and adsorptive forces on the soil matrix (Hillel, 1998). This negative pressure potential is then termed "matric potential", and this denotes the total effect resulting from the affinity of the water to the whole soil matrix, including its pores and particle surfaces together. The osmotic potential is regulated by the concentration of the solute in the soil water.

The potential energy of soil water tends to be lower where the concentration of solutes is higher. The water retention and movement in soil is a consequence of the energy status. The relationship between matric potential and water content is usually represented graphically by the "water retention curve (WRC)".

The water retention characteristics are related to the pore geometry as pointed out by Mualem (1976). The theory describes the flow of water in soil based on the capillary equation (Eq 2.2) (Hillel, 1998). The amount of water retained in the soil is dependent upon the volume of the water-filled pores. At saturation, all air-filled pores become water-filled and the total soil water potential is zero. No outflow may occur until, as matric potential is decreased, a critical value is exceeded at which the largest pores begin to drain and the water is displaced by air. A further decrease in matric potential would lead to further displacement of soil water by air in corresponding pore sizes. The relationship between pore size and matric potential may be estimated from the capillary equation:

$$\mathbf{P = 2\gamma/r \cos \alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{Eq 2.2}$$

Where **P** is the potential (Pa), γ is the surface tension of water ($N.m^{-1}$), **r** is the radius (m) of the capillary pore and α is the contact angle (in freely wetting soils, $\alpha = 0$).

Using equation (Eq 2.2) one is able to quantify the distribution of pores of various size ranges since the volume of water released during an incremental increase in matric potential is equal to the volume of pores between a corresponding increment in pore diameters. In fact, soils rarely conform closely to these requirements and, therefore, the calculated pore size distribution is only an approximation of the true effective porosity (Reeve and Carter, 1991).

2.2.2 Factors influencing soil water retention characteristics

Soil water retention is strongly dependent upon the particle size distribution, the texture of the soil and its structure (Klute, 1986). The organic matter content may also directly and/or indirectly control the water retention function, especially due to the hydrophilic nature of organic matter and its effects on soil structure (Reeve and Carter, 1991).

The texture of the soil and the clay mineralogy can affect the overall shape of the water retention curve. Both the shrinkage and swelling of clay change substantially the shape of the water retention curve. On the other hand, the porosity of coarse textured soils (e.g. sandy soils) is dominated by large pores, and therefore at the higher matric potential range (-1 to -10 kPa), the majority of water is released. At lower matric potentials (e.g. –1500 kPa), soil water retention is texturally related and depends less on pore size distribution. In contrast, clay soils will release only small amounts of water at high matric potentials (due to a smaller proportion of large pores) and will retain a substantial amount of water at low matric potentials (due to the large surface area available for water adsorption) (Hillel, 1998).

The structure of the soil can also affect the shape of the water retention curve. Many well-aggregated soils may have a relatively high proportion of large pores, resulting in the release of water at high matric potentials. Non-aggregated clayey soils, especially those susceptible to shrinkage and swelling, may be characterised by a high proportion of micropores, resulting in substantial retention of water at low matric potentials and in slow release of small amounts of water at high matric potentials (Hillel, 1998).

The compaction of well-aggregated soils or sandy soils is manifested mainly by a decrease in macroporosity and an increase in mesoporosity, the microporosity remaining unaffected. This may have important implications for water retention characteristics (Reeve and Carter, 1991).

2.2.3 Influence of tillage system on water retention

The magnitude and trends of change in soil water retention due to tillage systems depends on the size and volume fraction of pores. NT soils are generally wetter (Arshad *et al.*, 1995; Sharratt, 1996) and store more water at a given matric potential (Allmaras *et al.*, 1977; Mahboubi *et al.*, 1993). Evaporation is a primary source of water loss from soils during the first half of the growing season before the canopy has closed. Under NT, the surface residues form a mulch over the soil surface that greatly reduces evaporation (Heer and Krenzer, 1989; Radford *et al.*, 1995). Thus, soil water content is often higher, particularly early in the season, under NT than CT. The higher moisture content under NT can be related also to the greater infiltration capacity under NT and a change in pore size distribution (Larney and Lindwall, 1995, Singh *et al.*, 1998; Arshad *et al.*, 1999; Karunatilate *et al.*, 2000; McGarry *et al.*, 2000; Yavuzcan, 2000).

However, the magnitude of change in soil water retention due to tillage systems varies with soil texture and wheel traffic. For instance, as reported by Arshad *et al.* (1999), water retention over a selected range of soil matric potentials (0 to – 400 kPa) indicated that soil under NT retained more water than under CT in both a silt loam and a sandy loam (Figure 2.1). This was attributed to the greater volume fraction of micropores under NT than under CT, which is a result of compaction occurring in the surface soil under NT. Indeed, Roseberg and McCoy (1992) studying the effects of wheel traffic under the CT and NT systems on fine-loamy soils found that the water retention curve, calculated in the range of matric potential of 0 to – 3 kPa, showed greater volumetric water content for CT non-wheel traffic. The greatest difference between tillage treatments occurred at saturation, with differences decreasing as matric potential decreased to – 3 kPa. They attributed these findings to maximum changes in macropore water content. A similar trend was previously observed by Hill (1990) and Hill and Meza-Montalvo (1990) on silt loam soils, who, however, showed that CT soils retained more water for matric potentials of 0 to – 2 kPa, while NT soils retained more water for the – 3.9 to – 40 kPa matric potential (Figure 2.2).

In contrast, Karunatilate *et al.* (2000), studying the effect of soil water content on a clay loam soil under NT and CT, consistently found higher soil water contents in the topsoil under NT compared with CT. They attributed these findings to a higher volume fraction of large pores, providing greater gravitational drainage under CT compared to NT. The same trend was observed by Yavuzcan (2000) who reported a greater water content in NT- soil in the 0 – 50 mm layer compared to CT- soil. McGarry *et al.* (2000), studying a Vertisol in the semi-arid subtropics of Australia, found NT maintained a high water content up to 240 mm soil depth, in comparison to CT (Figure 2.3).

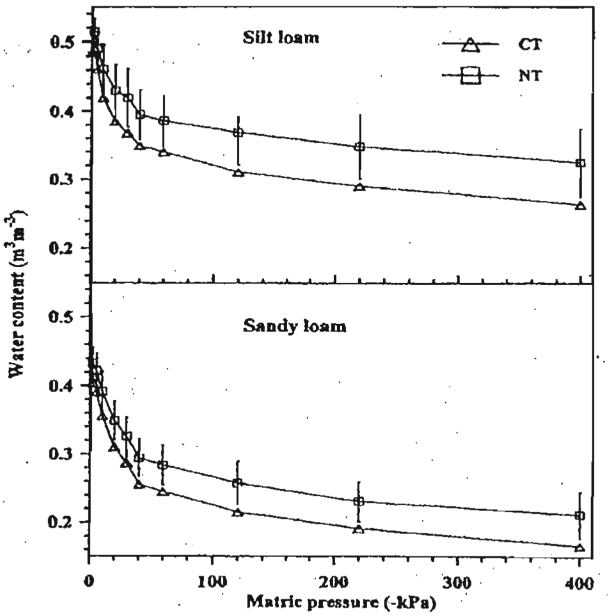


Figure 2.1. Water retention of the silt loam and sandy loam soils as affected by tillage system (CT: conventional tillage and NT: no-tillage) (Arshard *et al.*, 1999)

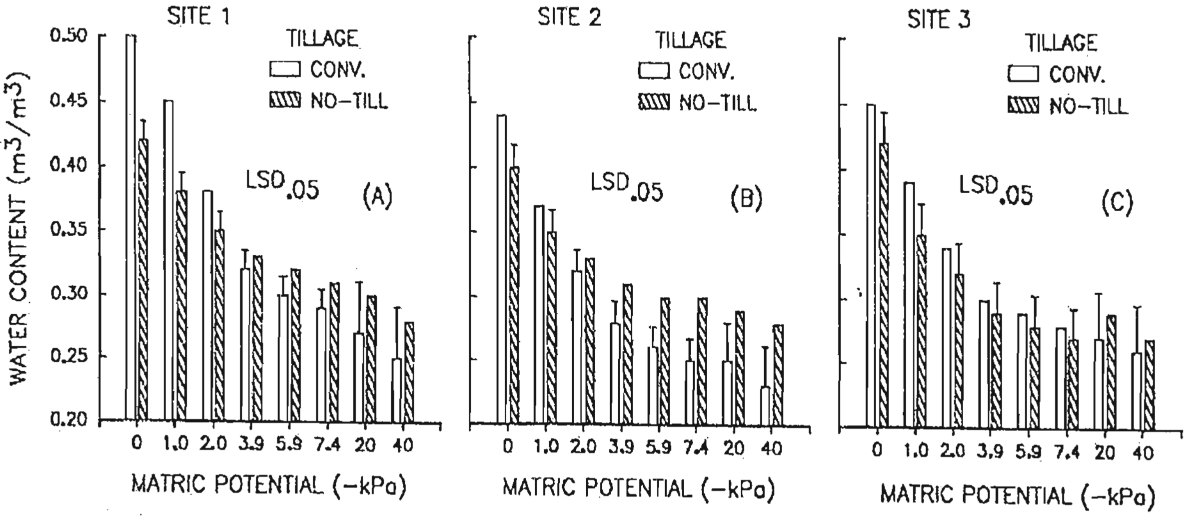


Figure 2.2. Relationship between volumetric water content and soil water potential for NT and CT systems on silt loam soils. Sites 1 (A) and 2 (B) are at coastral plain, while site 3 (C) is at piedmont (Hill, 1990).

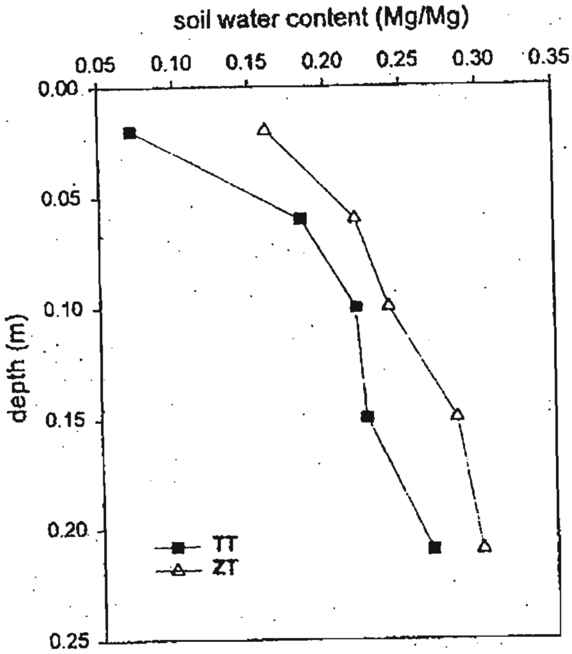


Figure 2.3. Soil water content of conventional tillage (TT) and no-tillage (ZT) soil profiles at the time of sampling (McGarry *et al.*, 2000)

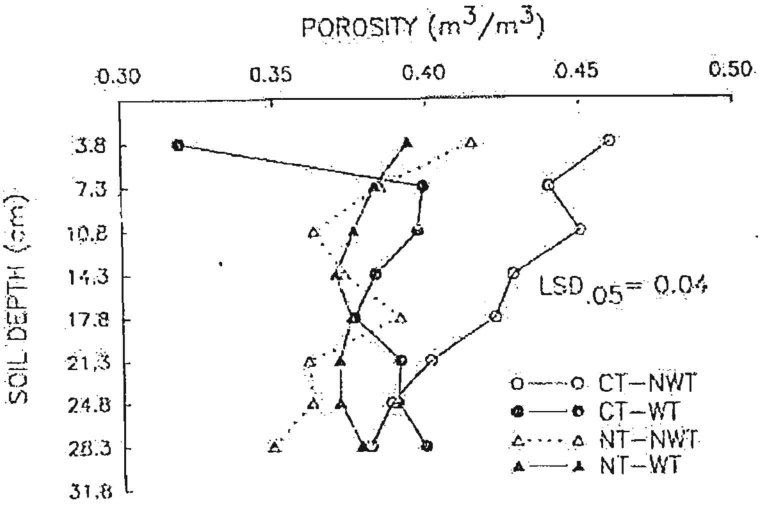


Figure 2.4. Total porosity for the 20 to 300 mm depth of wheel-tracked (WT) and non-wheel-tracked (NWT) interrows of CT and NT soil. Mean comparisons may be made between tillage and wheel-traffic treatments for a given depth using the LSD at the 0.05 level (Hill and Meza-Montalvo, 1990)

2.3 Influence of tillage system on soil porosity

Many researches (Hill, 1990; Logsdon *et al.*, 1990; Vyn and Raimbault, 1993; Lal *et al.*, 1994; Cassel *et al.*, 1995; Katsvairo *et al.*, 2002) have reported lesser total porosity in NT compared with CT during the early and mid-season corn growth. This was associated with greater bulk density and soil penetration resistance. Chaney *et al.* (1985) and Carter (1992) concluded from their experiments on loamy and fine sandy loam soils, respectively, that NT not only may reduce total pore space, but may also change pore size distribution, with larger pores disappearing and the smaller ones predominating. This is the result of compaction occurring in the surface soil under NT (see section 2.5). Similar trends were also reported by Rasmussen (1999). Similarly, for a moderately well drained loam soil, Ferreras *et al.* (2000) found a larger amount of its pore volume in larger pores (> 20 µm diameter) under CT than NT. Arshad *et al.* (1999) found that total porosity was not influenced by tillage method, whereas pore size distribution was affected. Soils under NT contained greater microporosity (< 0.75 µm diameter) and lower macroporosity (>15 µm diameter) than CT. Previously, Hill and Meza-Montalvo (1990) studying the effects of long-term wheel traffic on silt loam soils, reported that the presence of wheel traffic in the CT interrows significantly reduced the volume of pores > 15 µm in the upper 178 mm soil layer, but did not cause similar reductions in the NT interrows. However, CT soil exhibited more pore space in the 15 - to 0.1 µm radius range that should retain plant-available water, while wheel traffic did not exhibit significant effects for that pore-size range. They concluded that wheel traffic had resulted in greater increased soil strength under CT – soil whilst NT – soil was precompacted and, therefore, has sufficiently soil strength to carry wheel traffic (Figure 2.4).

[illegible]

and [illegible] improves soil structure.

On a Vertisol, McGarry *et al.* (2000) studied soil structure using image analysis. They found that total porosity under NT was more than double that of porosity under CT in the 10 – 20 mm layer, reflecting an obvious soil crust in the surface 25 mm under CT. Rasmussen (1984) observed a similar phenomenon due to the development of a surface crust under CT. In contrast, the surface 25 mm for NT consisted of strongly-aggregated material, surrounded by abundant and interconnected pores. The greater porosity in the wetter soil of NT may demonstrate that the aggregates and thus, pore structure, are more stable than those under CT. This has been ascribed to the high earthworm and termite activity that promotes aggregation (Radford *et al.*, 1995). In the 50 – 100 mm layer, McGarry *et al.* (2000) found that CT had up to 5-fold greater total porosity than NT, with a predominance of microporosity. In the 150 – 200 mm layer, the total porosity under NT was up to 10-fold more than that of CT, composed by meso- and microporosity. This was attributed to earthworm activity giving cast material that promoted stable soil aggregates, therefore, creating continuous vertical and horizontal channels throughout the soil profile.

2.4 Influence of tillage system on water movement

2.4.1 Hydraulic conductivity

Tillage effects on saturated hydraulic conductivity are not well defined as NT has promoted greater (Mielke et al., 1984; Mahboubi et al., 1993; Sharratt, 1996) or smaller conductivities (Datiri and Lowery, 1991) than CT. This apparent anomaly arises because changes in macroporosity and pore continuity, both of which govern hydraulic conductivity, vary with soil type, time of tillage, and length of time the soil has been under tillage.

Under CT, void and cracks formed by tillage and residue incorporation, or roots-channels can contribute to enhancing macroporosity, which may be effective in water transmission through the tilled layer (Heard *et al.*, 1988). Under NT, the hydraulic conductivity can be significantly affected by macroporosity formed by earthworms, soil insects or roots (McGarry *et al.*, 2000), but these macropores are often destroyed in tilled soils (Ehlers, 1976). These pores were very dense and easily observed under the NT field in the form of termite galleries and earthworm burrows. Similarly, Douglas *et al.* (1986) and Rydberg (1986) measured greater hydraulic conductivity in the topsoil and subsoil under NT compared with CT, owing to continuous earthworm channels at these soil depths.

Higher saturated hydraulic conductivity under NT can also be attributed to the surface residue cover that may prevent surface sealing (Heard *et al.*, 1988), and mainly to better soil pore continuity (Comia *et al.*, 1994). In contrast, lower saturated hydraulic conductivity under NT rather than under CT may be due to the higher bulk density of the NT system (Heard *et al.*, 1988). Regardless of tillage system, soil texture can affect hydraulic conductivity. Heard *et al.* (1988) reported lower saturated hydraulic conductivity in silt-loam soil compared with a well-structured silty-clay-loam. They concluded that other relevant soil properties (e.g. texture and organic C) effect on saturated hydraulic conductivity than the tillage system used. In contrast, investigating the relationship between the volume of macroporosity (> 0.3 mm) and saturated hydraulic conductivity on a heavy clay soil in Finland, Aura (1988) found (Table 2.1) that CT, which had the highest volume of macroporosity, showed the highest rate of hydraulic conductivity. The volume of macroporosity as well as the hydraulic conductivity was lower under NT than CT. A similar trend was previously reported by Gantzer and Blake (1978). The reason for this is that immediately after tillage, macroporosity and hydraulic conductivity are increased greatly. and decreasing as soil consolidate due to the impact of rain water. (simulated rain fall study)

However, over time natural consolidation occurs under CT and values for these parameters are much reduced. The extent of consolidation depends greatly on the extent of loss of organic matter under CT. Thus, results for comparisons between macroporosity and hydraulic conductivity under CT or NT can depend on the length of time that has elapsed between tillage and sampling and also how many years tillage has been practised.

Table 2.1. Soil tillage impacts on macropore (vol. %) and saturated hydraulic conductivity (K_S) in a heavy clay soil in Finland (Aura, 1988) ** $P < 0.01$

	Saturated hydraulic conductivity (K_S, m s^{-1})	Macropores > 0.3 mm (% of soil volume)
Ploughing and harrowing (or CT)	159	13.5
Direct drilling (or NT)	58	10.6
Harrowing	21	8.1
F – value	10.33**	3.94

Air permeability (K_a) has been used in attempts to characterize soil pore geometry and continuity (Ball, 1981; Hamblin and Tennant, 1981; Groenevelt *et al.*, 1984; Ball and O'Sullivan, 1987; Blackwell *et al.*, 1990). Roseberg and McCoy (1990) developed a technique that differentiates between macropres and air permeability by controlling matric potential and volumetric water content within the sample. From this technique, they found that macropores ranging in the matric potential of 0 to – 3 kPa (corresponding to pore-diameter of > 100 µm) are able to conduct air (at – 3 kPa) and water flowing by gravity. Roseberg and McCoy (1992) studying tillage and traffic effects on macroporosity and macropore geometry, found that wheel traffic significant decreased K_a at all matric potential range, 0 up to 3 kPa. In wheel traffic interrows, macropore air permeability was significantly less under CT than NT. Non-significant tillage differences were observed in K_a between NT wheel traffic and NT non-wheel traffic. Wheel traffic significantly decreased air permeabilty for CT, but not for NT. Once again, they attributed this trend to increased soil strength under CT soil whilst NT-soil was precompacted and, therefore, would have had sufficient soil strength to carry wheel traffic.

2.4.2 Influence of tillage system on soil infiltration and runoff

The effect of tillage systems on soil infiltration has been regarded mainly as an influence of good soil structure, particularly the presence of surface-connected macropores and the presence of surface mulch. No-tillage, conservation tillage and reduced tillage systems, by maintaining a substantial crop residue cover on the soil surface, increase infiltration and reduce water runoff compared with CT (Smika and Unger, 1986; Rydberg, 1990; Unger, 1990; Arshad *et al.*, 1999; McGarry *et al.*, 2000). The intact surface mulch protects the soil from raindrop impact, thereby reducing crust formation (Shipitalo *et al.*, 2000). Surface runoff from high intensity storms can be virtually eliminated due to the residue cover that permits the maintenance of high infiltration rate at the soil surface (Shipitalo *et al.*, 2000). NT was found to reduce surface runoff and increase infiltration, most notably during the growing season when high intensity rainstorms frequently occur and potential evapotranspiration is highest (Edwards *et al.*, 1995). An example of the massive reductions in runoff that can accrue from converting from CT to NT is shown in Table 2.2. The effectiveness of the NT system for controlling runoff and erosion and increasing infiltration rate ultimately depends greatly upon the amount of crop residue left on the soil surface (Lang and Mallett, 1984; Berry *et al.*, 1985). In addition, continuous, long-term, NT management tends to increase soil organic C content near the surface, and as a result

NB

aggregate stability is increased and therefore, the stability of the pore structure is improved (Arshad *et al*, 1999).

Indeed, greater infiltration rates under NT may occur due to large numbers and the more continuous network of pores compared to a discontinuous network of pores caused by tillage events under CT (Edwards *et al.*, 1988; Kay, 1990; Roserberg and McCoy, 1992; Arshad *et al.*, 1999). Lal (1978), Edwards and Norton (1985) and Edwards *et al.* (1988) attributed significantly higher infiltration rates observed in NT treatments to large surface-connected macropores, as a result of earthworm activity. However, with lower total porosity under NT, infiltration rate and water storage capacity should be less than that of CT-soil (Shipitalo *et al.,* 2000). Despite a greater portion of the total porosity being microporosity under NT compared with CT, Arshad *et al.* (1999) reported greater water infiltration under NT than CT (Figure 2.5) on silt loam and sandy loam soils.

NR

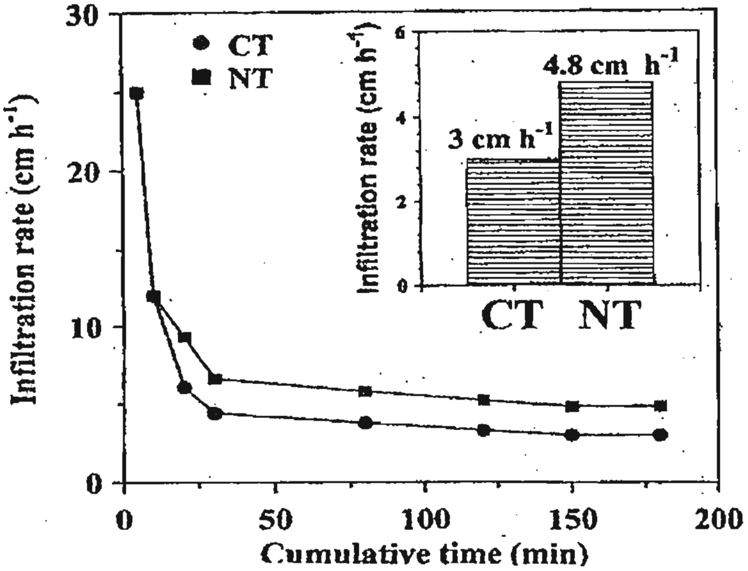


Figure 2.5. Infiltration in the silt loam as affected by tillage system (CT: conventional tillage and NT: no-tillage) (Arshad *et al.*, 1999)

Table 2.2. Four-year comparison of the amount of surface runoff from NT watershed (9 % slope) and CT watershed (6 % slope) at the North Appalachian Experiment Watershed (NAEW) (Shipitalo *et al.,* 2000)

Year	*Rainfall (mm)*	*Runoff (mm)*	
		No-tillage	*Conventional tillage*
1979	1124	3.8	140.2
1980	1176	4.9	316.8
1981	1057	0.2	142.2
1982	889	0	113.2
4-year total	4246	8.9	712.4
Average	1062	2.2	178.1

Table 2.3. Three water infiltration parameters for CT and NT treatments as measured by a rainfall simulator applying high and low energy rain at a rate of 100 mm h^{-1} for 1 h (After McGarry *et al.*, 2000)

Rainfall energy	Tillage practice	Time to ponding (min)	Final infiltration rate after 100 mm rain (mm h^{-1})	Total infiltration after 100 mm rain (mm)
Low	CT	7 (1)[a]	68 (2)[a]	88 (2)
	NT	22 (2)	25 (1)	64 (1)
High	CT	5 (1)	17 (3)	40 (3)
	NT	21 (2)	30 (1)	63 (1)

Means with the same number in parentheses are not significantly different ($P < 0.05$)

[a] *Leakage under plot edges occurred due to sub-surface ponding*

On the contrary, a change in rainfall energy under CT can dramatically decrease both final infiltration rate and cumulative infiltration apparently due to raindrop action sealing the unprotected soil surface (Arshad *et al.*, 1999). Using a rainfall simulator at high and low energy-rain, McGarry *et al.* (2000) measured three infiltration parameters for CT and NT (Table 2.3). The time to ponding was significantly greater under NT than CT with no significant effect of rainfall energy. Under low-energy rain, both the final infiltration rate and the total infiltration after 100 mm of rain were significantly greater under CT than NT. This was attributed to the large macropore volume induced by tilling the soil. However, ponding at a subsurface layer below the depth of cultivation was observed under CT. Moreover, under high-energy rain, a strong visible surface seal developed under CT, leading to a lower final infiltration rate and total infiltration than under NT. The stubble cover under NT protected the soil surface from raindrop impact.

However, repeated tillage operations induce low permeability by creating a plough pan layer that reduces infiltration capacity and can therefore, increase runoff and soil erosion (Zuzel *et al.*, 1990). The development of subsurface horizons can reduce water movement, promoting the development of a seasonally high water table. Under such conditions, the hydraulic conductivity of the surface is irrelevant because of a lack of water storage capacity within the profile and even a low intensity rainfall can produce surface runoff (Shipitalo *et al.*, 2000).

2.5 Influence of tillage system on soil structure

On a clay loam soil, Yavuzcan (2000) measured mean weight diameters of soil aggregates as affected by tillage systems and subsequent wheel traffic (Figure 2.6). After tillage, he found the largest soil aggregate diameters in the chisel + cultivator tooth-harrow treatment (S2), and smallest in the horizontal rotary tiller treatment (S5). The trend was similar whether measured before or after traffic had passed over the treatments. Nevertheless, differences between tillage and traffic were greatest in the plough + cultivator tooth-harrow (S3) and plough + disc treatments (S4). Conversely, there were no significant wheel traffic-induced differences in aggregate size on reduced tillage plots with horizontal rotary tiller (S5) and vertical rotary tiller (S6) tillage systems. Adam and Erbach (1992) also reported that the use of a cultivator instead of disc harrow resulted in smaller aggregate sizes. Aggregate stability was shown to increase, and aggregate size distribution found to become coarser as the amount of crop residues on the soil surface increased under NT (Mahboubi and Lal, 1998; Børresen, 1997; Børresen, 1999; Duiker and Lal, 1999).

Tillage practice not only affects the size distribution of aggregates but also their stability in relation to the degrading actions of water (i.e. aggregate stability). Indeed, many reports have shown that the proportion of stable aggregates in the topsoil is greater under NT than CT (Cannell and Hawes, 1994; Børresen, 1997; Mahboubi and Lal, 1998; Børresen, 1999; Arshad *et al.*, 1999; Rasmussen, 1999). Arshad *et al.* (1999) found, for example, greater soil aggregate stability owing to a greater soil organic carbon content in the topsoil under NT compared with CT. Mahboubi and Lal (1998) reported greater soil aggregation and formation of large soil aggregates under NT, especially in summer and autumn. The positive influence of no-tillage practices on soil aggregation is more evident where stubble is retained rather than burned (Cannell and Hawes, 1994) because there is greater accumulation of soil organic matter near the surface under the former practice.

Arshad *et al.* (1999) reported results of mean weight diameter of the water-stable aggregates, measured at a depth of 0 – 75 mm during a 15-year period (1980 – 1995) in a long-term tillage experiment on silty loam and sandy loam soils in north western Canada (Figure 2.7). Throughout the growing season during 1989 through 1991, mean weight diameter was greater under NT than under CT. Seasonal differences in mean weight diameter appeared to have been a result of crop rooting and/or soil drying that decreased the difference between NT and CT later in the year. Previous research demonstrated that water-stable macroaggregation (aggregates of > 0.25 mm diameter) of both soils was 50 – 60% greater under NT than under CT at a depth of 0 – 50 mm, but there were no significant differences at a depth of 125 – 200 mm (Franzluebbers and Arshad, 1996).

Some beneficial effects of plough-based methods of seedbed preparation on the enhancement of soil structure during spring may result from higher maximum soil temperature and ploughing-induced improvements in soil drainage (Mahboubi and Lal, 1998). Ploughing may, however, have some adverse effects on earthworm activity, and overall earthworm activity is usually more under NT compared with plough-based methods of seedbed preparation in most seasons (Edwards and Norton, 1986; Kemper *et al.*, 1987). Earthworm activity is important since earthworm casts are known to be the precursors for stable soil aggregates in many soils (Haynes and Beare, 1996).

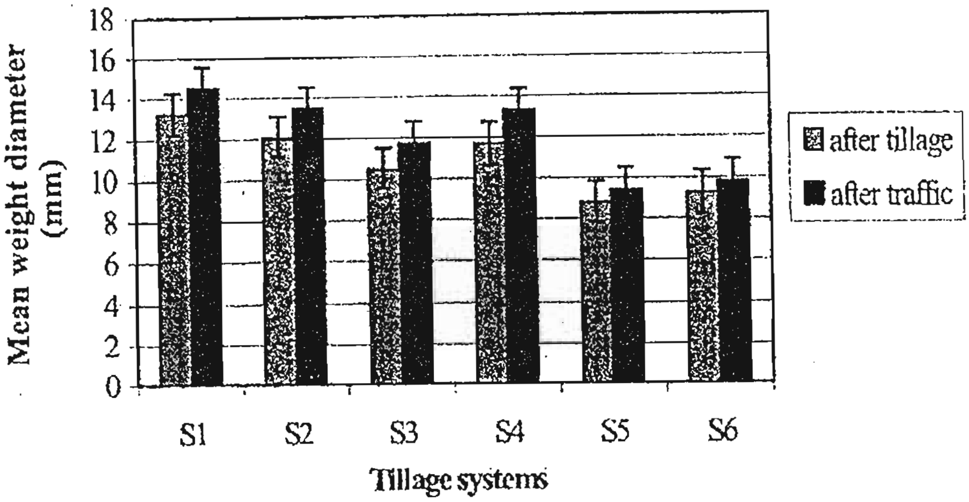


Figure 2.6. Mean weight diameter of soil aggregates as affected by tillage and subsequent field traffic (S1) chisel + disc; (S2) chisel + cultivator tooth-harrow; (S3) plough + cultivator-tooth harrow; (S4) plough + disc; (S5) horizontal rotary tiller; (S6) vertical rotary tiller (Yavuzcan, 2000)

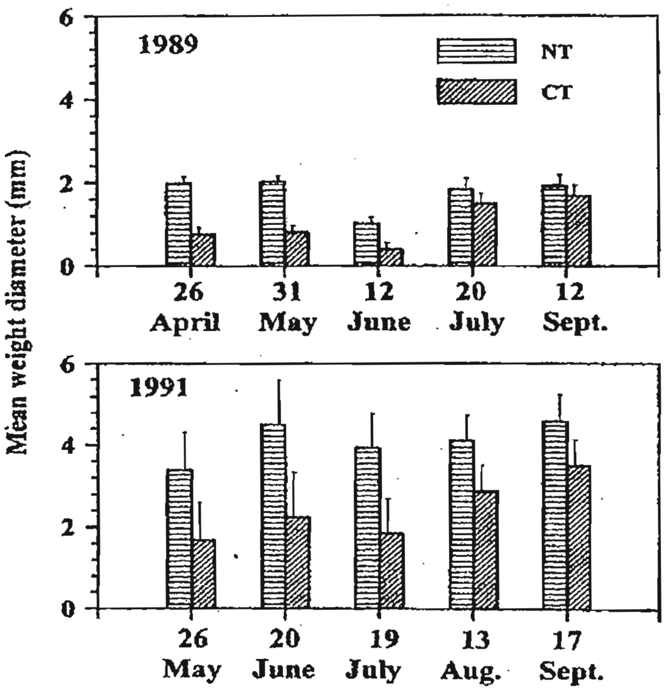


Figure 2.7. Mean weight diameter of water-stable aggregates in the surface 75 mm of a silt loam during 1989 – 1991 as affected by season and tillage system (C.T: conventional tillage and N.T: no-tillage) (Arshad *et al.*, 1999)

Aggregate stability correlated well with soil infiltration rate, which was explained by the fact that the disintegration of surface aggregates controls the rate of seal formation and the subsequent decrease in infiltration rate in soils exposed to rain (Levy and Miller, 1997). When sufficiently water stable, aggregates do not readily disperse or become subject to soil erosion and hence, are especially important for maintaining favourable water infiltration rates. They also result in good soil structure and soil erosion prevention, which are important for a good plant growth (Unger, 1990). W 8

2.6 Influence of tillage system on soil compaction

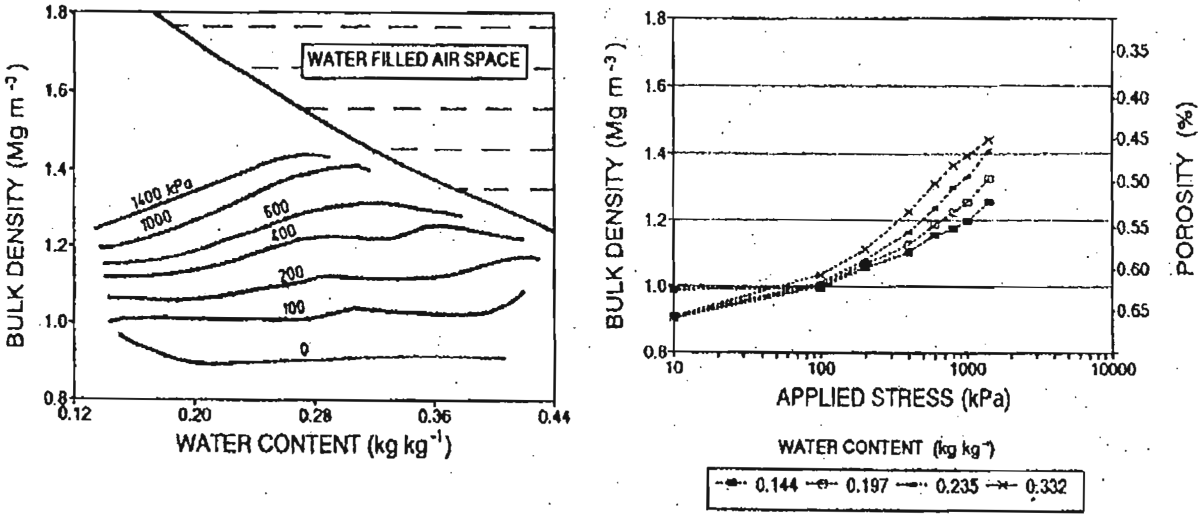
Soil compaction is defined as a process of rearranging soil particles to decrease pore space and increase bulk density (Raghavan *et al.*, 1992). Soil response to compaction is known to be a function of traffic characteristics, soil properties, and soil water content at the time of traffic. Examination of the soil matrix reveals a reduction in size and number of macropores and a change of shape and continuity of pores. These changes are associated with increased bulk density and soil strength, and a reduction of hydraulic conductivity, permeability and diffusivity of water and air through the soil pore system (Soane *et al.*, 1981). N 9

The passage of tractors or other vehicles over the soil surface to prepare a seedbed, to cultivate, to control weeds or to aid seedling emergence, and to harvest creates the possibility of increased bulk densities and destruction of soil porosity. Most serious compaction occurs when travel is random over the soil surface, and is either excessive (Hassett and Banwart, 1992) or, carried out at time when the soil is wet. Soil strength is much reduced when the soil is wet (Kirby and Kirchhoff, 1990).

Compaction can be evaluated by penetration resistance and bulk density measurements (Grant and Lafond, 1993). Hammel (1989) observed that bulk densities in the top 300 mm of silt loam soil were higher under NT that CT, while Unger and Jones (1998) working on a clay loam soil reported the same trend in the surface 100 mm layer. No definite trends for bulk density were evident below 100 mm depth. Hoffman (1990) also observed that bulk density of NT and minimum tillage increased from the surface of the soil to a depth of 150 mm. Conventional tillage bulk densities increased between the depths of 250 mm and 300 mm. Water content is the important factor influencing compaction in soils under cultivation during tillage operations.

Nevertheless, Smith *et al.* (1997) suggested that compaction behaviour can be similar for a wide range of water contents. From an assessment of the compaction susceptibility on South African forestry soils, these workers found low compactibility in high clay soils, whereas soils such as sandy loams, loams and sandy clay loams, showed a high susceptibility to compaction. The compaction behaviour was described using soil water content, applied pressure and bulk density (W-P-D) diagrams (Figure 2.8). The coarse-textured soils had high initial bulk densities and the frictional forces dominated the resistance of soils to compression. A high clay content reduces the magnitude of these frictional forces, thus resisting the compression of the soil to the applied pressure. Therefore, the compressibility decreases with an increase in clay content (Smith *et al.*, 1997). A pertinent feature of Figure 2.8 is, for a given applied pressure, increasing compaction occurs with increasing water content at relatively low water contents. However, as the soil becomes wetter, decreasing compaction is observed since the soil is less compressible as pores become increasingly water-filled. Relatively level, closely spaced iso-stress lines of the clay soil indicate little change in soil volume across a range of water contents and applied pressures. Widely spaced lines of the sandy clay soil illustrate a rapid increase in bulk density and loss in porosity for incremental increases of applied pressure.

(a) Clay



(b) Sandy clay

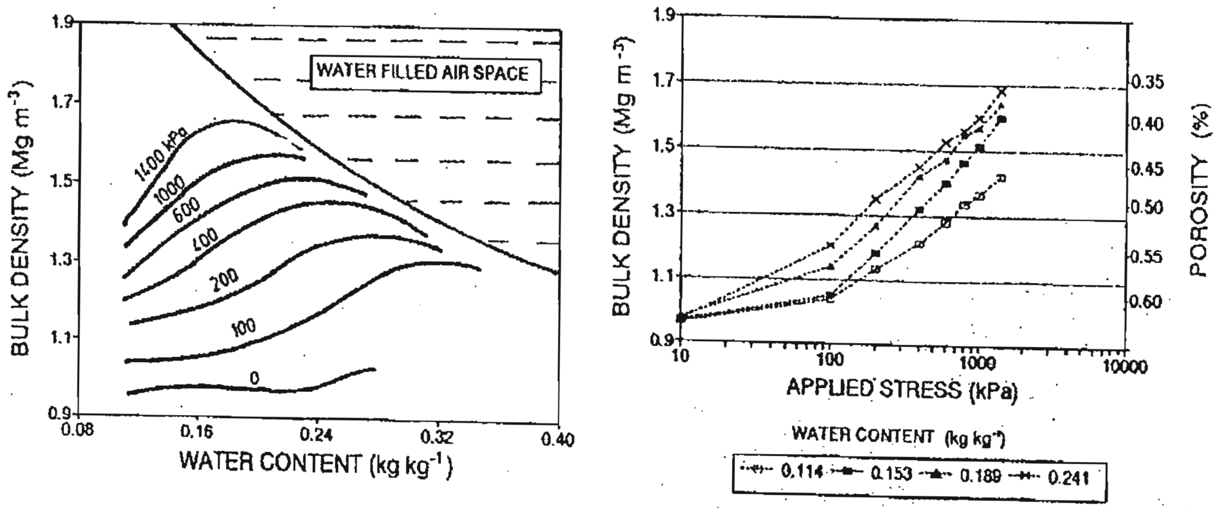


Figure 2.8. Water-Pressure-Density (W-P-D) diagrams (left) and compression curves (right) for clay (a) and sandy clay (b) soils (Smith *et al.*, 1997)

Penetration resistance has been observed to be more sensitive than bulk density to differentiate tillage management systems (Hammel, 1989; Sharratt, 1996; Ferreras *et al.*, 2000). Most studies have reported higher soil resistance under NT than CT (Chaney *et al.*, 1985; Douglas, 1986; Hill, 1990; Johnson *et al.*, 1990; Braim *et al.*, 1992; Home *et al.*, 1992; Liebig *et al.*, 1993; Sharratt, 1996; Materechera and Mloza-Banda, 1997; Karunatilake *et al.*, 2000; Krzic *et al.*, 2000; Yavuzcan, 2000). Hammel (1989) found higher penetration resistence in the top 250 mm in the NT treatment than in the CT treatment. Similarly, Materechera and Mloza-Banda (1997) measured penetration resistance as influenced by tillage system on ridges (Figure 2.9), and found that soils on ridges of CT had consistently lower penetration resistance and bulk density than did minimum tillage (MT). Penetration resistance in both tillage treatments was strongly related to soil water content. Differences in penetration resistance were more significant in the topsoil (0 – 200 mm) than in the subsoil (200 – 400 m). A strong and compact layer, a “plough-pan”, developed beneath the ridges in both treatments.

The depth of the compacted surface layer under NT varies widely, depending on the soil type, soil quality and soil moisture content (Unger and Jones, 1998). Johnson *et al.* (1990), Lowery and Schuler, (1991), Voorhees (1992), and Ngunjiri and Siemens (1995) found that soil penetration resistance (SPR) is often increased in the surface 300 mm layer under NT, whereas Sharratt (1996), Materechera and Mloza-Banda (1997), Karunatilake *et al.* (2000), Krzic *et al.* (2000), and Yavuzcan (2000) found higher SPR below the 150 or 200 mm soil depth. Hill (1990) found 2 to 5 times higher penetration resistances within the 160 mm depth under continuous NT cultivation compared to CT. The implication of this is that when the water content of soil is low (below field capacity), roots will find it easier to grow under CT than NT because of reduced soil penetration resistance (Gómez *et al.*, 1999).

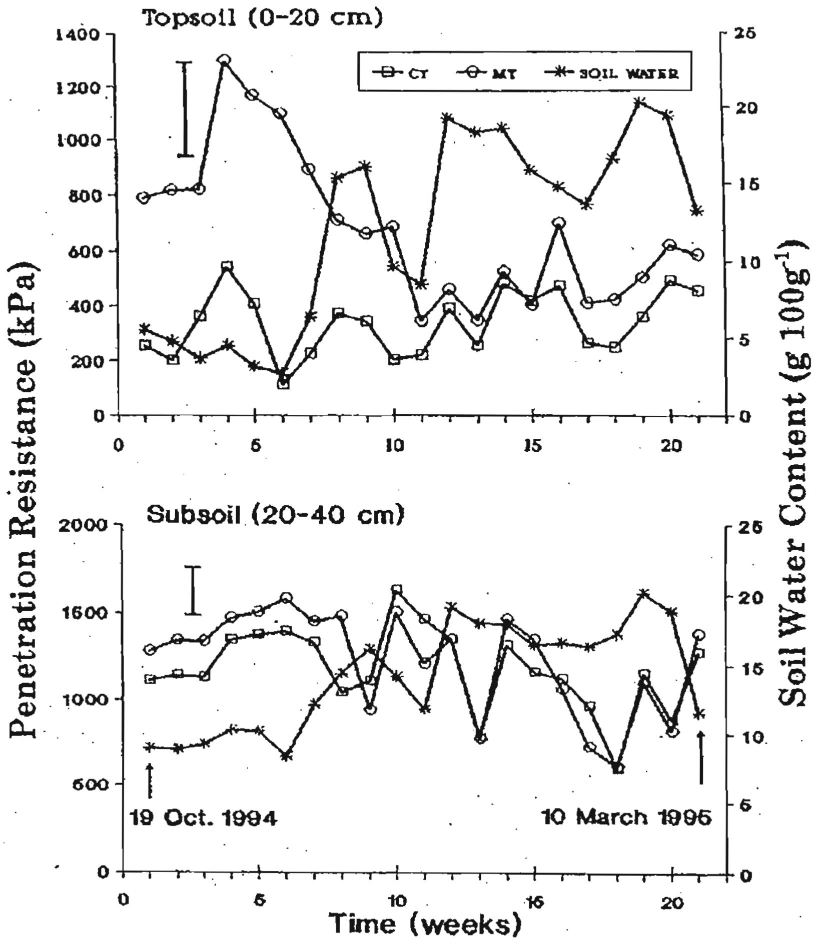


Figure 2.9. Soil penetration resistance and gravimetric water content for conventional tillage (CT) and no tillage (MT) systems during the 1994/1995 growing season (Materechera and Mloza-Banda, 1997)

On subarctic Alaskan soils, Sharratt (1996) measured the penetration resistance and bulk density under different tillage (no-tillage, conventional tillage, chisel plough, spring disk) and straw management strategies (Figure 2.10). He found that bulk density and penetration resistance were greater in the NT compared to other tillage systems. Differences in bulk density among tillage treatments were not entirely consistent with differences in penetration resistance. NT resulted in the greatest resistance to penetration to 50 mm depth before spring tillage and after planting. In addition, penetration resistance was greater for spring disk than CT and chisel plough on 1 May (before spring tillage). Sharratt (1996) emphasized that the greater penetration resistance observed under NT and spring disk methods might result from the greater soil stability compared to CT and chisel plough systems. Straw management also affected penetration resistance. Stubble and straw retained at the soil surface conserved soil water under NT, thus lower penetration resistance was associated with the greater soil water content. Francis *et al.* (1987) also found a similar phenomenon.

Care must be exercised when interpreting SPR measurements since they are greatly affected by soil water content. On a clay loam soil in New York, Karunatilake *et al.* (2000) measured soil penetration resistance as a function of soil water content, using a penetrometer (Figure 2.11). The general trend was an increase in soil resistance as the season progressed and as the soil dried out. For the 150 mm soil depth, the soil resistance values were below the 2 MPa, critical level above which root growth is generally considered to be slow for most of the growing season (Bengough and Mullins, 1990; Rapel *et al.*, 1993). Only NT recorded values above this level. For 300 and 450 mm depths, soil resistance values for both tillage systems were generally above the 2 MPa level, except during wet periods. Pikul *et al.* (1993) showed that soil resistance in the surface layer under NT exceeded that under CT by about 1 MPa in a poorly aggregated soil. In their study, Karunatilake *et al.* (2000) reported that soil resistance differences between tillage treatments were lower, and that was attributed to the larger number of failure zones in the well-aggregated soil. Also, the higher water contents in NT may have masked tillage-induced differences (Hill, 1990).

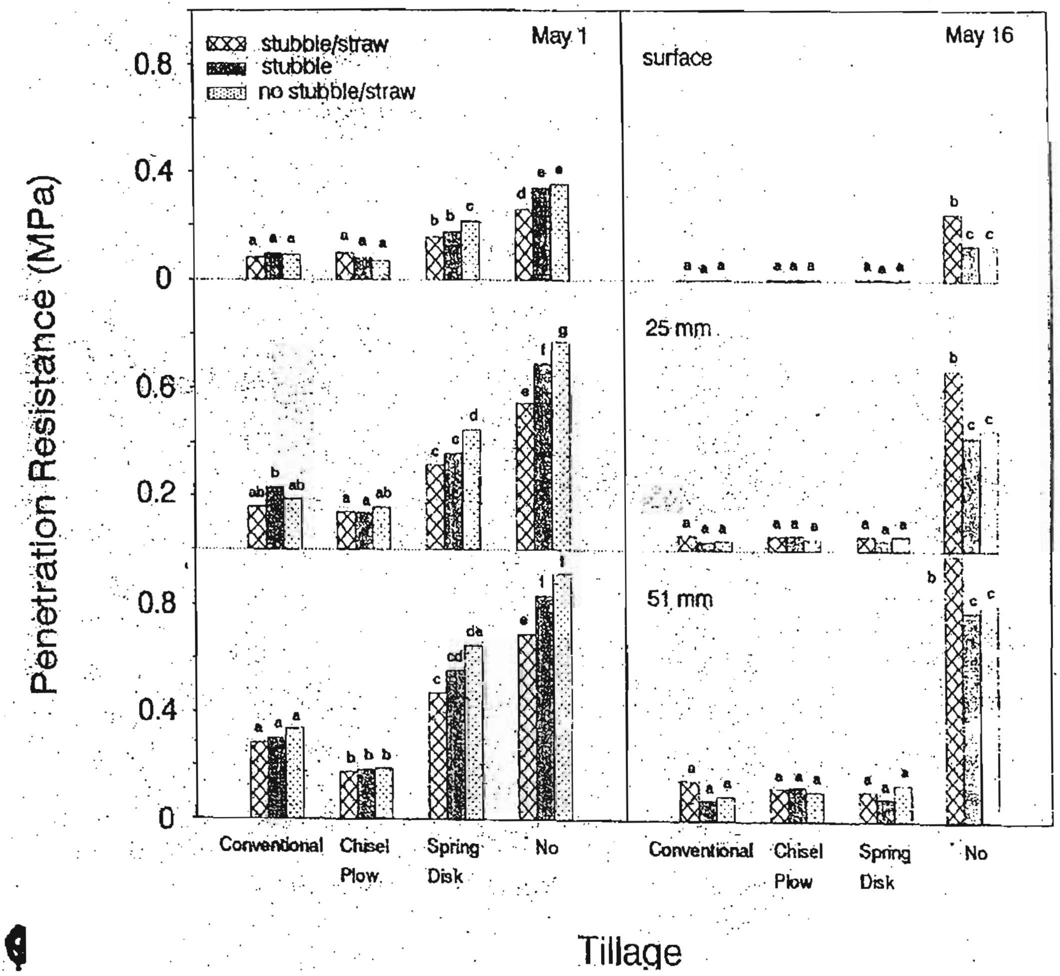


Figure 2.10. Soil penetration resistance to 50 mm in a soil, subject to various tillage and straw practices, before spring tillage (1 May) and after planting (16 May). Means with the same letter were not different at P = 0.05 (Sharratt, 1996)

2.7 Influence of tillage system on soil organic matter content

The soil tillage system (time, depth, type and intensity of tillage) affects the incorporation of crop residues and the rate of decomposition of the organic matter. Accumulation and stratification of soil organic matter in minimum tillage or NT is widely documented. The use of reduced tillage or NT systems generally increases the soil organic carbon (SOC) concentration near the soil surface when compared to CT (Riley and Ekeberg, 1998; Haynes, 1999; Yang and Wander, 1999). This was associated with the amount of crop residues left at the soil surface. The decline in SOC near the soil surface under CT was attributed to intensive cropping practices (Haynes, 1999). However, as the plough layer is often inverted each year to bury previous plant residues, the distribution of organic carbon content down the soil profile is fairly uniform (Figure 2.12) (Douglas *et al.*, 1986; Haynes and Knight, 1988).

In studies with three fine-textured, poorly drained, soils in Illinois, Wander *et al.* (1998) found that NT practices increased soil organic carbon in surface soil (0 – 50 mm) at the expense of soil organic carbon stored at 50 to 175 mm depth, as compared to CT. Campbell *et al.* (1995) observed in Saskatchewan a decline in soil organic carbon, when NT soil was tilled with a cultivator to 50 – 100 mm depth. A 150 mm deep disk-harrowing of short-term NT land in Georgia, reduced the organic carbon content in the top 15 mm, but hardly changed the content in the 15 – 80 mm layer (Bruce *et al.*, 1995). In Michigan, a single mouldboard ploughing to about 200 mm depth lowered the organic carbon content in the top 50 mm of long-term NT soil, while between 50 and 200 mm depth the content increased (Pierce *et al.*, 1994, Larney *et al.*, 1997).

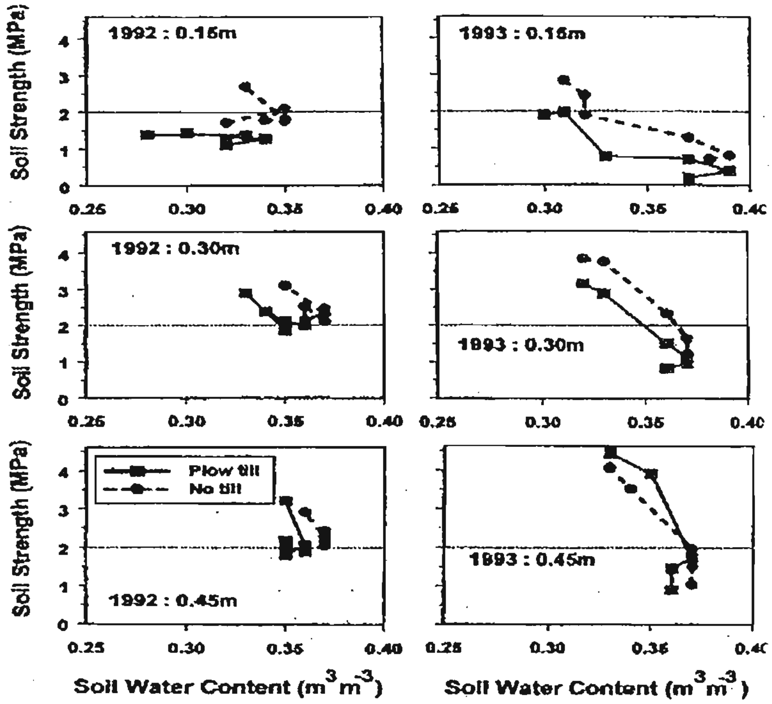


Figure 2.11. Soil strength – soil water content relationship in 1992 and 1993 for three depths (Karunatilake *et al.*, 2000)

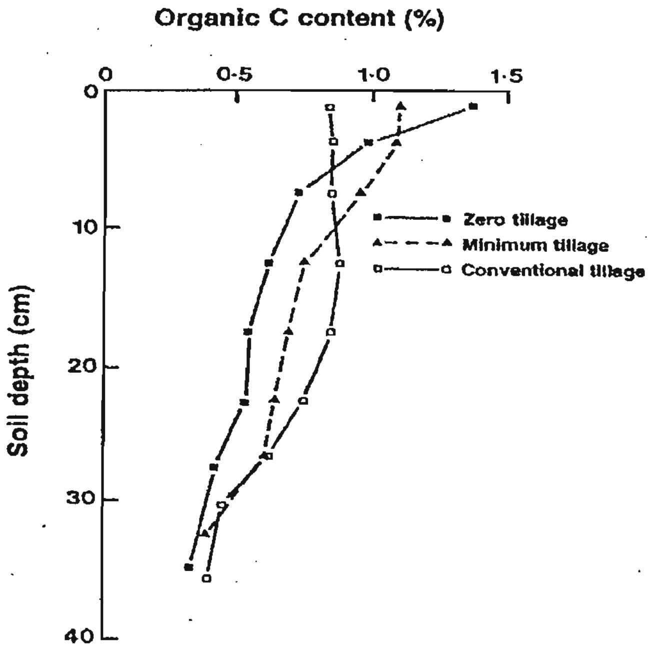


Figure 2.12. Profiles of organic C in a soil after 10 years of zero tillage, minimum tillage, conventional tillage (Douglas *et al.*, 1986)

Many studies have indicated that the use of a reduced or NT system better protects the soil resource by increasing soil organic carbon as compared to CT (Carter, 1992; Mahboubi *et al.*, 1993; Beare *et al.*, 1994; BØrresen and NjØs, 1994; Riley and Ekeberg, 1998; Mahboubi and Lal, 1998; Haynes, 1999; Yang and Wander, 1999). However, Carter and Rennie (1982), Angers *et al.* (1997) and Paustian *et al.* (1997) concluded that NT practices have a limited ability to increase soil organic carbon in fine-textured and poorly-drained soils and in sites where cold climate constrains organic matter decay.

The change in the distribution of organic carbon can influence aggregate stability and this may be important as far as the breakdown of SOC and consequently soil structure under CT is concerned (Haynes, 1993).

2.8 General Conclusions

The effects of different tillage systems on soil physical properties and organic matter content have been reported and discussed, using the findings of a large number of authors. Some of these induced-changes have positive effects and others can have negative impacts on plant growth and the soil environment. It is important to understand these changes since sustainable management of soils involves protecting them from negative factors such as soil compaction, poor soil aeration, poor soil drainage, soil runoff and erosion and low aggregate stability.

NT systems tend to retain more soil water than CT systems. This is related to an increased bulk density, which results in an increase in the volume fraction of meso- and micro-pores that retain water (Azooz *et al.*, 1996; Arshad *et al.*, 1999; Smith *et al.*, 2001). In addition, the retention of previous crop residues on the soil surface as a mulch, acts as a barrier to water vapour movement so soil water content is typically higher under NT than CT (Berry and Mallett, 1988; Hatfield and Stewart, 1994). The mulch of crop residues under NT protects the soil surface from raindrop impact, reduces runoff and increases infiltration (Van Doren *et al.*, 1984; Lal and Van Doren, 1990; Mahboubi and Lal, 1998). There is an accumulation of soil organic carbon near the soil surface under NT and this, in turn, may lead to more stable soil aggregation near the soil surface (Chaney and Swift, 1984; Prove *et al.*, 1990; Horne *et al.*, 1992; Lal *et al.*, 1994).

Despite surface compaction, there can be a large number of surface-connected macropores under NT due to cracking and/or the activity of soil macrofauna such as earthworms and termites. The cast material that is produced by such fauna enhances soil aggregation (Radford *et al.,* 1995). In addition, soil crusting in the topsoil of CT soil tends to reduce the total pore space, resulting in a decrease of soil water flow (Zuzel *et al*, 1990; Shipitalo *et al.*, 2000).

Soil compaction, as measured by bulk density and penetration resistance, has been shown to occur in the topsoil, particularly when wheel traffic occurs when the soil is wet. Subsoil compaction can occur with high axle loadings and/or repeated tillage to the same depth (Alakukku, 1996; Wu *et al.*, 1997). For a given applied pressure by tractor wheels, soil compaction increases with increasing soil water content, but decreases when all the pore space becomes water filled (Smith *et al.*, 1997). Bulk density and penetration resistance are often lower under tilled soils than non-tilled soils. This is associated with the lack of soil disturbance and natural soil consolidation under NT. Increases in bulk density and penetration resistance are generally detrimental for root growth (Voorhees, 1992).

Chapter 3

Site descriptions and cropping history

3.1 Introduction

The investigations reported in the present study were conducted at Winterton (28° 52' S, 29° 31' E, 1067 m altitude), Bergville (28° 48' S, 29° 23' E, 1310 m altitude) and at the Cedara Agriculture Research station (29° 32' S, 30° 17' E, 1076 m altitude) (Figure 3.1). A summary of the description of all the sites is presented in Table 3.1. Details of the soil profile description for each site can be found in Appendix 1.

Soil samples were collected during the summer period of 2001 (March to June), during the growing period and at harvest. At some sites, soil samples were taken on compacted inter-rows (wheel tracked inter-rows) and loose inter-rows (non- wheel tracked inter-rows).

These selected sites were established in different locations, with different soil types in order to assess clearly the soil physical changes. The sites were selected taking into account a certain number of criteria. Three important criteria were considered:

- The fields must be closed, arranged as a pair of plots of CT and NT;
- To be sure that the assessment of soil physical changes was due to long-term tillage, NT had to have been applied for > 7 years;
- Although several soil types occur at the selected site, the sampling area was selected on the dominant soil type, and this had to be as close as possible in both plots.

For each site, a plot of 7 m x 7 m was demarcated for core samplings for water retention, infiltration and air permeability, and penetrometer soil strength measurements (Figure 3.2).

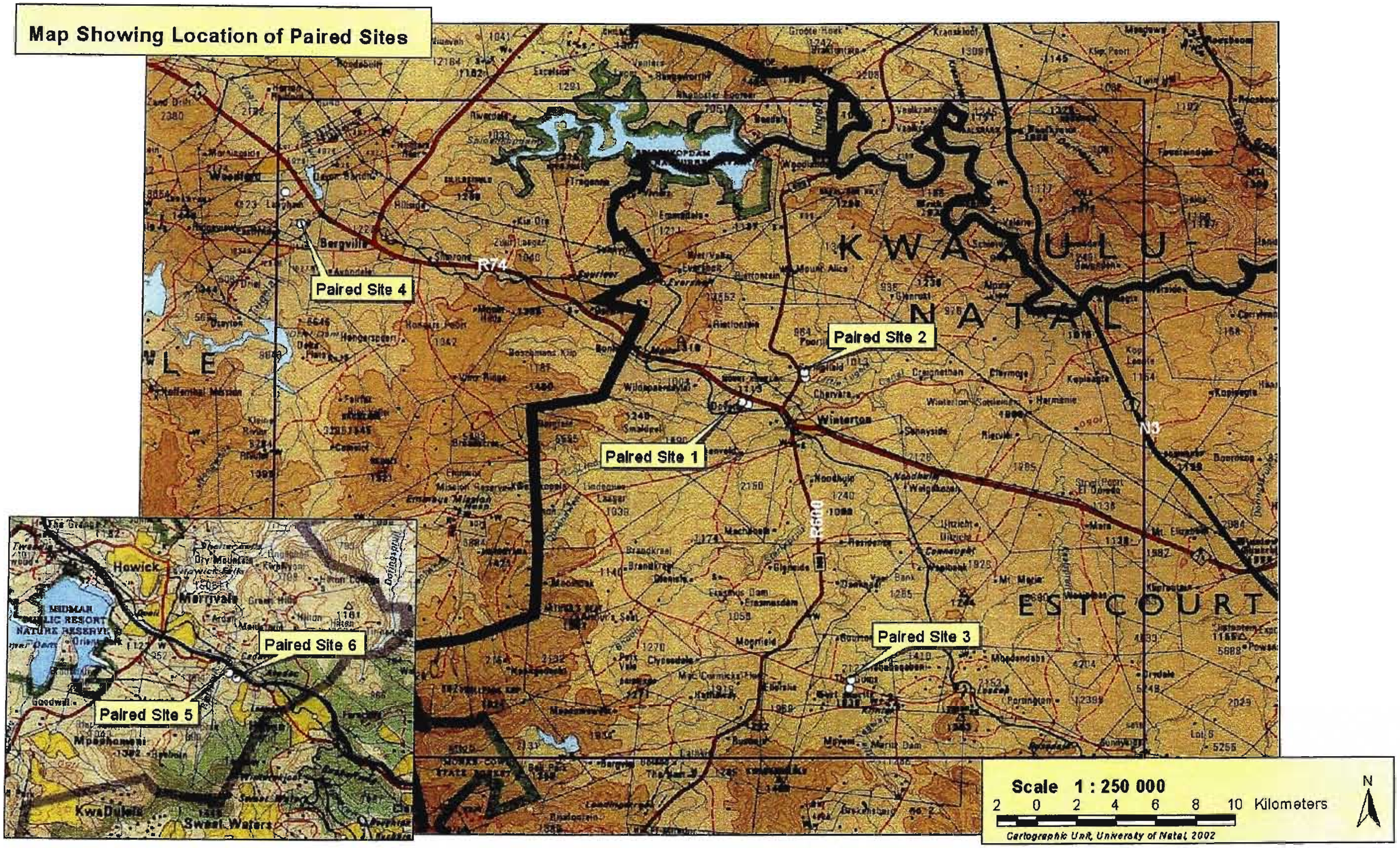


Figure 3.1. Map showing the location of the selected farms (as paired-sites). Taken from South Africa 1/250 000 Topo-cadastral sheet

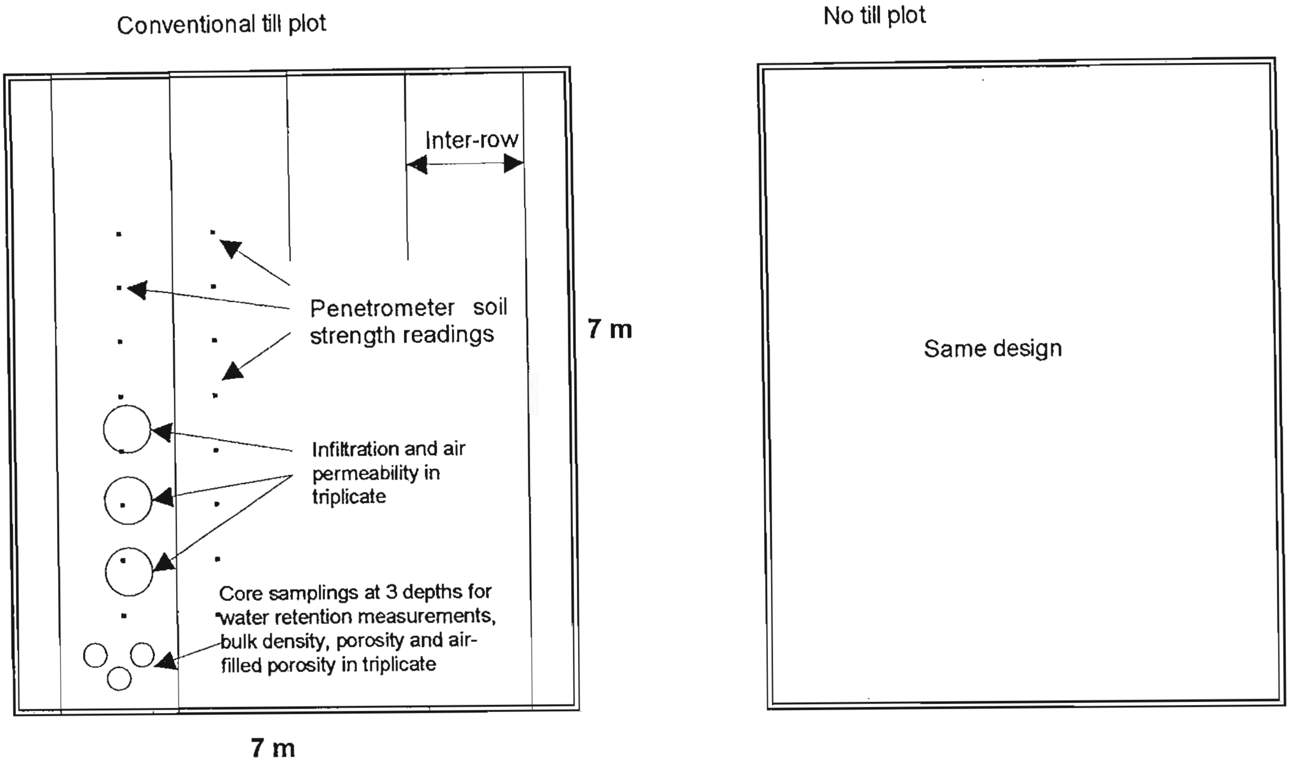


Figure 3.2. Field experiment design for soil samplings and measurements

3.2 Selected sites in the Winterton area

3.2.1 Soil and cropping history

At Winterton, six farms were selected all arranged as three pairs of plots of CT and NT systems:

- Paired site 1: Mr R. LUND's farm, referred to as site 1: NT, irrigated land maize
  Mr BOSCHOFF's farm, referred to as site 2: CT, dryland soybean

At these sites the soil is a deep, well-drained Hutton form soil (orthic A / red apedal B) (MacVicar *et al.*, 1977), with 50 to 65 % clay (Appendix 1). Site 1, which had been previously cropped to maize and wheat in the first season and second season respectively, is a NT maize field under irrigation. Site 2, which was cropped to soybeans, is a dryland CT soil, previously cropped to maize.

- Paired site 2: Mr Van Den AARDWEG's farm, referred to as site 3: NT, dryland maize
  Mr Van VUUVEEN's farm, referred to as site 4: CT, dryland maize

At these sites the soil is an Avalon form soil, very poorly drained, with soft plinthite at ± 420 mm soil depth (orthic A / yellow-brown apedal B / soft plinthic B) (MacVicar *et al.*, 1977), and ± 27 % clay (Appendix 1). Sites 3 and 4, which had been previously cropped to maize in both seasons, are considered as dryland under NT and CT systems, respectively.

- Paired site 3: Mr MIURHEAD's farm, referred to as site 5A: NT, irrigated maize
  Mr MIURHEAD's farm, referred to as site 5B: NT, dryland maize
  Mr MOSTERT's farm, referred to as site 6: CT, dryland maize; 6A is referred to as loose inter-row and 6B as compacted inter-row

At these sites the soil is a well-drained Hutton form soil (orthic A / red apedal B) (MacVicar *et al.*, 1977), with concretions at ± 300 mm soil depth and ± 44, 41, and 46 % clay at site 5A, 5B, and 6 respectively (Appendix 1). These four sites had been previously cropped to maize in both seasons, and only site 5A was under irrigation, sites 5B and 6 are considered as drylands under NT and CT systems, respectively.

Although the selected sites were in different locations, the tillage systems were almost the same. NT consisted of slot planting directly into the previous season's crop residues. Sites 1 and 3 have been in continuous NT system for 7 years, whereas sites 5A and 5B are in their 10th year. Surface plant residue cover averaged 100 %, ± 40 %, 100 % and ± 70 % at sites 1, 3, 5A and 5B, respectively. CT fields at sites 4 and 6 were older than ± 10 years and 50 years respectively, and were under continuous maize at the time of soil sampling. Site 2 was under soybean and had been also cultivated for about 50 years. The CT system consisted of ripping to 250 mm followed by discing, with incorporation of previous crop residues to a maximum of 150 mm soil depth. Both under NT and CT, tillage operations were conducted in a direction parallel to the crop rows, with wheel traffic following the same path.

3.2.2 Climate

Long-term average total rainfall, evaporation and temperatures for a 16 year-period (1974 – 1989) for the Winterton area (28° 52' S, 29° 31' E, 1067 m altitude) are shown in Figure 3.3. The mean annual total rainfall is approximately 871.3 mm, mostly falling between November and March with sometimes heavy storms. The mean annual evaporation and maximum and minimum temperatures are 4.23 mm, 26.66 °C and 7.89 °C, respectively. Maximum temperatures are observed between November to March, whereas minimum temperatures occur in June and July, - 1.6 and – 1.4 °C respectively.

3.3 Selected sites in the Bergville area

3.3.1 Soil and cropping history

The Bergville area is located approximately 150 km from Pietermaritzburg (29° 40' S, 30° 24' E). At Bergville (28° 48' S, 29° 23' E, 1310 m altitude), two farms have been selected, arranged as one pair of plots of CT and NT systems:

- Paired site 4: Mr John JACKSON's farm, referred to as site 7: NT, irrigated soybean
  Mr Jos JOUBERT's farm, referred to as site 8: CT, irrigated soybean

At these sites the soil is an Avalon form, moderately drained, with soft plinthite at ± 550 mm soil depth (orthic A / yellow-brown apedal B / soft plinthic B) (McVicar *et al.*, 1977). The soil is texturally a silt clay loam, with ± 32 to 39 % clay (Appendix 1). Both sites are in continuous rotation of maize-wheat-soybeans. Site 7, a NT field under irrigation, has been under the system since 1990 (12th year of NT). Site 8 was irrigated and had been under CT for about 25 years. Conventional tillage consisted of ripping to 250 mm followed by discing, with incorporation of previous crop residues to a maximum of 150 mm soil depth. At the time of soil sampling, these fields were under soybeans.

3.3.2 Climate

Long-term average rainfall (34 year-period) and maximum and minimum temperatures (16 year-period) for Bergville are shown in Figure 3.4. The mean annual total rainfall is approximately 857.31 mm, mostly falling between October and March. The mean maximum and minimum temperatures are 25.85 °C and 7.89 °C, respectively. Maximum temperatures occur between December and March, whereas minimum temperatures are observed in winter months, June and July.

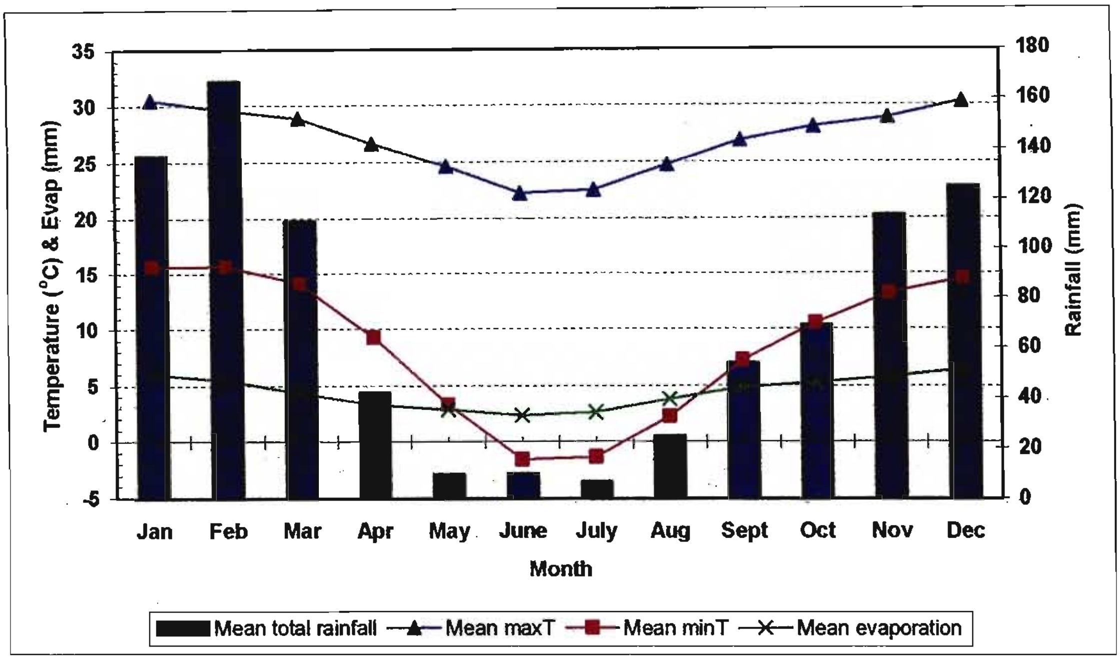


Figure 3.3. Mean monthly total rainfall and mean maximum and minimum temperatures and mean evaporation for Winterton over the period 1974 – 1989 (Soil and Irrigation Research Institute, 1991)

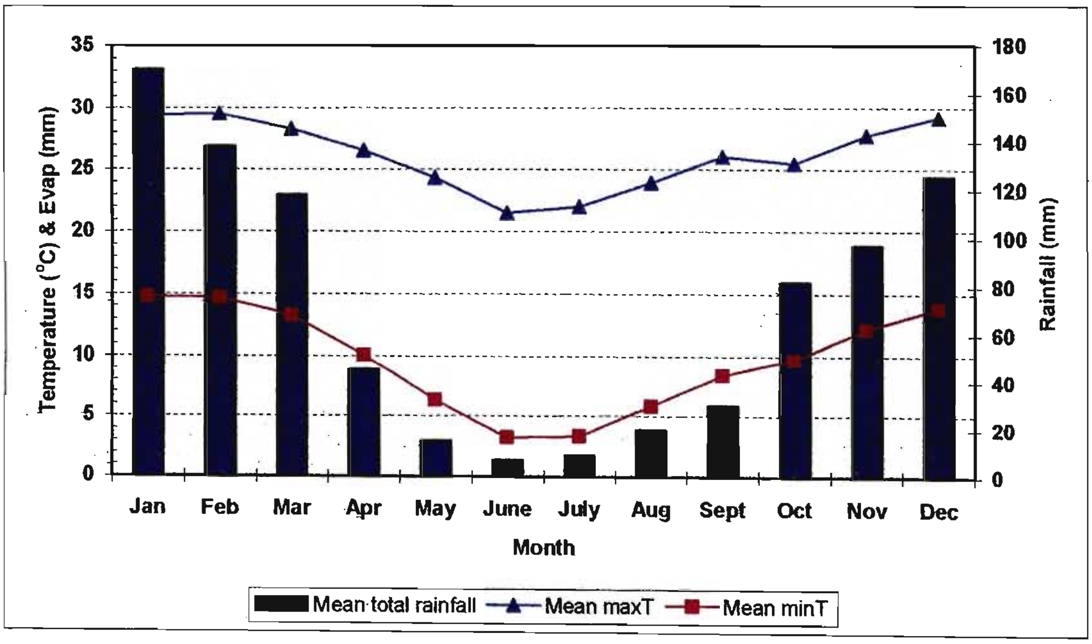


Figure 3.4. Mean monthly total rainfall and mean maximum and minimum temperatures for Bergville (Soil and Irrigation Research Institute, 1991 and South African wheather service, 2002)

3.4 Selected sites at the Cedara Agricultural Research Station

3.4.1 Soils and cropping history

The Cedara Agriculture Research station (CARS) is located approximately 21 km from Pietermaritzburg, geographically at 29°32'S, 30°17'E, and 1066 m altitude. From CARS, two pairs of plots have been selected. They are arranged in blocks of 60 m x 9 m:

- Paired site 5: Site 9: NT dryland maize; 9A is referred to as loose inter-row and 9B as compacted inter-row
  Site 10: CT (Mouldboard and Disc) dryland maize; 10A is referred to as loose inter-row and 10B as compacted inter-row

- Paired site 6: Site 11: NT dryland maize; 11A is referred loose inter-row and 11B as compacted inter-row
  Site 12: CT (chisel and disc) dryland maize; 12A is referred to as loose inter-row and 12B as compacted inter-row

At Cedara, the soil is a well-drained silt clay loam of the Hutton form (MacVicar *et al.*, 1977), containing 30 to 50 % clay (Appendix 1). Compared to the Hutton soil at Winterton, this soil is shallow, with a maximum soil depth of approximately 350 mm, and 20 to 35 % concretions (Appendix 1).

Sites 9 and 11 have been under NT since 1982 when the experiment was initiated, whilst sites 10 and 12 were under CT for more than 50 years. The CT for site 10 consisted of discing to 150 mm soil depth followed by mouldboard ploughing to 250 mm soil depth, whereas site 12 consisted of chisel ploughing to 120 mm and discing to 150 mm soil depth, and there were no previous crop residues incorporated. All these sites have been under continuous maize since they were initiated. Soil samples were taken in May 2001, one month before crop harvest.

3.4.2 Climate

Long term average rainfall, maximum and minimum temperatures, and evaporation for a 12 year-period (1990 to 2001) for the Cedara meteorological site (1076 m altitude) are presented in Figure 3.5. The mean annual total rainfall is approximately 883.7 mm, falling mostly between October and March. The mean annual evaporation and mean annual maximum and minimum temperatures are respectively 4.01 mm, 22.5 °C and 10.2 °C. The maximum temperatures occur in summer months, from November to March. Minimum temperatures are observed in winter, from June to July.

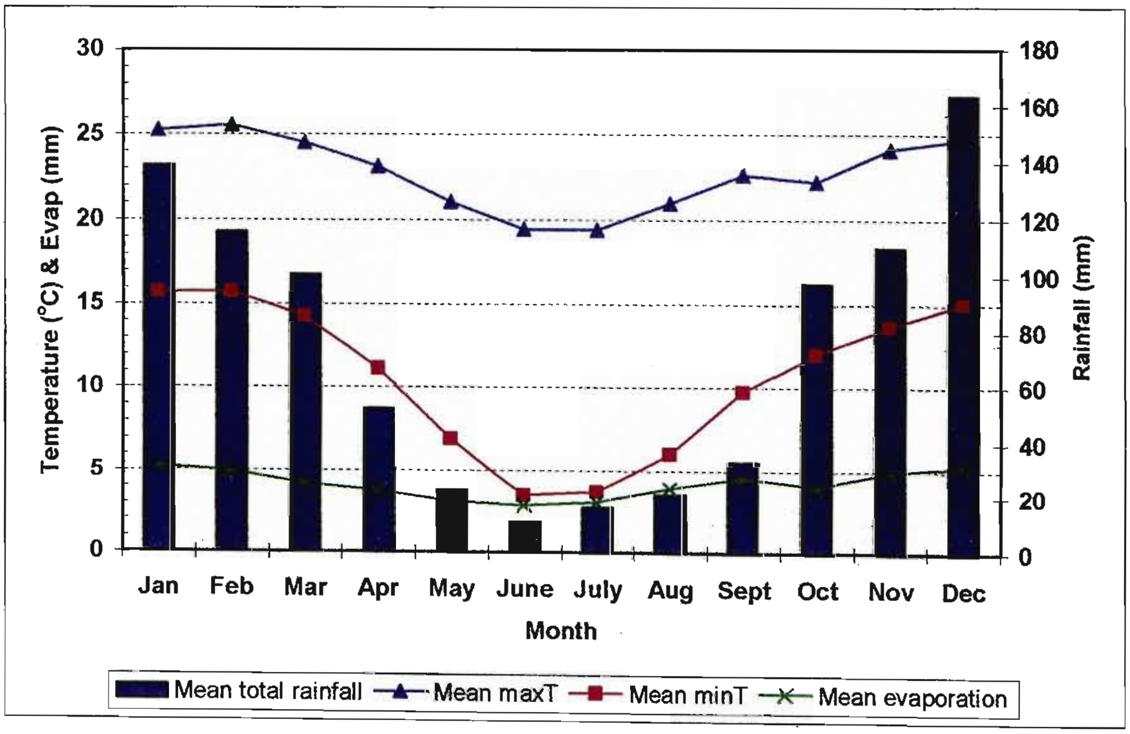


Figure 3.5. Mean monthly total rainfall and mean maximum and minimum temperatures and mean evaporation for Cedara Agricultural Research Station over the period 1990 - 2001 (United States Geological Survey, 2002)

Table 3.1: Summary of the description of sites and the cropping history

SITE	AREAS	COORDINATE AND ALTITUDE	CLIMATE *Rain/MaxT/MinT*	INITIALS + SURNAME	TILLAGE SYSTEM	DURATION OF SYSTEM (years)	TILLAGE IMPLEMENT USED	% COVER	PREVIOUS CROP	TEXTURAL GROUP	SOUTH AFRICAN SOIL FORM
1	***WINTERTON***	28° 52' S 29° 31' E 1067 m	Mean rainfall: 871.3mm Mean MaxT: 26.66 °C Mean MinT: 7.89 °C	R. LUND	NT, irrigated maize	7	Slot planter	100	maize + wheat	Clay	HUTTON
2	***WINTERTON***	"	"	BOSCHOFF	CT, dryland soybean	>50	Rip + Disc	0	soyabean	Clay	HUTTON
3	***WINTERTON***	"	"	V.D. AARDWEG	NT, dryland maize	7	Slot planter	40	maize	Loam	AVALON
4	***WINTERTON***	"	"	V. VUUVEEN	CT, dryland maize	> 10	Rip + Disc	0	maize	Loam	AVALON
5A	***WINTERTON***	"	"	MIURHEAD	NT, irrigated maize	10	Slot planter	100	wheat	Clay	HUTTON
5B	***WINTERTON***	"	"	MIURHEAD	NT, dryland maize	10	Slot planter	± 70	wheat	Clay	HUTTON
6A	***WINTERTON***	"	"	MOSTERT	CT, dryland maize, LIR	> 50	Rip + Disc	0	maize	Clay	HUTTON
6B	***WINTERTON***	"	"	MOSTERT	CT, dryland maize, CIR	> 50	Rip + Disc	0	maize	Clay	HUTTON
7	**BERGVILLE**	28° 48' S 29° 23' E 1310 m	Mean rainfall: 857.3mm Mean MaxT: 25.85 °C Mean MinT: 7.89 °C	J. JACKSON	NT, irrigated soybean	12	Slot planter	100	soya + wheat	Silt clay loam	AVALON
8	**BERGVILLE**	"		J. JOUBERT	CT, irrigated soybean	> 25	Rip + Disc	0	soya + wheat	Silt clay loam	AVALON
9A	**CEDARA**	29° 32' S 30° 17' E 1076 m	Mean rainfall: 883.7mm Mean MaxT: 22.5°C Mean MinT: 10.2 °C	CARS*	NT, dryland maize, loose inter-row	19	Slot planter	100	maize + wheat	Silt clay loam	HUTTON
9B	**CEDARA**	"	"	CARS*	NT, dryland maize, CIR	19	Slot planter	100	maize + wheat	Silt clay loam	HUTTON
0A	**CEDARA**	"	"	CARS*	CT, dryland maize, LIR	> 50	Mouldboard +Disc	0	maize	Silt clay loam	HUTTON
0B	**CEDARA**	"	"	CARS*	CT, dryland maize, CIR	> 50	Mouldboard +Disc	0	maize	Silt clay loam	HUTTON
1A	**CEDARA**	"	"	CARS*	NT, dryland maize, LIR	19	Slot planter	80	maize	Silt clay loam	HUTTON
1B	**CEDARA**	"	"	CARS*	NT, dryland maize, CIR	19	Slot planter	80	maize	Silt clay loam	HUTTON
2A	**CEDARA**	"	"	CARS*	CT, dryland maize, LIR	> 50	Chisel + Disc	± 60	maize	Silt clay loam	HUTTON
2B	**CEDARA**	"	"	CARS*	CT, dryland maize, CIR	> 50	Chisel + Disc	± 60	maize	Silt clay loam	HUTTON

*CARS: CEDARA AGRICULTURE RESEARCH STATION LIR : Loose inter-row CIR : Compacted inter-row

Chapter 4

The effects of tillage system on aggregate stability and organic carbon content

4.1 Introduction

Soil aggregation is important in protecting soils from the destructive forces of water including slaking, erosion, and other mechanical destructive forces. The resistance of soil aggregates to these destructive forces and dispersive actions of water is important for maintaining a porous soil structure (Haynes, 1993). Soil aggregation refers to the cementing or binding together of soil particles into a secondary unit or aggregate. The degree of soil aggregation is an excellent indication of soils' physical conditions. When sufficiently water stable, aggregates do not readily disperse, and soil porosity, infiltration and hydraulic conductivity are maintained. Stable aggregates also result in good soil structure and soil aeration, which are important for good plant growth (Unger, 1990). However, the degree of aggregation is a time-variable property, as aggregates form, disintegrate, and re-form periodically (Hillel, 1998).

Aggregate stability can be defined as the resistance of the bonds within the aggregates to external forces of impact, shearing, abrasion, or disruption arising from the escape of entrapped air (Angers and Mehuys, 1993).

Soil organic matter has a profound effect on the structure of many soils. The organic matter acts as a binding agent for aggregate formation (Tisdall and Oades, 1982). These aggregates create a loose porous structure and result in better water infiltration, promoting water retention. Large pores also permit better gaseous exchange between the soil and the atmosphere improving aeration for microbial and plant root activity. The loss of soil organic matter is the most important factor contributing to soil degradation (Hart et al., 1988; Haynes and Tregurtha, 1999). Adequate organic matter levels reduce the risk of compaction and simplify tillage operations and seedbed preparation. Other important functions of organic matter include its ability to buffer the soil against large changes in pH, its ability to form stable complexes with metal ions and its ability to complex withstand xenobiotics such as herbicides and pesticides.

The influence of tillage on soil stability is generally a function of the soil's organic matter content (Carter, 1992; Beare *et al.*, 1994; Franzluebbers and Arshad, 1996). The breakdown of soil organic matter is less rapid under NT than CT (Dick, 1983). NT generally improves soil aggregation (Carter, 1992; Beare *et al.*, 1994). Repeated traffic under CT tends to crush the aggregates remaining at the soil surface, and to compact the soil to the same depth (Capriel *et al.,* 1992).

Interest in the impacts of tillage practices on the distribution soil organic matter content has increased greatly during recent years. The soil tillage system (time, depth, type and intensity of tillage) affects the incorporation of crop residues and the rate of decomposition of the organic matter. Accumulation and stratification of soil organic matter in minimum tillage or NT is widely documented. The use of reduced tillage or NT systems generally increases the soil organic carbon (SOC) concentration near the soil surface when compared to CT soils (Haynes, 1999; Yang and Wander, 1999). Under CT, as the plough layer is often inverted each year, the distribution of organic carbon content through the cultivation layer is fairly uniform (Douglas *et al.,* 1986).

Most frequently, the concept of aggregate stability is applied in relation to the destructive action of water. The classical and most prevalent procedure for testing the water stability of soil aggregates is the “wet sieving method” (Yoder, 1936). In this study, mean weight diameter (MWD) will be used as an index of soil aggregate stability.

4.2 Materials and Methods

Samples from different soil depths were collected from different paired-sites of NT and CT systems.

4.2.1 Aggregate stability

Aggregate stability was determined with a wet sieving procedure, this being a modification of the method of Yoder (1936) as described by Haynes (1993). Air-dried samples were broken up to pass through a 6 mm mesh, and retained on a 2 mm sieve. The 2 to 6 mm diameter aggregates were then collected. Aggregate stability was then measured by a wet sieving apparatus. Three replications on each soil sample were carried out. Approximately 30 g of air-dried soil aggregates were spread to the upper of a set of three sieves having 2, 1, and 0.5 mm aperture meshes respectively. Soil aggregates on the upper sieve were allowed to wet by capillarity for 10 min, thereafter the water level was adjusted so that the aggregates on the upper sieve were submerged at the highest point of oscillation. The oscillation rate was 2.5 cycles per minute, the amplitude of sieving was 3.5 cm, and the standard time of sieving was 15 min. The mass soil fraction on each sieve was then weighed after oven drying at 105 °C. The coarse primary particles retained on each sieve were dispersed using sodium hexametaphosphate (5 %), and then washed back through the same sieve. The oven-dry weight of the stones after the second sieving was then subtracted from the total weight of non-dispersed soil.

Results were expressed as a mean weight diameter (MWD), which is the sum of the mass fraction of the soil remaining on each sieve after sieving for a constant period, multiplied by the mean aperture of the adjacent sieve meshes (Eq 4.1). The upper and lower limits of mean inter-sieve apertures were 4 and 0.250 mm, respectively.

$$\mathbf{MWD = \Sigma X_i W_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{Eq 4.1}$$

Where X_i is the mean diameter of the sieve size class midpoint (mm) and W_i is the proportion of the total sample retained on the sieve.

4.2.2 Organic carbon

Organic carbon was determined using the Walkley and Black method first described by Walkley (1947). Air-dried soil ground to pass through a 0.5 mm sieve was digested in a potassium dichromate/sulphuric acid mixture to oxidise the organic carbon. Soil organic carbon content is then determined by back-titration of the excess dichromate, using a 0.5 N ferrous ammonium sulphate solution.

4.2.3 Particle size distribution

Particle size distribution was determined by the pipette method as described by Gee and Bauder (1986), on air-dried soil samples ground to pass through a 2 mm sieve, and treated with a calgon dispersing solution and ultrasound. The soil texture for each selected horizon was then determined by using a measured percentage of sand, silt and clay on a textural class according to the classification system of the Soil Classification Working Group (1991).

4.2.4 Soil chemical analysis

Chemical analysis of soils was determined on air-dried samples by the Cedara Agricultural Research Station, Soil Fertility and Analytical Services, Kwazulu-Natal Department of Agriculture.

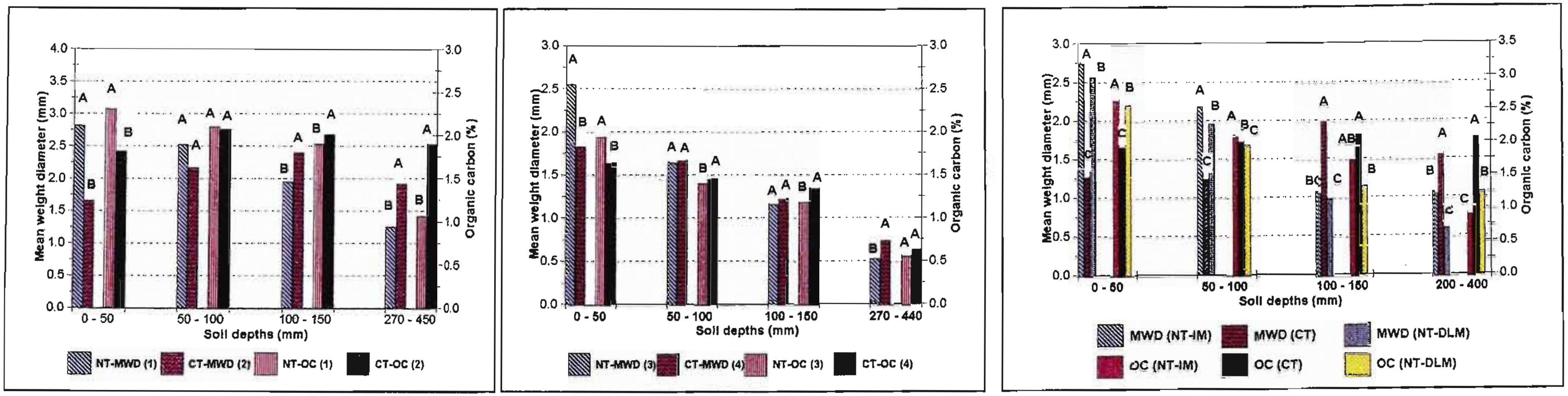
4.3 Results and Discussion

Detailed particle size distribution and soil chemical analysis results for all sites, together with their soil texture, are shown in Appendix 1. The soil aggregate stability expressed as mean weigh diameter (MWD) and results for organic carbon content as a function of soil depth are shown in Figure 4.1, A to F. Figure 4.2, A to F shows statistically the relationship between MWD and organic carbon content. Appendices 6 and 7 show a summary of statistical analysis of the effects of tillage on soil aggregate stability and organic carbon respectively.

(a) Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms

(b) Sites 3 and 4: Mr v. der Aardwerg's and Mr v. Vuuven's farms

Sites 5A, 5B and 6: Mr Miurhead's and Mr Mostert's farms



NT-IM: NT-irrigated maize NT-DLM: NT-Dryland maize

(d) Sites 7 and 8: Mr J. Jackson's and Mr J. Joubert's

(e) Sites 9 and 10: Cedara Agricultural Research

(f) Sites 9 and 10: Cedara Agricultural Research Station

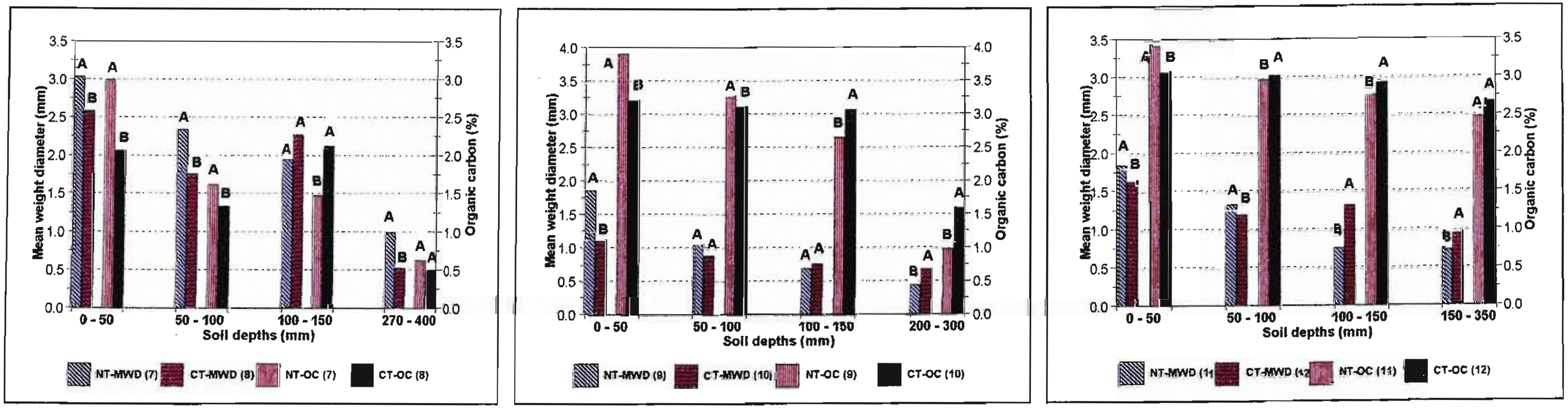
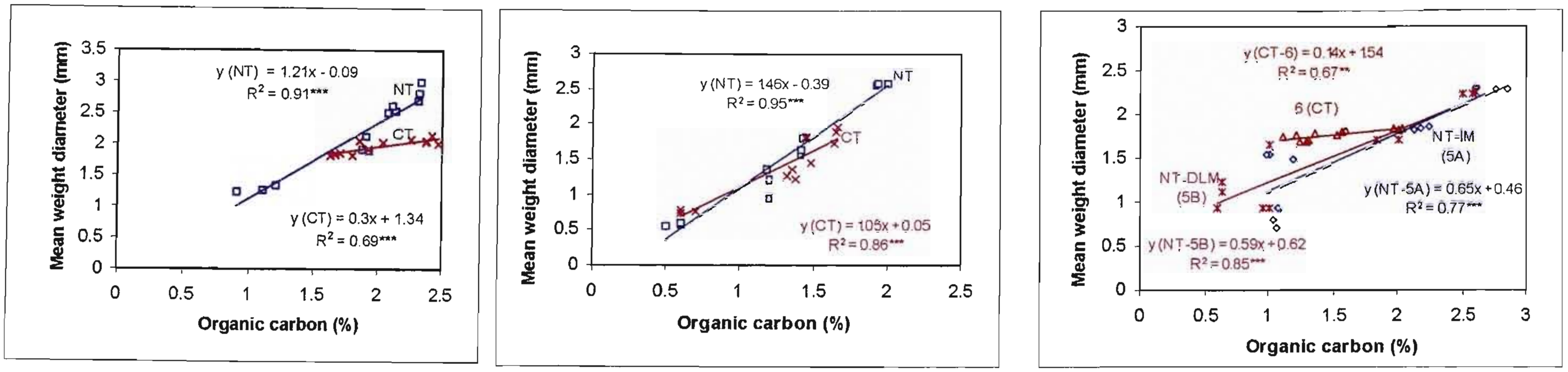


Figure 4.1. Mean weight diameter of water stable aggregates and organic carbon content for the study sites. Each data point represents the mean of three replicates. Means followed by the same letter at same depth are significantly similar (NT: No tillage; CT: Conventional tillage; LIR: Loose inter-row; CIR: Compacted inter-row)



(a) Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms

(b) Sites 3 and 4: Mr v. der Aardwerg's and Mr v. Vuuven's farms

(c) Sites 5A, 5B and 6: Mr Miurhead's and Mr Mostert's farms

NT-IM: NT-irrigated maize NT-DLM: NT-Dryland maize

(d) Sites 7 and 8: Mr J. Jackson's and Mr J. Joubert's

(e) Sites 9 and 10: Cedara Agricultural Research

(f) Sites 9 and 10: Cedara Agricultural Research Station

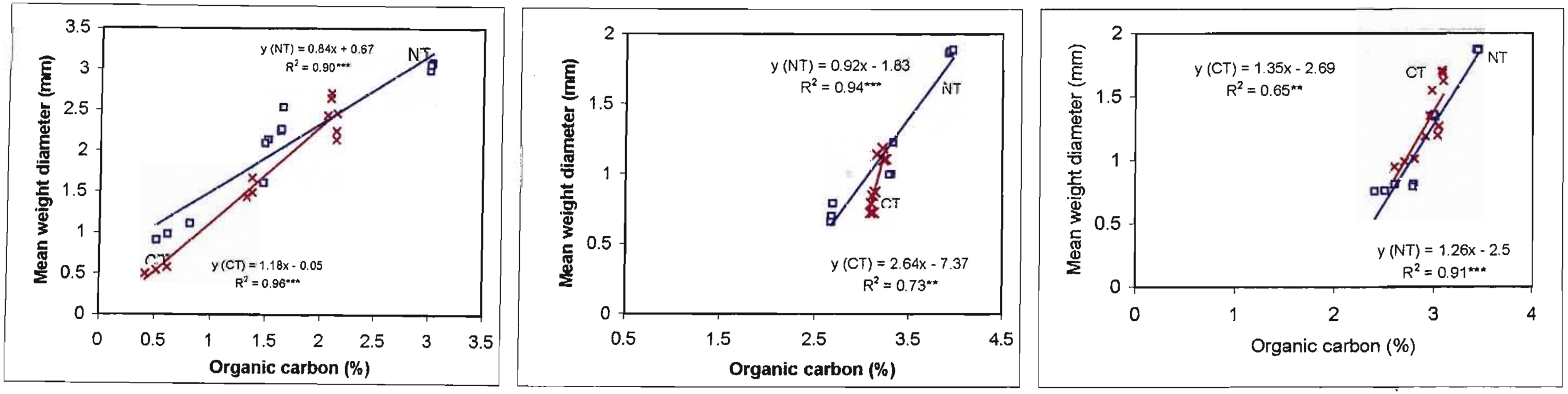


Figure 4.2. The relationship between mean weight diameter of water stable soil aggregates and organic carbon content for the study-sites. Each data point represents the mean of three replicates (NT: No tillage; CT: Conventional tillage; LIR: Loose inter-row; CIR: Compacted inter-row)

The results showed high levels of variability between tillage regimes, especially in the topsoil (0 – 50 mm depth). NT had significantly higher aggregate stability near the soil surface compared to CT, especially at the 0 - 50 mm layer ($P < 0.001$). The effect of NT on MWD decreased with soil depth at all sites (Figure 4.1, A to F).

Corresponding to this higher aggregate stability, NT soils were found to have a significantly higher organic carbon content than the conventionally tilled soils for the top 50 mm depth ($P < 0.001$) (Appendix 7). In fact, the pattern of variation of organic carbon, decreasing with soil depth, followed closely that of the aggregate stability (Figure 4.1, A to F). The decomposition of crop residues left at the soil surface each season promoted an increase in organic carbon and aggregate stability in the topsoil under the NT system (Franzluebbers and Arshad, 1996; Arshad et al., 1999; Rasmussen, 1999). In addition, when relating MWD and organic carbon content by linear regression analysis, highly significant R^2 values ($P < 0.001$) were obtained (Figure 4.2, A to C). Many other workers have also observed a linear relationship between soil organic carbon content and aggregate stability, among them, Haynes (1993), Franzluebbers and Arshad (1996), Arshad et al. (1999), Rasmussen (1999). Soil organic matter promotes aggregation through the binding and cementing actions of humic materials and soil polysaccharides (Zhang and Miller, 1996; Hillel, 1998).

Under CT, the soil is inverted each year and crop residues are buried to a depth of approximately 100 mm or 150 mm. As a result, MWD was more or less evenly distributed down the soil profile (Figure 4.1, A to F). This followed the same distribution as organic carbon. Indeed, as already noted, the two soil properties (of MWD and SOC) were related to one another linearly (R^2 ranging from 0.65** to 0.96***) (Figure 4.2, A to F). From these findings, it was apparent that the lower MWD under CT, especially at the topsoil (0 – 50 mm soil depth), was attributable to the breakdown of soil aggregates due to lower level of organic carbon content. This was, indeed the case because, once the 2 – 6 mm soil aggregates were spread on the top 2 mm sieve, visual observations revealed that they were immediately dispersed at the beginning of the wet-sieving test. CT characteristically promotes the breakdown of soil organic matter by breaking up soil aggregates during tillage operations and exposing organic matter to microbial attack, which was previously physically protected from decomposition within the aggregate structure and by, increased soil aeration status that promotes microbial activity (Beare *et al.*, 1994; Haynes and Beare, 1996). This results in rapid decomposition and loss of native organic carbon and mineralization of organic N, P and S at parallel rates. In addition, the amount of organic matter returned to the soil under CT is generally much lower than under NT. This resulted from the reduction of organic matter input due to the fact that the crop plants under the system are usually spaced widely apart in rows, resulting in fewer roots and often much of the plant residue materials are removed from the field with, or as, the crop is harvested. On the other hand, the topsoil erosion can also contribute to the loss of organic matter owing to the absence of a surface cover under CT.

The following discussion has been focused on the interpretation of soil stability changes through the soil profile, taking into account mainly three major soil depths, that is 0 – 50 mm, 50 – 100 mm, and 100 – 150 mm. As already discussed above, the greater soil aggregate stability in the 0 – 50 mm soil layer under NT was of considerable significance when compared with the lower aggregate stability under CT, and this was likely to be related to the accumulation of organic matter near the soil surface under NT. However, for the 50 - 100 mm soil layer, the results showed non-significant differences in MWD at sites 1 and 2 ($P = 0.108$), 3 and 4 ($P = 0.876$), 9 and 10 ($P = 0.328$) (Appendix 6). In contrast, aggregate stability and organic carbon content were significantly higher under NT ($P < 0.001$) in this depth at sites 5A, 5B and 6, 7 and 8, 11 and 12 (Appendices 6 and 7). The lack of differences in MWD between tillage regimes at this depth can be attributed mainly to downward redistribution of organic matter content under CT and the lack of such redistribution under NT (Haynes, 1999).

For the next layer below (100 – 150 mm), aggregate stability was highly significant only under CT ($P < 0.05$), as compared to NT (Appendix 6). The corresponding higher level of organic carbon found in that layer was probably brought down from the surface by ploughing at 150 mm depth. This was also pointed out by Pierce *et al.* (1994) and Lamey *et al.* (1997). On the other hand, this increase in aggregate stability could also be attributed to the rate of annual decomposition of crop residues incorporated to a maximum depth of 150 mm under conventional tillage (CT) (Franzluebbers and Arshad, 1996). Nevertheless, as also suggested by Haynes and Knight (1988), total organic matter content was not the major factor influencing aggregate stability in deeper soil layers. The distribution of some other specific binding agents like extensive network of roots, root exudations and the continual death of roots, and particularly root hairs was involved in increasing aggregate stability by promoting microbial activity that results in the production of humic cements (Metting, 1993).

However, for the same soil layer, non-significant differences in MWD were observed under certain CT sites compared with NT ones, while the organic carbon content was found highly significant (Sites 4, 8, 10: P< 0.001). The lack of any difference in MWD could presumably be related to an insufficient decomposition of annual inputs of organic matter in the form of crop residues (buried at ± 150 mm depth), roots and root exudations. Therefore, the type of organic matter produced was probably insufficient or inadequate to promote soil aggregate stability.

4.4 Conclusion

The above results highlight the fragile nature of the soil under both NT and CT systems in terms of changes in the distribution of organic carbon content and the associated soil aggregate stability related to soil depth. The objective of this chapter was to evaluate these changes by comparing both systems, and to subsequently suggest the type of tillage best suited to manage the sites.

With considerations to the amount of crop residues retained at the soil surface, NT ensures a good soil surface stability, and this will significantly reduce the breakdown of soil aggregates dispersed by raindrop impact. This is the result of the concentration of soil organic carbon near the soil surface under NT (Riley and Ekeberg, 1998; Yang and Wander, 1999; Haynes, 1999). If aggregate stability needs to be maintained in the long-term, organic matter must be replenished and supplied continually.

The decline in both soil organic carbon and aggregate stability near the surface under CT was caused by intensive tillage practices that promoted decomposition of soil organic matter as well as a downward redistribution of organic matter. Any soil cultivation which results in soil mixing and bringing up of subsoil would be detrimental to soil surface stability, but would increase aggregate stability at the plough-depth, owing to either organic matter brought down by soil ploughing or crop residues being buried. The soil surface under CT is susceptible to surface sealing and slumping (McIntyre, 1958; Burch *et al.*, 1986) because of the lower soil organic matter content and aggregate stability.

From the viewpoint of these findings, NT may be assumed to be a suitable tillage system that would improve topsoil structure.

Chapter 5

The effects of tillage system on soil water retention

5.1 Introduction

5.1.1 General principles

Soil water retention is a basic property of soil that regulates storage and water movement and ultimately plant growth (Kern, 1995; Chen and Wheater, 1999). A soil water retention curve refers to the relationship between water content and matric potential in a drying or wetting soil, where water content is most usefully expressed on a volumetric basis and matric potential in terms of pressure (Klute, 1986).

The focus of this chapter is to evaluate the extent to which tillage systems, namely CT and NT, affect water retention, and consequently soil aeration. In this context, a pair of sites selected in different areas has been studied in order to describe and understand the situation in the context of soil variability.

5.1.2 Quantification of plant available water

The concepts of field capacity, permanent wilting point and plant available water capacity have provided, and continue to provide a useful framework on which to quantify the soil water availability and soil aeration.

The availability of water to plants is regulated by the water retention properties of soil. Under saturated conditions, water in the soil matrix is considered to be at atmospheric pressure ($\varphi_m = 0$). As the soil drains, water is subjected to a series of matric potentials. The upper and lower boundaries of plant available water are termed *"field capacity"* and *"wilting point"*, respectively. The matric potential corresponding to *"field capacity"* is not the same for all soils, and also is not expressed consistently in the literature on either a volumetric or a mass basis (Smith, 1995). Despite these limitations, *"field capacity"* is usually defined as being the water content of a freely draining soil that has been saturated with water in the field and allowed to drain for 2 to 3 days (Soil Classification Working Group, 1991). In Southern Africa, *"field capacity"* is often defined as being the water content retained at a matric potential of – 10 kPa (Smith, 1995). *"Wilting point"* is a point in the range of soil water content below which a majority of plants wilt permanently and do not recover turgidity (Soil Classification Working Group, 1991).

Plant available water (PAW) is defined as being the amount of water held in the soil between field capacity (- 10 kPa) and wilting point (- 1500 kPa), while readily available water (RAW) refers to the difference in volumetric water content between field capacity (– 10 kPa) and stress point (– 100 kPa: matric potential where after the plant could be expected to start experiencing water stress). These definitions provide an indication of the availability of water between the respective matric potential boundaries. Nevertheless, according to a number of studies (Richards and Wadleigh, 1952; Thornthwaite and Marther, 1955; Philip, 1957; Pierce, 1958; Gardner, 1960; Ritchie *et al.*, 1972; Cassel and Nielsen, 1986), there are some limitations linked to the dynamic nature of soil water flow and the influences of plant uptake and atmospheric demand.

5.1.3 Soil aeration status

The process of soil aeration is an important determinant of soil productivity. Adequate soil aeration is required for plant root growth and for micro-organisms living within the soil.

Soil aeration is largely dependent on the volume of air-filled pores. These may be interconnected and open to the atmosphere, and thus they facilitate the exchange of gases. Restricted aeration can also be the result of poor soil drainage and waterlogging conditions, or of mechanical compaction of the soil (Hillel, 1998).

Since the flow of air through soil is considerably non-destructive, aeration can be used as an indication of the physical condition of soils in relation to their structure and stability (Smith *et al.*, 1997). Most changes in soil structure are reflected in changes in the number of large pores (macropores) and intermediate pores (mesopores), while the micropores remain unchanged. Microporosity, which is responsible for the storage of surface adsorbed water at low matric potentials, is essentially a function of particle size distribution and surface area, and is, therefore, not affected by changes in soil structure (Bullock *et al.*, 1985).

Air permeability is another measurement that has been used to assess the transmission aspects of pore geometry, in order to evaluate the effects of soil compaction (Phillips and Kirklam, 1962), cropping rotations (Evans and Kirklam, 1949; Groenevelt *et al.*, 1984), and tillage systems (Janse and Bolt, 1960; Ball, 1981; Hamblin and Tennant, 1981; Douglas *et al.*, 1986; Mielke *et al.*, 1986).

5.2 Materials and Methods

5.2.1 Soil water retention

5.2.1.1 Field sampling of undisturbed cores

The Water Retention Curve (WRC) was obtained on undisturbed soil cores. At each site, a soil profile was excavated down to approximately 1 m. From each soil profile cores were taken in triplicate, and were collected in steps at approximately 50 mm, 150 mm and 320 mm using a specially designed soil core sampler, after ponding water on the soil surface overnight before sampling (this was considered approximately at field capacity) to reduce the influence of swelling and shrinkage, and to avoid the risk of fracturing the soil core during sampling.

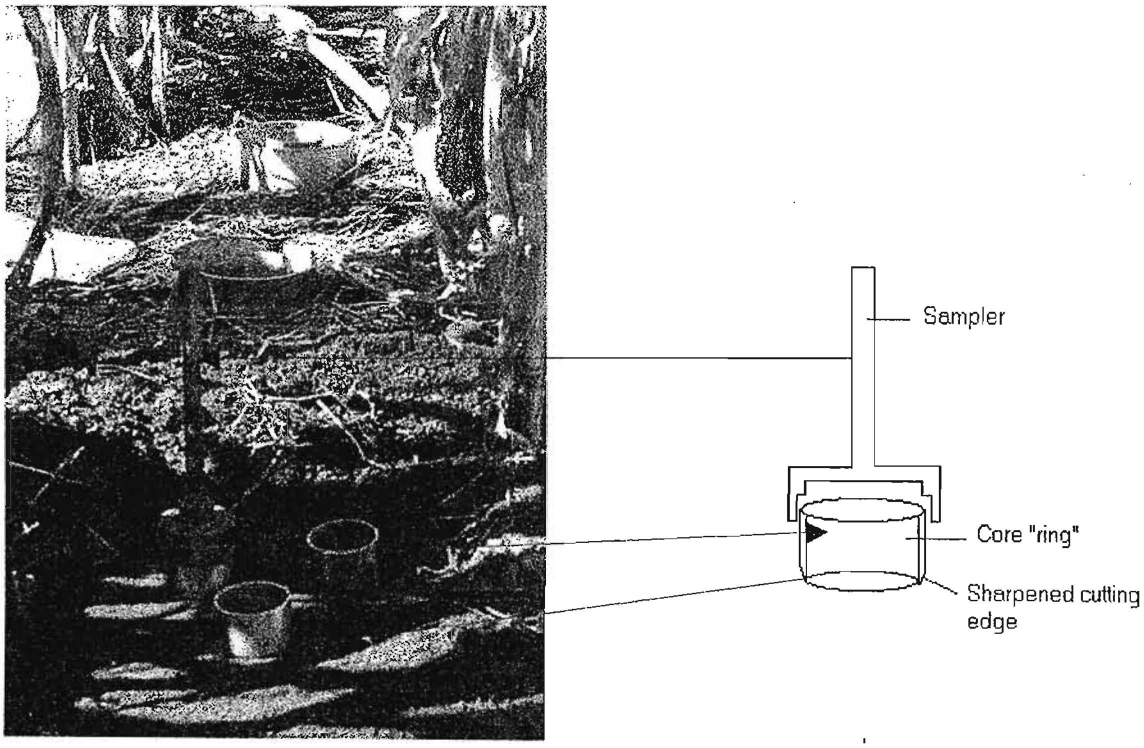


Figure 5.1.The field soil core sampler used to collect undisturbed soil samples between maize rows

The rigid stainless steel rings of 50 mm long and 75 mm internal diameter were hammered vertically into the soil to the appropriate depth, using a mallet (Figure 5.1).

Then the soil core rings were removed from the soil with a minimum disturbance using a spade and a big knife. The soil core samples were covered carefully in a plastic bag, and transported to the laboratory.

5.2.1.2 Laboratory procedure in the high matric potential range (0 – 10 kPa)

Once in the laboratory, the cores were trimmed flush with the edge of the steel sleeve using a hacksaw blade. The bottom face was covered with thin cloth, held on the steel ring by a rubber band. The cores were then weighed to determine the initial water content. Thereafter, the soil core samples were placed in a water-bath, and left there for saturation by capillary movement (overnight for loose soils and at least three days for the very compacted soils). During this stage, the water in the bath was raised to within 5 mm of the top of the core samples. After wetting, each core was removed from the water-bath, and immediately weighed in order to estimate the saturated water content. The saturated soil cores were then transferred to a tension table (Figure 5.2), set at 0.10 m tension. The soil cores were allowed to equilibrate for 48 hours, after which the mass of the core was measured before adjusting to the next tension. The matric potential sequence used was: 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.75 and 1.00 m.

Thereafter, the soil cores were transferred to a pressure pot (Figure 5.3) by placing the soil cores on a 1 bar ceramic plate. A pressure of 30 kPa was then applied until the negative pressure of water in the soil core samples matched the positive air pressure. Once equilibrated, the mass of each soil core sample was recorded. This took approximately seven days for the equilibrium to be reached. Once the soil cores were replaced in the pressure pot, the same procedure was repeated at a pressure of 100 kPa. The air permeability of the soil core was also measured at the matric potential of – 10 and – 100 kPa (see section 5.2.2.2). The soil cores were then left for saturated hydraulic conductivity measurements (see section 6.3.2). Maximum care was taken to minimize the loss of any soil during the rewetting and the saturated hydraulic conductivity processes. Finally, the soil cores were oven-dried at 105 °C to constant mass.

At each matric potential (- 0.10, - 0.20, - 0.30, - 0.40, - 0.50, - 0.60, - 0.75, - 1.0, - 3.0, and – 10.0 m), a mean water content was calculated from three or four replicate soil cores for each soil depth to obtain the water retention curve. The oven dry mass was used to determine the mass water content at each matric potential. The volumetric water content was calculated using the equation (Eq 5.2):

$$\theta_V = \theta_m \times \rho_b \times \rho_W^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{Eq 5.2}$$

Where θ_V is the volumetric water content ($m^3\ m^{-3}$), θ_m is the mass water content ($kg\ kg^{-1}$), ρ_W is the density of water ($kg\ m^{-3}$), and ρ_b is the bulk density ($kg\ m^{-3}$) determined from the oven dry mass of the soil core divided by its volume.

The size of drained pores can be related to the pressure below the atmospheric pressure of the soil water according to the capillary equation (Eq. 2.2) (Hillel, 1998). This was then used to estimate the pore size distribution (section 5.2.2).

5.2.1.3 Laboratory procedure in the low matric potential range (at – 1500 kPa)

Soil water retention at – 1500 kPa was determined by placing pre-weighed rubber rings (10 mm high x 50 mm internal diameter) on a ceramic plate (15 bar). The rubber rings were thereafter filled with air-dried soil (< 2 mm). The samples were saturated for 24 to 48 hours on the 15 – bar ceramic plate and thereafter, placed in the high-pressure chamber (Figure 5.4). A high-pressure of 1500 kPa was then applied. The equilibration of the samples occurred in approximately ten days. The mean water content was calculated from three replicate soil cores for each soil depth. The oven dry mass was used to determine the mass water content, and the volumetric water content was calculated using the equation (Eq. 5.2).

Water retention data were also used to estimate PAW and RAW according to their ranges of soil matric potentials. These constants represent the volume of available water held in the soil between the corresponding matric potentials boundaries. Therefore, RAW was determined as a volume of water held between – 10 and – 100 kPa, while PAW was estimated as water held in soil between matric potential of – 10 and – 1500 kPa.

The data were statistically analysed by "one-way and/or two-way analysis of variance (ANOVA)" using the Genstat V statistical package. Both tillage systems were considered as treatments and matric potential and soil depth as factors. Least significant differences (LSD's) were statistically used to separate means of treatments (i.e. NT and CT).

5.2.1.3 Laboratory procedure in the low matric potential range (at – 1500 kPa)

Soil water retention at – 1500 kPa was determined by placing pre-weighed rubber rings (10 mm high x 50 mm internal diameter) on a ceramic plate (15 bar). The rubber rings were thereafter filled with air-dried soil (< 2 mm). The samples were saturated for 24 to 48 hours on the 15 – bar ceramic plate and thereafter, placed in the high-pressure chamber (Figure 5.4). A high-pressure of 1500 kPa was then applied. The equilibration of the samples occurred in approximately ten days. The mean water content was calculated from three replicate soil cores for each soil depth. The oven dry mass was used to determine the mass water content, and the volumetric water content was calculated using the equation (Eq. 5.2).

Water retention data were also used to estimate PAW and RAW according to their ranges of soil matric potentials. These constants represent the volume of available water held in the soil between the corresponding matric potentials boundaries. Therefore, RAW was determined as a volume of water held between – 10 and – 100 kPa, while PAW was estimated as water held in soil between matric potential of – 10 and – 1500 kPa.

The data were statistically analysed by "one-way and/or two-way analysis of variance (ANOVA)" using the Genstat V statistical package. Both tillage systems were considered as treatments and matric potential and soil depth as factors. Least significant differences (LSD's) were statistically used to separate means of treatments (i.e. NT and CT).

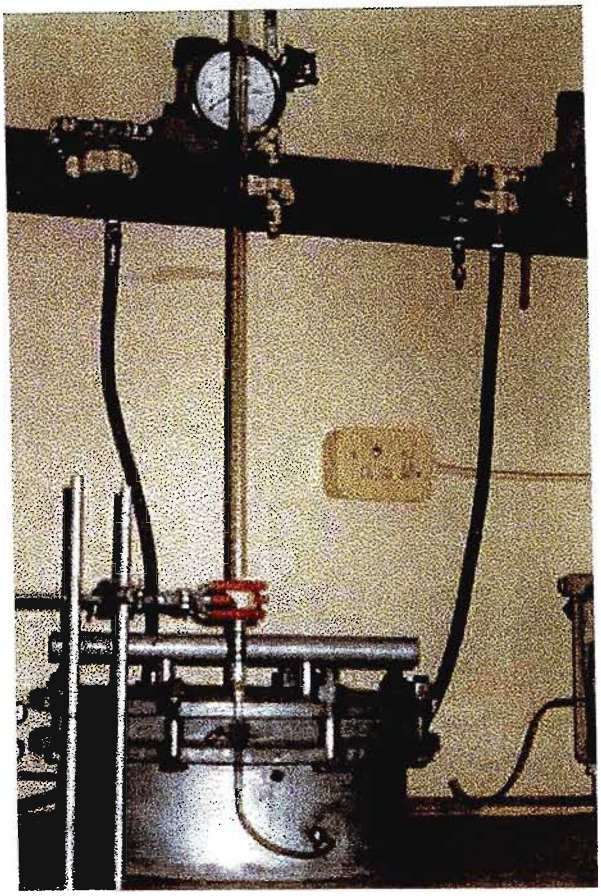


Figure 5.4. High-Pressure chamber apparatus (Richards, 1949)

5.2.2 Soil aeration

5.2.2.1 Air-filled porosity

The air-filled porosity (AFP) was estimated using both the total porosity and the saturated water content, and in both cases they were very close. AFP at – 5 and – 10 kPa was calculated from the total porosity **P** (or the saturated water content θ_{sat}) minus the volumetric water content (θ_V):

$$\mathbf{AFP = P - \theta_V} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{Eq 5.3}$$

Where $\mathbf{P = 1 - \rho_b/\rho_s}$ is the total porosity ($m^3\,m^{-3}$) .... **Eq 5.4**

and **AFP** is the air-filled porosity ($m^3\,m^{-3}$), θ_V is the volumetric water content ($m^3\,m^{-3}$), $\boldsymbol{\rho_b}$ is the bulk density ($kg\,m^{-3}$), and $\boldsymbol{\rho_s}$ is the measured particle density ($kg\,m^{-3}$).

The particle density (ρ_s) of soil samples was determined using the method described by Blake (1965). The particle density was calculated from two measured quantities, namely the mass of the soil sample and its volume (Eq 5.5). The mass of the soil sample was determined by weighing, and the volume by calculation from the mass and density of water displaced by the soil sample. Particularly for the Cedara soil samples, the particle density was determined according to the percentage of gravel.

$$\rho_S = \rho_w \times (Ms - Ma) / (Ms - Ma) - (Msw - Mw) \quad \dots\dots\dots\dots\dots \textbf{Eq 5.5}$$

Where ρ_w is the density of water at temperature observed (kg m^{-3}), **Ms** (kg) is the mass of pycnometer/flask plus soil sample corrected to oven-dry condition, **Ma** (kg) is the mass of pycnometer/flask empty, **Msw** (kg) is the mass of pycnometer filled with soil and water, **Mw** (kg) is the mass of pycnometer filled with water at temperature observed.

Air-filled porosity at – 10 kPa (i.e. pores > 29.2 μm diameter) was regarded as macroporosity. However, mesoporosity was considered to be pores that retained a volume of water content between – 10 and – 1500 kPa (i.e. pore-diameter of between 29.2 and 0.2 μm respectively), while microporosity was related to pores < 0.2 μm diameter.

5.2.2.2 Air permeability

a. Field measurements

Air permeability measurements can provide useful information on the soil aeration status. The simplified field air permeability apparatus used was based on the design of Kirklam (1947), and used by Evans and Kirkham (1949) and Grover (1955).

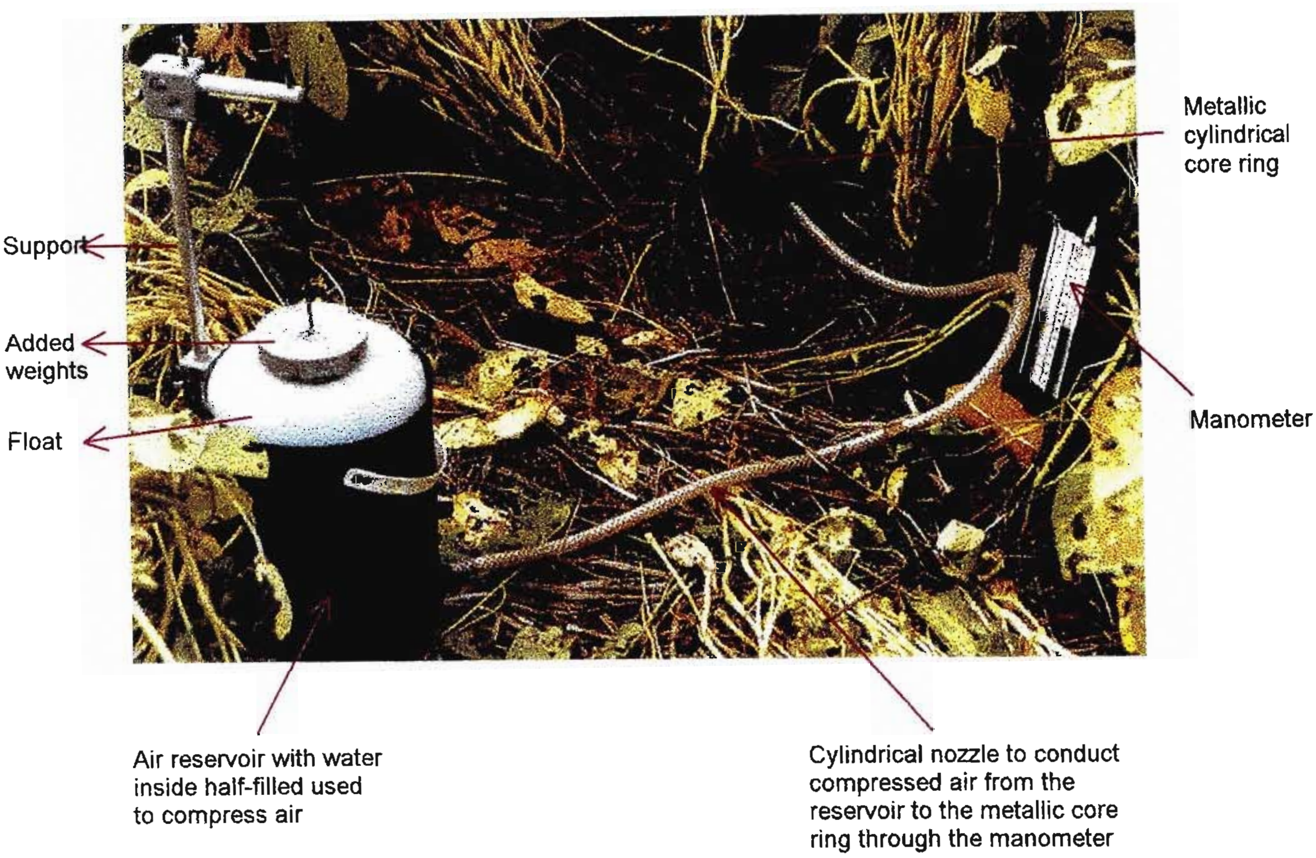


Figure 5.5. A simplified field air-permeameter

The field air permeability apparatus consisted of four principal elements (Figure 5.5): an air chamber where air can be compressed; a metallic cylindrical core ring that is pushed into the ground at approximately 20 mm depth; a cylindrical nozzle used to conduct compressed air from the air chamber to the metallic core ring through a manometer. The air chamber unit consists of a float and a small cylindrical tube inside the reservoir. As the float is raised to a certain height (with weights on the top, depending on the compactibility of the soil), water in the reservoir produces compressed air pressure (read on the manometer) that is collected by the small cylindrical tube (inside reservoir), and conducted directly through the cylindrical nozzle to the soil. As the air enters into the soil, the float falls down slowly, and its weight maintains a constant pressure ΔH independent of the rate of the fall. The volume of air entering the soil per unit time is a measure of the air permeability of the soil.

The air permeability was calculated using the equation of Corey (1986), based on Darcy's law:

Darcy's equation: $$q = -K_S \times \frac{\Delta H}{L} = \frac{V}{A \times t} \quad \text{...................... Eq 5.6}$$

Equation of Corey (1986): $$K_a\ (m^2) = \frac{\eta_a \times Q \times L}{A \times \rho_w \times g \times \Delta H} \quad \text{............... Eq 5.7}$$

Where ΔH is the air pressure difference or manometer displacement (m), **Q** is the measured air flow rate ($m^3\ s^{-1}$), **L** is the length of the cylindrical ring entered into the soil (m), **A** is the cross sectional area of the ring (m^2), **V** is the measured volume of air (m^3) entered into the soil at time **t** (sec), ρ_w is the density of water in the manometer at the measured temperature ($kg\ m^{-3}$), η_a is the air viscosity at the measured temperature (Pa s), and **g** is the acceleration due to gravity ($g\ m^{-2}$).

The measurements of air permeability in the field were made in the inter-rows. Water was ponded on the soil surface, and left overnight before taking measurements the following day. Compressed air was passed directly into the soil and allowed to escape through uncontrolled pathways to the atmosphere. Three to four readings (depending on the variability of the readings) were taken on each position.

b. Laboratory measurements

The simplified air-permeameter used in the laboratory is based on the design of Corey (1986) (Figure 5.6). A soil core sample is fitted between two stainless steel chambers with an internal diameter slightly larger than that of the core ring. A double system of rubber seals tightly around the soil core, and helps to improve air-flow and prevent air from escaping from the system. The top and bottom of the disc steel chambers are fixed to the air inflow and outflow tubes respectively. The air inflow tube is connected to an air supply while the air outflow tube is discharged to the atmosphere. A flow meter comprising a water manometer plus capillary outflow tube is used to measure the air pressure drop across the soil core sample (Corey, 1986).

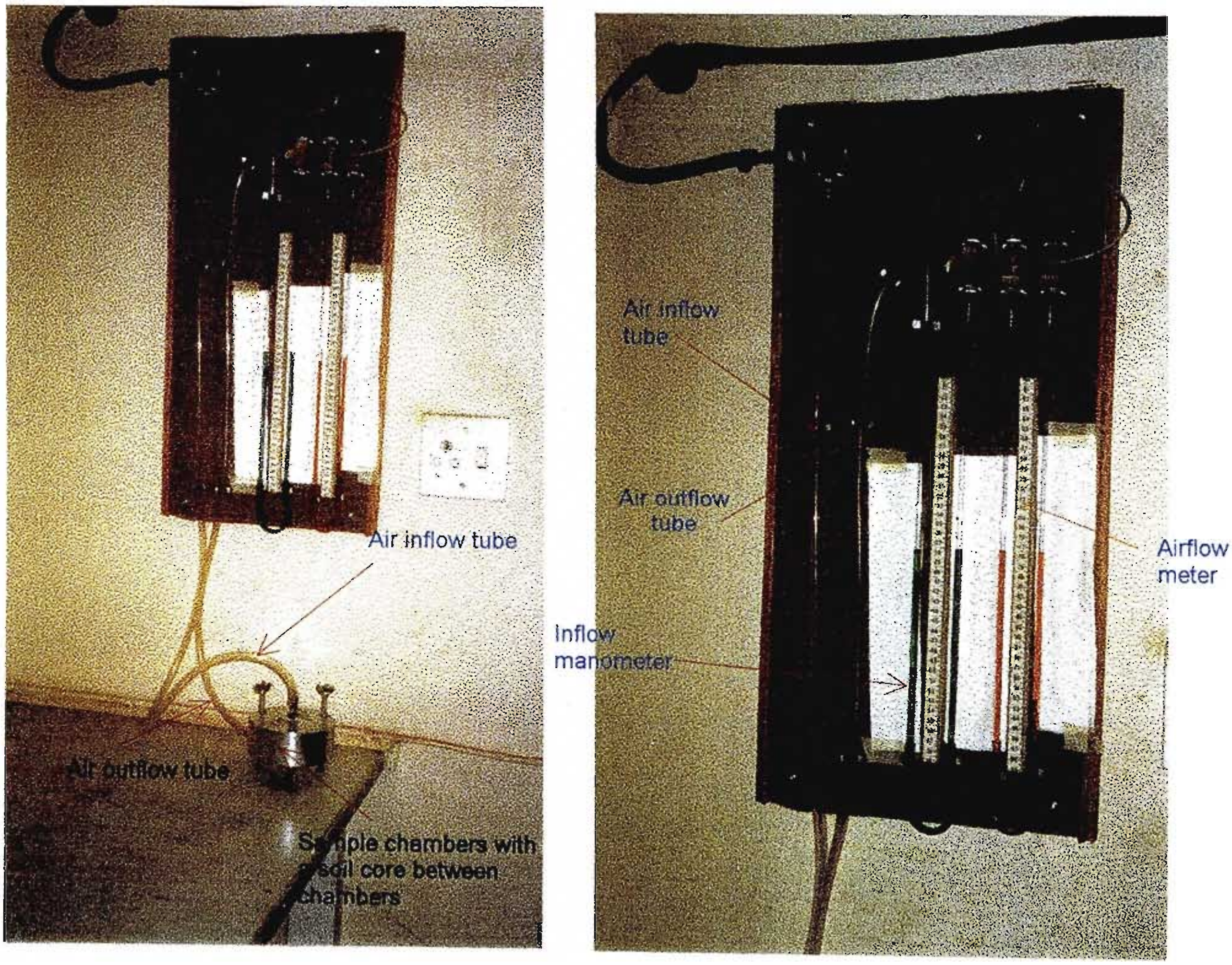


Figure 5.6. Laboratory air-permeameter used for K_a measurement on undisturbed soil cores

Air permeability measurements were carried out on undisturbed soil cores (75 mm in diameter by 50 mm length) at - 10 kPa and - 100 kPa matric potentials. Two readings were then taken. The air permeability was calculated using the equation of Corey (1986) (Eq. 5.7).

5.3 Results

The general effects of tillage system on water retention, bulk density and pore-size distribution for all the selected sites are presented in the following illustrations: Figure 5.7 (for sites 1 and 2), Figure 5.8 (for sites 3 and 4), Figure 5.9 (for sites 5A, 5B and 6), Figure 5.10 (for sites 7 and 8), Figure 5.11 (for sites 9 and 10), and Figure 5.12 (for sites 11 and 12). The Appendix 2 reports the determination of various soil properties measured on undisturbed soil cores. Results for statistical analysis are reported in Appendix 3. For clarity, the following codes will be used at the appropriate paragraph and can be referred when necessary.

Code	**Meanning**
NT - IM	No tillage irrigated maize
NT - DLM	No tillage dryland maize
NT - LIR	No tillage loose inter-row
NT - CIR	No tillage compacted inter-row
CT - LIR	Conventional tillage loose inter-row
CT - CIR	Conventional tillage compacted inter-row

5.3.1 Tillage effects on water retention

5.3.1.1 Mr R. Lund's and Mr Boschoff's farms (sites 1 and 2: clay soil)

The influence of tillage on water retention and total porosity, as calculated according to Equations 5.2. and 5.4 respectively, is shown in Figure 5.7. Site 1 is described as being a NT plot, whereas site 2 is described as being a CT-plot.

At the 50 mm depth, the bulk density was substantially greater under NT than CT, accompanied by a lower total porosity and volume fraction of macro- and meso-pores. On the other hand, the proportion of micropores was high. The CT – soil had a higher volumetric water content at saturation than the NT – soil, but between – 1 and – 10 kPa (corresponding to pore-diameter of between 292 and 29.2 μm respectively) there was a rapid drainage of water in the CT soil. The WRCs crossed at about – 3 kPa. Similar, but less clear-cut trends were evident at the 150 and 320 mm depths. The NT – soil showed a more gradual release of water with decreasing matric potential shown by the volumetric WRC. However, at the 320 mm depth, bulk densities and WRCs were relatively similar for the NT and CT soils. This was, however, accompanied by a tendency for the total porosity and percentage macroporosity to be lower and the meso- and micro-porosity to be greater under NT than under CT.

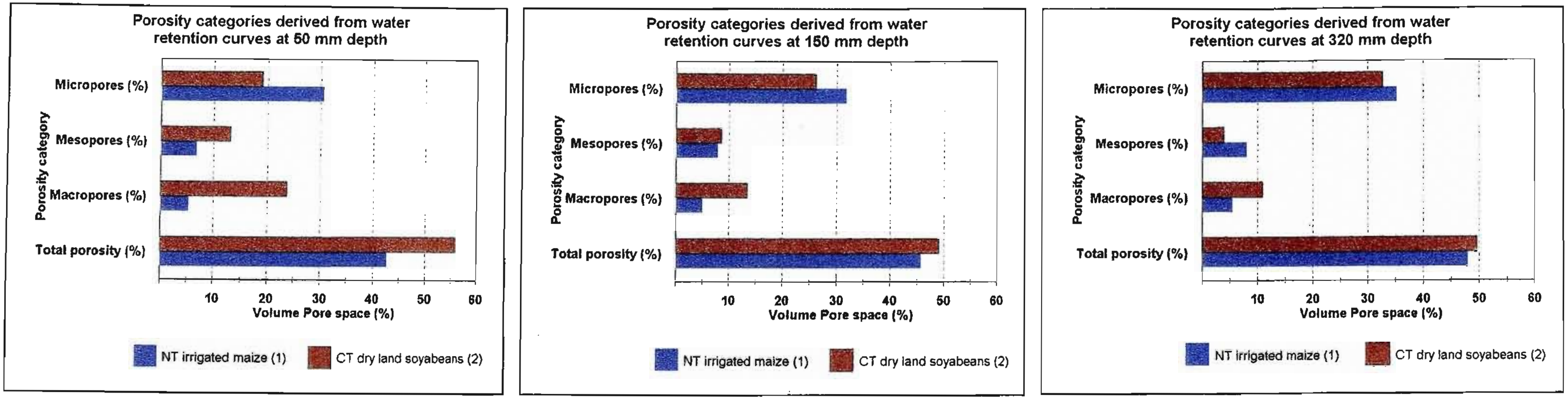
The analysis of variance (Appendix 3) showed that tillage effects on water retention at the 50 mm depth were significant ($P < 0.05$) over the selected matric potential range (i.e. the potential range at which ANOVA was carried out). In the subsoil, non-significant differences were observed over this matric potential range.

5.3.1.2 Mr van Der Aardweg's and Mr van Vuuveen's farms (sites 3 and 4: loam soil)

Figure 5.8 displays the effects of tillage on water retention and pore-size distribution on a loam soil. Site 3 is described as being a NT plot, and site 4 as being a CT plot.

The bulk density was substantially higher under NT than CT at the 50 and 320 mm depths, accompanied by a substantial decrease in total porosity and volume fraction of mesopores. At these two soil depths, the water retention curves showed similar trends with volumetric water content under CT, being significantly greater than that under NT ($P < 0.05$) between saturation and – 10 kPa matric potential (Appendix 3).

At the 150 mm depth, WRCs for NT and CT were similar and bulk density values for the two systems were also similar (i.e. 1.66 under CT and 1.72 Mg m^{-3} under NT). As a result, total porosity was only slightly higher under CT than NT although the volume fraction of macropores was much lower under NT than CT, whilst the reverse was the case for meso- and micro-pores. These results suggest that there has been compaction in the soil at this depth under both tillage systems. Under CT, this could be caused by the formation of a compacted layer at the depth of cultivation. This may also be the case at the NT site since the field was under CT prior to conversion to NT ten years ago.



Macroporosity (0 – 10 kPa) = Σ(θvi – θvj); Mesoporosity (10 – 100 kPa) = Σ(θvj – θvz); Microporosity = TP – (Meso- + Macroporosity)

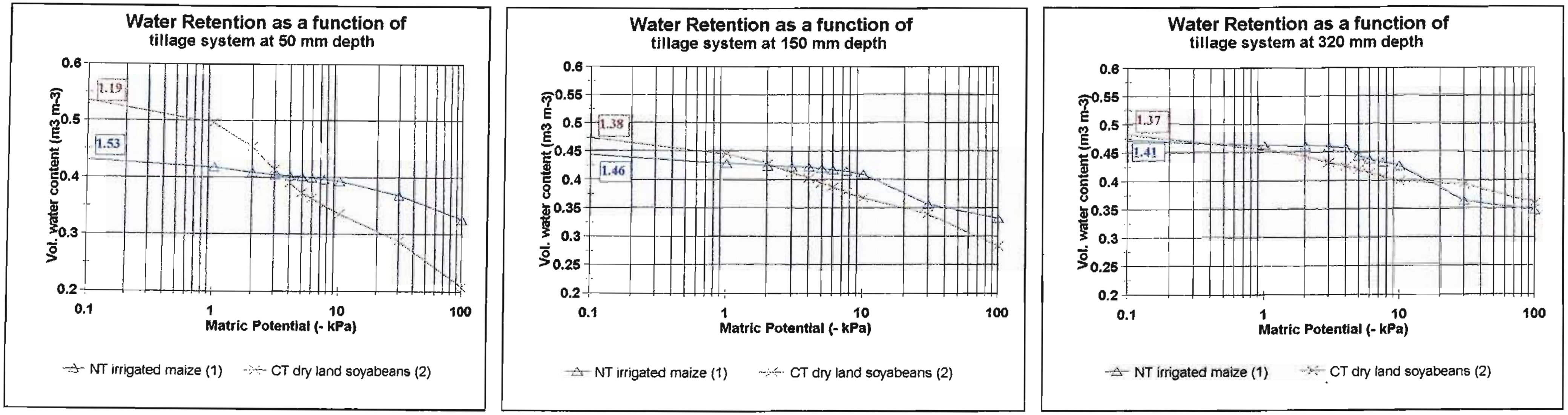
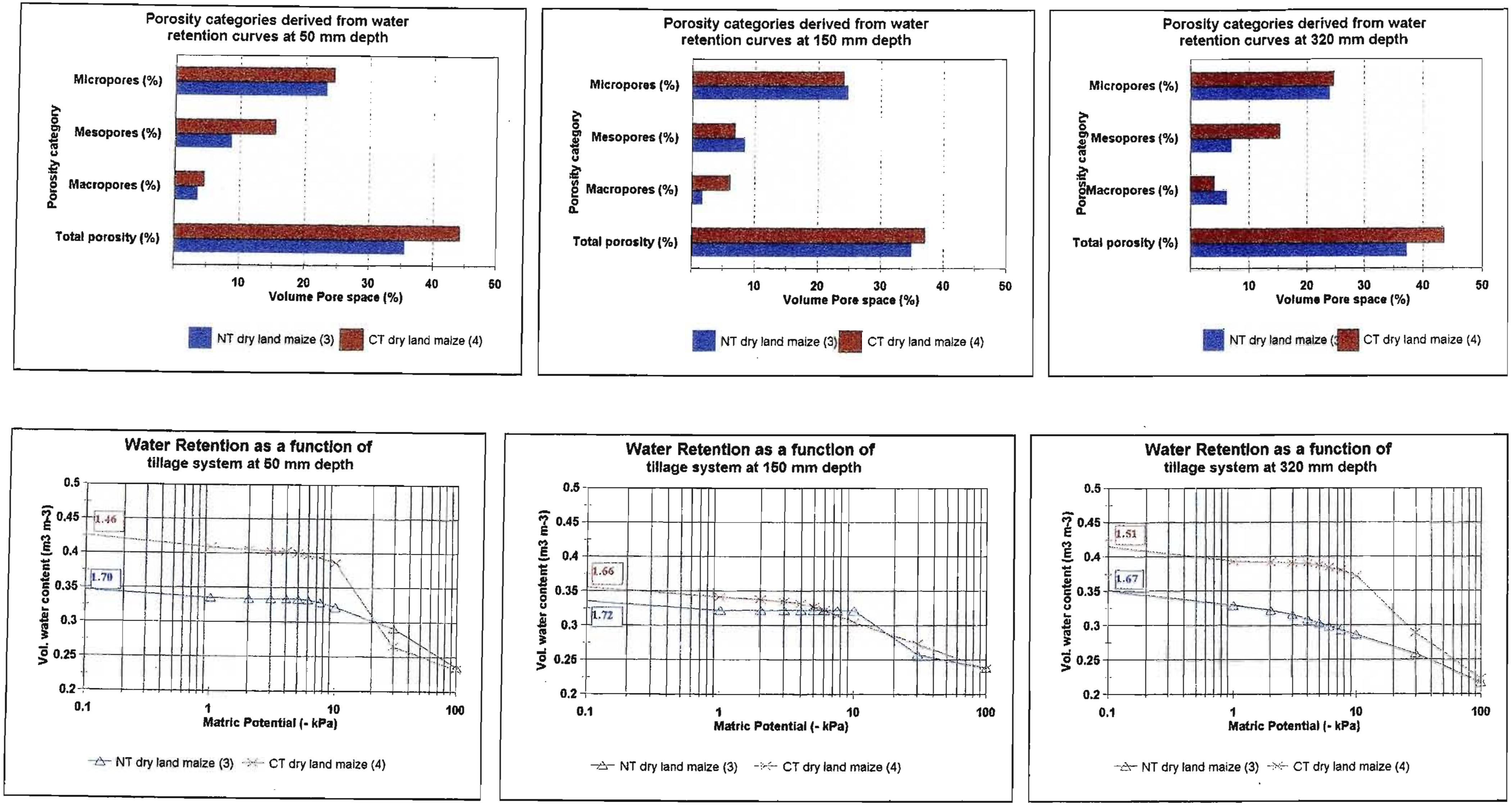


Figure 5.7. Water retention and porosity categories over a range of soil depths at Mr R. Lund's and Mr Boschoff's farms (NT and CT respectively: clay soils). Each point on the WRCs represents the mean of three replicates. The values in the boxes on the WRCs represent the bulk density in Mg m^{-3} (LIR: loose inter-row; CIR: compacted inter-row)


Porosity categories derived from water retention curves at 50 mm depth

Porosity categories derived from water retention curves at 150 mm depth

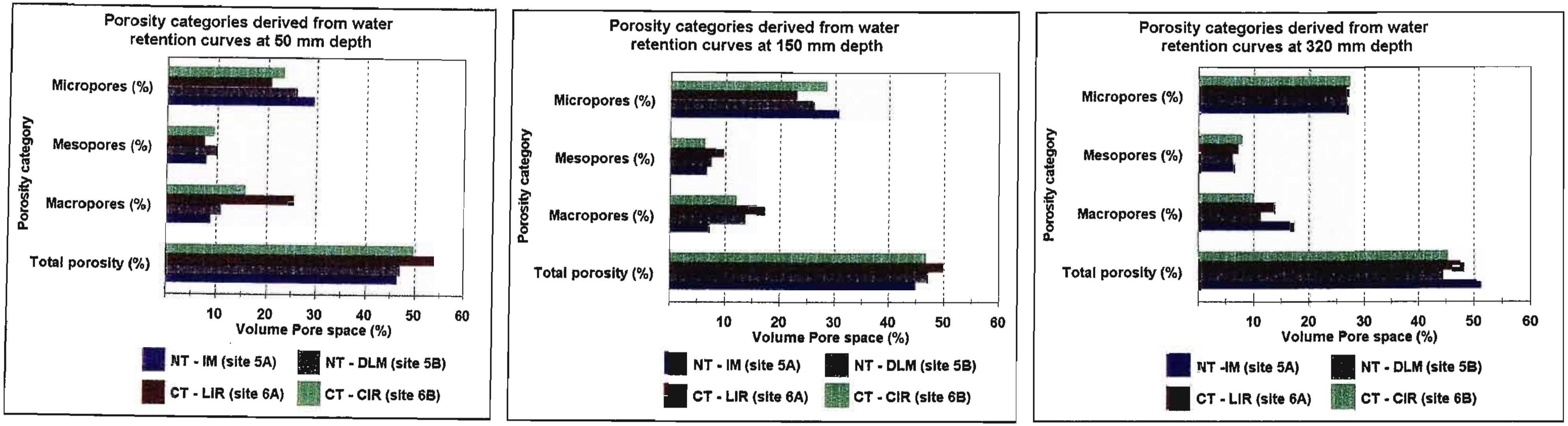
Porosity categories derived from water retention curves at 320 mm depth

Water Retention as a function of tillage system at 50 mm depth

Water Retention as a function of tillage system at 150 mm depth

Water Retention as a function of tillage system at 320 mm depth

Figure 5.8. Water retention and porosity categories over a range of soil depths at Mr van Der Aardweg's and Mr van Vuuven's farms (NT and CT respectively: loam soils). Each point on the WRCs represents the mean of three replicates. The values in the boxes on the WRCs represent the bulk density in Mg m^{-3} (LIR: loose inter-row; CIR: compacted inter-row)



NT—IM: No tillage irrigated maize, NT-DLM: No tillage dryland maize; CT-LIR: Conventional tillage loose inter-row; CT-CIR: Conventional tillage compacted inter-row

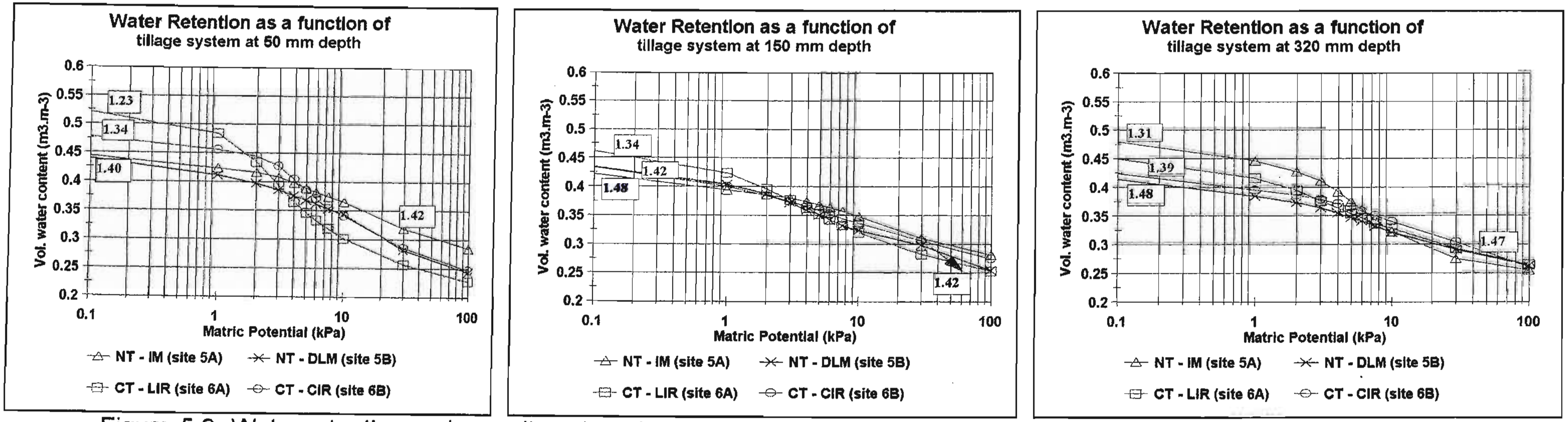


Figure 5.9. Water retention and porosity categories over a range of soil depths at Mr Miurhead's and Mr Mostert's farms (Clay soils). Each point on the WRCs represents the mean of three replicates. The values in the boxes on the WRCs represent the bulk density in Mg m^{-3} (LIR: loose inter-row; CIR: compacted inter-row)

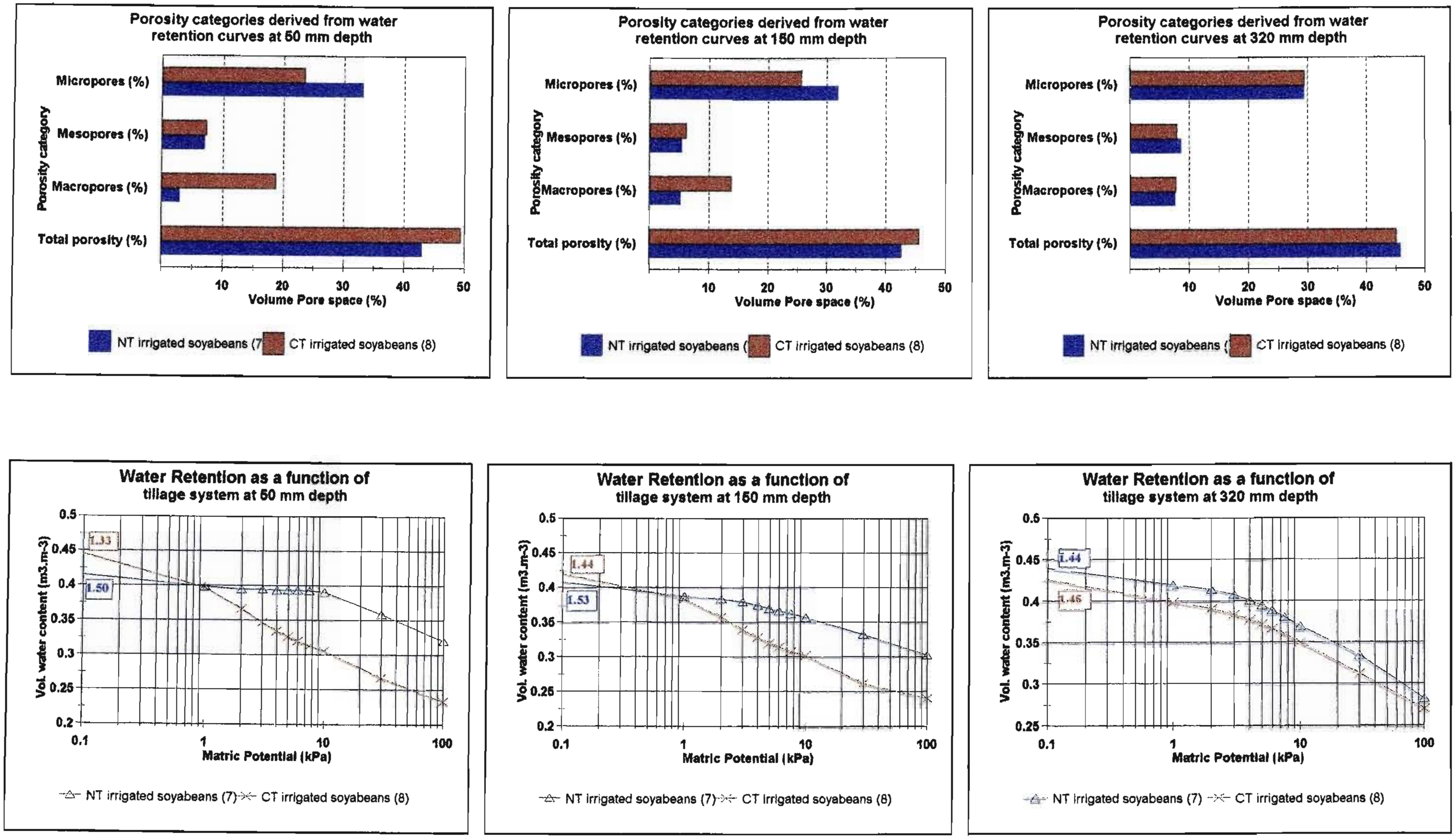
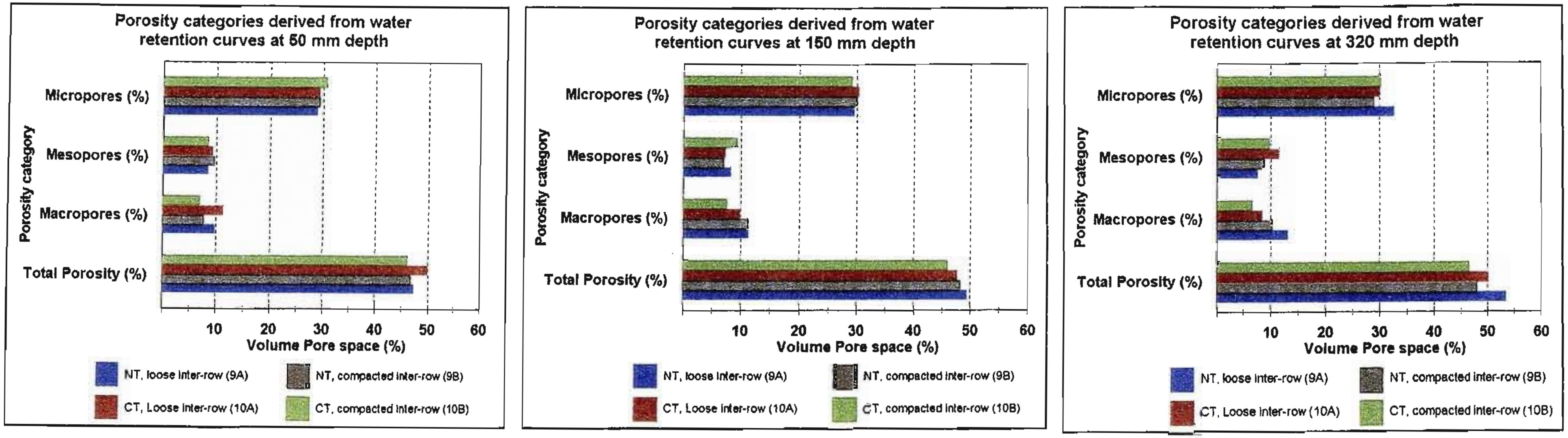


Figure 5.10. Water retention and porosity categories over a range of soil depths at Mr J. Jackson's and Mr J. Joubert's farms (NT and CT respectively: Silt-clay-loam soils). Each point on the WRCs represents the mean of three replicates. The values in the boxes on the WRCs represent the bulk density in Mg m^{-3} (LIR: loose inter-row; CIR: compacted inter-row)



NT—IM: No tillage irrigated maize, NT-DLM: No tillage dryland maize; CT-LIR: Conventional tillage loose inter-row; CT-CIR: Conventional tillage compacted inter-row

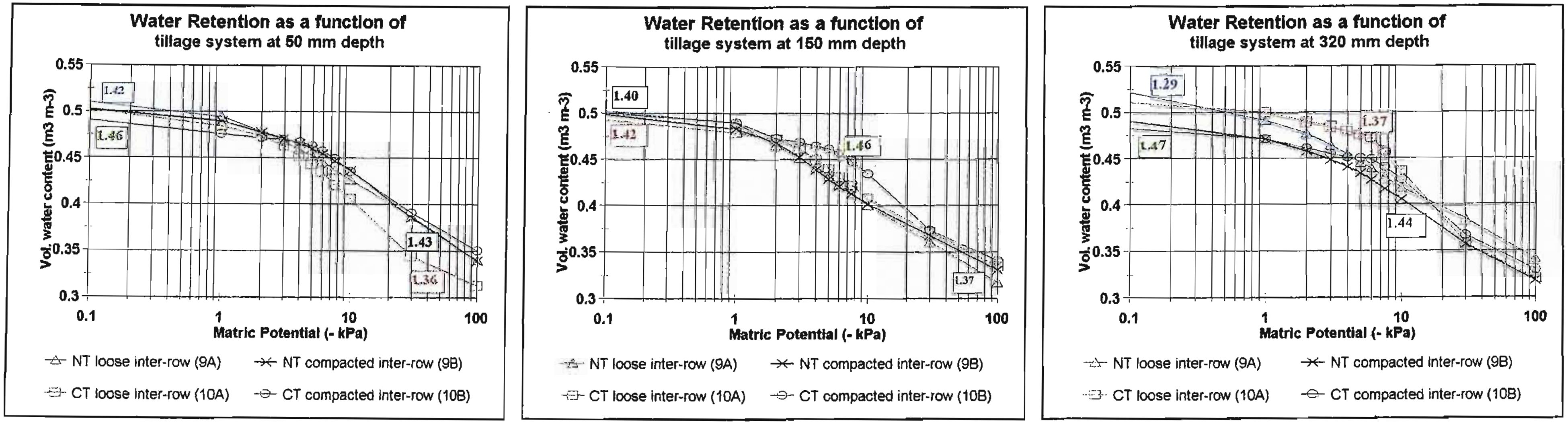


Figure 5.11. Water retention and porosity categories over a range of soil depths at the Cedara Agricultural Research Station fields (Silt-clay-loam soils). Each point on the WRCs represents the mean of three replicates. The values in the boxes on the WRCs represent the bulk density in Mg m^{-3} (LIR: loose inter-row; CIR: compacted inter-row)

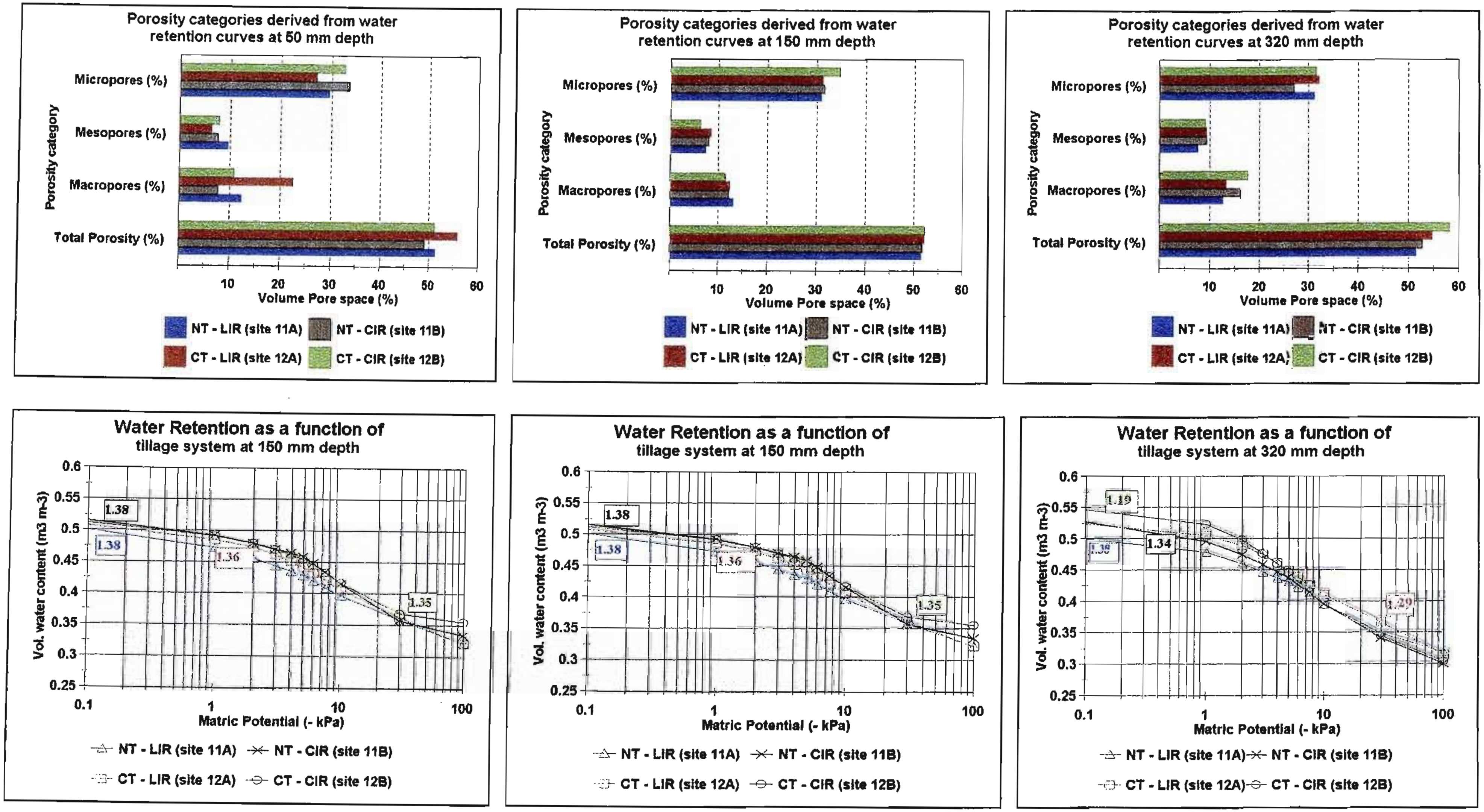


Figure 5.12. Water retention and porosity categories over a range of soil depths at the Cedara Agricultural Research Station fields (Silt-clay-loam soils). Each point on the WRCs represents the mean of three replicates. The values in the boxes on the WRCs represent the bulk density in Mg m^{-3} (LIR: loose inter-row; CIR: compacted inter-row)

5.3.1.3 Mr Miurhead and Mostert's farms (sites 5A, 5B and 6: clay soil)

The WRCs and pore-size distribution of these sites are presented in Figure 5.9. Site 5A is described as being a NT irrigated maize field (**NT- IM**), site 5B as a NT dryland maize (**NT-DLM**), site 6A as a CT dryland maize loose inter-row (**CT- LIR**), and site 6B as a CT dryland maize compacted inter-row (**CT- CIR**). At site 6, the codes A and B refer to the conditions of inter-rows. The comparison between **CT- LIR** or **CT- CIR** and **NT-DLM** or **NT- IM** gives a comparison similar to that described in Figures 5.7 and 5.8. However, the comparison between **CT- LIR** and **CT- CIR** shows the effect of tractor wheels on soil compaction.

At the 50 mm depth, the bulk density under NT soils (5A: 1.42 and 5B: 1.40 Mg m^{-3}) was greater than that under CT soils (6A: 1.23 and 6B: 1.34 Mg m^{-3}). This trend was accompanied by a considerably increase in total porosity and volume fraction of macropores, and a high volumetric water content between saturation and a matric potential of about – 2 kPa under CT soils. The volume fraction of micropores markedly increased. Similarly, by comparison with **CT- LIR**, the compacted **CT- CIR** had a greater bulk density at this soil depth, accompanied by an increase in the volume fraction of micropores and a decrease in volumetric water content between saturation and a matric potential of about – 1 kPa (corresponding to pore-diameter of > 0.292 mm). In addition, the ANOVA showed significant difference in water retention between treatments ($P < 0.05$) over the matric potential range (- 1 to - 100 kPa) (Appendix 3). From – 10 kPa to – 100 kPa, significant volumetric water content was observed under **NT- IM** ($P < 0.005$), related to this was the increase in volume fraction of microporosity that corresponds to pore-diameter of < 2.92 μm.

At the 150 mm depth, there were few differences in WRCs and porosity categories between treatments. Statistically, non-significant differences in water retention were observed between treatments above – 10 kPa (Appendix 3). The **CT- LIR** tended to have a higher total porosity and volume fraction of meso- and macro-pores than the other treatments.

At the 320 mm depth, differences in porosity were not great. The **NT- IM** and **CT- LIR** treatments tended to have lower bulk density and greater total - and macro-porosity, as compared to the other treatments. However, the analysis of variance showed that all treatments were significantly different ($P < 0.05$), water retention changing differently between tillage systems over the matric potential range (Appendix 3).

5.3.1.4 Mr J. Jackson's and Mr J. Joubert's farms (sites 7 and 8: Silt-clay-loam)

The WRCs and pore-size distribution for the CT plot (site 8) and NT plot (site 7) are shown in Figure 5.10.

At the 50 and 150 mm depths, bulk density was greater under NT than CT, accompanied by a decrease in total porosity and volume fraction of macropores, and a corresponding increase in the fraction of micropores. At these two depths, the CT soil had high volumetric water content at saturation. The NT soil showed significant volumetric water content ($P < 0.05$) after – 1 kPa (corresponding to pore-diameter of 0.292 mm) (Appendix 3). The small increase in bulk density under CT at the 150 mm depth, accompanied by a decrease in total porosity and volume fraction of macropores, could be related to the formation of a compacted layer at the ploughing depth.

For the 320 mm depth, bulk density and WRCs were relatively similar under CT and NT as were total porosity and the volume fraction occurring as macro-, meso-, and micropores. The analysis of variance at this depth showed significant difference however in water retention between treatments ($P < 0.05$) (Appendix 3).

5.3.1.5 The Cedara Agricultural Research station's fields (sites 9 and 10: silt-clay-loam soil)

The WRCs and pore-size distrubition of these sites are presented in Figure 5.11. Site 9A is described as a NT loose inter-row (**NT- LIR**), site 9B as a NT compacted inter-row (**NT- CIR**), site 10A as a CT loose inter-row (**CT- LIR**), and site 10 B as a CT compacted inter-row (**CT- CIR**). The codes A and B refer to the conditions of inter-rows.

Differences in WRCs, bulk density and porosity categories were not great at the 50 and 150 mm soil depths. Only at the 50 mm soil depth, significant differences in water retention between treatments were observed at – 30 and – 100 kPa ($P < 0.05$) (Appendix 3). However, the WRC for the **CT- LIR** showed a great decline in volumetric water content to occur between about – 3 kPa and – 100 kPa. The treatment had the highest total porosity and volume fraction of macropores. On the other hand, at the 150 mm depth, the statistical analysis showed significant differences in water retention between treatments at - 5, - 10 and – 100 kPa ($P < 0.05$) (Appendix 3).

Similarly, at the 320 mm depth, differences were only discerned on inter-row conditions. The bulk density of **CT- LIR** and **NT- LIR** were than that of the compacted inter-row treatments (**CT- CIR** and **NT- CIR**) and thus, the two former treatments had a greater total porosity than the others. However, **NT- LIR** showed greater volume fraction of macro- and micro-pores. The statistical analysis showed that water retention was significantly different between treatments at this soil depth (Appendix 3), particularly between 0 and – 10 kPa ($P < 0.05$), with greater volumetric water content under **CT-**

LIR than other treatment. This treatment showed a sharp decline in volumetric water content below about – 6 kPa, corresponding to pore-diameter of < 0.048 mm.

5.3.1.6 The Cedara Agricultural Research station's fields (sites 11 and 12)

The WRCs and pore-size distrubition of these sites are presented in Figure 5.12. Site 11A is described as a NT loose inter-row (**NT- LIR**), site 11B as a NT compacted inter-row (**NT- CIR**), site 12A as a CT loose inter-row (**CT- LIR**), and site 12B as a CT compacted inter-row (**CT- CIR**). The codes A and B refer to the conditions of inter-rows.

At the 50 mm depth, significant differences in volumetric water content between treatments were observed over the matric potential range ($P < 0.05$) (Appendix 3). However, the **CT- LIR** treatment had the lowest bulk density, the highest total porosity and greatest volume fraction of macropores. At saturation, this treatment had the greatest volumetric water content, which decreased from – 1 kPa to – 100 kPa matric potential.

At the 150 mm depth, values of bulk density, porosity and WRCs were slightly similar between treatments. Statistically, no significant differences in volumetric water content between treatments were observed at – 10 kPa (FC) and – 30 kPa matric potentials (Appendix 3).

At the 320 mm depth, for both CT and NT, the compacted inter-row treatments (12B and 11B) had lower bulk densities and greater total porosity and volume fraction of macropores than their loose inter-row counterparts (12A and 11A). By statistically analysing these trends, significant effects were observed between treatments between saturation and – 5 kPa ($P < 0.05$), corresponding to pore-diameter of between 0.058 and > 0.292 mm (Appendix 3).

5.3.1.7 Discussion

To illustrate the effects of tillage systems on soil water retention characteristics through water retention curves is a complex task since they reflect complex changes in pore-size distribution and pore geometry and available water capacity. From the viewpoint of the above results, it is evident that soil water retention was strongly influenced by pore-size distribution and bulk density. This was also reported by many other workers among them, Ahuja *et al.* (1998), Arshad *et al.* (1999), Aura (1999) and recently Smith *et al.* (2001).

The results from water retention curves showed that the greater the bulk density is the lower the volumetric water content is in the high range of matric potentials, becoming greater in the low range of matric potentials (– 10 to – 100 kPa). In fine-textured soils, the bulk density was substantially greater under NT than CT at the 50 mm depth. This was accompanied by a lower total porosity and volume fraction of macro- and mesopores and an increased volume fraction of micropores, attributable to increased soil compaction due to the lack of topsoil disturbance under NT (Azooz *et al.*, 1996). In addition, as a result of soil compaction, NT showed lower saturated volumetric water content than CT. However, the substantial proportion of microporosity resulted in the flattening of the NT water retention curves in fine-textured soils, resulting in substantial water retention at low matric potentials, and slow release of small amounts of water at high matric potenial range (0 – 10 kPa). That could be related to the texture of clay soils, having a greater soil-particle surface area available for water adsorption than coarse-textured soils (Hillel, 1998). However, there was a decrease in volumetric water content with increasing bulk density in the high matric potential range. Below a certain matric potential, increasing bulk density under NT resulted in an increase in volumetric water content (Smith *et al.*, 2001). At field capacity, taken as - 10 kPa matric potential, greater volumetric water content was observed under NT than CT. Indeed, the "crossover" between NT and CT water retention curves occurred at volumetric water contents corresponding to matric potentials ranging from – 1 kPa and – 100 kPa, depending on the soil type and the degree of soil compaction. Smith *et al.* (2001) suggested that this kind of "crossover" occurs frequently in the range of matric potentials designated as field capacity (FC) of the soil, although FC designations vary so much in the literature.

The CT soils had a higher volumetric water content at saturation than NT soils, accompanied by greater total porosity and volume fraction of macropores, and associated with a lower bulk density. This was the result of the topsoil ploughing under CT, which influenced a rapid release of volumetric water content at high matric potential range, owing to the substantial proportion of large pores (Ahuja *et al.* 1998; Aura, 1999; Arshad *et al.*, 1999).

In addition, bulk density decreased with soil depth under NT, while under CT it increased from the 50 mm to the 320 mm depth. This was associated with a corresponding change in the distribution of pore-sizes as well as total porosity. In fact, owing to increased soil compaction in the topsoil under NT, total porosity and volume fraction of macropores decreased (Azooz *et al.*, 1996), whereas under CT the same effects were observed in the subsoil due to a soil consolidation (Ahuja *et al.*, 1998; Arshad *et al.*, 1999; Smith *et al.*, 2001).

Differences in the subsoil physical characteristics were not great between NT and CT in fine-textured soils, and bulk density values were also similar for both tillage systems. Indeed, the statistical analysis showed non-significant differences between the treatments. This could be related to the subsoil consolidation (Ahuja *et al.*, 1998; Arshad *et al.*, 1999; Smith *et al.*, 2001). However, in coarse-textured soils, although bulk density was greater under CT at the 320 mm than at the 50 mm depth, the soil porosity and the distribution of pore-sizes were sometimes similar for both soil depths. The greater volumetric water content observed in the topsoil under NT was probably partly associated with the concentration of organic matter content near the soil surface (Ohu *et al.*, 1986; see Chapter 4), as crop residues were left at the soil surface for decomposition. In addition, the role of surface cover under NT in preserving topsoil moisture content and reducing soil evaporation could presumably explain this trend (Berry and Mallett, 1989). This was also the case at site NT – IM (5A). Due to the soil irrigation conditions and presence of a dense surface cover (100 %) (see Table 3.1), significant volumetric water content was observed in the topsoil at FC at this site ($P < 0.05$), as compared to the other treatments.

From the water retention curves and bulk density for NT and CT at the 150 mm depth (Figures 5.7 to 5.12), it seems that the soil has been compacted at this depth. The ANOVA showed non-significant differences between tillage systems at this depth and in the subsoil at the 320 mm depth. The increase in bulk density with depth resulted in the rearrangement of pore-sizes with the predominance of microporosity that correspond to pore-diameter of < 2.92 µm. These results suggest the development of a compacted layer at the depth of cultivation under CT (Bennie and Krynauw, 1985; Gómez *et al.*, 1999; Rasmussen, 1999), and under NT this was also the case because the field was under CT prior to its conversion to a NT a couple of years ago. In addition, significant volumetric water content was observed under NT over the matric potential range particularly between – 10 and – 100 kPa, resulting in the high level of soil compaction. A high percentage of microporosity (with pore-diameter of between 2.92 and 29.2 µm) was accompanied by this trend. In the high matric potential range (0 to – 10 kPa, corresponding to macropore sizes of ≥ 29.2 μm diamter), non-significant differences were found, suggesting the disruption of macropores squeezed into mesopores due to an increase in soil compaction.

In conclusion, differences in soil water retention characteristics between the study sites may be explained by a combination of soil structural effects and soil texture. For instance, the effects of matric potential on soil water retention indicated that there was a range of pore-size distribution in each soil that retained water. Differences in volumetric water content at different soil depths indicated that, in each soil, there was a percentage of available pore space for water storage. Differences in this available pore space may influence differences in plant available water capacity. This will be discussed in the next sections.

5.3.2 Tillage effects on plant available water and readily available water

Measurements of both plant available water (PAW) and readily available water (RAW) content were carried out on undisturbed soil cores for the laboratory experiment. The quantification of PAW and RAW for all sites is presented in Figure 5.13.

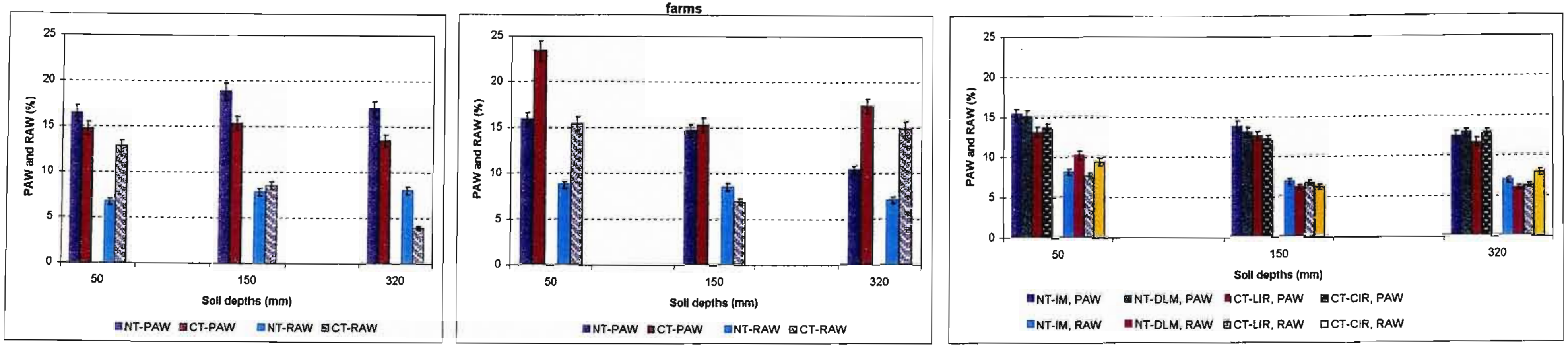
5.3.2.1 Mr R. Lund's and Mr Boschoff's farms (sites 1 and 2: clay soil)

PAW was substantially greater under NT than CT at the three selected depths whilst the reverse was the case for RAW at the 50 mm depth. PAW tended to be lower at the 320 than 150 mm depths, and this was also true for RAW under CT.

5.3.2.2 Mr van Der Aardweg's and Mr van Vuuveen's farms (sites 3 and 4: loam soil)

PAW and RAW were substantially higher under CT than NT at the 50 mm and 320 mm soil depths. This was associated with a greater volumetric water content recorded near field capacity (- 10 kPa), resulting in a decrease in bulk density, a substantial increase in total porosity and volume fraction of mesopores (see section 5.3.1.2).

However, at the 150 mm depth, PAW as well as RAW was similar under both tillage systems. This was linked to the similar bulk density values for both NT (1.72 Mg m^{-3}) and CT (1.66 Mg m^{-3}), resulting in almost similar total porosity and volume fraction of mesopores and micropores (see section 5.3.1.2). Compared to the other depths, PAW was lower at this soil depth under CT, and this was accompanied by a substantial decrease in total porosity and a great increase in bulk density (see section 5.3.1.2 and Figure 5.8).

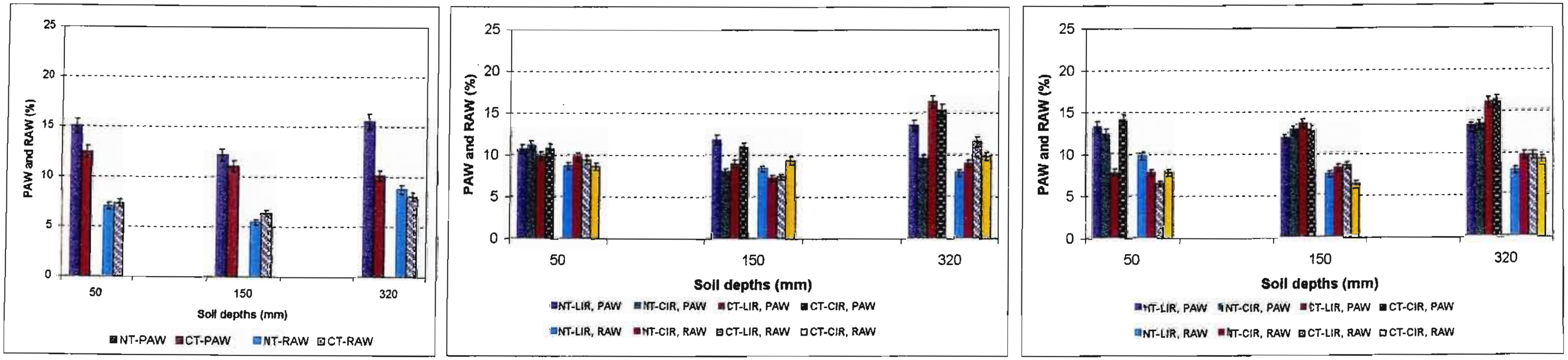


(a) Sites 1(NT) and 2(CT): Mr R. Lund's and Mr Boschoff's farms

(b) Sites 3(NT) and 4(CT): Mr van der Aardweg's and Mr van Vuuven's farms

(c) Sites 5A(NT-IM), 5B(NT-DLM), and 6(CT): Mr Muirhead's and Mr Mostert's farms

Note. NT - IM: NT - irrigated maize
NT - DLM: NT - dryland maize
CT - LIR: CT - loose inter-row
CT - CIR: CT - compacted inter-row



(d) Sites 7(NT) and 8(CT): Mr J. Jackson's and Mr J. Joubert's farms

(e) Sites 9(NT) and 10(CT): Cedara Agricultural Research Station

(f) Sites 11(NT) and 12(CT): Cedara Agricultural Research Station

Note. NT - LIR: NT - loose inter-row
NT - CIR: NT - compacted inter-row
CT - LIR: CT - loose inter-row
CT - CIR: CT - compacted inter-row

Note. NT - LIR: NT - loose inter-row
NT - CIR: NT - compacted inter-row
CT - LIR: CT - loose inter-row
CT - CIR: CT - compacted inter-row

Figure 5.13. Plant available water (PAW) and Readily available water (RAW) for the studied sites, derived from water retention curves over three soil depths. The error bars represent the standard error of the mean at $P < 5$ %

5.3.2.3 Mr Miurhead's and Mr Mostert's farms (sites 5A, 5B and 6)

PAW and RAW for sites 5A (**NT- IM**), 5B (**NT- DLM**), 6A (**CT- LIR**) and 6B (**CT- CIR**) are presented in Figure 5.13c. At site 6, the codes A and B refer to the conditions of inter-rows.

At the 50 mm depth, the PAW was greater under **NT- IM** and **NT- DLM** than that under **CT- LIR** and **CT- CIR**. However, RAW was greater under **NT- DLM** and **CT- CIR** compared with **NT- IM** and **CT- LIR**. These trends were associated with the distribution of pore sizes and bulk density. In fact, a marked decrease in total porosity and volume fraction of macropores, and a considerable increase in volume fraction of micropores were observed under both **NT- IM** and **NT- DLM**, accompanied by high bulk density as compared to **CT- LIR** and **CT- CIR** (see section 5.3.1.3).

At the 150 mm depth, few differences in PAW and RAW were observed between treatments. The **NT- IM** treatment tended to have slightly higher PAW and RAW than others treatments. This was associated with a slightly higher bulk density observed for this treatment (5A: 1.5 Mg m^{-3}) compared with similar bulk density values observed for the others treatments (1.4 Mg m^{-3}, 1.3 Mg m^{-3}, and 1.4 Mg m^{-3} at **NT- DLM**, **CT- LIR** and **CT- CIR** respectively).

At the 320 mm depth, differences in PAW and RAW were not great. The **NT- DLM** and **CT- CIR** treatments tended to have the highest PAW, while the highest RAW was observed only under **CT- CIR**. These trends were mainly associated with higher bulk density and lower total porosity and volume fraction of macropores under **NT- DLM** and **CT- CIR**.

5.3.2.4 Mr J. Jackson's and Mr J. Joubert's farms (sites 7 and 8: Silt-clay-loam)

At the 50 mm and 150 mm soil depths, PAW was greater under NT than CT, while differences in RAW were negligible. This was associated with a higher bulk density and higher volumetric water content at FC (- 10 kPa) under NT than under CT, the result of a corresponding marked decrease in volume fraction of macropores (see section 5.3.1.4).

At the 320 mm depth, PAW was considerably greater under NT (almost double) than under CT, whilst differences in RAW were very few. Similar bulk density values were observed under both NT and CT, accompanied by a slightly greater volume fraction of mesopores and higher volumetric water content at FC under NT than CT (see section 5.3.1.4).

Comparing both PAW and RAW from the three depths, lowest PAW and RAW values were observed at the 150 mm depth under both CT and NT. As emphasized above (section 5.3.2.3), the decrease in PAW and RAW at the 150 mm depth was accompanied by a corresponding decrease in total porosity, and volumetric water content at FC, and a substantial increase in bulk density (see section 5.3.1.4). These results suggested the formation of a compacted layer at the depth of cultivation under CT, and may also be the case under NT site because the field was under CT prior to its conversion to NT 12 years ago.

5.3.2.5 The Cedara Agricultural Research station's fields (sites 9 and 10: silt-clay-loamy soil)

Site 9A is described as being a NT loose inter-row (**NT- LIR**), site 9B as a NT compacted inter-row (**NT- CIR**), site 10A as a CT loose inter-row (**CT- LIR**), and site 10B as a CT compacted inter-row (**CT- CIR**). The codes A and B refer to the conditions of inter-rows.

At these sites, few differences in PAW and RAW were observed at the 50 mm depth. This trend was accompanied by similar bulk density values (1.4 Mg m^{-3}). However, at the 150 mm depth, PAW and RAW were greater under **NT- LIR** and **CT- CIR** than the other treatments. This was accompanied by a highly volumetric water content at FC and a substantial increase in total porosity and volume fraction of mesopores under both treatments (see section 5.3.15). PAW and RAW decreased with soil depth from 50 mm to 150 mm under **CT- LIR**, then increased from 150 to 320 mm, whilst under **CT- LIR** they increased with soil depth from 50 mm to 320 mm. Such trend suggested the formation of a compacted layer at the 150 mm depth under both **NT- CIR** and **CT- LIR**.

At the 320 mm depth, PAW of the **NT- CIR** treatment (9B) was less than that of the other treatments, accompanied by a lower volumetric water content measured at FC. RAW was less under **NT- LIR**, associated with a lower bulk density and volume fraction of mesopores (see section 5.3.1.5).

5.3.2.6 The Cedara Agricultural Research station's fields (sites 11 and 12: silt-clay-loam soil)

Site 11A is described as being a NT inter-row (**NT- LIR**), site 11B as a NT compacted inter-row (**NT- CIR**), site 12A as a CT loose inter-row (**CT- LIR**), and site 12B as a CT compacted inter-row (**CT- CIR**). The codes A and B refer to the conditions of interrows.

At the 50 mm depth, the **CT- LIR** treatment had the lowest PAW and RAW, associated with a lower bulk density, a higher total porosity and a greater volumetric water content and volume fraction of macropores than other treatments (see section 5.3.1.6). The highest RAW under **NT- LIR** was associated with a higher volume fraction of mesopores, as compared to the other treatments (see section 5.3.1.6).

At the 150 mm depth, there were few differences in PAW and RAW between treatments. This was accompanied by similar bulk density values (1.4 Mg m^{-3}) for all the treatments (see section 5.3.1.6 and Figure 5.12).

At the 320 mm depth, greater PAW and RAW were observed at these sites under CT than NT, and was accompanied by low bulk density values, a higher total porosity and volumetric water content at FC (see section 5.3.1.6 and Figure 5.12). In addition, the PAW and RAW values obtained at this soil depth were substantially higher than those at the 50 and 150 mm depths. This was associated with the practice of soil turning to bury crop residues, which influenced organic matter concentration at the plough depth resulting in increased volumetric water content. The increase in available water capacity with soil depth under **NT- CIR** was the result of a decreased bulk density in the wheel-tracked inter-row (CIR), which was accompanied by a corresponding increase in total porosity, a substantial increase in volume of macro- and meso-porosity with soil depth from 50 mm to 320 mm (see section 5.3.1.6 and Figure 5.12).

5.3.2.7 Discussion

The values of PAW and RAW were influenced mainly by bulk density, the rearrangement of total porosity and pore-size distribution. Similar results have been previously pointed out by other workers such as Riley *et al.* (1994), Smith *et al.* (1997) and Aura (1999).

In fine-textured soils, greater PAW and RAW were associated with high bulk density due to increased soil compaction. This resulted in a marked decrease in the volume fraction of macropores, a substantial increase in the volume fraction of meso- and micropores, and therefore an increase in volumetric water content near field capacity (FC at - 10 kPa). In coarse-textured soils, greater PAW and RAW were associated with low bulk density, and a high volumetric water content at FC because of a greater total porosity and volume fraction of mesopores. As the macropores were quickly drained, the soil water content was retained in the meso- and micro-pores. These trends were also reported by Riley *et al.* (1994) and Rasmussen (1999), who emphasized that the increase in the volume of available water content was associated with increased volume fraction of mesopores. Besides, the amount of water retained between matric potential ranges is a function of the size and volume of the water-filled pores and the soil-particle surfaces (Hillel, 1998). These trends were observed in the compacted topsoil under NT due to a lack of soil disturbance, and in the subsoil under CT due to soil consolidation. However, PAW and RAW decreased with soil depth under NT whilst under CT they increased from the 50 mm to the 320 mm depth. This showed that the lack of soil disturbance under NT had increased soil compaction in the surface soil, whereas under CT subsoil compaction predominated. Large increases in bulk density, however, induced a decline in volumetric water content, affecting therefore the water available capacity. Smith *et al.* (1997) observed that this kind of soil compaction behaviour is similar over a wide range of water contents, partly due to the high clay plus silt content and high organic carbon content. In fact, the accumulation of organic matter near the soil surface under NT had influenced the increase in volumetric water content, and subsequently, increased water availability constants.

With regards to inter-row conditions, water availability constants (PAW and RAW) increased with soil depth under the wheel-tracked inter-row, and this was accompanied by a corresponding increase in total porosity, a substantial increase in volume of macro- and meso-porosity with soil depth from 50 mm to 320 mm. This was associated with the high bulk density in the compacted topsoil, which decreased with increasing soil depth (Smith *et al.*, 2001).

Substantially higher bulk densities, accompanied by a lower total porosity and volume fraction of macropores were, however, observed at that depth under both NT and CT, suggesting the formation of a compacted layer at the nominated soil depth. Under CT, the compacted layer was formed at the depth of cultivation due to the frequent use of tillage implements at the same depth. The presence of a compacted layer under NT could be explained presumably because the fields were under CT prior to conversion to NT. The compcation had induced higher or lower PAW and RAW, depending on the soil texture. In fact, in fine-textured soils, the increase in soil compaction at the 150 mm depth was accompanied by a substantial decrease in total porosity and a marked increase in volumetric water content near FC (- 10 kPa), owing to an increase in volume fraction of mesopores and micropores and greater soil-particle surface areas for these soils. In coarse-textured soils, the formation of the compacted layer had substantially increased bulk density and reduced total porosity and volume fraction of macropores. This had resulted in a substantial decrease in volumetric water content near FC, and therefore lower PAW and RAW since these soils have lower soil-particle surface areas.

5.3.3 Tillage effects on soil aeration

Air-filled porosity (AFP) was estimated using the equation (Eq. 5.3). Air permeability (K_a) was determined using the equation (Eq 5.7). A mean of three replicates for AFP (at – 5 and – 10 kPa) and K_a (at – 10 and – 100 kPa) is presented in Figures 5.14 and 5.15 respectively, and in Appendix 2. As expected, AFP and K_a increased with decreasing matric potential as large pores are drained progressively.

5.3.3.1 Mr R. Lund's and Mr Boschoff's farms (sites 1 and 2)

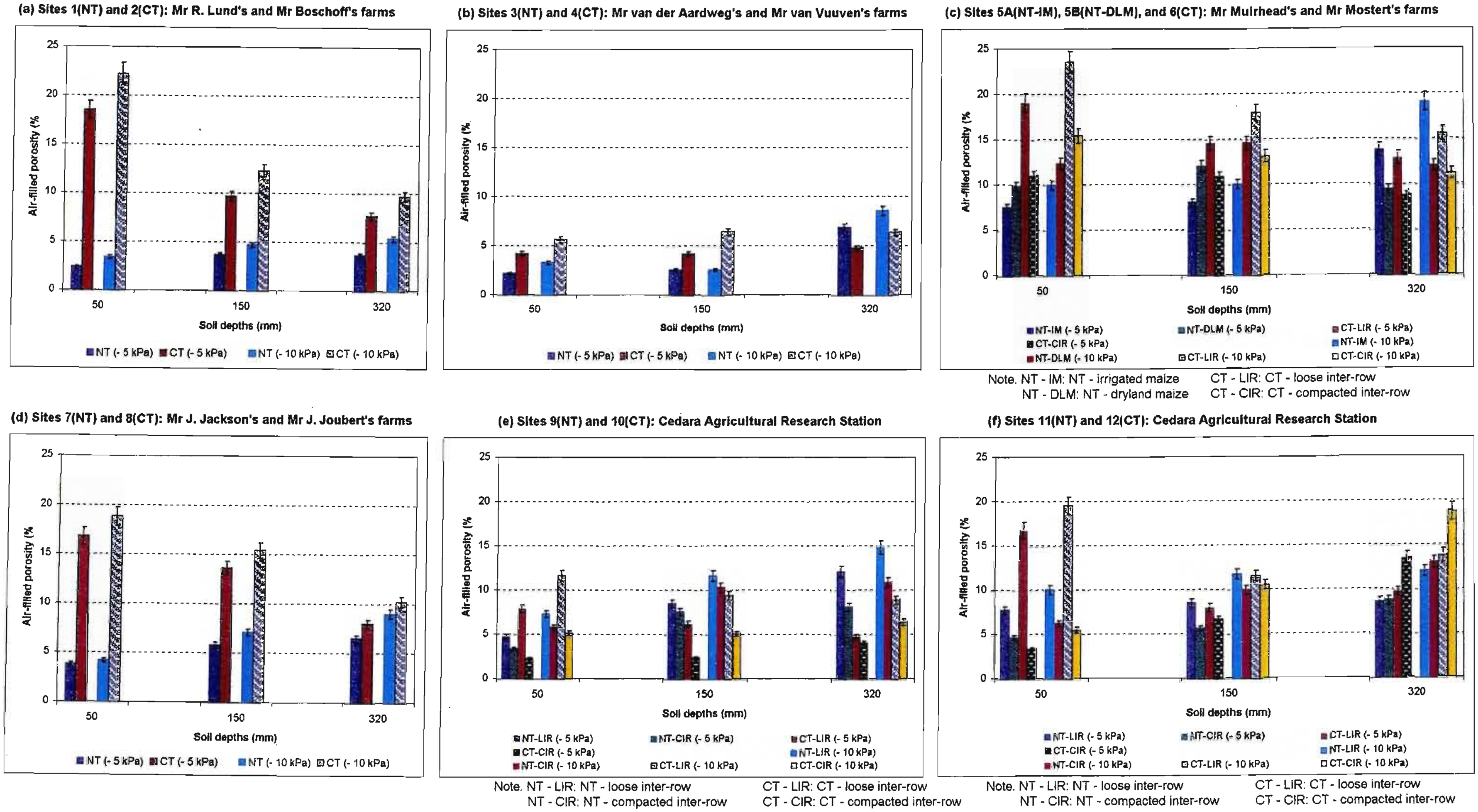
AFP at – 5 and – 10 kPa (corresponding to pore-diameter of 0.058 and 0.029 mm respectively) was much greater in the 50 mm topsoil under CT than NT, reflecting the high proportion of large pores under the treatment (see Figure 5.7). However, both AFP at – 5 and – 10 kPa were very critical (<10 %) under NT, attributable to increased soil compaction due to lack of soil disturbance and due to natural soil consolidation. However, results for SPR (see Chapter 7, Figure 7.2a) showed a greater soil resistance value under NT than CT at this depth.

Through the soil profile, AFP decreased with soil depth under CT. The opposite trend was found with bulk density, which increased with soil depth under CT (1.2 Mg m^{-3} to 1.4 Mg m^{-3}) and decreased with soil depth under NT (1.5 Mg m^{-3} to 1.4 Mg m^{-3}) (see Figure 5.7 and Appendix 2). This was found to be consistent with a subsoil compaction, clearly showed by field penetrometer soil resistance (SPR) results (see Chapter 7, Figure 7.2).

K_a measured at – 10 and – 100 kPa (corresponding to pore-diameters of 29.2 and 2.92 µm) was substantially greater in the 50 mm topsoil under CT than NT. This was associated with the greater AFP measured at – 5 and – 10 kPa, and suggests a greater pore continuity resulting in greater K_S (see Chapter 6, Figure 6.4a). However, through the soil profile, K_a decreased dramatically with soil depth under CT. This suggested that there had been a breakdown of pore continuity under CT at the ploughing depth (Douglas, 1986). Under NT, K_a at – 100 kPa (reflecting mesoporosity) increased slightly at the 150 mm depth, while K_a at – 10 kPa (reflecting macroporosity) did not change significantly throughout the soil profile.

5.3.3.2 Mr van Der Aardweg's and Mr van Vuuveen's farms (sites 3 and 4: loam soil)

AFP at – 5 and – 10 kPa was slightly high under CT at the 50 and 150 mm depths, becoming lower at the 320 mm depth compared to NT. The same trend was observed for K_a at – 10 and – 100 kPa. The AFP's were however critical (< 10 %) down the soil profile under both treatments, suggested an increase in soil compaction under both tillage systems. The results for penetrometer soil resistance were later found to be consistent with the above results (see Chapter 7, Figure 7.2b). Nevertheless, the slight increase in AFP and K_a at the 320 mm depth under NT was attributable to a slight increase in volume and continuity of the macroporosity fraction, since the same trend was observed for K_S (see Chapter 6, Figure 6.4b).



(a) Sites 1(NT) and 2(CT): Mr R. Lund's and Mr Boschoff's farms

(b) Sites 3(NT) and 4(CT): Mr van der Aardweg's and Mr van Vuuven's farms

(c) Sites 5A(NT-IM), 5B(NT-DLM), and 6(CT): Mr Muirhead's and Mr Mostert's farms

Note. NT - IM: NT - irrigated maize CT - LIR: CT - loose inter-row
NT - DLM: NT - dryland maize CT - CIR: CT - compacted inter-row

(d) Sites 7(NT) and 8(CT): Mr J. Jackson's and Mr J. Joubert's farms

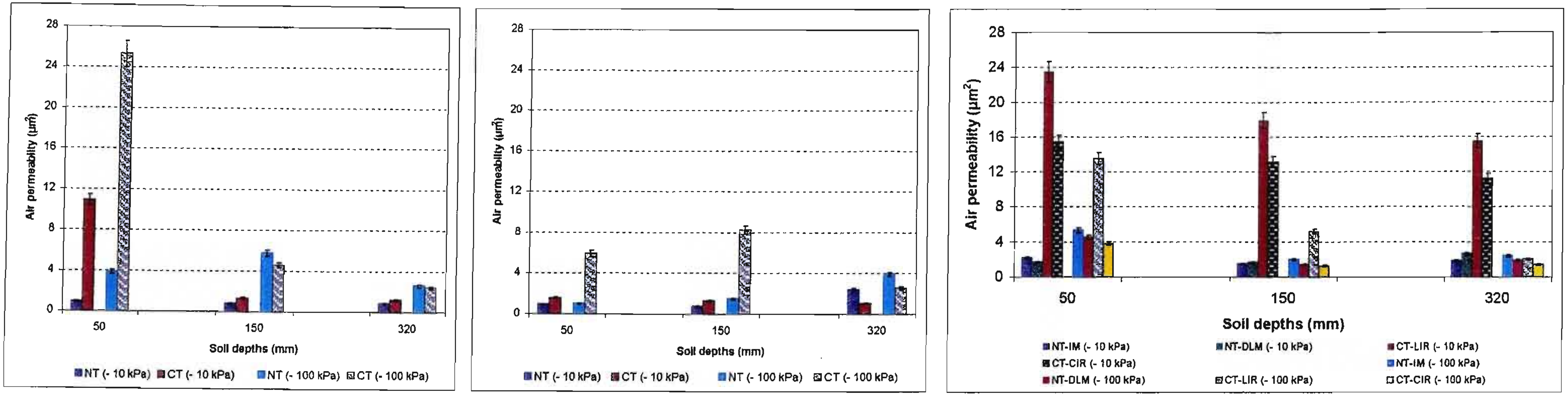
(e) Sites 9(NT) and 10(CT): Cedara Agricultural Research Station

Note. NT - LIR: NT - loose inter-row CT - LIR: CT - loose inter-row
NT - CIR: NT - compacted inter-row CT - CIR: CT - compacted inter-row

(f) Sites 11(NT) and 12(CT): Cedara Agricultural Research Station

Note. NT - LIR: NT - loose inter-row CT - LIR: CT - loose inter-row
NT - CIR: NT - compacted inter-row CT - CIR: CT - compacted inter-row

Figure 5.14. Air-filled porosity measured on undisturbed soil cores at – 5 and – 10 kPa matric potentials. Each data represents the mean of three replicates. The error bars represent the standard error of the mean at P < 5 % (NT: no – tillage; CT: conventional tillage; LIR: loose inter-row; CIR: compacted inter-row)

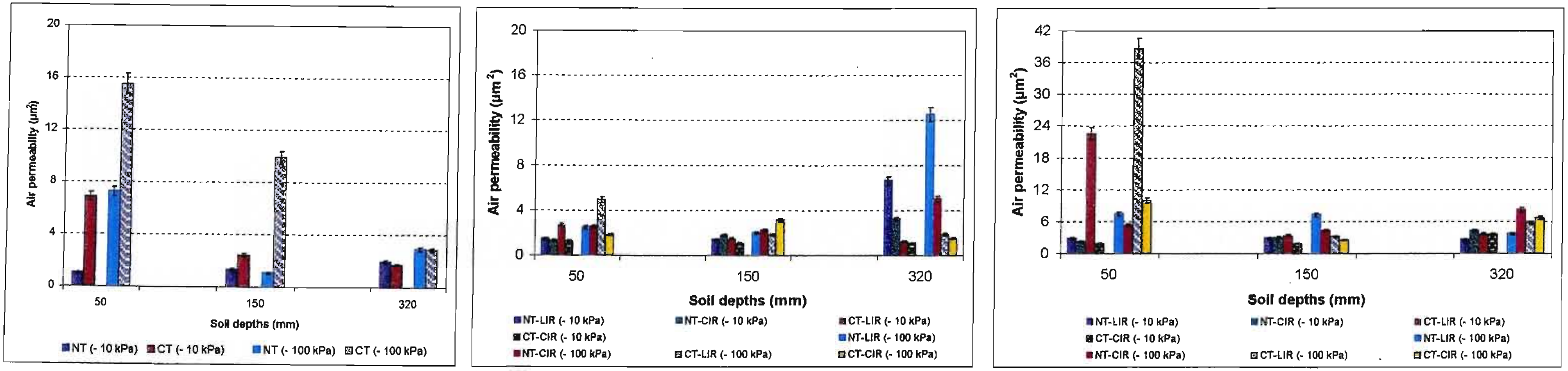


(a) Sites 1(NT) and 2(CT): Mr R. Lund's and Mr Boschoff's farms

(b) Sites 3(NT) and 4(CT): Mr van der Aadwerg's and Mr van Vuuven's farms

(c) Sites 5A(NT-IM), 5B(NT-DLM), and 6(CT): Mr Muirhead's and Mr Mostert's farms

Note. NT - IM: NT - irrigated maize CT - LIR: CT - loose inter-row
NT - DLM: NT - dryland maize CT - CIR: CT - compacted inter-row



(d) Sites 7(NT) and 8(CT): Mr J. Jackson's and Mr J. Joubert's farms

(e) Sites 9(NT) and 10(CT): Cedara Agricultural Research Station

(f) Sites 11(NT) and 12(CT): Cedara Agricultural Research Station

Note. NT - LIR: NT - loose inter-row CT - LIR: CT - loose inter-row
NT - CIR: NT - compacted inter-row CT - CIR: CT - compacted inter-row

Note. NT - LIR: NT - loose inter-row CT - LIR: CT - loose inter-row
NT - CIR: NT - compacted inter-row CT - CIR: CT - compacted inter-row

Figure 5.15. Air permeability measured on undisturbed soil cores at – 10 and – 100 kPa matric potentials. Each data represents the mean of three replicates. The error bars represent the standard error of the mean at P < 5 % (NT: no – tillage; CT: conventional tillage; LIR: loose inter-row; CIR: compacted inter-row)

5.3.3.3 Mr Miurhead's and Mr Mostert's farms (sites 5A, 5B, and 6: clay soil)

For clarity, site 5A is described as being a NT irrigated maize field (**NT- IM**), 5B as NT dryland maize (**NT- DLM**), 6A as CT loose inter-row (**CT- LIR**), and 6B as CT compacted inter-row (**CT- CIR**). At site 6, the codes A and B refer to the conditions of inter-rows.

Throughout the soil profile, the AFP's and K_a's were substantially greater under **CT- LIR** compared to the other treatments. This was also consistent with SPR results, especially in the 100 mm layer (see Chapter 7, Figure 7.2c). However, the AFP's and K_a's decreased with soil depth under CT while the reverse was the case under NT treatments. At the 50 mm depth, **CT- CIR** showed greater values of K_a at - 100 kPa than **CT- LIR**, dropping dramatically at the 150 and 320 mm depths, which suggests a breakdown of pore continuity. There were few differences in AFP's between treatments at these depths. Accordingly, K_S results showed very low values compared to the 50 mm depth (see Chapter 6, Figure 6.4c), suggesting the breakdown of pore continuity due to the presence of a subsurface compacted layer. Under NT, AFP and K_a at – 10 kPa increased slightly with soil depth, showing slight differences only at the 50 mm depth. **NT- IM** showed slightly lower AFP's values in the topsoil (50 and 150 mm depths) than **NT- DLM,** whilst K_a and bulk density were fairly similar. These results showed an opposite trend to the SPR results (see Chapter 7, Figure 7.2). Presumably, this could be explained by the time of year of the core sampling (March: wet season), which was at a quite different time from the field SPR measurements (May: dry season). The lower AFP under **NT – IM** was, therefore, attributable to the presence of water-filled macropores since the field was under irrigation, while **NT- DLM** was a dryland site. This trend was supported by higher PAW and RAW values observed under **NT- DLM** than **NT- IM** (see section 5.3.2.3, Figure 5.13c). Nevertheless, the higher organic carbon content and aggregate stability measured under both **NT- DLM** and **NT- IM** (see Chapter 4, Figure 4.1c) suggested an increase in the rate of decomposition of organic matter content left at the soil surface, resulting in increased macropore stability under NT (Haynes, 1993).

5.3.3.4. Mr J. Jackson's and Mr J. Joubert's farms (sites 7 and 8: Silt-clay-loam)

AFP at – 5 and – 10 kPa was greater at the 50 and 150 mm soil depth under CT than NT. However, at the same soil depths, the level of AFP was very critical (< 10 %) under NT. These trends were similar to those observed at sites 1 and 2 (see section 5.3.3.1).

Through the soil profile, AFP decreased with soil depth under CT, while the reverse was the case under NT. This was the opposite trend found for bulk density, which increased with soil depth under CT (from 1.3 Mg m^{-3} to 1.5 Mg m^{-3}) and decreased with soil depth under NT (from 1.5 Mg m^{-3} to 1.4 Mg m^{-3}) (Appendix 2). In addition, only slight differences in AFP and K_a were observed between treatments at the 320 mm depth, which was also consistent with SPR results (see Chapter 7, Figure 7.4d).

K_a was substantially greater in the 50 mm topsoil, dropping dramatically with soil depth at the 150 and 320 mm depths under CT than under NT (Figure 5.15d). This was associated with the greater AFP, and subsequently greater K_S (see Chapter 6, Figure 6.4d). The drop of K_a at the 150 mm depth was clearly observed at – 10 kPa, suggesting that there has been a breakdown of macropore continuity. Under NT, K_a at – 10 kPa increased slightly with soil depth, whilst K_a at – 100 kPa decreased from 50 mm to 320 mm. This affected consistently K_S (see Chapter 6, Figure 6.4d).

5.3.3.5 The Cedara Agricultural Research station's fields (sites 9 and 10: silt-clay-loam soil)

Site 9A is described as being a NT loose inter-row (**NT- LIR**), 9B as a NT compacted inter-row (**NT- CIR**), 10A as a CT loose inter-row (**CT- LIR**), and 10B as a CT compacted inter-row (**CT- CIR**). The codes A and B refer to the conditions of interrows.

At the 50 mm depth, the AFP's were greater under **CT- LIR** compared to the other treatments. In addition, AFP's under the same treatment (**CT- LIR**) decreased slightly with soil depth, AFP at – 10 kPa becoming critical at the 150 mm and 320 mm depths (< 10 %). This was accompanied by an increased in SPR (see Chapter 7, Figure 7.2e). AFP (- 5 and – 10 kPa) was low (< 10%) at the 50 mm depth under NT treatments, increasing at the 150 mm and 320 mm depths, and this trend was also the case throughout the soil profile under **CT- CIR**. These results reflected soil compaction in the topsoil under the **NT** – and **CT** – **CIR** treatments compared with the **CT- LIR** treatment, and were consistent with SPR results at approximately the same soil depths (see Chapter 7, Figure 7.2e).

5.3.3.6 The Cedara Agricultural Research station's fields (sites 11 and 12: silt-clay-loam soil)

Site 11A is described as being a NT loose inter-row (**NT- LIR**), 11B as a NT compacted inter-row (**NT- CIR**), 12A as a CT loose inter-row (**CT- LIR**), and 12B as a CT compacted inter-row (**CT- CIR**). The codes A and B refer to the conditions of interrows.

At the 50 mm depth, AFP (– 5 and – 10 kPa) was low (< 10 %) under NT and CT compacted inter-row treatments. However, throughout the soil profile, the AFP (– 5 and – 10 kPa) increased with soil depth under the NT treatments and **CT- CIR**, while it decreased with soil depth under **CT- LIR**. This showed the opposite trend for bulk density and SPR, which decreased with soil depth under **NT-** and **CT-CIR** and increased with soil depth under **CT- LIR**. AFP at – 5 and – 10 kPa was greater at the 320 mm depth under **CT- CIR** than other treatments, resulting in lower bulk density and SPR values, and volume fraction of macropores (see Figures 5.12 and 7.2f).

K_a at – 10 and – 100 kPa was substantially higher at the 50 mm depth under **CT-LIR**, decreasing dramatically with soil depth. Very few differences in K_a at – 10 and – 100 kPa were observed between treatments at the 50 and 150 mm depths. These results were accompanied by a similar trend for the K_S (see Chapter 6, Figure 6.4f), showing a breakdown of macropore continuity that resulted in the formation of a compacted layer at the ploughing depth (150 mm).

5.3.3.7 Discussion and conclusion

Tillage practice had greatly affected AFP and K_a, and this could be related to changes in bulk density, total porosity and pore-size distribution (Douglas *et al.,* 1986; Heard *et al.*, 1988; Roserberg and McCoy, 1992). The changes in pore-size distribution affected mostly the volume fraction of macroporosity (Douglas, 1986; Roserberg and McCoy, 1992).

At the 50 mm depth, AFP was generally greater under CT than NT. This was accompanied by a substantial increase in proportion of macropores than other pore-sizes and as well as a substantial increase in total porosity. The trend was found to be consistent with lower bulk density and SPR values, presumably owing to the effects of ploughing. However, down the soil profile, AFP decreased with soil depth under CT-trials, becoming critical especially at the 150 mm and/or 320 mm depths (AFP < 10 %), depending on the soil type and the degree of soil compaction of the pan-layer. The formation of the compacted layer under CT occurred at the depth of cultivation due to the frequent use of tillage implements at the same depth, and this was consistent with higher SPR values (see Chapter 7, Figure 7.2 for more details). Under NT, AFP increased consistently with soil depth, showing critical values of AFP (< 10%) at the 50 mm and/or 150 mm topsoil or through the whole soil profile, depending strongly on the degree of soil compaction (occurring due to lack of soil disturbance and to natural consolidation) and soil texture. In fact, in fine-textured soils, critical values of AFP down the soil profile under NT were accompanied by substantially higher bulk density and SPR values, and lower total porosity and volume fraction of macropores than was the case under CT. In coarse-textured soils, critical values of AFP under NT were observed at the 50 mm depth as a result of the formation of a hard-layer near the surface soil due to the lack of soil tillage, and/or at the 150 mm depth (e.g sites 3 and 7), resulting from the previous formation of a compacted layer at the depth of cultivation when the field was still under CT. Similar trends were also observed under **CT-CIR**, owing to increased soil compaction compared with **CT- LIR**. The critical level of AFP at FC (< 10 %) observed in some of the **NT-** and **CT- CIR** treatments, could result in a poor crop growth (Groenevelt *et al.*, 1984; Heard *et al.*, 1988), that is poor soil aeration could limit root growth. Indeed, AFP at FC of ± 10 to 15 % is regarded as a convenient reference for a good soil aeration and therefore crop growth (Ball *et al.*, 1988; Holt *et al.*, 1993; Brady and Weil, 1996).

The presence of greater total porosity and volume fraction of macropores observed particularly in coarse-textured soils under NT resulted in increased AFP. This was clearly observed under **NT- LIR**, presumably because of an increase in either organic matter content or other specific binding agents (soil micro-organisms, roots and roots exudates) that stabilized the soil aggregates (Haynes, 1993). However, under **NT- CIR**, AFP was strongly affected by topsoil compaction

Particular trends in AFP were also observed when comparing **NT- IM** and **NT- DLM** at the 50 and 150 mm depths, where **NT- IM** showed a slightly lower AFP than **NT- DLM**. This was associated with a slight higher volumetric water content at FC under **NT- IM** than found in **NT- DLM** (Appendix 2). This suggested the presence of water-filled macropores under **NT-IM** because the field was under irrigation, while **NT- DLM** was a dryland site. Nevertheless, the higher organic carbon content and aggregate stability measured under both **NT- DLM** and **NT- IM** (see Chapter 4, Figure 4.1) suggested an increase in the rate of accumulation of organic matter left at the soil surface, resulting in increased macropore stability under NT-treatments (Haynes, 1993).

K_a was substantially greater at the 50 mm depth under CT than under NT. This was associated with greater AFP. Douglas (1986) and Roserberg and McCoy (1992) also reported similar results, and attributed these trends to the greater total porosity and volume fraction of macropores resulting from topsoil cultivation. Under NT, K_a at FC was similar down the soil profile, increasing sometimes at the 320 mm depth in coarse textured soils. This was accompanied by greater values of bulk density in the topsoil under NT, which was the result of increased soil compaction (Smith *et al.*, 2001). However, from the viewpoint of inter-row conditions, **CT- CIR** treatments showed the same trend as NT treatments throughout the soil profile, suggesting an increase in soil compaction due to excessive wheel traffic over the soil surface.

Through the soil profile, K_a decreased dramatically, especially at the 150 mm depth under CT, while under NT however there was a slight decrease in K_a with soil depth.

The decrease in K_a under CT, was presumably related to a breakdown in pore continuity (Douglas, 1986; Roserberg and McCoy, 1992), resulting from the development of a compacted layer below the depth of cultivation under CT (Bennie and Krynauw, 1985; Gómez *et al.*, 1999; Rasmussen, 1999). Under NT, where the same trend was sometimes observed, the decrease in K_a could be associated also with the formation of a compacted layer because the NT-field has been under CT practices prior to its conversion to NT.

However, differences in AFP and K_a between NT and CT at FC were only small in the subsoil in fine-textured soils, and this phenomenon was accompanied by similar bulk density and SPR values under both tillage systems. Benjamin (1993), Azooz *et al.* (1996), Ahuja *et al.* (1998), Arshad *et al.* (1999), Smith *et al.* (2001) attributed these changes to subsoil compaction due to the high clay content of these soils. In coarse-textured soils, consistent differences were observed at the 50 mm depth, resulting from wheel traffic effects on inter-rows and tillage managements. Differences in AFP and K_a at the 150 and 320 mm soil depths were attributable to either the structural stability of subsurface-connected macropores under NT or the formation of a slowly permeable subsurface compacted layer, which may, subconsequently, affect soil hydraulic conductivity (see Chapter 6, Figure 6.4).

5.4 General Conclusions

The aim of this chapter was to identify and quantify the effects that a NT system might have on soil water retention, pore-size distribution, and water availability constants, as compared to a CT system. The effects of NT and CT on soil aeration and air permeability were also studied and reported on in this chapter.

5.4.1 Soil water retention and pore-size distribution

From a practical viewpoint, in the present study, findings have shown that soil water retention was strongly influenced by the pore-size distribution, which in turn is influenced by the soil aggregate stability (Kravchencko and Zhang, 1998). The rapid release of volumetric water content under CT, especially at higher matric potential range (0 to – 10 kPa), showed very stable soil aggregates, depending on the soil type. This resulted in a high proportion of macropores that can record high-saturated volumetric water content (Ahuja *et al.*, 1998; Arshad *et al.*, 1999 and Smith *et al.*, 2001). The steady and gradual decrease of volumetric water content observed was accompanied by an increase in air-filled porosity (AFP) (to be discussed below).

The overall effect of increased soil compaction in the topsoil under NT also influenced an increase in volumetric water content at the lower range of matric potentials (- 100 to – 1500 kPa), the volume of microporosity tending to increase compared to CT (Smith *et al.*, 2001). The small volume of macropores observed under NT may induce negative impacts related to soil drainage, soil aeration, crop growth, and plant-water availability (Ball *et al.*, 1988; Holt *et al.*, 1993; Brady and Weil, 1996). It was also noticed that, at this low matric potential range, water retention became strongly an attribute of soil texture rather than soil structure (Smith *et al.,* 1997). Generally, at field capacity (FC) taken as – 10 kPa, the effect of the high degree of soil compaction under NT was to increase volumetric water content. But NT increased or decreased water content, depending on the soil type (Hill and Sumner, 1967; Katou *et al.*, 1987; Smith *et al.*, 1997). This observation was explained by the "crossover" of WRCs for NT and CT, the two systems causing different levels of soil compaction, and occurring at a wide range of matric potentials between – 1 and – 100 kPa.

On the other hand, the amount of crop residues retained at the soil surface under NT treatments influenced partly the soil water retention. In addition, the higher volumetric water content observed in the topsoil under NT was also associated with the concentration of organic matter content near the soil surface (Ohu *et al.*, 1986), as crop residues were left at the soil surface. However, under CT turning the soil each year to bury crop residues has influenced, in some cases, greater volumetric water content, owing to the accumulation of organic carbon at the plough depth resulting in an increased rate of annual organic matter decomposition (Douglas *et al.*, 1986).

The distribution of pore-sizes and soil total porosity were also of great importance in characterizing physical changes to the soil due to different tillage systems. Under CT, the topsoil had a great volume of total porosity, decreasing with increased bulk density in the subsoil, owing to the soil consolidation or an inherent pan-layer at the 150 mm depth (Bennie and Krynauw, 1985; Gómez *et al.*, 1999; Rasmussen, 1999). Macro- and meso-porosity were the most predominant pore-size distribution in the topsoil, decreasing markedly as bulk density increased. Whereas under NT, due to high bulk density in the topsoil, both total porosity in general and macroporosity in particular were lower compared with CT, and increased in the subsoil as bulk density decreased.

5.4.2 Water availability constants

The estimation of PAW and RAW varied according to soil type and tillage system. It should be noted that PAW and RAW, as derived from water retention data, were influenced by pore-size distribution and bulk density. In general, PAW and RAW decreased with soil depth from 50 mm to 320 mm under the NT system, due to the high level of soil compaction in the topsoil.

On the other hand, the increased bulk density under NT had influenced higher volumetric water content recorded near field capacity, owing to the rearrangement of total porosity and pore-size distribution based on soil texture (Musto, 1994; Riley *et al.*, 1994, Smith *et al.*, 1997 and Aura, 1999). In fact, PAW and RAW were mainly affected by an increase in volume fraction of mesoporosity and microporosity, resulting in an increased volumetric water content near field capacity. However, the increase in water storage capacity under NT could also presumably be ascribed to the accumulation of organic carbon content near the soil surface. However, in the subsoil, differences in PAW and RAW were very slight, due to the consolidation of the soil under both tillage systems. Riley *et al.* (1994) and Aura (1999) also pointed out similar observation.

Nervertheless, at those sites where compacted or loose inter-row conditions were considered, the effects of tillage system on water available capacity were consistently observed on compacted inter-rows under both tillage systems. It was evident that, due to increased bulk density with soil depth (from 50 to 320 mm) only under compacted inter-rows, PAW and RAW also increased.

5.4.3 Soil aeration and air permeability

The changes in pore-size distribution markedly affected the volume fraction of macroporosity, converted into mesoporosity and microporosity. Air-filled porosity (AFP) increased following an increase in volume fraction of macroporosity, and decreased with increased volume of mesopores and micropores, affecting consequently plant available water (PAW) and readily available water (RAW). Similar trends have been also found by Riley *et al.* (1994) and Rasmussen (1999). In the subsoil, differences in AFP were negligible, as the bulk density increased in both systems, presumably due to the soil consolidation.

Air permeability (K_a) was observed to be great in the topsoil under CT, resulting in increased AFP. K_a and AFP have been found to be affected by bulk density. Large differences in K_a, AFP and bulk density suggested the deterioration of soil pore structure, as a result of soil cultivation, depending on the soil texture. High K_a and AFP suggested a good soil structure, with some improvements in soil properties. Low values of K_a and AFP reflected an increase in soil compaction.

On the other hand, the distribution of organic matter content near the soil surface under NT had influenced the resistance of soil porosity to increased soil compaction, by increasing soil pore stability (Haynes, 1993). However, ploughing the topsoil under CT broke down the transmission aspects of pores (Roserberg and McCoy, 1992). This was shown by the higher and moderate values of K_a in the topsoil under CT, which decreased dramatically with increasing bulk density at the depth of cultivation.

Chapter 6

The effects of tillage systems on infiltration rate and soil hydraulic conductivity

6.1 Introduction

The entry of water into the soil is a dynamic process (Banton, 1993; Bosch and West, 1998). When water is applied to the soil surface either by irrigation or as a result of rainfall, it subsequently infiltrates the soil. If the rate of water supply is higher than the rate of entry, then the excess will tend to flow over the soil surface as runoff, contribute to surface storage or be evaporated back to the atmosphere (Hillel, 1998). Water that infiltrates will tend to move downwards under gravity and to eventually recharge the groundwater reservoir (Bras, 1990). Knowledge of the infiltration process is therefore important for soil, water and crop management, particularly as this process is affected by soil properties and transient conditions (Vanderlinden *et al.*, 1998).

Quantitatively, infiltration can be defined as the volume of water that flows downward through all or part of the soil surface, whereas the infiltration rate is the volume of water entering into the soil per unit area in an unit of time when subjected to hydraulic potential gradient (Hillel, 1998). The infiltration rate is high at the beginning (because of a large hydraulic potential gradient near the surface) then it decreases rapidly and then more slowly until it approaches a constant value as the potential gradient approaches unity (Radcliffe and Rasmussen, 2000).

Subsequently, Hillel (1998) emphasized the term "infiltrability" to define the infiltration flux that occurs when water, at atmospheric pressure, is made freely available at the soil surface. Gradual deterioration of soil structure can decrease soil infiltrability from an initially high rate (Hillel, 1998). However, the dispersion of soil aggregates results in a downward migration of detached soil particles, blocking pore channels and cracks. Accordingly, the consequent partial sealing of the soil profile takes place by the formation of a dense surface crust (Hillel, 1998).

The effect of air entrapment during the infiltration process, the swelling of clay, and the compression of air present in the soil cannot be ignored. Entrapped air and compressed air bubbles in the soil are believed to reduce the soil infiltration rate (Hillel, 1998), leading subsequently to an underestimation of hydraulic conductivity (Wilson *et al.*, 1982; Bosch and West, 1998). The formation of air pockets in the transmission zone during infiltration was pointed out as being a cause of the unsaturated condition of the soil profile (Constantz *et al.*, 1988).

6.2 The effects of tillage on soil infiltration

6.2.1 General principles

The effects of tillage systems on soil infiltration has been regarded mainly to have a good influence of soil structure (particularly maintenance of high total porosity) during the growing season of the crop (Arshad *et al.*, 1999). NT, by maintaining a substantial crop residue cover on the soil surface, increases infiltration and reduces water runoff compared with CT (Arshad *et al.,* 1999; McGarry *et al.*, 2000).

Indeed, tillage effects on soil infiltration are largely influenced by surface roughness and other additional factors. The most pronounced factors are: tractor speed, tillage method, tillage implement, depth of tillage operation, and mulch left on the soil surface (Linden and Doren, 1986).

Since, the soil infiltrability and the infiltration rate depend on a number of factors mainly the time, initial soil water content, matric potential, soil texture, structure and the uniformity of the soil profile, to estimate approximately accurate values for the final infiltration rate, an empiric equation has been used. This was achieved by using the Philip's equation (Philip, 1957).

6.2.2 Predicted soil infiltration based on the Philip's equation

Many empirical equations have been proposed to describe the infiltration of water into soils. The earliest equation was introduced by Green and Ampt (1911):

$$\mathbf{i = i_c + b / I} \quad \ldots\ldots \quad \textbf{Eq 6.1}$$

Where $\mathbf{i_c}$ is the steady infiltration rate (mm/h), **b** is a constant, and **I** is the cumulative infiltration (mm).

This was followed by Kostiakov (1932), who showed that:

$$\mathbf{i = b\, t^{-n}} \quad \ldots\ldots \quad \textbf{Eq. 6.2}$$

Where **i** is the infiltration rate (mm/h), **b** and **n** are constants, and **t** is the time (h)

The Kostiakov and Green and Ampt equations are relevant to horizontal infiltration process (in the absence of a gravity gradient) (Hillel, 1998).

The following empirical equation was that of Horton introduced in 1940:

$$\mathbf{i = i_C + (i_O - i_C)\, e^{-kt}} \quad \ldots\ldots \quad \textbf{Eq 6.3}$$

Where **i** is the infiltration rate (mm/h), $\mathbf{i_C}$ is the steady infiltration rate (mm/h), $\mathbf{i_O}$ is the initial infiltration rate (mm/h) when the time $\mathbf{t = 0}$, **k** is a constant that determines how quickly **i** will decrease from $\mathbf{i_O}$ to $\mathbf{i_C}$.

These three equations have been shown to contain parameters that are difficult to predict. In deriving the Green-Ampt equation, Mein and Larson (1973) assumed that the infiltration occurred in two phases, infiltration prior to runoff and infiltration after runoff. The soil was considered as a homogenous medium with uniform initial water content. Additional assumptions are that rainfall is of constant intensity until runoff begins, and that the infiltration process is "one dimensional" at a given location.

In recognition of these factors, Philip (1957) developed an equation to better describe the vertical infiltration process:

Cumulative infiltration (mm): $\mathbf{I = S\, t^{1/2} + A\, t}$ .... **Eq 6.4**

Where **I** is the cumulative infiltration as a function of time **t**, **S** is the sorptivity (mm $h^{-1/2}$), which depends upon the soil pore configuration, the initial water content and the water depth above the soil (Corey, 1986), and **A** is approximately equal to the saturated hydraulic conductivity of the soil (K_S) when **t** is large. For early time intervals the sorptivity **S** component dominates, but at larger units of time, once a steady infiltration rate is reached, **S** becomes negligible.

In differential form, Equation 5.4 may be written as:

Infiltration rate (mm/h): $\mathbf{i = dI/dt = \frac{1}{2}\, S\, t^{1/2} + A}$ .... **Eq 6.5**

6.2.3. Materials and Methods

Since the measurement of soil infiltration in the field is a time consuming exercise (Smith, 1999), several techniques have been presented in the literature for soil infiltration measurements. Of significance among these, are the constant-head well permeameter methods (Reynolds *et al.,* 1983; Amoozegar, 1989 and Elrick and Reynolds, 1992), the falling-head lined borehole method (Philip, 1993), the double ring infiltrometer method (Bouwer, 1986), and the disk permeameter method (Perroux and White, 1988). For this study, the double ring infiltrometer (DRI) method was selected because of its simplicity to set up, its advantage as a less time-consuming method, in that several DRIs can be run at the same time, and its relatively low cost of operation.

Figure 6.1. Scheme of the double-ring infiltrometer used for field infiltration measurements

DRIs were placed between crop rows (inter-rows) in triplicate within plots of 7 m x 7 m. They were hammered carefully to a depth of approximately 0.03 m using a hammer and a block of wood. The diameters of the inner and outer rings (height of 0.15 m) used in this study were 0.10 m and 0.20 m, respectively (Figure 6.1). The insertion of the rings into the soil was adjusted in such a way that they were at the same height as each other. They were then immediately filled with water, first the outer ring and then the inner ring in order to minimise the potential error caused by lateral water flow. Timing started immediately. Cumulative infiltration was measured from the inner ring (using a tape ruler stuck inside the inner ring) at regular times by noting the depth of water that had infiltrated the soil. When the water level had dropped by about 50 mm, both the inner and outer rings were refilled. However, when necessary, water was added to the outer ring to maintain the same hydraulic head as that of the inner ring. Measurements were taken until the infiltration rate became constant, usually after 2 to 6 hours depending on the soil conditions. At all sites, measurements were completed before any additional rainfall.

The cumulative infiltration of water into the soil was determined as a function of time and depth of infiltrated water (Eq 6.6). The infiltration rate was then calculated by measuring the time it took for the water to drop a certain distance (Eq 6.7) (Bouwer, 1986). From triplicated measurements, an arithmetic mean of final infiltration rate **(FIR)** was calculated, as FIR is often very variable.

Cumulative infiltration (mm) : $\mathbf{I = I_1 + I_2 + \ldots + I_n}$ .... **Eq 6.6**

Where 1, 2, ..., n are depths of infiltrated water

Infiltration rate (mm/h) : $\mathbf{i = (\Delta I_n - \Delta I_m) / \Delta t}$ .... **Eq 6.7**

Where ΔI_n : cumulative infiltration at depth "n" ; Δt : time that water takes to drop from "n" to "m" depths; ΔI_m : cumulative infiltration at depth "m"

The equation (Eq 6.7) shows that water depth affects infiltration rate most at the beginning while the depth of the wetting front is still small. As infiltration progresses and the depth of the wetting front increases, the infiltration rate decreases and eventually becomes negligible.

Due to great spatial variability, soil infiltration rates may vary, depending on sorptivity "S" and factor "A" (Eq 6.4) (Philip, 1957). To obtain an accurate value for the infiltration rate, results from the measured infiltration rates were expressed in terms of two parameters using the Philip equation (Eq 6.4) to "predict the infiltration rate". This was achieved by using multiple regression (Savage, 2001, personal communication):

$$\mathbf{y} = \alpha \mathbf{x}_i + \beta \mathbf{x}_i + \mathbf{C}_i \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ \textbf{Eq 6.8}$$

Where **y** is the predicted infiltration, α and β are constants determined by linear regression; α corresponds to the sorptivity "S", and β to the factor "A" of the Philip equation (1957). In this study, the constant **C** was considered as zero ($C = o$).

The overall T-test was used to show whether the NT and CT means are different. The F-test determined from ANOVA, was used to reveal whether the difference is significant.

6.2.4. Results and Discussion

The mean FIR and mean estimated final infiltration rate (Est FIR) for each DRI is presented in Table 6.1 and Appendix 4. The estimated infiltration rate quoted was predicted from the measured infiltration rate using the multiple regression equation (Eq 6.8). Mean FIR's were determined by averaging the nearly similar infiltration rates at the end of the measurement period and assuming that these mean FIR's represent steady-state conditions. From each site, a mean value for the measured and estimated final infiltration rate was then obtained from the three replicates. Figures for cumulative infiltration and infiltration rate for all the sites studied, and their respective predicted curves are presented in Appendix 4 together with the equations used to predict the infiltration rate. In general, a good fit between the measured and predicted infiltration rates was obtained as shown by the high R^2 values (Appendix 4).

Except at paired-site 5 (sites 9 and 10), the FIR results presented in Table 6.1 showed greater values under CT than NT. The increase in FIR under CT compared to NT can be attributed to an increase in total soil porosity, and particularly to the volume of macropores (Appendix 4) that occur in response to ploughing of the topsoil. This greatly decreased bulk density and reduced soil compaction. This observation was consistent with that of other researchers (Hill, 1990; Vyn and Raimbault, 1993; Lal *et al.*, 1994; Cassel *et al.*, 1995; Shipitalo *et al.*, 2000; Katsvairo *et al.*, 2002). As reported previously (see Chapter 5), the NT soils had high bulk density due to the lack of soil disturbance and to natural soil consolidation. Since the transmission of water through the soil profile is enhanced by macropore flow (Hillel, 1998; Rasmussen, 1999), a decrease in soil macropores is likely to reduce total flow (Shipitalo *et al.*, 2000). This trend was found to be similar in both fine and coarse textured soils. Indeed, high infiltration rate values under CT could be attributable also to high dry condition at the surface soil due to the absence of mulch cover, which may relatively increase the contribution of macropores to infiltration.

Particularly, paired-sites 1 and 4 showed huge and highly significant differences in FIRs between tillage systems (Table 6.1). Such big differences were hard to believe at first. Since the insertion of double rings for infiltration measurements was problematic only under the NT plots (sites 1 and 7), these results showed primarily higher soil compaction in the surface soil. This was also supported by lower AFP at – 5 and – 10 kPa (corresponding to pore-diameter of 0.058 - and 0.029 mm, respectively) in the topsoil, as compared with their paired-plots (sites 2 and 8) (Figure 5.14). Topsoil compaction at these sites (site 1 and 7) was also reported in Chapter 5 and has resulted in the flattening of the WRC especially between saturation and – 10 kPa (see section 5.3.1, Figures 5.7 and 5.10). However, Figure 7.2 (see Chapter 7) showed that compaction was a limitating factor only at site 1. It was not clear why SPR at site 7 was not sensible while bulk density at both paired-sites showed increased soil compaction (± 1.5 Mg m^{-3}: see Chapter 5, Figures 5.7 and 5.10 for more details). Results for the aggregate stability and organic C showed soils at these respective sites were substantially stable (see Chapter 4, Figure 4.1). As much runoff was noted under these NT plots after irrigation, these results showed that soil compaction and natural consolidation occurred in these soils after converting CT to NT. In addition, this was also associated with the natural condition of Avalon soils (Site 7), which are recognized as poorly drained soils. This is demonstrated by the lower percentage of total porosity and volume of macropores of these soils compared with those at the other sites (see section 5.3.1, Figure 5.8). However, the lower values of FIR at site 7 could, on the other hand, be partially related to the initial water content since the field had received rainfall overnight before the infiltration measurements were made. The FIR can vary widely within a single soil type, depending upon initial water content as well as tillage practices (Ghildyal and Tripathi, 1987).

However, at sites 9 and 10, NT showed a higher final infiltration rate (FIR) than CT. This was also supported by the test of wet aggregate stability (see Chapter 4, Figure 4.1e). Although, AFP at – 5 and – 10 kPa in the topsoil under NT was critical (< 10 %), it increased with soil depth (Figure 5.14). Similarly, results for air permeability (K_a) at – 10 and – 100 kPa (corresponding to macropore- and mesopore-diameter of 29.2 – and 2.92 μm) were lower in the topsoil, with few differences between tillage systems, but increasing however in the subsoil under NT. This suggests that at this site, there were a greater number of surface-connected macropores to depth under NT than CT. This may be resulted in the positive effect of crop residue cover under NT, increasing subsequently the structural stability of soil pores and hence, soil infiltration rate (McGarry *et al.*, 2000).

Indeed, maintaining crop residues under NT may prevent the soil surface from sealing. Aggregates in the topsoil under CT were not strong enough to resist any slaking and/or dispersion. During the infiltration process, weak soil aggregates slaked and dispersed, resulting in the downward movement of fine particles that clogged the pore spaces and cracks. The greater the blockage of pore spaces the greater the decrease in infiltration rate will be (Hillel, 1998). This was probably the case at the end of the experiment when a strongly visible surface sealing was noted, especially under CT compacted inter-row.

Table 6.1. Mean measured and estimated final infiltration rate (FIR), as affected by tillage system. The quoted value of FIR represents the mean of three replicates (n = 3). Means followed by the same letter are significantly similar.

	T-test or ANOVA Mean FIR (mm h^{-1})	F-Test significance (5 %) or $P_{0.05}$	$LSD_{0.05}$
Paired-site 1			
NT (1)	28.3b	0.010	281.8
CT (2)	781.4a		
Paired-site 2			
NT (3)	1.37b	0.010	9.23
CT (4)	20.3a		
Paired-site 3			
NT-IM (5A)	46.1b	0.003	122.7
NT-DLM (5B)	31.8b		
CT-LIR (6A)	294.8a		
CT-CIR (6B)	57.7b		
Paired-site 4			
NT (7)	1.73b	< 0.001	209.2
CT (8)	732.3a		
Paired-site 5			
NT-LIR (9A)	144.5	0.304 (NS)	140.6
NT-CIR (9B)	131.3		
CT-LIR (10A)	114.3		
CT-CIR (10B)	29.9		
Paired-site 6			
NT-LIR (11A)	69.1b	0.003	338.5
NT-CIR (11B)	21.0b		
CT-LIR (12A)	758.2a		
CT-CIR (12B)	176.5b		

Note: NT = No tillage; CT = Conventional tillage; IM = irrigated maize; DLM = Dryland maize; LIR = Loose inter-row; CIR = Compacted inter-row, FIR = Final infiltration rate; $P_{0.05}$ = Probability at 5 %; NS = No significance

Similar trends may also be the case at site 4 (CT, loamy soil). Situated in the region commonly characterized by heavy storm rainfall (see Chapter 3, section 3.2.2), sealing of soil surface from raindrop impact is quite evident (this was visible even after infiltration measurements). The unprotected aggregates at the surface soil were poorly stable, and were quickly degraded, resulting, therefore, in a strong reduction in infiltration rate. This was evident and would explain the lower values of FIR obtained compared with other CT fields. Under NT (site 3), the lower FIR found compared with the paired CT field (site 4) (Table 6.1) was attributable to the above trend since the field was under CT prior to its conversion to NT practices. This observation was consistent with the findings of Arshad *et al.* (1999). On the other hand, as previously reported, this was also demonstrated by the presence of a compacted subsurface layer under both systems (BD= ± 1.7 Mg m^{-3}) (see Chapter 5, section 5.3.1, Figure 5.8), which may have broken the uniformity of the soil profile and reduced the soil infiltration rate. Figure 5.15b (see Chapter 5) also confirmed this trend. This was irrelevant since even low intensity rainfall can induce waterlogging conditions and surface runoff. However, the greater bulk density values observed in the soil profile under NT (site 3: 1.7 Mg m^{-3}) compared with CT (site 4: 1.5 Mg m^{-3}), also showed soil compaction due to the lack of soil disturbance under NT (Azooz *et al.*, 1996).

The overall trend for FIR on inter-row conditions under both CT and NT was clearly observed on coarse-textured soils (sites 9 and 10, 11 and 12). As expected, differences in inter-row effects were strongly affected by wheel traffic, with loose inter-rows (LIR) showing greater values of FIR than compacted inter-rows (CIR). These results were accompanied by lower total porosity and volume of macropores measured on undisturbed soil core samples taken on the same CIR position (see Chapter 5, Figures 5.11 and 5.12). AFP at – 5 and – 10 kPa and K_a at – 10 and – 100 kPa were also strongly affected by wheel traffic, especially at the 50 mm depth (see Chapter 5, Figures 5.14 and 5.15). This can be attributed to increased soil compaction near the surface due to tractor traffic over the same inter-row. Under CT, more than two tractor operations were carried out on the field during the growing season. Thus, soil compaction occurred all over the wheel-tracked inter-row (CIR), resulting in decreased soil porosity, particularly macroporosity. Soil compaction effects were observed more under NT than CT, owing to the soil consolidation and lack of soil disturbance under the former system. As the soil infiltration occurs through preferential macropores, FIR was restricted.

6.3 The effects of tillage on saturated hydraulic conductivity measured on undisturbed soil cores

6.3.1 General principles

Saturated hydraulic conductivity is the measure of the ability of a saturated soil to transmit water. It is of considerable importance in many ways, particularly to the drainage of soils for agricultural purposes.

The measurements of hydraulic conductivity of saturated soils in the laboratory are based on the direct application of the Darcy equation to a saturated soil column of uniform cross-sectional area. A hydraulic head difference is imposed on the soil column, and the resulting flux of water is measured.

The measurement of saturated hydraulic conductivity are influenced by the texture and the structure of the soil. Saturated hydraulic conductivity tends to be high in coarse-textured soils and increases with an increase in the number and size of large, highly water conductive pores. Consequently, coarse-textured and/or well-structured soils tend to have larger values of saturated hydraulic conductivity than fine-textured and/or structureless soils (Shainberg *et al.*, 1989). In addition, the texture and structure can interact in such a way that a fine-textured, but structured soil (e.g. structured clay soil) can have a larger saturated hydraulic conductivity value than a coarse-textured, but structureless soil (e.g. structureless sand soil) (Shainberg *et al.*, 1989).

The dissolved salt concentration in the water can affect saturated hydraulic conductivity through flocculation or dispersion of clay within the porous medium. The measured saturated hydraulic conductivity will increase if the clay is flocculated and decrease if the clay is dispersed (Shaingberg *et al.*, 1989).

6.3.2 Laboratory procedure

Saturated hydraulic conductivity was measured on undisturbed soil core samples after the determination of water retention (on the same undisturbed soil cores used for water retention curves). The constant-head method was used to assess the saturated hydraulic conductivity (Klute, 1986), using the Darcy equation (Eq. 5.6):

$$\mathbf{K_S\ (mm\ h^{-1}) = \frac{V \times L}{A \times t \times \Delta H}} \quad \text{.................................} \quad \textbf{Eq 6.9}$$

Where **V** is the volume of the percolated water (ml) that flows through the sample in a known time **t** (h), **L** is the length of the soil core (mm), **A** is the cross sectional area of the core sample (mm^2), and **ΔH** is the hydraulic head difference across the soil sample (mm).

The soil cores were completely saturated from the bottom for 24 hours or more, depending on the compactibility of the soil. After saturation, the soil cores were placed on the saturated hydraulic conductivity apparatus. Each soil core was bound from the top to an empty core ring of the same size. The system was supported at the bottom with a circular piece of cloth held with a rubber band plus a metallic screen and funnel, and then transferred to the constant head, saturated hydraulic conductivity apparatus. After stabilising the water level on top of each sample, the percolated volume of water that passed through the soil core in a known interval of time, was collected in a beaker and measured. From the three replicates, an arithmetic mean was calculated at each soil depth considered.

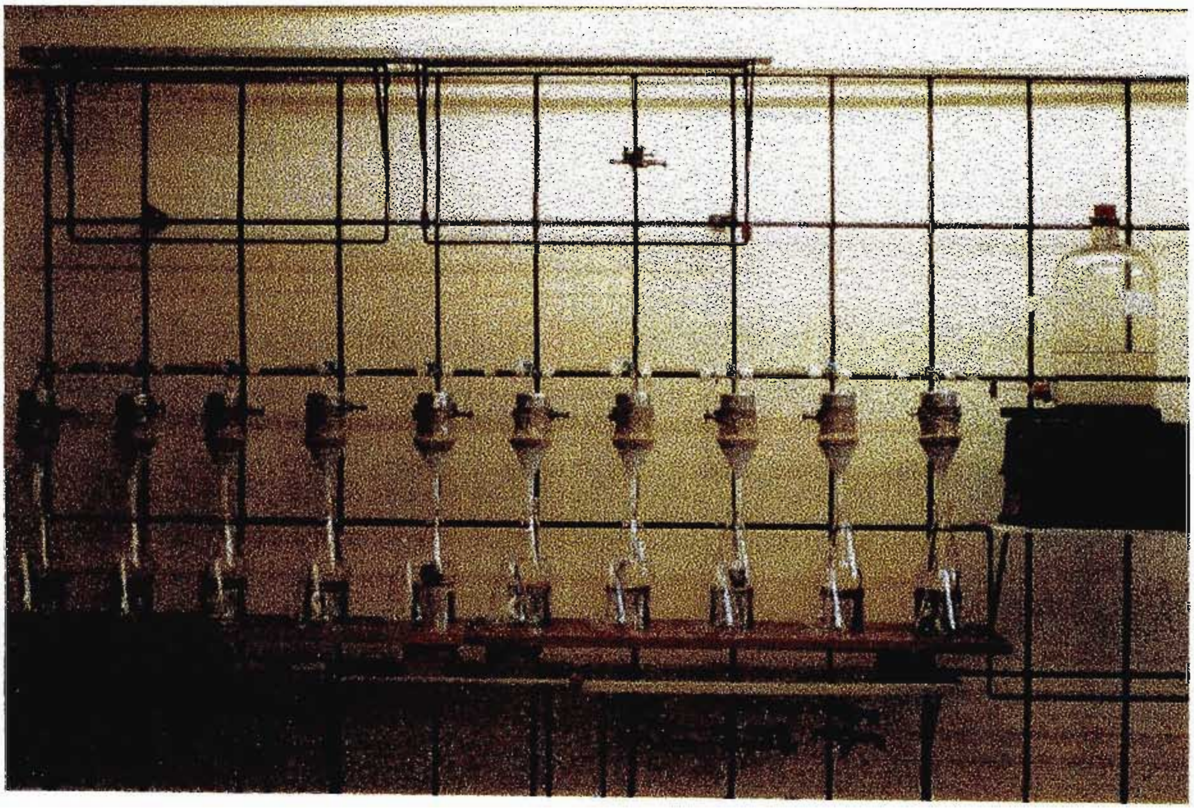


Figure 6.2. Scheme of the saturated hydraulic conductivity measured on undisturbed soil core samples, using the "constant head method" (Klute, 1986).

The mean data were statistically analysed by "one-way and/or two-way analysis of variance (ANOVA)" using the Genstat V statistical package. The overall F-test, determined from ANOVA, was used to reveal whether there were differences between means. Least significant differences (LSD's) were statistically used to separate means of treatments (i.e. NT and CT).

6.3.3 Results and Discussion

The data values of the saturated hydraulic conductivity (K_S) are presented in Figure 6.3. Where appropriate, reference is made to corresponding values for bulk density, pore-size distribution and air permeability, which were presented in Chapter 5.

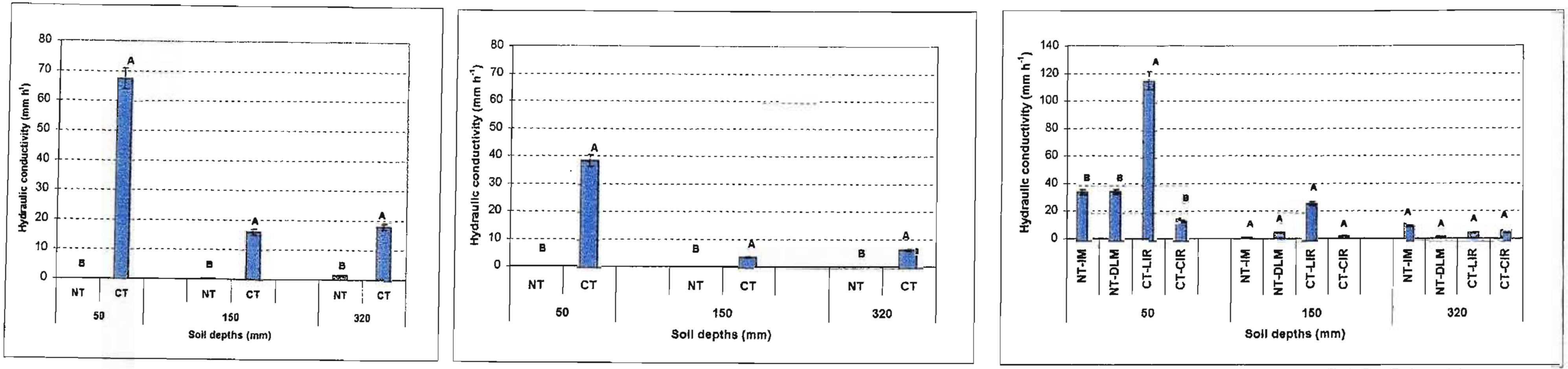
At the 50 mm depth, K_S was greater under CT than NT, and it decreased with soil depth. The reason for this trend is associated with an increased total porosity and, especially volume of macropores (see Chapter 5), occurring due to the ploughing of the soil under CT. This was also supported by greater values of AFP (Figure 5.14) measured at – 5 and – 10 kPa matric potential, which correspond to macropore diameters of 0.058 – and 0.029 mm respectively. Indeed, greater K_s values in the topsoil under CT were also attributable to higher values of K_a measured at – 10 and – 100 kPa (Figure 5.15), which suggested greater pore continuity. The observation was consistent with the findings of Shipitalo *et al.* (2000). Under NT, the magnitude of AFP, K_a and bulk density was limited by the lack of soil tillage associated with the natural soil consolidation (see Chapter 5), which increased soil compaction and reduced strongly the hydraulic conductivity. Similar trends were also pointed out by Aura (1988) and Heard *et al.* (1988), who reported that the decrease in K_S

occurred when soil compaction occurred, affecting the rearrangement of soil porosity and pore continuity.

However, down the soil profile, K_S generally decreased sharply at the 150 mm depth under CT, remaining however lower under NT compared to CT (except sites 9 and 10) (Figure 6.3). The decrease of K_S under CT was similarly followed by a decrease in K_a (at – 10 and – 100 kPa) and AFP (at – 5 and – 10 kPa) (see Chapter 5, Figures 5.14 and 5.15), presumably due to tillage management. In addition, the sharp decrease of K_S at the 150 mm depth was accompanied by a greater bulk density and a lower volume fraction of macropores and total porosity (see Chapter 5). These results confirmed previous indications (see Chapter 5, Figures 5.7, 5.8 and 5.12), which showed that there had been formation of a compacted layer at this soil depth. The formation of a compacted layer under CT occurred at the depth of cultivation, due to the frequent use of tillage implements at the same soil depth. Under NT, this was also the case since the field has been under CT cultivation prior to its conversion to NT. All these trends suggested the reduction of macropore volume and their discontinuity (Edwards *et al.*, 1995, 1997; Rasmussen, 1999). Since the transmission of water through the soil profile is a characteristic of macropore flow (Rasmussen, 1999), the disruption of these pore's continuity would reduce their contribution to the soil total flow (Shipitalo *et al.*, 2000).

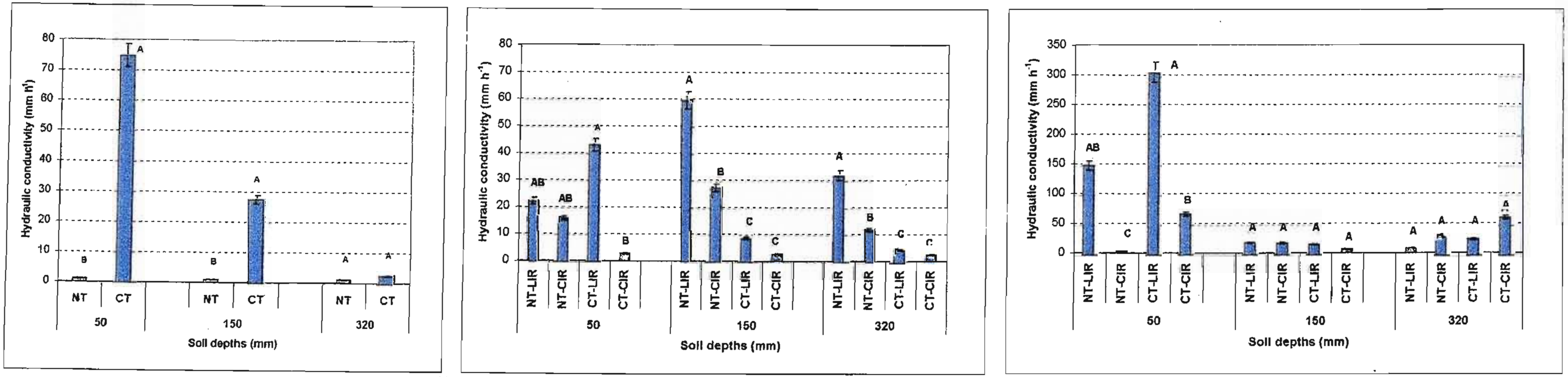
At the 320 mm depth, the overall trend of K_S was similar to the other depths. That is, it decreased in association with an increase in bulk density and a decrease in total porosity and the volume of macropores (see Chapter 5). Where the soil porosity was similar (see Chapter 5, Figure 5.10), owing to the natural soil consolidation (Ahuja *et al.*, 1998; Arshad *et al.*, 1999; Smith *et al.*, 2001), there was no significant difference in K_S (Figure 6.3d).

(a) Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms **(b) Sites 3 and 4: Mr van der Aardweg's and Mr van Vuuven's farms** **(c) Sites 5A, 5B, and 6: Mr Miurhead's and Mr Mostert's farms**



Note. NT - IM: NT - irrigated maize CT - LIR: CT - loose inter-row
NT - DLM: NT - dryland maize CT - CIR: CT - compacted inter-row

(d) Sites 7 and 8: Mr J. Jackson's and Mr J. Joubert's farms **(e) Sites 9 and 10: Cedara Agricultural Research Station** **(f) Sites 11 and 12: Cedara Agricultural Research Station**



Note. NT - LIR: NT - loose inter-row CT - LIR: CT - loose inter-row
NT - CIR: NT - compacted inter-row CT - CIR: CT - compacted inter-row

Note. NT - LIR: NT - loose inter-row CT - LIR: CT - loose inter-row
NT - CIR: NT - compacted inter-row CT - CIR: CT - compacted inter-row

Figure 6.3. Saturated hydraulic conductivity measured on undisturbed soil cores. Each data represents the mean of three replicates. The error bars represent the standard error of the mean at P < 5 %. Means with same letter at same depth are significantly similar (NT: No tillage; CT: Conventional tillage; LIR: Loose inter-row; CIR: Compacted inter-row)

The overall trend of the effects of wheel traffic on inter-row conditions under both CT and NT was clearly observed on fine and coarse textured soils, with a significant difference at the 50 mm depth [i.e. Figure 6.3, (c), (e), (f)]. As expected, K_S was greater under loose inter-row (LIR) than compacted inter-row (CIR) throughout the soil profile, which was characterized by greater total porosity and volume of macropores (see Chapter 5). AFP at – 5 and – 10 kPa and K_a at – 10 and – 100 kPa followed similarly the K_S - trend (see Chapter 5, Figure 5.14 and 5.15). This resulted from increased soil compaction in the CIR near the soil surface. Under CT, soil compaction occurred due to excessive tractor traffic over the same wheel-tracked interrow, reducing therefore the contribution of soil macropores to total water flow. In somes cases, this was accompanied by the presence of a slowly permeable subsurface layer, resulting in non-significant differences in K_S in the subsoil. Under NT, soil compaction occurred due to the lack of soil disturbance and natural soil consolidation over time (Azooz *et al.*, 1996). The inadequate conversion from CT to NT may, however, result in the formation of the subsurface compacted layer, which may reduce K_S and disrupt the continuity of pores. However, reverse trends (for K_S, AFP and K_a) were observed at the 150 and 320 mm depths only at paired-site 5 (sites 9 and 10), with substantially greater values under NT (Figures 5.3e, 5.14e and 5.15e). These results suggested that at this site there was a greater number of surface-connected macropores to soil depth. This could be due to the same reasons given for the similar trend observed for the infiltration rate at sites 9 and 10 (see section 6.2.4, paragraph 4).

On the other hand, the extent of increased K_S depends on the extent of stability of soil aggregates to resist external forces. The stability of aggregates depends greatly on the concentration of organic carbon that may influence a good soil structure (Franzluebbers and Arshad, 1996; Arshad *et al.*, 1999). For instance, the results for K_S for the CIR showed that aggregates at the surface soil were not sufficiently stable to resist wheel-tractor pressure. Repeated traffic over the same interrow resulted in breakdown of the soil aggregates, and in increased soil compaction near the surface soil, decreasing therefore K_S.

6.3.4 General conclusions

The objective of this study was to evaluate changes in soil transport properties, in this case the saturated hydraulic conductivity and infiltration rates, as affected by tillage management practices. In general, the overall trend of saturated hydraulic conductivity (K_S) and final infiltration rate (FIR) was explicable in terms of pore-size distribution, AFP and particularly K_a.

The results of K_S and FIR generally showed greater values in the topsoil under CT than NT, which decreased with soil depth. This followed similarly the trend for AFP and K_a. The greater the AFP and K_a the greater K_S and FIR values will be. This suggested greater continuity of macropores, preferential pore category of soil total flow (Shipitalo *et al.*, 2000). High levels of variation in K_S and FIR were observed within the same type of soil, suggesting the natural heterogeneity of the field. However, the variability of K_S and FIR was also characteristic of the tillage management system. The effect of wheel traffic on interrows was observed when NT-compacted inter-row (**NT- CIR**) was compared with CT-compacted inter-row (**CT- CIR**). The mulch on the surface soil under NT promoted stable aggregates that partially resisted the applied wheel-pressure of the tractor. Consequently, slaking and dispersion of soil aggregates and the blockage of water conductive pores was less under **NT- CIR**, owing to the promotion of pore structural stability.

However, opposite trends to the above were observed at sites 9 and 10, where NT showed greater FIR and K_S than CT. This was attributable to the increase in the structural stability of surface-connected macropores under NT. Critical low FIR and K_s values were observed under some NT treatments with fine and medium textured soils, attributable mainly to excessive wheel traffic, and this was sometimes accompanied by the presence of a compacted subsoil layer caused by CT prior to conversion to NT. The presence of a slowly permeable subsurface layer throughout the soil profile (indication from Chapter 5) resulted in the disruption of pore continuity. This was characterized by lower values of K_a at the 150 mm depth, which consequently has lowered FIR and K_S. On the other hand, owing to lower level of aggregate stability measured under CT, and the absence of a mulch cover, unprotected aggregates at the surface soil slaked and dispersed, resulting in a surface sealing occurring due to heavy storm rainfall that blocked pore spaces and cracks and, subsequently, reduced strongly the soil total flow (Hillel, 1998; Shipitalo *et al.*, 2000).

Chapter 7

The effects of tillage system on soil penetration resistance

7.1 Introduction

The resistance of the soil to penetration is an index of soil compaction. Most serious compaction occurs when the travel of the tractors over the soil surface is random and is either excessive (Hasset and Banwart, 1992), or done at the time when the soil is wet. This is because water plays a major role in soil strength development since it affects soil cohesion by influencing the strength of inter-particle water bonds (Kirby and Kirchhoff, 1990).

The measurement of soil penetration resistance (SPR) in the field has been reviewed by Zimbone *et al.* (1996). A penetrometer is an instrument consisting of a conical probe, which is driven into the soil usually at a constant rate of entry. The penetration resistance is therefore the force on the penetrometer per unit basal area of the cone (Jayawardene and Blackwell, 1990). The greater the force encountered by the probe, the gretear is the soil penetration resistance.

Soil penetration resistance is strongly influenced by water content (Sharratt, 1996; Materechera and Mloza-Banda, 1997; Smith *et al.,* 1997; Unger and Jones, 1998). Factors such as rainfall, evaporation and biological activity among others exert meaningful changes on soil structure and therefore on soil resistance. However, SPR is influenced by the exact location of the conical probe in relation to the macropores and the associated wetting patterns. In this regard, soil penetration resistance should be regarded as a point measurement rather than as a bulk soil measurement (O' Sullivan *et al.*, 1987).

The high mechanical strength in compacted soils can also alter the soil pore size distribution, owing to applied pressure on the soil surface (Smith *et al.,* 1997). Excessive mechanical strength is extremely undesirable as it often leads to reduced seedling emergence, poor soil aeration, reduced hydraulic flow and increased risk of sediment scour and entrainment (Mullins *et al.,* 1987; Mullins *et al.*, 1990; Proffitt *et al.,* 1995). Soil strength is therefore of particular importance, since tillage systems can generate excessive soil strength development. To evaluate this, the effects of tillage systems on soil penetration resistance were studied.

7.2 Materials and Methods

To avoid the complications associated with the effect of water content on SPR, measurements were made at or near field capacity, which was assumed and achieved by ponding water at the soil surface approximately 48 hours before taking measurements. The penetrometer used to measure soil strength was of the constant recording type manufactured and marketed by Geotron Systems, South Africa (Figure 7.1). The conical probe of the penetrometer was a 30° circular stainless steel cone, with a basal area of 130 mm^2 and a 12.83 mm diameter, mounted at the end of a 0.8 m driving shaft of 9.53 mm diameter.

Once the setting of the Hand-penetrometer was done, and the footplates properly flattened on the soil surface to ensure a good contact (footplates soil surface contact) and stability of the unit, the handle was then turned to force the rod into the ground. The rod was pushed into the soil at a uniform rate of approximately 30 mm/per sec. The surface reading was measured (0 mm) at the instant the base of the cone was flush with the soil surface. Subsequent readings were made continuously or as frequently as possible while maintaining the penetration rate of 30 mm per second. Measurements were randomly taken down to a depth of 600 mm at the positions where infiltration measurements, undisturbed soil cores and other samples were taken. The maximum pressure and depth that can be measured are 5000 kPa and 0.8 m, respectively. Ten penetration measurements were taken between crop-rows immediately after setting the penetrometer. The penetrometer has a control unit and memory to store penetration reading data taken in the field, and it is downloaded to a computer at a later stage.

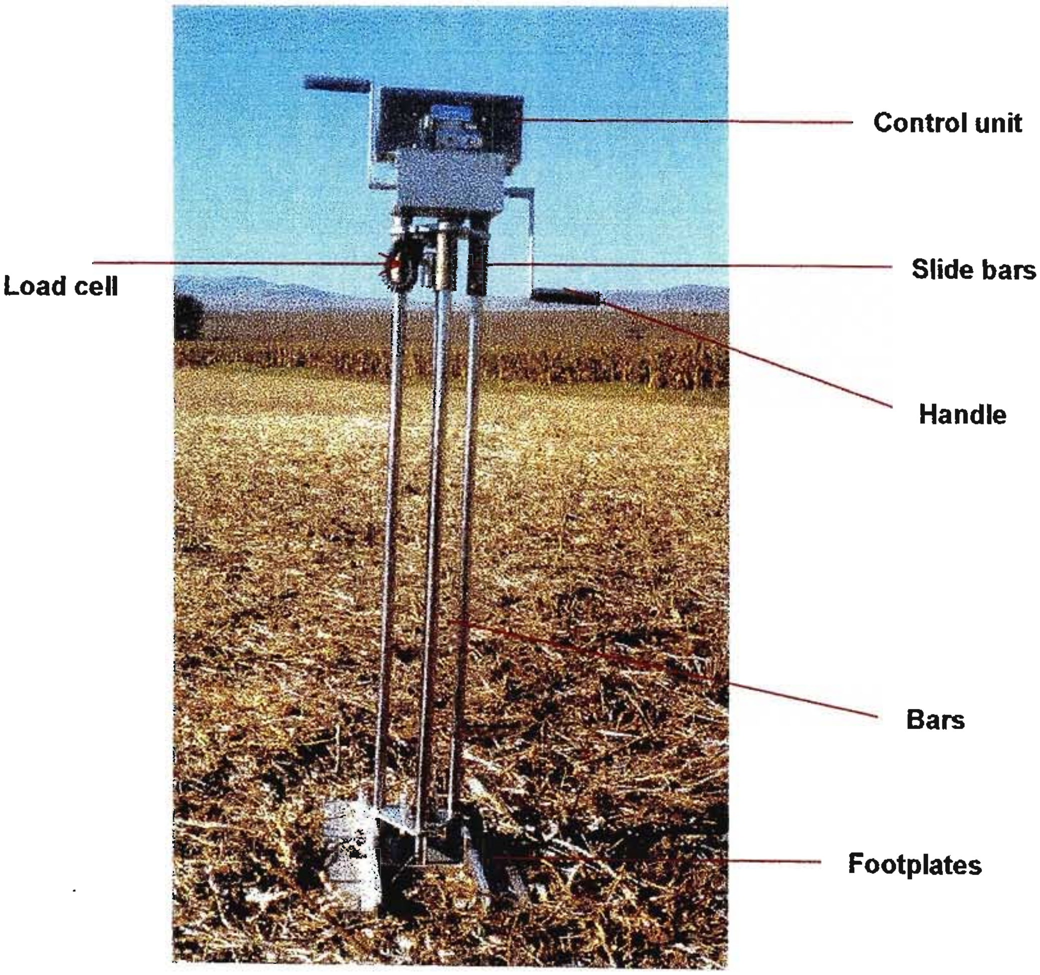


Figure 7.1. Constant recording penetrometer of Geotron Systems used in the study

7.3 Results and Discussion

7.3.1 The effects of tillage on soil penetration resistance (SPR)

Figure 7.2, (a) to (f) shows the effect of tillage systems on SPR. The effect of tillage systems on SPR was highly significant ($P < 0.001$) (Appendix 8). Within the 150 mm topsoil depth, SPR was generally greater under NT than CT, with greatest changes occurring at the 100 mm depth. With regard to inter-row conditions under CT, a similar trend was observed in the topsoil under compacted inter-row (CIR). The increase in soil mechanical strength in the topsoil under NT and CT-CIR can be related to the lack of soil disturbance and natural soil consolidation and/or excessive tractor traffic over the same inter-row. Similar results were also reported by, among others, Johnson *et al.* (1990), Braim *et al.* (1992), Pikul *et al.* (1993), Sharratt (1996), Materechera & Mloza-Banda (1997), Karunatilake *et al.* (2000), Krzic *et al.* (2000) and Yavuzcan (2000). In general, results for the bulk density measured on undisturbed soil cores did not sensibly illustrate soil compaction, as did SPR measurements. This could be attributable to the period during which core sampling was done (March: wet season), which differed from the time during which SPR measurements were taken (May: dry season).

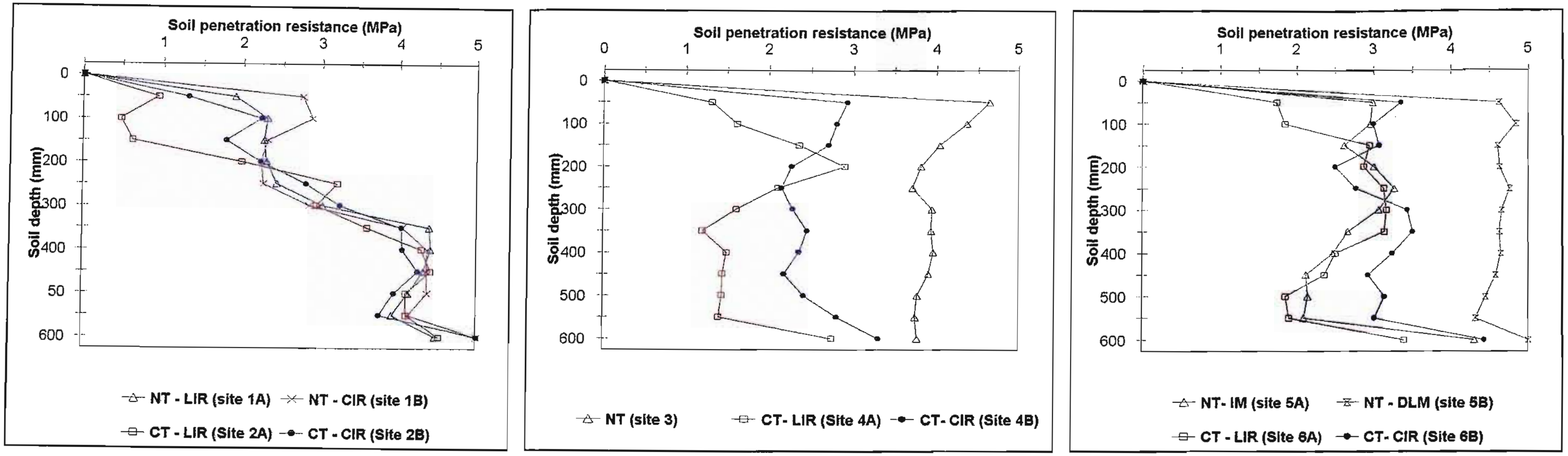
In fine-textured soils, from a soil depth of 150 mm downwards (below the plough layer), the SPR increased sharply up to ± 4.0 MPa at sites 1 and 2 [Figure 7.2, (a)], whereas at sites 5 and 6 it increased gradually up to ± 3.0 MPa [Figure 7.2 (c)], except **NT- DLM** (site 5B). The trend of the **NT- DLM** site will be later discussed. Similar trends, where SPR increased with soil depth, have previously been reported by O'Sullivan *et al.* (1987), Alakukku (1996), Wu *et al.* (1997) and Moodley (2001). This suggests that excessive tractor traffic over the soil surface has induced progressive subsoil damage. Under NT (particularly sites 1 and 5B), repeated passes of tractor over the field, especially at harvest, were carried out (this was reported by the farmers). Under CT (sites 2 and 6), this was also the case since the heavy machinery came over the field for multiple operations. Indeed, in these clay soils, this could result in excessive subsoil compaction, especially under NT plots since the soil was moisturized by the mulch cover (Hillel, 1998). Nevertheless, statistically non-significant differences in SPR between treatments were observed in the subsoil in fine-textured (sites 1 and 2; 5A, 5B and 6) and medium-textured soils (sites 3 and 4; 7 and 8) (Appendix 8).

The magnitude of soil water content is of great importance as a factor influencing soil compaction under cultivation during tillage operations. It was shown in Chapter 5 that there was an increase in water storage in the topsoil under NT. This trend was associated with increasing organic matter content that strengthened wet soils and weakened dry ones (Causarano, 1993). Subsequently, high mechanical resistance was then observed under NT, particularly in fine-textured rather than medium-textured soils. These results showed that, in fine-textured soils, despite the presence of a high organic matter content, soil particles might strongly be subjected to cohesion due to the greater surface area of clay soils that reduced the magnitude of frictional forces (Gupta and Allmaras, 1987; Smith *et al.*, 1997).

However, more pronounced increases in SPR had occurred at sites 3 [Figure 7.2, (b)] and 5B [Figure 7.2, (c)], both NT-drylands. Statistically, both treatments were significantly different from others at all soil depths (Appendix 8). This may be primarily related to the greater cohesion observed in fine and medium textured soils. The high percentage of clay and silt found in these soils could presumably influence this trend (see Appendix 1). Previous results had demonstrated that these soils were characterized by high degree of compaction, which was accompanied by a decrease in total porosity and pore-size distribution, and higher values of bulk density (see Chapter 5, Figures 5.8 and 5.9). At site 5B (**NT- DLM**: clay soil), this was the case since random tractor traffic was noticed, and was also reported by the farm owner. At site 3, high soil compaction could be primarily attributable to the nature of Avalon soils. Indeed, these soils had been under CT (prior to conversion to NT) for a substantial number of years. This has resulted in lowered soil organic matter contents, and therefore, the soils could be predisposed to natural consolidation and to soil compaction. Nevertheless, the wetting sieving aggregate test showed that these soils were highly stable when measurements were taken, owing to the greater organic matter content. Despite the presence of greater organic matter content, fine textured soils are more strongly liable to compression than coarse textured soils, owing to their greater surface area (Gupta and Allmaras, 1987).

With regards to the mechanical induced-effects on inter-row conditions, SPR was greater under compacted than loose inter-rows under both NT and CT. Greater differences in inter-row effects were generally observed under CT in the 150 mm topsoil rather than subsoil. The negative impacts of repeated wheel traffic has resulted in excessive soil compaction and soil structural breakdown under CT. In fact, soil surface aggregates were vulnerable to settling under the influence of excessive applied tractor-pressure and raindrop action, which resulted in close packing of soil (Hillel, 1998). This occurred due to the absence of surface cover under CT that could, firstly prevent raindrop impact. Under rainfall or irrigation, dispersed fine particles formed a puddle of mud, which might dry and form a strong surface sealing. The formation of a surface sealing when the puddles dries, combined with soil compression due to applied pressure of the tractor, resulted in increased SPR in the few centimetres of surface soil. Similar results have been reported by Kirby and Kirchhoff (1990) and Hassett and Banwart (1992).

(a) Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms (b) Sites 3 and 4: Mr v. d. Aardweg's and Mr v. Vuuven's farms (c) Sites 5A, 5B and 6: Mr Miurhead's and Mr Mostert's farms



(d) Sites 7 and 8: Mr J. Jackson's and Mr J. Joubert's farms (e) Sites 9 and 10: Cedara Agricultural Research Station (f) Sites 11 and 12: Cedara Agricultural Research Station

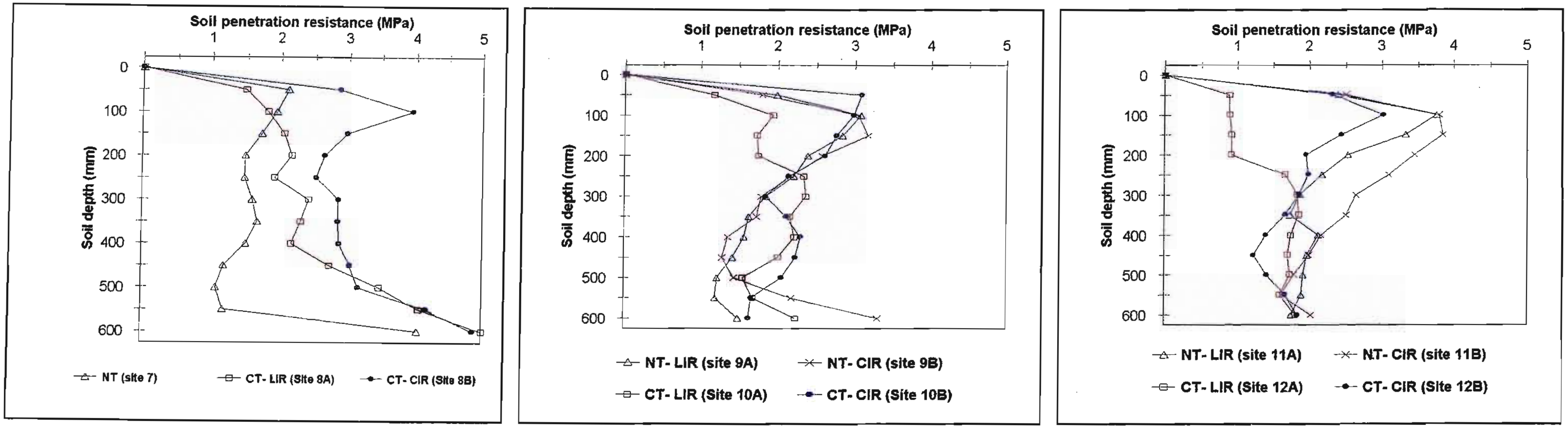


Figure 7.2. Mean soil penetration resistance (SPR) as affected by the NT and CT systems. Each data point represents the mean of 10 observations (LIR: loose inter-row; CIR: compacted inter-row)

It is important to emphasize that the magnitude of SPR changes can be affected by soil texture. By contrasting for instance Figures 7.2 (a) and (b), one can observe lower SPR in the topsoil in high clay soils [Figure 7.2, (a)] compared with loam soils [Figure 7.2, (b)]. Fine-textured soils may reduce the magnitude of frictional forces. Owing to the greater surface area of clay soils, these soils showed resistance to compression. On the other hand, loamy soils are highly susceptible to soil compaction (Smith *et al.,* 1997).

The formation of a compacted layer ("plough-pan") was noted under CT, and in some cases under NT (due to previous CT practices). This corresponds to the point of maximum SPR in the topsoil. Nevertheless, the depth of the compacted layer varied under both tillage systems. Factors contributing to this will include the soil water content at cultivation, the depth of cultivation and the soil texture (Unger and Jones, 1998). In fine-textured soils [Figure 7.2, (a) and (c)], the compacted layer appeared at 100 mm soil depth. In medium soils [Figure 7.2, (b) and (d)], it occurred between 100m m and 200 mm soil depths, whereas in coarse-textured soils [Figure 7.2, (e) and (f)] it was observed between 100 mm and 150 mm soil depths. Under CT, the compacted layer was observed just below the depth of cultivation since the frequent use of tillage implements at the same depth resulted in compaction of the soil below (Bennie and Krynauw, 1985; Gómez *et al.*, 1999; Rasmussen, 1999).

7.4 The impacts of SPR on soil aeration and hydraulic flow

Findings from Chapter 6 showed that the saturated hydraulic conductivity and final infiltration rate were a function of soil total porosity, particularly the volume fraction of macropores. Depending on the soil texture, higher SPR occurred with increased soil compaction. In fact, by forcing soil particles closer together, soil compaction increased SPR, increasing the number of interparticle contacts. This resulted in increased cohesion and frictional forces, accompanied by a loss in soil porosity, and particularly volume fraction of macropores (Smith *et al.*, 2001). Air-filled porosity and water movement (soil infiltration, hydraulic conductivity, soil drainage) were then restricted (Shipitalo *et al.*, 2000).

Excessive tractor traffic under CT had also resulted in increased soil compaction and soil structural deterioration. This was associated with the soil settling under the influence of raindrop action and the alternate wetting-drying cycle, which resulted in close packing of soil (Hillel, 1998). In fact, under raindrop action, soil surface aggregates are slumped and dispersed due to the absence of surface cover, which resulted in little organic matter content. Dispersed fine particles moved downward through soil pores and cracks, which resulted in soil clogging, which in turn induced surface sealing. The formation of surface sealing on drying may increase SPR near the soil surface, and may reduce strongly the volume of larger pores. Accordingly, this resulted in restriction of the movement of water and air through the soil, since water flow and air permeability are preferentially prone to macropore flow, in terms of volume and continuity (Edward *et al.*, 1995, 1997; Rasmussen, 1999; Shipitalo et *al.*, 2000),

The results have also shown the presence of a compacted layer under CT, and in some cases under NT, which may be the result of similar causes to those outlined above. A practical consequence of this is that root penetration may be inhibited when the volume and continuity of larger pores is reduced. This can occur due to soil compaction when the pore diameters become narrower than their root caps. When the soil water content is below the field capacity, the plant will try to find water by orientating its roots horizontally above the compacted layer (Rasmussen, 1999), or by displacing soil particles to widen the pores by exerting a pressure greater than the soil's mechanical strength. As suggested by Bengough and Mullins (1991), Rapel *et al.* (1993), Karunatilake et *al.* (2000), and Yavuzcan (2000), among others, the penetration of plant roots is restricted when SPR exceeded 2 MPa, depending on the soil type. Many of the experimental sites had SPR values above this value (Figure 7.2) in the surface 200 – 300 mm. Indeed, values above 4 MPa were observed even under NT at sites 3 and 5. Thus, crop root growth is likely to be restricted at many of the sites due to the compacted surface layer of soil.

7.5 Conclusions

The objective of this chapter is to evaluate the effects of CT and NT systems on SPR and the relative impacts on soil aeration and water movement.

The effect of these tillage systems on SPR was highly significant ($P < 0.001$). SPR was generally greater in the topsoil under NT than CT, especially within the 150 mm topsoil depth due mainly to the lack of soil disturbance under the system. With regards to inter-row conditions, a similar trend was also observed in the topsoil under the compacted inter-row, this being the result of excessive tractor traffic over the same inter-row. Differences in SPR were strongly related to bulk density and clay content of the soil. In the subsoil, SPR increased sharply up to ± 5 MPa in fine-textured soils, with non-significant differences observed between treatments. This was associated with subsoil damage. In coarse-textured soils, SPR decreased substantially with soil depth.

The magnitude of changes in SPR were clearly observed to be greater than those recorded for bulk density. Both Hammel (1989) and Ferreras *et al.* (2000) also pointed out this feature, and emphasized that the lack of differences in bulk density between tillage systems as a characteristic of soil compaction may be caused by the absence of soil disturbance and the formation of a stable and rigid soil structure under NT. However, soils with high organic matter and high clay content induced low bulk density, the organic matter presenting a resistance to soil compression, and the high clay contents reducing the magnitude of frictional forces (Smith *et al.*, 1997).

The frequent use of tillage implements at the same depth under CT had resulted in the formation of a compacted layer below the depth of cultivation. In some cases under NT also, this was the case because the field had been under CT prior to its conversion to NT. However, under both tillage systems, the depth of the compacted layer varied with the depth of cultivation and soil texture. Compaction will result in restriction of water movement and air-flow through the soil, since the volume and continuity of the macroporosity is substantially reduced (Shipitalo *et al.*, 2000). In addition, root growth might also be inhibited, suggesting that these systems need periodic deep tillage to break the hard-layer.

The major task of soil management should be to minimize soil compaction to the fullest extent possible, and alleviate the unavoidable compaction caused by tillage and tractor traffic. The most effective approach to preventing soil compaction is to reduce the number of tractor operations to only those necessary and profitable operations. This can be achieved by minimum and zero tillage. Such systems avoid unnecessary tillage operations, resulting in time, labour and energy savings. These systems also retain crop residues as a protective mulch over the soil surface, and lead to the preservation of soil structure. Tractor traffic must be restricted when the soil is wet, and some soil loosening (i.e. minimum rather than zero tillage) may be necessary at some of the experimental sites.

Chapter 8

General Discussion, Conclusions and Recommendations

The objective of the present study was to evaluate the comparative effects of NT and CT on soil physical properties. From a practical point of view, the findings of this study have shown that soil water retention, pore-size distribution and bulk density are greatly affected by different tillage practices. In fine-textured soils, bulk density was substantially greater in the topsoil under NT than under CT, accompanied by a lower volume of macro- and mesopores and an increase in volume of micropores. This was attributable to natural soil consolidation and increased soil compaction under NT. Soil compaction in the topsoil under NT was confirmed by high values for SPR, especially within the 150 mm soil layer. The rearrangement of pore-size distribution and change in total porosity helped to explain measured differences in soil aeration and hydraulic properties.

Saturated volumetric water content was lower under NT than under CT due to the lower total porosity. NT also resulted in a flattening of the WRC owing to the changes in pore-size distribution and the greater proportion of meso – and micropores. This resulted in substantial water retention at low matric potentials, and slow release of small amounts of water in the high matric potential range. At field capacity, the effect of soil compaction under NT resulted in increased or decreased volumetric water content, depending on the site characteristics and soil type. This feature was partially explained by the crossover of WRCs for NT and CT soils, which occurred over a wide range of matric potentials namely between – 1 and – 100 kPa. The range of matric potentials at which the crossover occurred differed in different soils. Crossover frequently occurs in the range of matric potentials designated as field capacity (Smith *et al.,* 1997). However, the higher volumetric water content observed at field capacity in the topsoil under NT was presumably partly associated with the concentration of organic matter near the surface, as crop residues were left at the surface soil for decomposition. Subsequently, this resulted in increased water availability constants (PAW and RAW) under NT.

The overall effect of increased soil compaction in the topsoil under NT resulted in reduced macroporosity and reduced pore continuity and, as a further result, air-filled porosity (AFP), air permeability, infiltration rate and hydraulic conductivity were also all reduced. In contrast, the presence of a greater total porosity and volume fraction of macropores observed particularly in coarse-textured soils under NT resulted in increased AFP. This was clearly observed under NT non-wheel tracked interrow, presumably because of an increase in either organic matter content or other specific binding agents (soil micro-organisms, roots and roots exudates) that stabilized soil aggregates (Haynes, 1993). However, under NT wheel-tracked interrow, AFP was strongly affected by the topsoil compaction. Indeed, a greater infiltration rate and hydraulic conductivity under NT suggested greater number of surface-connected macropores to soil depth. This could be the result of the positive effect of the mulch cover, which influenced the accumulation of organic carbon and subsequently, the structural stability of soil macropores. The mulch would also promote earthworm activity that could create surface-connected macropores.

The presence of a pan layer and/or subsoil compaction at the depth of cultivation was observed at several sites. Under CT, increased SPR with soil depth occurred presumably due to excessive tractor traffic and frequent use of heavy tillage implements at the same soil depth. Indeed, continued cultivation under CT caused the breakdown of soil organic matter and subsequently, the reduction of soil aggregation and structural stability, and hence a dense, compact plough layer was formed. Under NT, this was also the case because the field had been under CT for more than 50 years prior to conversion to NT.

The task of maintaining good soil physical conditions is an important consideration for a substainable farming system. Preventive and/or remedial actions should be practised to minimize soil compaction, alleviate the unavoidable compaction caused by tillage and tractor traffic, and to increase soil organic matter content. The most effective approach to prevent soil compaction is to reduce the number of tractor operations to only necessary and profitable operations. Loosening compacted topsoil is generally practised in CT, but under NT this does not occur. Since the topsoil under CT is characterized by low organic carbon contents, measures to build up soil organic matter such as retaining and incorporating crop residues should be adopted. Soil organic matter is an important factor that influences positively soil compactibility (Haynes, 1995; Smith *et al.*, 1997). Increases in organic matter may reduce compactibility by increasing the stability and strength of aggregates and, therefore, their resistance to deformation, and also by increasing the elasticity of the soil (Haynes, 1995). Indeed, results demonstrated substantial soil compaction in wheel-tracked areas, particularly under CT. However, subsoil compaction can also be a major concern since it can limit root and crop growth, and therefore yields (Haynes, 1995). Preventive and/or remedial actions involve the restriction of any tractor traffic when the soil is wet, and changing the depth of soil cultivation from year to year. Subsoil tillage should be practised where subsoil compaction has been identified. This will have beneficial effects on crop growth and performance. However, for subsoiling to be effective, it needs to be carried out at optimum soil water content and the depth and interval between subsoiler tines needs to be considered carefully (Haynes, 1995).

Changing directly from CT to NT has caused an alteration of soil physical properties. In particular, there has generally been a consolidation of the surface soil layer. This compaction has been observed to result in waterlogging in the surface soil and uneven germination and seedling growth, particularly in wet years. It is also, sometimes, suggested that it can be suspected to limit crop root growth and thus, crop yields. Nevertheless, in dry years, yields are typically greater under NT because of conservation of soil water promoted by the surface mulch. In addition, NT is recommended by many advisors as a measure to reduce soil erosion and land degradation.

It is important that good soil physical conditions predominate prior to conversion from CT to NT. Soils that have been under CT for a substantial number of years are likely to have lowered soil organic matter contents, and to be predisposed to natural consolidation and to compaction caused by surface traffic. Prior to converting to NT, it is important that any subsoil compacted layers are broken up by subsoil tillage. In addition, measures to increase the soil organic matter content would also be beneficial. Surface-connected macropores could be created, for example, by incorporating straw by a conventional tillage operation. Introduction of earthworms to NT systems might also be benefiacial in creating surface-connected macropores. Nevertheless, it may well be that a minimum tillage system would be more appropriate rather than NT in many cases since in minimum tillage residues would still be retained at the soil surface thus, conserving soil water and protecting the soil surface. The surface soil layer would not be inverted each year thus, conserving the organic matter content particularly near the soil surface. The minimum tillage operation would, moreover, create some macroporosity and surface-connected macropores through the surface soil layer. Some research comparing minimum tillage systems with NT, with particular emphasis on their effects on soil physical conditions, seems appropriate in the study locality.

References

Adam, K.M. and D.C., Erbach. 1992. Secondary tillage tool effect on soil aggregation. *Trans., ASAE*, 35(6): 1771 – 1776.

Ahuja, L.R. Fiedler, F., Dunn, G.H., Benjamin, J.G., and A. Garrison. 1998. Changes in water retention curves due to tillage and natural reconsolidation. *Soil Sci. Soc. Am. J.,* 62: 1228 – 1233.

Alakukku, L. 1996. Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. *Soil and Tillage Res.,* 37: 223 – 238.

Allmaras, R.R., Rickman, R.W., Ekin, L.G., and B.A. Kimball. 1977. Chiseling influences on soil hydraulic properties. *Soil Sci. Soc. Am. J.*, 41: 796 – 803.

Amoozegar, A. 1989. A compact constant – head permeameter for measuring saturated hydraulic conductivity in the vadose zone. *Soil Sci. Soc. Am. J.*, 53: 1356 – 1361.

Angers, D.A. and G.R. Mehuys. 1993. Aggregate stability to water. In Carte, M.R. (ed). Soil aggregation, organic matter and microbial biomass. *Soil Sci. Soc. Am. J.*, 56: 115 – 119.

Angers, D.A, Bolinder, M.A., Carter, M.R., Gregorish, E.G., Drury, C.F., Liang, B.C., Voroney, R.P, Simard, R.R., Donald, R.G., Beyaert, R.P., and J. Martel. 1997. Impact of tillage practices on organic carbon and nitrogen storage in cool humid soils of eastern Canada. *Soil and Tillage Res.*, 41: 191 – 201.

Ankey, M.D., Kaspar, T.C., and R. Horton. 1990. Characterisation of tillage and traffic effects on unconfined infiltration measurements. *Soil Sci. Soc. Am. J.*, 54: 837 – 840.

Arshad, M.A., Gill, K.S., and G.R. Coy. 1995. Barley, Canola, and weed growth with decreasing tillage in a cold, semiarid climate. *Agron. J.,* 87: 49 – 55.

Arshad, M.A., Franzluebbers, A.J., and R.H. Azzoz. 1999. Components of surface soil structure under conventional and no-tillage in Northwestem Canada. *Soil and Tillage Res.,* 53 :41 – 47.

Aura, E. 1988. Inverkan av reducerad jordbearbetning på jordstrukur òch markens dräneringsegenskaper. *In*: Hansen, L. and K.J., Rasmussen (eds.). Proceedings of NJF-Seminar. Reduced cultivation, *Div. Soil management* Uppsala, Sweden. Report No. 56. pp 58 – 63.

Aura, E. 1999. Effects of shallow tillage on physical properties of clay soil and growth of spring cereals in dry and moist summers in southern Finland. *Soil and Tillage Res.,* 50: 169 – 176.

Azooz, R.H., Arshad, M.A., and A.J. Franzluebbers. 1996. Pore size distribution and hydraulic conductivity affected by tillage in northwestern Canada. *Soil Sci. Soc. Am. J.,* 60: 1197 – 1201.

Ball, B.C. 1981. Pore characteristics of soils from two cultivation experiments as shown by gas diffusivities and permeabilities and air-filled porosities. *J. Soil Sci.,* 32: 483 - 498.

Ball, B.C. and M.F. O'Sullivan. 1987. Cultivation and nitrogen requirements for drilled and broacast winter barley on a surface water gley (Gleysol). *Soil and Tillage Res*., 9: 103 – 122.

Ball, B.C., O'Sullivan, M.F., and R. Hunter. 1988. Gas diffusion, fluid flow and derived pore continuity indices in relation to vehicle traffic and tillage. *J. Soil Sci.,* 39: 327-339.

Banton, O. 1993. Field and laboratory determined hydraulic conductivities considering anisotropy and core surface area. *Soil Sci. Soc. Am. J.*, 57: 10 – 15.

Beare, M.H., Hendrix, P.F. and D.C. Coleman. 1994. Water stable aggregates and organic matter fractions in conventional and no-tillage soils. *Soil sci. Soc. Am. J.*, 58: 777 – 786.

Bengough, A.G. and C.E. Mullins. 1991. Penetrometer resistance, root penetration resistance and root elongation rate in two sandy loam soils. *Plant and Soil*, 131: 59 – 66.

Benjamin, J.G. 1993. Tillage effects on near-surface soil hydraulic properties. *Soil and Tillage Res.,* 26: 277 – 288.

Bennie, A.T.P and G.N. Krynauw. 1985. Causes, adverse effects and control of soil compaction. *South Afric. J. Plant and Soil, 2: 21 - 26.*

Berry, W.A.J, and J.B. Mallett. 1988. The effect of tillage: maize residue interactions upon soil water storage. *South Afric. J. Plant and Soil,* 5(2).

Berry, W.A.J., Mallett, J.B., and M.A. Johnston. 1985. Soil-water conservation as affected by primary tillage practices. *South Afric. J. Plant and Soil*, 2: 21 – 26.

Blackwell, P.S., Ringrose-Voase, P.S., Jayawardane, N.S., Olsson, K.A., McKenzie, D.C., and W.K. Mason. 1990. The use of air-filled porosity and intrinsic permeability to air to characterize structure of macropore space and saturated hydraulic conductivity of clay soils. *J. Soil Sci.*, 41: 215 – 228.

Blake, G.R. 1965. Particle density. *In:* C.A. Black (ed), *Methods of soil analysis*, Part 1, American Society of Agronomy, Madison, WI. pp: 381 – 390.

Blevins, R.L. Thomas, G.W., Smith, M.S., Frye, W.W., and P.L. Cornelius. 1983. Changes in soil properties after ten years continuous non-tilled and conventionally tilled corn. *Soil and Tillage Res.*, 3: 135 – 145.

Børresen, T. 1997. The effect of straw management and shallow tillage/direct drilling on soil properties and crop yield on a loam and a silty loam soil in south-east Norway. Internal report, *Department of Soil and Water Sciences*, Agricultural University of Norway.

Børresen, T. 1999. The effect of straw management and reduced tillage on soil properties and crop yields of spring-sown cereals on two loam soils in Norway. *Soil and Tillage Res.,* 51: 91 – 102.

Børresen, T. and A. Njøs. 1994. The effect of ploughing depth and seedbed preparation on crop yields, weed infestation and soil properties from 1940 to 1990 on a loam soil in Southeastern Norway. *Soil and Tillage Res.*, 32: 21 – 39.

Bosch, D.D., and L.T. West. 1998. Hydraulic variability for two sandy soils. *Soil Sci. Soc. Am. J.*, 62: 90 - 98.

Bouwer, H. 1986. Intake rate: Cylinder infiltrometer. Pages 825-844. In A. Klute, Ed. Methods of soil analysis. Part 1. Physical and mineralogical methods. 2nd ed. Monograph No. 9. *Am. Soc. of Agron.* and *Soil Sci. Soc. Am. J.*, Madison, W.I

Braim, M.A., Chaney, K., and D.R. Hodgson. 1992. Effects of simplified cultivation on the growth and yield of spring barley on a sandy loam soil. II. Soil physical properties and root growth; root: shoot relationships, inflow rates of nitrogen; water use. *Soil and Tillage Res.,* 22: 173 – 187.

Brady, N.C. and R.R. Weil. 1996. *The nature and properties of soils*. Prentice Hall., N-Y.

Bras, R.L. 1990. "*Hydrology: An introduction to hydrology science*". Addison Wesley, Reading, MA.

Brooks, R.H. and A.T. Corey. 1966. Properties of porous media affecting fluid flow. J. *Irrigation Div., Am. Soc. Civ. Eng.*, 92 (IR2): 61 – 88.

Brown, H.J., Cruse, R.M., and T.S. Clovin. 1989. Tillage system effects on crop growth and production costs for a corn-soybean rotation. *J. Prod. Agric.*, 2: 273 – 279.

Bruce, R.R., Langdale, G.W., West, L.T., and W.P. Miller. 1995. Surface soil degradation and soil productivity restoration and maintenance. *Soil sci. Soc. Am. J.,* 59: 654 – 660.

Bullock, P., Newman, A.C.D., and A.J. Thomasson. 1985. Porosity aspects of the regeneration of soil structure after compaction. *Soil and Till. Res.*, 5: 325 – 341.

Burch, G.J., Mason, I.B., Fischer, R.A., and I.D. Moore. 1986. Tillage effects on soils: physical and hydraulic resposnses to direct drilling at Lockhart, N.S.W. *Austr. J. Soil Res.* 24: 377 – 391.

Cannell, R.Q. and J. Hawes. 1994. Trends in tillage practices in ralation to sustainable crop production with special reference to temperate climates. *Soil and Tillage Res.,* 30: 245 – 282.

Campbell, C.A., McConkey, B.G., Zentner, R.P., Dyck, F.B., Selles, F., and D. Curtin. 1995. Carbon sequestration in a brown chernozem as affected by tillage and rotation. *Can. J. Soil Sci.*, 75: 449 – 458.

Capriel, P., Harter, P., and D. Stephenson. 1992. Influence of management on the organic matter of a mineral soil. *Soil Sci.*, 153: 122 – 128.

Carter, M.R. 1992. Characterizing the soil physical condition in reduced tillage systems for winter wheat on a fine sandy loam using small cores. *Can J. Soil Sci.,* 72: 395 – 402.

Carter, M.R. and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: distribution of microbial biomass and mineralizable C and N potentials. *Can. J. Soil Sci.*, 62: 587 – 597.

Cassel, D.K. and D.R. Nielsen. 1986. Field capacity and available water capacity. *In:* Klute, A. (ed). *Methods of soil analysis, Part 1: Physical and mineralogical methods*. Agronomy, monograph no. 9 (2nd ed.). ASA and SSSA.

Cassel, D.K., Raczkowski, C.W., and H.P. Denton. 1995. Tillage effects on corn production and soil physical conditions. *Soil Sci. Am. J.,* 59: 1436 – 1443.

Causarano, H. 1993. Factors affecting the tensile strength of soil aggregates. *Soil and Tillage Res.*, 28: 15 – 25.

Chagas, C.I., Marelli, H.J., and O.J. Santanatoglia. 1994. Propiedades fisicas y contenido hidrico de un Argiudol tipico bajo tres sistemas de labranza. *Ciencia del Suelo*, 12: 11 – 16.

Chan, K.Y., and J.A. Mead. 1989. Water movement and macroporosity of an Australian Alfisol under different tillage and pasture conditions. *Soil and Tillage Res.,* 14:301–310.

Chaney, K., Hodgson, D.R., and M.A. Braim. 1985. Effects of direct drilling, shallow cultivation and ploughing on some soil physical properties in a long-term experiment on spring barley. *J. Agric. Sci.,* 104: 125 – 133.

Chaney, K. and R.S. Swift. 1984. The influence of organic matter on aggregate stability in some British soils. *J. Soil Sci.*, 35: 223 – 230.

Chen, J. and H.S. Wheather. 1999. Identification and uncertainty analysis of soil water retention models using lysimeter data. *Water Resour. Res.*, 35: 2401 – 2414.

Constantz, J., Herkelrath, W.N., and F. Murphy. 1988. Air encapsulation during infiltration. *Soil Sci. Soc. Am. J.*, 52: 10 – 16.

Comia, R.A., Stenberg, M., Nelson, P., Rydberg, T., and I. Hakansson. 1994. Soil and crop responses to different tillage systems. *Soil and Tillage Res.,* 29:335 – 355.

Corey, A.T. 1986. Air permeability. Pages 1121 – 1136. *In* A. Klute, Ed. *Methods of soil analysis. Part 1. Physical and mineralogical methods.* 2nd ed. Monograph No. 9. American society of Agronomy, and Soil Sci. Soc Am. J., Madison, W.I.

Datiri, B.C. and B. Lowery. 1991. Effects of conservation tillage on hydraulic properties of a Griswold silt loam soil. *Soil and Tillage Res.*, 21: 257 – 271.

Dick, W.A. 1983. Organic carbon, nitrogen and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. *Soil Sci. Soc Am. J.*, 47: 102 – 107.

Douglas, J.T., 1986. Effects of season and management on the vane shear strength of a clay topsoil. *J. Soil Sci,* 37: 669 – 679.

Douglas, J.T., Jarvis, M.G., Howse, K.R., And M.J. Goss. 1986. Structure of a silty soil in relation to management. *J. Soil Sci.,* 37: 137 – 151.

Duiker, S.W. and R. Lal. 1999. Crop residue and tillage effects on carbon sequestration in Luvisol in Central Ohio. *Soil and Tillage Res.*, 52: 73 – 81.

Edwards, W.M. 1982. Predicting tillage effects on infiltration. *In:* Unger, P.W. and D.M., Van Doren (eds.), Predicting tillage effects on soil physical properties and process. *ASA*. Special publication No 44, Madison, WI, pp. 105 – 115.

Edwards, W.M., Bonta, J.V., Shipitalo, M.J., and L.B. Owens. 1995. Parent material affects preferential flow in Cochocton lysimeters. *Agronomy Abstr.*, pp. 201.

Edwards, W.M., Riess, F., Bonta, J.V., Shipitalo, M.J., and L.B. Owens. 1997. Preferential flow in Coshocton lysimeters shows importance to sustained production. *In*: Proceedings of the Seventh Gumpensteiner Lysimeter Conference "Lysimeters and Substainable Land-use". BAL Gumpenstein, Austria, pp. 1 – 10.

Edwards, W.M. and L.D. Norton. 1985. Characterizing macropores after 20 years of continuous no-tillage corn. *Agronomy Abst.* p.205.

Edwards, W.M. and L.D. Norton. 1986. Effects of macropores on infiltration into non-tilled soils. *13th Int. conf. Soil Sci.*, 5:47 – 48.

Edwards, W.M., Norton, L.D., and C.E. Redmond. 1988. Characterizing macropores that affect infiltration into non-tilled soil. *Soil Sci. Soc. Am. J.*, 52: 483 – 487.

Ehlers, W. 1976. Rapid dertemination of undisturbed hydraulic conductivity in tilled and untilled loess soil. *Soil Sci. Soc. Am. J.*, 40: 837 – 840.

Elrick, D. E. and W.D. Reynolds. 1992. Infiltration from constant head well permeameters and infitrometers. *In:* Topp, G.C., Reynolds, W.D. and R.E., Green (eds.). *Advances in the measurement of soil physical properties: Bringing theory into practices.* Special Publ. No. 30. Soil Sci. Soc. Am., Madison, WI.

Evans, D.D. and D. Kirkham. 1949. Measurement of air permeability of soil in situ. *Soil Sci. Soc. Am. proc., 19: 65 - 73.*

Ferreras, L.A., Costa, J.L., Garcia, F.O., and C. Pecorari. 2000. Effect of no-tillage on some soil physical properties of a structural degraded Petrocalcic paleudoll of the southern "Pampa" of Argentina. *Soil and Tillage Res.,* 54: 31 – 39.

Francis, G.S., Cameron, K.C., and R.S. Swift. 1987. Soil physical conditions after six years of direct drilling or conventional cultivation on a silt loam soil in New Zealand. *Australian J. Soil Res.,* 25: 517 – 529.

Franzluebbers, A.J. and M.A. Arshad. 1996. Water-stable aggregation and organic matter in four soils under conventional and zero tillage. *Can. J. Soil Sci.*, 76: 387 – 393.

Gantzer, C.J. and G.R. Blake. 1978. Physical characteristics of Le Sueur clay loam soil following no-till and conventional tillage. *Agron. J.,* 70: 853 – 857.

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

Gardner, W.R., Hillel, D., and Y. Benyamini. 1970. Post irrigation movement of soil water: I. Redistribution. *Water Resour. Res.*, 6: 851 – 861.

Gee, G.W. and J.W. Bauder. 1986. Particle size analysis. Pp 383 – 411. In: Klute A. (ed). *Methods of soil analysis Part I. Physical and Mineralogical Methods.* 2nd edition. Am. Soc. Agron. Sol Sci. Soc. Am. Madison., Wisconsin, USA.

Ghildyal, B.P. and R.P. Tripathi. 1987. *Soil Physics.* John & Wiley and Sons. N-Y, USA.

Gómez, J.A., Giráldez, J.V., Pastor, M., and E. Fereres. 1999. Effect of tillage method on soil physical properties, infiltration and yield in an olive orchard. In *Soil and Tillage Res.,* 52: 167 – 175.

Grant, C.A. and G.P. Lafond. 1993. The effects of tillage systems and crop sequences on soil bulk density and penetration on a clay soil in southern Saskatchewan. *Can. J. Soil Sci.*, 73: 223 – 232.

Green, W.H. and G.A. Ampt. 1911. Studies on soil physics: I. Flow of air and water through soils. *J. Agr. Sci.*, 4: 1 – 24.

Gregorich, E.G., Reynolds, W.D., Culley, J.L.B., McGovern, M.A., and W.E., Curnoe. 1993. Changes in soil physical properties with depth in a conventionally tilled soil after no tillage. *Soil and Till. Res.,* 26: 289 – 299.

Groenevelt, P.H., Kay, B.D., and C.D. Grant. 1984. Physical assessment of a soil with respect to rooting potential. *Geoderma*, 34: 101 – 114.

Grover, B. L. 1955. Simplified air permeameters for soil in place*. Soil Sc. Soc. Am. Proc.,* 19: 414 - 418.

Gupta, S.C. and R.R. Allmaras. 1987. Models to assess the susceptibility of soil to compaction. *Adv. Soil Sci.*, 6: 65 – 100.

Hamblin, A.P. and D. Tannant. 1981. The influence of tillage on soil water behavior. *Soil Sci.*, 132: 233 – 239.

Hammel, J.E. 1989. Long-term tillage and crop rotation effects on bulk density and soil impedance in Northern Idaho. *Soil Sci. Soc. Am. J.*, 53: 1515 – 1519.

Hart, P.B.S., August, J.A., Ross, C.W., and J.F. Julian. 1988. Some biochemical and physical properties of Tokomaru silt loam under pasture after 10 years of cereal cropping. *New Zealand J. Agric. Res.*, 31: 77 – 86.

Hassett, J.J. and W.L. Banwart. 1992. *Soils and their environment.* Prentice Hall *Inc.* Englewood Cliffs, New Jersey.

Hatfield, J.L. and B.A. Stewart. 1994. Crops residue management. *Adv. Soil Sci.* Lewis Publ., Boca Rato, FL.

Haynes, R.J. 1993. Effects of samples pretreatments on aggregate stability measured by wet sieving or turbidimetry on soils of different cropping history. *J. Soil Sci.*, 44: 261 – 270.

Haynes, R.J. 1995. Soil Structural breakdown and compaction in New Zealand soils. Towards Substainable Agriculture. A report prepared for MAF Policy. Technical paper 95/5.

Haynes, R.J. 1999. Size and activity of the soil microbial biomass under grass and arable management. *Biol. Fertil. Soils.*, 30: 210 – 216.

Haynes, R. J. and M.H. Beare. 1996. Aggregation and organic matter storage in meso-thermal, humid soils. *In*: Carter M.R., Stewart, B.A. (eds). *Advances in Soil Science. Structure and organic matter storage in agricultural soils.* CRC Lewis, Boca Raton, pp. 213 – 262.

Haynes, R.J. and T.L. Knight. 1988. Comparison of soil chemical properties, enzyme activities, levels of biomass N and aggregate stability in the soil profile under conventional and no-tillage in Canterbury, New Zealand. *Soil and Tillage Res.*, 14: 197 – 208.

Haynes, R.J. and R. Tregurtha. 1999. Effects of increasing periods under intensive arable vegetable production on biological, chemical and physical indices of soil quality. *Biol. Fertil. Soils.*, 28: 259 – 266.

Heard, J.R., Kladivko, E.J. and J.V. Mannering. 1988. Soil macroporosity, hydraulic conductivity and air permeability of silty soils under long-term conservation tillage in Indiana. *Soil and tillage Res.*, 11: 1 – 18.

Heer, W.F. and E.G. Jr. Krenzer. 1989. Soil water availability for spring growth of winter wheat (*Triticum aestivum L.*) as influenced by early growth and tillage. *Soil & Tillage Res.*, 14: 185 – 196.

Hill, P.R. and J.E. Lake. 1992. PEP$ A dollar-and-cent approach to conservation tillage. *J. Soil water conserv.*, 47: 131 – 133.

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

Hill, R.L. 1990. Long-term conventional and No-tillage effects on selected soil physical properties. *Soil Sci. Soc. Am. J.,* 54: 161 - 166.

Hill, R.L. and M. Meza-Montalvo. 1990. Long-term wheel traffic effects on soil physical properties under different tillage systems. *Soil Sci. Soc. Am. J.*, 54: 856 – 870.

Hillel, D. 1980a. *Fundamentals of soil physics.* Academic press Inc. (London) Ltd.

Hillel, D. 1980b. *Applications of soils physics.* Academic press. New York. USA

Hillel, D. 1998. *Environmental soil physics.* Academic press. San Diego. USA.

Hoffman, J.E. 1990. *Die invloed van grondbewerkingspraktyke op die waterbalans van 'n Avalongrond onder koring te Bethlehem.* Unpublished M.sc. Thesis. University of the Orange Free State, Bloemfontein.

Holt, J.A, Robertson, L.N., and B.J. Radford. 1993. Effects of tillage and stubble residue treatments on termite activity in two central Queensland Vertisols. *Austr. J. Soil Res.*, 31: 311 – 317.

Horne, D.J., Ross, C.W., and K.A. Huges. 1992. Ten years of a maize oats rotation under three tillage systems on a silt loam in New Zealand. 1. A comparison of some soil properties. *Soil and Tillage Res.,* 22: 131 – 143.

Janse, A.R.P. and G.H. Bolt. 1960. The determination of the air permeability of soils. *Neth. J. Agric. Sci,* 8: 124 - 131.

Jayawardene, N.S. and P.S. Blackwell. 1990. Use of the neutron method in assessing the changes in soil strength of undisturbed and ameliorated transitional red-brown earths during soil drying cycles. *Austr. J. Soil Res.*, 28: 167 – 176.

Johnson, J.F., Voorhees, W.B., Nelson, W.W., and G.W. Randall. 1990. Soybean growth and yield as affected by surface and subsoil compaction. *Agron. J.,* 82: 973 – 979.

Johnston, M.A. 2001. Personnal communication. Soil Science Department. University of Natal Pietermaritzburg.

Katou, H., Miyaji, K., and T. Kubota. 1987. Susceptibility of undisturbed soils to compression as evaluated from the changes in the soil water characteristic curves. *Soil Sci. Plant Nutri.*, 33: 539 – 554.

Katsvairo, T., Cox, J.W, and H.M. van Es. 2002. Tillage and rotation effects on soil physical characteristics. *Agron. J.*, 94: 299 – 304.

Karunatilake, U., Van Es, H.M., and R.R. Schindelbeck. 2000. Soil and maize response to plow and no-tillage after alfalfa-to-maize conversion on a clay loam soil in New-York. *Soil and Tillage Res., 55: 31 – 42.*

Kay, B.D. 1990. Rates of change of soil structure under different cropping systems. *Adv. in soil Sci.,* 12: 1 – 52.

Kemper, W.D., Trout, T.J., Segren, A., and M. Bullock. 1987. Worms and water. *J. Soil Water Cons.*, 42: 401.

Kern, J.S. 1995. Evaluation of soil water retention models based on basic soil properties. *Soil Sci. Soc. Am. J.,* 59: 1134 – 1141.

Kirby, J.M. and G. Kirchhoff. 1990. The compaction process and factors affecting soil compactibility. In: Hunter, M.N., Paull, C.J., Smith, G.D. (eds*), Proceedings of the queensland department of primary industries. Soil compaction workshop.* Toowoomba, Australia.

Kirkham, D. 1947. Field method for determination of air permeability of soil in its undisturbed state. *Soil Sci. Soc. Am. Proc.,* 11: 93 - 99.

Klute, A., 1986. *Methods of soil analysis, Part 1: Physical and mineralogical methods.* Agronomy, monograph no. 9. (2nd ed.). ASA and Soil Sci. Soc. Am.

Kostiakov, A.N. 1932. On the dynamics of the coefficient of water percolation in soils and on the necessity for studying it from a dynamic point of view for purposes of amelioration. *Trans. Com. Int. Soc. Soil Sci.*, Moscow, Part A, pp 17 – 21.

Kravchenko, A. and R. Zhang. 1998. Estimating the soil water retention from particle-size distributions: a fractal approach. *Soil Sci.*, 163: 171 – 179.

Krzic, M., Fortin, M.C., and A.A. Bomke. 2000. Short-term responses of soil physical properties to corn tillage-planting systems in a humid maritime climate. *Soil and Tillage Res.,* 54: 171 – 178.

Lal, R. 1978. Influence of tillage methods and residue mulches on soil structure and infiltration rate. pp. 393 - 402. *In:* Emerson, W.W, Bond, R.D. and Dexter, A.R. (eds). *Modification of soil structure*. John Wiley and Sons, New York.

Lal, R. and D.M. Van Doren. 1990. Influence of 25 years of continuous corn production by three tillage methods on water infiltration for two soils in Ohio. *Soil and Tillage Res.*, 16: 71 – 84.

Lal, R., Mahboubi, A.A., and N.R. Fausey. 1994. Long-term tillage and rotation effects on properties of a central Ohio soil. *Soil Sci. Soc. Am. J.* 58: 517 – 522.

Laliberte, G.E. 1969. A mathematical function for describing capillary pressure-desaturation data. *Bull. Int. Ass. Sci. Hydrol.*, 14: 131 – 149.

Lang, P.M. and J.B. Mallett. 1984. Effect of the amount of surface maize residue on infiltration and soil loss from a clay loam soil. *South Afric. J. Plant and Soil,* 1: 97 – 98.

Larney, F.J. And C.W. Lindwall. 1995. Rotation and tillage effects on available soil water for winter wheat in a semi-arid environment. *Soil and tillage Res.*, 36: 111 – 127.

Larney, F.J., Bremer, E., Janzen, H.H., Johnston, A.M., and C.W. Lindwall. 1997. Changes in total, mineralizable and light fraction soil organic matter with cropping and tillage intensities in semi-arid southern Alberta, Canada. *Soil and Tillage Res.*, 42: 229 – 240.

Lawrance, K.F. 2000. *The sustainability of different levels of tillage for maize production on two different soil types in KwaZulu-Natal.* Unpublished M.Sc. in Sustainable Agric. Thesis. University of Orange Free State, Centre for Substainable Agriculture, Faculty of Agriculture.

Lawrance, K.F., M.A. Prinsloo, and W.A.J. Berry. 1999. Long and short term effects of tillage systems on grain yield, the incidence of diseases and production costs of maize. *South Afric. J. Plant and Soil,* 16 (2).

Lehrsch, G.A., Whisler, F.D., and M.J.M. Romkens. 1988. Spatial variation of parameters describing soil surface roughness. *Soil Sci. Soc. Am. J.,* 52 (2): 311 – 319.

Levy, G.J. and W.P. Miller. 1997. Aggregate stabilities of some Southeastern U.S. soils. *Soil Sci. Soc. Am. J.*, 61: 1176 – 1182.

Liebig, M.A., Jones, A.J., Mielke, L.N., and J.W. Doran. 1993. Controlled wheel traffic effects on soil properties in ridge tillage. *Soil Sci. Soc. Am. J.* 57: 1061 – 1066.

Linden, D.R. and D.M. Van Doren. 1986. Parameters for characterizing tillage induced soil surface roughness. *Soil Sci. Soc. Am. J.,* 50 (6): 1560 – 1565.

Lindstrom, M.J., Voorhees, W.B., and G.W. Randall. 1981. Long-term tillage effects on inter-row runoff and infiltration. *Soil Sci. Soc. Am. J.*, 45: 945 – 948.

Logsdon, S.D, Allmars, R.R., Wu, L., Swan, J.B., and G.W. Randall. 1990. Macroporosity and its relationship to saturated hydraulic conductivity under different tillage practices. *Soil Sci. Soc. Am. J.*, 54: 1096 – 1101.

Lowery, B. and R.T. Schuler. 1991. Temporal effects of subsoil compaction on soil strength and plant growth. *Soil Sci. Soc. Am. J.* 55:216 – 223.

Mahboubi, A.A. and R. Lal. 1998. Long-term tillage effects on changes in structural properties of two soils in central Ohio. *Soil and Tillage Res.,* 45: 107 – 118.

Mahboubi, A.A., Lal, R., and N.R. Fausey. 1993. Twenty eight years of tillage effects on two soils in Ohio. *Soil Sci. Soc Am. J.,* 57: 506 – 512.

Mannering, J.V and C.R. Fenster. 1983. What is conservation tillage? *J. Soil Water Cons.*, *38 (3):* 141 – 143.

Marshall, T.J. and J.W. Holmes. 1979. *Soil Physics*. Cambridge University Press. Cambridge, UK.

Marshall, T.J. and J.W. Holmes. 1988. *Soil Physics.* 2nd edition. Cambridge University Press. Cambridge, UK.

Materechera, S.A. and H.R. Mloza-Banda. 1997. Soil penetration resistance, root growth and yield of maize as influenced by tillage system on ridges in Malawi. *In Soil and Tillage Res.,* 41: 13 – 24.

McGarry, D., Bridge, B.J., and B.J. Radford. 2000. Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. *Soil and Tillage Res.* 53: 105 – 115.

McIntyre. D.S. 1958. Permeability measurements on soil crusts formed by raindrop impact. *Soil Sci.,* 85: 185 – 189.

Mcvicar, C.N., De Villiers, J.M., Loxton, R.F., Verster, E., Lamprechts, J.J.N., Merryweather, F.R., Le Roux, J., Van Rooyen, T.H., and H.J. von M. Harmse. 1977. Soil classification: a taxonomic system for South Africa. The Department of Agricultural Development, South Africa.

Meek, B.D., De Tar, W.R., Rolph, D., Rechel, E.R., and L.M. Carter. 1990. Infiltration rate as affected by an alfalfa and no-till cotton cropping system. *Soil sci. Soc. Am. J.,* 54: 505 – 508.

Metting, F.B. 1993. *Soil Microbial Ecology: Applications in agricultural and environmental management.* Marcel Dekker, New York.

Mein, R.G. and C.L. Larson. 1973. Modelling infiltration during a steady rain. *Water Resource Research*, 9(2): 384 – 394.

Mielke, L.N., Doran, J.W., and K.A. Richards. 1986. Physical environment near the surface of plowed and no-tilled soils. *Soil and Tillage Res.*, 7: 355 – 366.

Mielke, L.W., Wilhelm, W.W., Richards, K.A., and C.R. Fenster. 1984. Soil physical characteristics of reduced tillage in a wheat-fallow system. *Trans. ASAE*, 27: 1724 – 1728.

Miller, R.W. And R.L. Donahue. 1995. *Soils in our environment.* 7th ed.- Prentice Hall Inc. Englewood Cliffs, New Jersey.

Moodley, M. 2001. *Effects of the land disposal of water treatment sludge on soil physical quality.* Unpublished PhD thesis, University of Natal Pietermaritzburg.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.,* 12: 513 – 522.

Mullins, C.E., Young, I.M., Bengough, A.G. and G.J. Ley. 1987. Hard-setting soils. *Soil use and Management,* 3: 79 – 83.

Mullins, C.E., McLeod, D.A., Northcote, K.H., Tisdall, J.M. and I.M. Young. 1990. Hard-setting soils: Behaviour, occurrence and management. *Adv. in Soil Sci.,* 11: 37 – 108.

Musto, J.W. 1994. Changes in soil physical properties and related hydraulic characteristics caused by *Eucalyptus* plantations. Unpublished Msc Thesis, Dept. of Agron. University of Natal, Pietermaritzburg.

Ngunjiri, G.M.N. and J.C. Siemens. 1995. Wheel traffic effects on corn growth. *Trans. ASAE*, 38: 691 – 699.

Ohu, J.O., Raghavan, G.S.V., Mckyes, E., and G. Mehuys. 1986. Shear strength prediction of compacted soils with varying organic matter content. *Trans. ASAE*, 30(4): 351 – 355.

O'Sullivan, M.F., Dickson, J.W. and D.J. Campbell. 1987. Interpretation and presentation of cone resistance data in tillage and traffic studies. *J. Soil Sci.,* 38: 137 – 148.

Paustian, K. Collins, H.P., and E.A. Paul. 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K, Elliott, E.T., and C.V., Cole. (eds.), *Soil organic matter in temperate agroecosystems: Long-term experiments in North America*. CRC. Press. Boca Raton, USA. pp 15 – 49.

Perroux, K.M., and I. White. 1988. Designs for disc permeameter. *Soil sci. soc. Am. J.* 52: 1205 – 1215.

Philip, J.R. 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. *Soil Sci.* 84: 257 – 264.

Philip, J.R. 1993. Constant-rainfall infiltration on hillslopes and slopercrests. *In*: Russo, D. and Dagan, G. (eds.). *Water flow and solute transport in soils: Developments and applications*. Springer-Verlag, Berlin.

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

Pierce, L.T. 1958. Estimating seasonal and short-term fluctuations in evapotranspiration in meadow crops. *Bull. Am. Meteorol. Soc.*, 39: 73 – 78.

Pierce, F.J., Fortin, M.C., and M.J. Staton. 1994. Periodic plouwing effects on soil properties in a no-till farming system. *Soil Sci. Soc. Am. J.*, 58: 1782 – 1787.

Pikul Jr, J.L., Ramig, R.E., and D.E. Wilkins. 1993. Soil properties and crop yield among four tillage systems in a wheat-pea rotation. *Soil and Tillage Res.,* 26: 151 – 162.

Proffitt, A.P.B., Bendotti, S. and D. McGarry. 1995. A comparison between continuous and controlled grazing on a red-duplex soil. I. Effects on soil physical characteristics. *Soil and Tillage Res.*, 35: 199 – 210.

Prove, B.G., Loch, R.J., Foley, J.L., Anderson, V.J., and D.R. Younger. 1990. Improvements in aggregation and infiltration characteristics of a krasnozem under maize with direct drill and stubble retention. *Austr. J. Soil Res.*, 28: 577 – 590.

Radcliffe, D.E. and T.C. Rasmussen. 2000. Soil water movement. *In* Summer, M.E. (Ed.) Handbook of soil science. CRC Press, Boca Raton, Florida.

Radford, B.J., Key, A.J., Robertson, L.N., and G.A. Thomas. 1995. Conservation tillage increases soil water storage, soil animal populations, grain yield and response to fertilizer in the semi-arid subropics. *Australian J. Exp. Agric.,* 35:223 - 232.

Raghavan, G.S.V., Alvo, P., and E. Mckyes. 1992. Soil compaction in agriculture: a view toward managing the problem. *Adv. In Soil Sci.,* 11:1 – 35.

Rapel, R.L., Reeves, D.W., Burt, E.C., and H.A. Torbert. 1993. Conservation tillage and traffic effects on soil condition. *Trans. ASAE*, 37: 763 – 768.

Rasmussen, K.J. 1984. Methods of tillage for spring barley on coarse sandy soils. *Dan. J. Plant Soil Sci.,* 88: 443 – 452.

Rasmussen, K.J., 1999. Impact of ploughless soil tillage on yield and soil quality: A Scandinavian review. *Soil and Tillage Res.,* 53: 3 –14.

Reeve, M.J. and A.D. Carter. 1991. Water release characteristic. *In:* Smith, K.A. and Mullins, C.E. (eds.) Soil analysis: physical methods. Publ. Marcel Dekker, Inc. N-Y.

Reynolds, W.D., Elrick, D.E., and G.C. Topp. 1983. A re-examination of the constant head well permeameter method for measuring saturated hydraulic conductivity above the water table. *Soil Sci.*, 136: 250 – 268.

Richards, L.A. 1949. Methods of measuring soil moisture tension. *J. Soil Sci.*, 68:95 - 112.

Richards, L.A. And C.H. Wadleigh. 1952. Soil water in plant growth. *In:* Soil physical conditions and plant growth. *Agronomy* 2, 13.

Riley, H., Børresen, T., Ekeberg, E., and T., Rydberg. 1994. Trends in reduced tillage research and practice in Scandinavia. In: Carter, M.R. (ed), Conservation Tillage *In*: temp. Agroecosystems. Lewis Publishers, pp. 23 – 45.

Riley, H. and E. Ekeberg. 1998. Effects of depth and time of ploughing on yields of spring cereals and potatoes and on soil properties of a morainic loam soil. *Acta Agric. Scand. Sect.. B* 48: 193 – 200.

Ritchie, J.T., Burnet, E., and R.C. Henderson. 1972. Dryland evaporative flux in a subhumid climate: III. Soil water influence. *Agron. J.*, 64: 168 – 173.

Roseberg, R.J. and E.L. McCoy. 1990. Measurement of soil macropore air permeability. *Soil Sci. Soc. Am. J.,* 54: 969 – 974.

Roseberg, R.J. and E.L. McCoy. 1992. Tillage and traffic induced changes in macroporosity and macropore continuity: air permeability assessment. *Soil Sci. Soc. Am. J.,* 56: 1261 – 1267.

Rydberg, T. 1986. Effects of ploughless tillage on soil physical and soil chemical properties in Sweden. *Div. Soil Management*, Uppasala, Sweden. Report No 70, 35pp.

Rydberg, T. 1990. Effects of ploughless tillage and straw incorporation on evaporation. *Soil and Tillage Res.*, 17: 303 – 314.

Savage, M. 2001. Personnal communication. Agrometeorology Department. University of Natal Pietermaritzburg.

Shainberg, I., M.E. Summer, W.P. Miller, M.P.W. Farina, M.A. Pavan, and M.V. Fey. 1989. Use of gypsum on soils. *Adv. in Soil Sci.,* Vol. 9.

Sharratt, B.S. 1996. Tillage and straw management for modifying physical properties of a subarctic soil. *Soil and Tillage Res.,* 38: 239 – 250.

Shipitalo, M.J., Dick, W.A., and W.M. Edwards. 2000. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. *Soil and Tillage Res.*, 53 : 167 – 183.

Singh, B., Chansyk, D.S., and W.B. McGill. 1998. Soil water regime under barley with long-term tillage-residue systems. *Soil and Tillage Res.,* 45: 59 – 74.

Smika, D.E. and P.W. Unger. 1986. Effects of surface residues on soil water storage. *In*: Stewart, B.A., (ed), *Adv in Soil Sci.,* 5: 111 – 138.

Smith, C.W. 1995. *Assessing the compaction susceptibility of South African forestry soils.* Unpublished PhD Thesis. University of Natal Pietermaritzburg.

Smith, R.E. 1999. Technical note: rapid measurement of soil sorptivity. *Soil Sci. Soc. Am. J.*, 63: 55 – 57.

Smith, C.W, Johnston, M.A., and S. Lorentz. 1997. Assessing the compaction susceptibility of South African forestry soils. I. The effect of soil type, water content and applied pressure on uni-axial compaction. *Soil and Till Res.,* 41: 53 - 73.

Smith, C.W, Johnston, M.A., and S. Lorentz. 2001. The effect of soil compaction on the water retention characteristics of soils in forest plantations. *South Afric. J. Plant and Soil,* 18 (3): 87 – 97.

Smith, P. and J. Thonasson. 1974. Density and water-release characteristics. *In*: Avery, B.W. and C.L Bascomb (eds). *Soil survey laboratory methods.* Technical monograph No 6. Rothamsted Experimental station, Harpenden, Herts, UK.

Soane, B.D., Blackwell, P.S., Dickson, J.W., and D.J. Painter. 1981. Compaction by agricultural vehicles: A review, I. Soil and wheel characteristics. *Soil and Tillage Res.*, 1: 207 – 237.

Soil and Irrigation Research Institute. 1991. Long term meteorological data for the Natal region. Report no GB/A/91/33. Agrometeorology. Department of agricultural Development. Pretoria.

Soil Classification Working Group. 1991. *Soil Classification*: a Taxonomic System for South Africa. *Memoirs on the Agricultural Natural Resources of South Africa*. No. 15. Department of Agricultural Development. Pretoria, pp 257.

South African Wheather Service. 2002. *http:/www.weathersa.co.za.*

Sprague, M.A. and G.B. Triplett. 1986. No-tillage and surface tillage agriculture - The tillage revolution. John Wiley and Sons. New York.

Su, C., and R.H. Brooks. 1975. Soil Hydraulic properties from infiltration tests. Watershed Management Proceedings, *Irrigation and Drainage Div., ASCE*, Logan,Utah, August 11 – 13. pp 516 – 542.

Thornthwaite, C.W. and J.R. Marther. 1955. The water budget and its use in irrigation. USDA Yearb. *Agric.,* 346 – 358.

Tisdall, J.M. and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. *J. Soil Sci.*, 33: 141 – 163.

United States Geological Survey. 2002. *http://edcimswww.cr.usgs.gov/ims-bin/pub/nph-ims.cgi*

Unger, P.W. 1990. Conservation tillage systems. In Singh et al. (eds), *Adv. In Soil Sci.* 13: 27 – 68. Springer, New-York.

Unger, P.W. and O.R. Jones. 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. *Soil and Tillage Res.*, 45: 39 - 57.

Van Doren Jr., D.M., Moldenhauer, W.C., and G.B. Triplett Jr. 1984. Influence of long-term tillage crop rotations on water erosion. *Soil Sci. Sco. Am. J.*, 48: 636 – 640.

Vanderlinden, K., Gabriels, D., And J.V. Giraldez. 1998. Evaluation of infiltration measurements under olive trees in Cordoba. *Soil and Tillage Res.,* 48: 303 – 315.

Van Genuchten, M.Th. 1978. Calculating the unsaturated hydraulic conductivity with a new closed-form analytical model. Research report 78-WR-08. Dept. of Civil Eng., Princeton Univ., Princeton, New Jersey. pp 63

Visser, W.C. 1966. Progress in the knowledge about the effect of soil moisture content on plant production. *Tech. Bull.* No 45. Inst. Land Water Management, Wageningen, Netherlands.

Voorhees, W.B. 1992. Wheel-induced soil physical limitations to root growth. *Adv. in Soil Sci.,* 19 - 95.

Vyn, T.J. and B.A. Raimbault. 1993. Long-term effect of five tillage systems on corn response and soil structure. *Agron. J.*, 85: 1074 – 1079.

Walkley, A. 1947. A critical examination of a rapid method for determining organic carbon in soils-effects of variations in digestion conditions and of inorganic constituents. *Soil Sci.*, 63: 251 – 264.

Wander, M.M., Bidart B.G., and S. Aref. 1998. Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. *Soil Sci. Soc. Am J.*, 62:1704–1711.

White, N.F., Duke, H.F., Sunade, D.K., and A.T. Corey. 1970. Physics of desaturation in porous materials. *J. Irrig. – Drainage Div. Am. Soc. Civ. Eng.*, 96: 165 – 191.

Wilson, B.N., Slack, D.C., and R.A. Young. 1982. A comparison of three infiltration models. *Trans. ASEA*, 25 (11): 1309 – 1313.

Wu, L., Allmaras, R.R., Gimenez, D., and D.M. Huggins. 1997. Shrinkage and water retention characteristics in a fine textured Mollisol compacted under different tractor loads. *Soil and Tillage Res.*, 44: 179 - 194.

Wu, L. Swan, J.B., Paulson, W.H., and G.W. Randall. 1992. Tillage effects on measured soil hydraulic properties. *Soil and Tillage Res.,* 25: 17 – 33.

Yang, X. and M.M. Wander. 1999. Tillage effects on soil organic carbon and storage in a silt loam soil in Illinois. *Soil and Tillage Res.*, 52: 1 – 9.

Yavuzcan, H.G. 2000. Wheel traffic impact on soil conditions as influenced by tillage system in Central Anatolia. *Soil and Tillage Res.*, 54: 129 – 138.

Yoder, R.E. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of soil erosion losses. *J. Am. Soc. Agron.*, 28: 337 – 351.

Zhang, X.C. and W.P. Miller. 1996. Polycrylamide effects on infiltration and erosion in furrows. *Soil Sc. Soc. Am. J.*, 60: 866 – 872.

Zimbone, S.M., Vickers, A., Morgan, R.P.C., and P. Vella. 1996. Field investigations of different techniques for measuring surface soil shear strength. *Soil Technology* 9: 101 – 111.

Zuzel, J.F, J.L. Pikul, Jr., and P.E. Rasmussen, 1990. Tillage and fertilizer effects on water infiltration. *Soil Sci. Soc. Am. J.*, 54: 205 – 208.

Appendices

Appendix 1. Profile description, site information and detailed soil physical and chemical properties for each site

Profile 1: Mr R. Lund's farm (site 1)

Soil Form	: Hutton
Location	: Winterton
Latitude/Longitude	: 28° 52' S / 29° 31' E
Altitude	: 1067 m
Land use	: Irrigated maize under NT
Tillage system	: NT by 7 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark reddish brown (5YR 3/4); clay; weak, medium subangular blocky; moist, firm; gradual transition to A2
A2	10 - 27	Yellowish red (5 YR/ 4/4); clay; weak, medium subangular blocky; moist, firm; abrupt transition to B
B	27 - 45	Red (2.5 YR 4/6); clay; weak, medium subangular blocky; moist, friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 - 10	50.6	30.0	9.1	7.0	1.4	1.0	Silt clay
A2	10 - 27	57.1	24.8	9.2	6.9	1.1	0.9	Silt clay
B	27 - 45	64.7	21.5	7.0	5.6	0.8	0.6	Clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	42	502	1214	311	12.2	35	0.18	10.08	2	4.25
2.5 - 5	12	572	1127	292	9.6	21	0.14	9.63	1	4.48
5 - 10	9	502	1134	268	8.3	20	0.07	9.22	1	4.51
10 - 15	4	419	1169	282	5.9	16	0.06	9.29	1	4.60
10 - 27	4	409	1092	277	5.5	70	0.06	8.83	1	4.85
27 - 45	1	221	854	252	0.9	50	0.07	6.97	1	4.73

Profile 2: Mr Boschoff's farm (site 2)

Soil Form	: Hutton
Location	: Winterton
Latitude/Longitude	: 28° 52' S / 29° 31' E
Altitude	: 1067 m
Land use	: Dryland soybean under CT
Tillage system	: CT by more than 50 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Yellowish red (5YR 7/6); clay; weak subangular blocky; slightly moist, friable; wavy transition to A2
A2	10 - 28	Dark reddish brown (5 YR 3/4); clay; weak, medium subangular blocky; moist, slightly firm; abrupt transition to B
B	28 - 43	Red (2.5 YR 4/8); clay; weak, medium subangular blocky; slightly moist and firm.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 - 10	56.7	22.9	9.8	7.9	1.2	0.8	Clay
A2	10 - 28	58.5	22.9	9.3	7.6	0.9	0.7	Clay
B	28 - 43	60.6	23	7.8	6.9	0.9	0.9	Clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	17	306	1043	358	4.4	31	0.18	9.11	2	4.41
2.5 - 5	11	255	962	338	3.9	19	0.17	8.40	2	4.37
5 - 10	14	243	1019	362	4.8	24	0.13	8.82	1	4.42
10 - 15	19	154	882	296	3.3	21	0.36	7.59	5	4.12
10 - 28	8	108	782	228	2.6	120	0.35	6.40	5	4.11
28 - 43	2	69	978	277	.08	50	0.09	7.43	1	4.72

Profile 3: Mr van Der Aardweg's farm (site 3)

Soil Form	: Avalon
Location	: Winterton
Latitude/Longitude	: 28° 52' S / 29° 31' E
Altitude	: 1067 m
Land use	: Irrigated maize under NT
Tillage system	: NT by 7 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark grayish brown (10YR 4/2); loam; weak, medium subangular blocky; moist, friable; gradual transition to A2
A2	10 - 27	Dark grayish brown (10YR/ 4/3); loam; weak, medium subangular blocky; moist, friable; abrupt transition to B
B	27 - 42	Yellowish brown (10YR 5/4); clayey loam; weak, medium subangular blocky; moist, friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 - 10	24.4	22	21.3	22.3	6.9	2.1	Loam
A2	10 - 27	25.1	26	17.8	21.8	6.7	2.1	Loam
B	27 - 42	32.6	20.2	17.1	21.1	6.6	2.1	Clay loam

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	51	420	778	176	17.3	29	0.28	6.68	4	4.07
2.5 - 5	77	280	539	123	9.2	13	0.71	5.13	14	3.88
5 - 10	29	196	549	120	7.5	12	0.62	4.85	13	3.93
10 - 15	13	133	601	128	5.7	10	0.77	5.16	15	3.93
10 - 27	21	191	651	131	6.6	32	0.47	5.29	9	4.00
27 - 42	1	97	787	180	1.1	5	0.11	5.77	2	4.43

Profile 4: Mr van Vuuven's farm (site 4)

Soil Form	: Avalon
Location	: Winterton
Latitude/Longitude	: 28° 52' S / 29° 31' E
Altitude	: 1067 m
Land use	: Dryland maize under CT
Tillage system	: CT by more than 10 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark grayish brown (10YR 4/2); loam; weak subangular blocky; slightly moist, loose; wavy transition to A2
A2	10 - 27	Brown (10YR/ 4/3); loam; weak, medium subangular blocky; moist, friable; abrupt transition to B
B	27 - 44	Yellowish brown (10YR 5/6); clayey; weak, medium subangular blocky; moist, friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 - 10	24.4	19.4	19.4	24.0	7.8	3.7	Loam
A2	10 - 27	23.4	20.1	19.8	24.0	8.4	3.8	Loam
B	27 - 44	34.0	20.5	14.1	19.9	5.3	5.5	Clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	47	419	590	169	10.1	14	0.43	5.84	7	4.06
2.5 - 5	40	281	543	149	10.7	13	0.48	5.13	9	4.02
5 - 10	46	230	612	160	10.7	12	0.62	5.58	11	4.00
10 - 15	29	201	639	167	11.1	19	0.56	5.64	10	4.07
10 - 27	38	172	511	131	10.3	28	0.34	4.41	8	4.14
27 - 44	1	92	903	186	1.5	2	0.05	6.32	1	4.93

Profile 5: Mr Miurhead's farm (site 5A)

Soil Form	: Hutton
Location	: Winterton
Latitude/Longitude	: 28° 52' S / 29° 31' E
Altitude	: 1067 m
Land use	: Irrigated maize under NT
Tillage system	: NT by 10 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark reddish brown (5YR 3/4); clay; weak, medium subangular blocky; moist, slightly sticky, friable; gradual transition to A2
A2	10 - 20	Dark reddish brown (2.5YR 3/4); clay; weak, medium subangular blocky; moist, sticky, friable; abrupt transition to B
B	20 - 40	Red (2.5YR 4/8); clay; weak, medium subangular blocky; moist, sticky, slightly friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
0 - 10	A1	37.9	25.2	11.1	17.1	6.4	1.4	Clay
10 - 20	A2	48.1	18.5	11.5	15.6	4.9	0.6	Clay
20 - 40	B	46.3	22.8	10.4	15.6	4.5	0.6	Clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	54	147	1443	355	13.7	11	0.06	10.56	1	5.16
2.5 - 5	59	104	1345	311	14.5	7	0.07	9.61	1	5.32
5 - 10	11	74	1094	261	7.8	6	0.05	7.85	1	5.05
10 - 15	2	79	785	210	1.6	3	0.03	5.88	1	5.09
10 – 20	2	52	864	248	0.8	8	0.07	6.56	1	5.14
20 - 40	1	35	461	164	0.5	4	0.31	4.05	8	4.42

Profile 6: Mr Miurhead's farm (site 5B)

Soil Form	: Hutton
Location	: Winterton
Latitude/Longitude	: 28° 52' S / 29° 31' E
Altitude	: 1067 m
Land use	: Dryland maize under NT
Tillage system	: NT by 10 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Brown (7.5YR 4/4); clay; weak, medium subangular blocky; moist, slightly sticky, friable; gradual transition to A2
A2	10 - 20	Yellowish red (5YR 4/6); clay; weak, medium subangular blocky; moist, sticky, friable; abrupt transition to B
B	20 - 40	Red (2.5YR 4/6); clay; weak, medium subangular blocky; moist, sticky, slightly friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 – 10	41.5	23.3	12.0	15.6	5.3	1.9	Clay
A2	10 – 20	40.3	25.7	11.2	16.3	5.5	1.0	Clay
B	20 - 40	39.6	26.4	10.3	16.8	6.2	0.9	Clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	24	249	1296	242	4.9	5	0.08	9.18	1	5.60
2.5 - 5	14	208	982	169	8.8	15	0.19	7.01	3	4.46
5 - 10	6	84	857	168	9.1	12	0.42	6.29	7	4.20
10 - 15	12	64	728	165	9.7	11	0.72	5.87	12	4.04
10 - 20	10	71	476	117	5.4	19	0.83	4.35	19	3.95
20 - 40	1	48	430	148	1.4	11	0.92	4.41	21	4.07

Profile 7: Mr Mostert's farm (site 6)

Soil Form	: Hutton
Location	: Winterton
Latitude/Longitude	: 28° 52' S / 29° 31' E
Altitude	: 1067 m
Land use	: Dryland maize under CT
Tillage system	: CT by more than 50 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark reddish brown (2.5YR 3/4); clay; weak subangular blocky; moist, loose; wavy transition to A2
A2	10 - 20	Yellowish red (5YR 4/6); clay; weak, medium subangular blocky; moist, slightly friable; abrupt transition to B
B	20 - 40	Red (2.5YR 4/6); clay; weak, medium subangular blocky; moist, sticky, slightly friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 - 10	45.2	24.0	11.7	13.8	3.7	1.2	Clay
A2	10 - 20	44.7	24.3	11.3	13.7	4.4	1.1	Clay
B	20 - 40	49.3	20.7	12.0	14.0	3.6	0.9	Clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	11	139	1121	186	2.0	7	0.11	7.59	1	5.12
2.5 - 5	14	105	1375	229	2.3	5	0.07	9.08	1	5.57
5 - 10	9	78	1237	230	2.1	15	0.06	8.33	1	5.53
10 - 15	9	58	1034	190	2.3	10	0.11	6.98	2	4.58
10 - 20	32	52	545	105	2.2	29	0.37	4.09	9	4.05
20 - 40	1	54	463	117	1.0	14	0.91	4.32	21	4.09

Profile 8: Mr J. Jackson's farm (site 7)

Soil Form	: Avalon
Location	: Bergville
Latitude/Longitude	: 28° 48' S / 29° 23' E
Altitude	: 1310 m
Land use	: Irrigated soyabean under NT
Tillage system	: NT by 12 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark grayish brown (10YR 4/2); silty clay; medium subangular blocky; moist, friable; gradual transition to A2
A2	10 - 20	Brown (10YR 5/3); silty clay; weak, medium subangular blocky; moist, slightly friable; abrupt transition to B
B	28 - 40	Yellowish brown (10YR 5/4); silty clay; weak, medium subangular blocky; moist, slightly friable; soft plinthite.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 – 10	33.9	30.5	17.8	12.7	2.7	1.7	Silt-clay-loam
A2	10 – 20	39.6	28.6	18.9	10.9	1.5	0.3	Silt-clay-loam
B	28 - 40	44.3	26.5	17.1	10.1	1.4	0.3	Silt-clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	62	145	819	246	16.9	38	0.77	7.25	11	3.86
2.5 - 5	24	108	525	178	7.6	17	1.60	5.96	27	3.87
5 - 10	20	76	499	157	7.2	13	1.47	5.45	27	3.89
10 - 15	44	75	495	152	6.7	12	1.57	5.48	29	3.89
10 - 20	8	69	470	140	3.9	27	1.01	4.68	22	3.94
20 - 28	5	63	466	132	2.8	22	0.99	4.56	22	3.96
28 - 40	1	51	442	102	0.4	5	0.32	3.50	9	4.46

Profile 9: Mr Joubert's farm (site 8)

Soil Form	: Avalon
Location	: Bergville
Latitude/Longitude	: 28° 48' S / 29° 23' E
Altitude	: 1310 m
Land use	: Irrigated soybean under CT
Tillage system	: NT by 25 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Grayish brown (10YR 5/2); clay loam; weak, medium subangular blocky; wet, slightly sticky, slightly plastic; wavy transition to A2
A2	10 - 20	Yellowish brown (10YR 5/4); clay loam; medium subangular blocky; moist, friable; abrupt transition to B
B	27 - 40	Brown (10YR 5/3); clay; medium subangular blocky; moist, friable to slightly friable; soft plinthite.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Soil texture
		Clay	Silt	Sand				
				VfiSa	fiSa	meSa	coSa	
A1	0 – 10	27.4	33.3	17.3	20.1	1.7	1.2	Silt-clay-loam
A2	10 - 20	30.2	29.0	23.8	16.4	1.1	0.4	Clay-loam
B	27 - 40	41.2	30.2	16.8	11.3	0.7	0.8	Silt-clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	42	109	578	139	6.2	18	1.04	5.35	19	3.88
2.5 - 5	26	87	588	134	5.7	14	1.10	5.36	21	3.79
5 - 10	40	100	622	143	6.6	16	1.14	5.68	20	3.84
10 - 15	33	93	607	132	5.6	13	0.95	5.30	18	3.84
10 - 20	40	104	519	113	5.1	17	1.31	5.10	26	3.75
20 - 27	10	80	420	77	2.7	13	1.71	4.64	37	3.75
27 - 40	1	48	585	95	0.7	8	0.51	4.33	12	4.16

Profile 10: Cedara (site 9)

Soil Form	: Hutton
Location	: Cedara
Latitude/Longitude	: 29° 32' S / 30° 17' E
Altitude	: 1076 m
Land use	: Dryland maize under NT
Tillage system	: NT by 19 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark brown (7.5YR 3/3); gravely silty clay loam; weak, medium subangular blocky; moist, friable; gradual transition to A2
A2	10 - 20	Dark brown (7.5YR 3/4); gravely silty clay loam; weak, medium subangular blocky; moist, friable; abrupt transition to B
B	20 - 40	Dark reddish brown (2.5YR 3/4); gravely silty clay; weak, medium subangular blocky; moist, friable to hardpan concretions.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)							Soil texture
		Clay	Silt	Sand				Gravel (%)	
				VfiSa	fiSa	meSa	coSa		
A1	0 – 10	31.2	44.7	10.5	4.4	1.4	8.8	22.3	Slit-clay-loam
A2	10 – 20	32.4	42.0	9.7	5.1	1.4	10.0	21.3	Slit-clay-loam
B	30 - 40	41.4	33.5	7.8	5.4	1.7	10.9	34	Slit-clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	33	267	1622	254	6.5	4	0.10	10.97	1	5.03
2.5 - 5	33	340	1827	289	6.9	4	0.10	12.46	1	5.26
5 - 10	9	114	362	59	7.4	7	2.20	4.78	46	4.10
10 - 15	41	141	454	76	7.1	5	2.57	5.82	44	4.01
10 - 20	11	71	516	61	4.7	18	2.06	5.32	39	4.06
20 - 30	9	70	723	82	2.6	12	0.74	5.20	14	4.29
30 - 40	1	68	796	92	0.9	6	0.11	5.01	2	4.83

Profile 11: Cedara (site 10)

Soil Form	: Hutton
Location	: Cedara
Latitude/Longitude	: 29° 32' S / 30° 17' E
Altitude	: 1076 m
Land use	: Dryland maize under CT
Tillage system	: CT by more than 50 years

Horizon	Depth (cm)	Description
A1	0 - 10	Dark brown (7.5YR 3/3); gravely silty clay loam; weak, medium subangular blocky; moist, friable; wavy transition to A2
A2	10 - 20	Dark brown (7.5 YR 3.4); gravely silty clay loam; weak, medium subangular blocky; moist, friable; abrupt transition to B
B	30 - 40	Dark reddish brown (2.5 YR 3/4); gravely silty clay; weak, medium subangular blocky; moist, hardpan concretions.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)						Gravel (%)	Soil texture
		Clay	Silt	Sand					
				VfiSa	fiSa	meSa	coSa		
A1	0 – 10	37.0	40.7	9.2	4.4	1.2	8.7	25.3	Slit-clay-loam
A2	10 – 20	35.6	38.3	9.3	5.7	2.4	8.7	25	Slit-clay-loam
B	30 - 40	47.6	32.4	8.0	4.0	1.1	8.0	19	Silt-clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	16	109	788	164	4.9	7	1.02	6.58	15	4.22
2.5 - 5	17	52	782	154	5.2	7	1.13	6.43	18	4.19
5 - 10	18	53	735	147	5.5	8	1.44	6.45	22	4.11
10 - 15	16	59	711	139	5.2	7	1.30	6.14	21	4.14
10 - 20	17	141	721	142	5.5	14	1.09	6.22	18	4.22
20 - 30	11	66	603	103	4.3	11	1.12	5.15	22	4.23
30 - 40	2	96	914	144	1.1	7	0.16	6.15	3	4.71

Profile 12: Cedara (site 11)

Soil Form	: Hutton
Location	: Cedara
Latitude/Longitude	: 29° 32' S / 30° 17' E
Altitude	: 1076 m
Land use	: Dry land maize under NT
Tillage system	: NT by 19 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark brown (7.5YR 3/3); gravely silty clay loam; medium subangular blocky; moist, friable; gradual transition to A2
A2	10 - 20	Dark brown (7.5YR 3/4); gravely silty clay loam; medium subangular blocky; moist, slightly firm; abrupt transition to B
B	20 - 35	Dark reddish brown (2.5YR 3/4); gravely silty clay loam; weak, medium subangular blocky; moist, friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)							Soil texture
		Clay	Silt	Sand				Gravel (%)	
				VfiSa	fiSa	meSa	coSa		
A1	0 – 10	35.4	42.5	8.7	4.5	1.1	8.5	25.4	Slit-clay-loam
A2	10 – 20	37.6	39.8	8.3	5.5	1.5	7.6	25.4	Slit-clay-loam
B	20 - 35	38.6	42.1	8.4	4.5	1.4	7.2	24.3	Slit-clay-loam

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	38	338	1570	322	5.5	4	0.06	11.41	1	5.22
2.5 - 5	26	236	1336	253	4.9	3	0.10	9.45	1	4.87
5 - 10	15	102	1028	195	3.7	2	0.16	7.16	2	4.54
10 - 15	13	83	711	140	4.9	5	0.76	5.67	13	4.23
10 - 20	15	197	844	169	3.9	13	0.66	6.77	10	4.31
20 - 35	8	97	1034	163	2.1	9	0.16	6.91	2	4.56

Profile 13: Cedara (site 12)

Soil Form	: Hutton
Location	: Cedara
Latitude/Longitude	: 29° 32' S / 30° 17' E
Altitude	: 1076 m
Land use	: Dryland maize under CT
Tillage system	: CT by more than 50 years

Horizon	**Depth (cm)**	**Description**
A1	0 - 10	Dark brown (7.5YR 3/3); gravely silty clay loam; weak, medium subangular blocky; moist, friable; wavy transition to A2
A2	10 - 15	Dark brown (7.5YR 3/4); gravely silty clay loam; weak, medium subangular blocky; moist, friable; abrupt transition to B
B	15 - 35	Dark reddish brown (2.5YR 3/4); gravely silty clay loam; weak, medium subangular blocky; moist, friable.

Selected physical properties

Horizon	Soil depth (cm)	Particle size distribution (%)							Soil texture
		Clay	Silt	Sand				Gravel (%)	
				VfiSa	fiSa	meSa	coSa		
A1	0 – 10	37.0	41.2	8.5	4.5	0.8	9.1	20.9	Silt-clay-loam
A2	10 – 15	39.9	38.9	8.2	5.3	1.1	8.1	23	Silt-clay-loam
B	15 - 35	49.0	30.8	8.1	3.9	0.8	8.6	35	Silt-clay

Selected chemical properties

Soil depth (cm)	Cations (mg/L)						Exch. Acid (Cmol/L)	Tot. Cations (Cmol/L)	Acid. Sat. (%)	pH (KCl)
	P	K	Ca	Mg	Zn	Mn				
0 – 2.5	18	166	1476	366	4.9	5	0.08	10.88	1	5.17
2.5 - 5	18	122	1073	219	5.2	4	0.05	7.52	1	4.83
5 - 10	17	109	1562	307	5.6	3	0.06	10.66	1	5.24
10 - 15	9	56	1168	240	2.9	2	0.05	8.00	1	4.85
15 - 35	1	28	834	145	0.5	4	0.02	5.45	0	4.78

Appendix 2. Selected parameters derived from the water retention data determined on undisturbed soil cores for the study sites over a range of soil depths. Each value represents a mean of three replicates

NO TILLAGE

Site	Depth	ρ_b	ρ_s	θ_v ($m^3 m^{-3}$)	θ_v ($m^3 m^{-3}$)	θ_v ($m^3 m^{-3}$)	RAW	PAW	TP	AFP (%)	AFP (%)	AFP (%)	Mean k_a (μm^2)		Mean K_s
	(mm)	(Mg m^{-3})	(Mg m^{-3})	at - 10 kPa	at - 100 kPa	at - 1500 kPa	($m^3 m^{-3}$)	($m^3 m^{-3}$)	(%)	at - 5 kPa	at - 10 kPa	at - 100 kPa	at -10 kPa	at -100 kPa	(mm h^{-1})
1	50	1.527	2.655	0.393	0.326	0.229	0.067	0.164	42.50	2.4	3.4	9.5	0.94	3.83	0.119
(IM)	150	1.463	2.691	0.409	0.331	0.221	0.078	0.188	45.60	3.7	4.7	13.3	0.79	5.72	0.389
Clay	320	1.407	2.706	0.426	0.346	0.257	0.080	0.169	48.00	3.7	5.4	13.6	0.83	2.58	1.56
3	50	1.695	2.627	0.322	0.235	0.164	0.087	0.158	35.50	2.2	3.3	5.1	0.92	0.97	0.2
(DLM)	150	1.723	2.641	0.322	0.238	0.176	0.084	0.146	34.80	2.6	2.6	4.1	0.75	1.48	0.16
Loam	320	1.723	2.652	0.286	0.216	0.183	0.070	0.103	37.20	6.9	8.6	7.4	2.40	3.90	0.272
5A	50	1.421	2.655	0.365	0.285	0.213	0.080	0.152	46.50	7.6	10.0	18.2	2.12	5.31	35.1
(IM)	150	1.475	2.680	0.348	0.281	0.212	0.067	0.136	44.90	8.1	10.1	16.8	1.43	1.93	1
Clay	320	1.306	2.682	0.322	0.255	0.200	0.067	0.122	51.30	13.8	19.1	26.0	1.81	2.39	10.7
5B	50	1.397	2.631	0.345	0.244	0.196	0.101	0.149	46.90	9.9	12.4	24.4	1.66	4.50	35.4
(DLM)	150	1.398	2.648	0.325	0.265	0.196	0.060	0.129	47.20	12.1	14.6	21.7	1.62	1.38	4.7
Clay	320	1.477	2.655	0.322	0.264	0.195	0.058	0.127	44.40	9.5	12.1	17.9	2.58	1.87	1.4
7	50	1.494	2.626	0.390	0.320	0.24	0.070	0.150	43.10	3.8	4.2	12.3	1.01	7.22	1.1
(IS)	150	1.528	2.666	0.356	0.302	0.235	0.054	0.121	42.70	5.8	7.1	11.8	1.28	1.03	1
Silt clay loam	320	1.441	2.664	0.369	0.282	0.214	0.087	0.155	45.90	6.5	9.0	17.7	1.94	2.91	1.1
9A	50	1.418	2.829	0.426	0.340	0.32	0.086	0.106	49.90	4.7	7.3	15.8	1.43	2.43	22.2
(LIR)	150	1.365	2.823	0.400	0.317	0.283	0.083	0.117	51.60	8.5	11.6	19.9	1.37	1.97	59.7
Silt clay loam	320	1.285	2.962	0.418	0.341	0.284	0.077	0.134	56.60	12.1	14.8	22.5	6.62	12.50	31.91
9B	50	1.429	2.829	0.437	0.340	0.326	0.097	0.111	49.50	3.4	5.8	15.5	1.26	2.49	16
(CIR)	150	1.397	2.823	0.402	0.331	0.323	0.071	0.079	50.50	7.6	10.3	17.4	1.77	2.18	27.5
Silt clay loam	320	1.438	2.962	0.406	0.318	0.312	0.088	0.094	51.60	8.1	10.9	19.7	3.21	5.01	12.02
11A	50	1.385	2.847	0.413	0.317	0.282	0.096	0.131	51.30	7.8	10.1	19.6	2.79	7.36	150
(LIR)	150	1.384	2.847	0.396	0.322	0.279	0.074	0.117	51.40	8.6	11.8	19.2	2.85	7.19	20.5
Silt clay loam	320	1.375	2.840	0.395	0.318	0.265	0.077	0.130	51.60	8.6	12.1	19.8	2.52	3.59	7.7
11B	50	1.453	2.847	0.426	0.350	0.304	0.076	0.122	49.00	4.7	6.3	14.0	2.21	5.27	3
(CIR)	150	1.379	2.847	0.416	0.335	0.289	0.081	0.127	51.60	5.7	10.0	18.1	2.97	4.28	19.9
Silt clay loam	320	1.344	2.840	0.396	0.301	0.264	0.095	0.132	52.70	8.8	13.1	22.5	4.14	8.03	29.9

Note:

IM: Irrigated maize
CIR:Compacted inter-row
RAW: Readily available water
IS: Irrigated soybean
DLM: Dryland maize
PAW: Plant available water
DLS: Dryland soybean
LIR: Loose inter-row
θ_v : Volumetric water content
AFP : Air-filled porosity
TP : Total porosity
K_a: Air permeability
ρ_b : Bulk density
ρ_s : Particle density

Appendix 2 (Continued)

CONVENTIONAL TILLAGE

Site	Depth	ρ_b	ρ_s	θ_v ($m^3 m^{-3}$)	θ_v ($m^3 m^{-3}$)	θ_v ($m^3 m^{-3}$)	RAW	PAW	TP	AFP (%)	AFP (%)	AFP (%)	Mean k_a (μm^2)		Mean K_s
	(mm)	($Mg\ m^{-3}$)	($Mg\ m^{-3}$)	at - 10 kPa	at - 100 kPa	at - 1500 kPa	($m^3 m^{-3}$)	($m^3 m^{-3}$)	(%)	at - 5 kPa	at - 10 kPa	at - 100 kPa	at -10 kPa	at -100 kPa	($mm\ h^{-1}$)
2	50	1.194	2.699	0.336	0.208	0.189	0.128	0.147	55.76	18.5	22.2	34.5	10.90	25.30	67.54
(DLS)	150	1.381	2.711	0.367	0.282	0.214	0.085	0.153	49.06	9.7	12.3	21.9	1.31	4.55	16.02
Clay	320	1.367	2.712	0.399	0.360	0.265	0.039	0.134	49.60	7.7	9.7	14.1	1.17	2.38	18.12
4	50	1.463	2.622	0.386	0.232	0.153	0.154	0.233	44.20	4.2	5.6	20.8	1.55	5.91	38.5
(DLM)	150	1.664	2.637	0.305	0.237	0.153	0.068	0.152	36.90	4.2	6.4	11.7	1.27	8.24	3.84
Loam	320	1.512	2.680	0.372	0.223	0.198	0.149	0.174	43.60	4.8	6.4	21.9	1.03	2.53	6.54
6A	50	1.226	2.652	0.302	0.227	0.172	0.075	0.130	53.80	19.1	23.5	31.5	6.36	13.50	115.7
(LIR)	150	1.338	2.667	0.320	0.253	0.195	0.067	0.125	49.90	14.6	17.9	24.7	2.66	5.16	26.9
Clay	320	1.388	2.684	0.328	0.265	0.214	0.063	0.114	48.30	12.9	15.5	12.0	1.62	2.00	4.3
6B	50	1.339	2.652	0.341	0.247	0.206	0.094	0.135	49.50	11.0	15.4	25.0	1.69	3.77	14.4
(CIR)	150	1.421	2.667	0.336	0.274	0.216	0.062	0.120	46.73	10.9	13.1	18.7	1.06	1.24	2
Clay	320	1.470	2.684	0.340	0.261	0.213	0.079	0.127	45.23	8.8	11.2	19.2	1.32	1.36	6
8	50	1.329	2.625	0.306	0.233	0.182	0.073	0.124	49.40	16.8	18.8	26.1	6.85	15.50	74.9
(IS)	150	1.441	2.648	0.302	0.240	0.192	0.062	0.110	45.60	13.6	15.4	23.8	2.41	9.87	27.4
Silt clay loam	320	1.446	2.640	0.350	0.270	0.249	0.080	0.101	45.20	8.0	10.2	18.3	1.69	2.84	2.62
10A	50	1.359	2.846	0.406	0.313	0.308	0.093	0.098	52.20	7.9	11.6	21.0	2.64	4.93	43
(LIR)	150	1.417	2.844	0.408	0.335	0.319	0.073	0.089	50.20	6.2	9.4	16.7	1.44	1.81	8.8
Silt clay loam	320	1.372	2.891	0.436	0.320	0.273	0.116	0.163	52.60	4.8	8.9	20.6	1.25	1.86	4.71
10B	50	1.463	2.846	0.435	0.350	0.328	0.085	0.107	48.60	2.3	5.1	13.6	1.23	1.79	2.8
(CIR)	150	1.464	2.844	0.434	0.341	0.325	0.093	0.109	48.50	2.4	5.1	14.5	1.05	3.12	2.6
Silt clay loam	320	1.472	2.891	0.427	0.329	0.275	0.098	0.152	49.10	4.1	6.4	16.2	1.08	1.49	2.51
12A	50	1.246	2.821	0.363	0.300	0.286	0.063	0.077	55.80	16.8	19.5	25.8	22.50	38.60	306
(LIR)	150	1.358	2.833	0.405	0.321	0.270	0.084	0.135	52.10	8.0	11.5	20.0	3.36	3.09	17.7
Silt clay loam	320	1.288	2.844	0.410	0.315	0.251	0.095	0.159	54.70	9.8	13.8	23.2	3.61	5.64	26.8
12B	50	1.379	2.821	0.431	0.353	0.292	0.078	0.139	51.10	3.4	5.5	15.8	1.79	9.98	69
(CIR)	150	1.354	2.833	0.417	0.355	0.290	0.062	0.127	52.20	6.7	10.5	16.7	1.80	2.48	6.5
Silt clay loam	320	1.19	2.844	0.394	0.304	0.233	0.090	0.161	58.10	13.5	18.8	27.8	3.54	6.65	63.7

Appendix 3. Summary of analysis of variance for the effect of tillage on water retention at different matric potential ranges over three selected soil depths. The values quoted are the mean of three replicates (LSD: means followed by same letter on same row are significantly similar; NS: non-significant; S.E: standard errors of difference of means)

A. Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms

Soil depth (mm)	Matric potentials (- kPa)	Treatments - means		S.E - means	LSD	F	P
		T1	T2				
50	1	0.416 B	0.496 A	0.012	0.033	44.31	0.003
	5	0.401 A	0.373 B	0.005	0.013	36.86	0.004
	10	0.391 A	0.336 B	0.004	0.011	182.72	< 0.001
	30	0.368 A	0.288 B	0.0005	0.001	2.8×10^{4}	< 0.001
	100	0.326 A	0.208 B	0.0005	0.001	6.3×10^{4}	< 0.001
150	1	0.428	0.445	0.008	NS	4.60	0.099
	5	0.419	0.393	0.011	NS	5.78	0.074
	10	0.409 A	0.367 B	0.011	0.032	13.84	0.020
	30	0.353 A	0.338 B	0.004	0.010	17.46	0.014
	100	0.330 A	0.280 B	0.002	0.006	570.03	< 0.001
320	1	0.462	0.463	0.027	NS	0.00	0.981
	5	0.442	0.427	0.028	NS	0.30	0.611
	10	0.426	0.407	0.030	NS	0.41	0.555
	30	0.361	0.375	0.031	NS	0.21	0.670
	100	0.346	0.348	0.022	NS	0.01	0.922

NB. T1: NT (Site 1); T2: CT (Site 2) Degree of freedom for each matric potential = 5

Appendix 3. (Continued)

B. Sites 3 and 4: Mr van Der Aardweg and Mr van Vuuven's farms

Soil depth (mm)	Matric potentials (- kPa)	Treatments - means		S.E - means	LSD	F	P
		T1	T2				
50	1	0.335 B	0.410 A	0.011	0.031	46.84	0.002
	5	0.333 B	0.393 A	0.011	0.032	34.26	0.004
	10	0.322 B	0.385 A	0.010	0.026	44.32	0.003
	30	0.294 A	0.265 B	0.005	0.015	28.14	0.006
	100	0.238	0.232	0.003	NS	3.03	0.157
150	1	0.322 B	0.342 A	0.006	0.015	13.24	0.022
	5	0.322	0.327	0.006	NS	1.06	0.361
	10	0.322 A	0.305 B	0.004	0.012	15.63	0.017
	30	0.255 B	0.273 A	0.004	0.010	27.75	0.006
	100	0.235	0.236	0.003	NS	0.150	0.721
320	1	0.329 B	0.394 A	0.011	0.031	34.72	0.004
	5	0.303 B	0.387 A	0.011	0.030	61.06	0.001
	10	0.286 B	0.372 A	0.011	0.029	67.08	0.001
	30	0.256 B	0.286 A	0.005	0.013	40.5	0.003
	100	0.213	0.220	0.005	NS	2.20	0.212

NB. T1: NT (Site 3); T2: CT (Site 4)   Degree of freedom for each matric potential = 5

Appendix 3. (Continued)

C. Sites 5A, 5B and 6: Mr Miurhead's and Mr Mostert's farms

Soil depth (mm)	Matric potentials (- kPa)	Treatments - means				S.E. - means	LSD	F	P
		T1	T2	T3	T4				
50	1	0.421 BC	0.413 C	0.482 A	0.460 A	0.013	0.031	11.86	0.003
	5	0.387 AB	0.370 ABC	0.349 C	0.391 A	0.011	0.026	5.53	0.024
	10	0.364 A	0.345 AB	0.304 C	0.343 AB	0.011	0.024	11.29	0.003
	30	0.319 A	0.283 C	0.257 D	0.286 BC	0.002	0.005	273.3	< 0.001
	100	0.285 A	0.24C C	0.227 D	0.247 BC	0.002	0.004	326.7	< 0.001
150	1	0.397	0.404	0.433	0.403	0.015	NS	2.43	0.141
	5	0.371	0.355	0.347	0.361	0.009	NS	2.45	0.139
	10	0.351 A	0.327 BC	0.313 C	0.339 AB	0.007	0.016	11.15	0.003
	30	0.310 A	0.299 ABC	0.282 C	0.306 AB	0.005	0.011	12.64	0.002
	100	0.281 A	0.255 BC	0.253 C	0.274 A	0.004	0.010	23.75	< 0.001
320	1	0.440 A	0.385 D	0.417 B	0.393 CD	0.009	0.021	14.53	0.001
	5	0.374 A	0.349 D	0.352 CD	0.362 B	0.004	0.009	16.34	< 0.001
	10	0.324 AB	0.322 AB	0.326 B	0.339 A	0.003	0.007	13.91	0.002
	30	0.275 D	0.292 C	0.293 BC	0.304 A	0.002	0.004	74.25	< 0.001
	100	0.255 C	0.264 AB	0.265 A	0.261 ABC	0.003	0.007	4.62	0.037

NB. T1: NT-IM (Site 5A); T2: NT-DLM (Site 5B); T3: CT-LIR (6A); T4: CT-CIR (6B)

Degree of freedom for each matric potential = 11

Appendix 3. (Continued)

D. Sites 7 and 8: Mr J. Jackson's and Mr J. Joubert's farms

Soil depth (mm)	Matric potentials (- kPa)	Treatments - means		S.E - means	LSD	F	P
		T1	T2				
50	1	0.402	0.404	0.012	NS	0.05	0.832
	5	0.396 A	0.329 B	0.009	0.024	58.39	0.002
	10	0.391 A	0.308 B	0.009	0.025	85.97	< 0.001
	30	0.358 A	0.268 B	0.012	0.033	59.23	0.002
	100	0.320 A	0.235 B	0.009	0.026	84.56	< 0.001
150	1	0.385	0.392	0.008	NS	0.650	0.465
	5	0.371 A	0.321 B	0.003	0.009	259.6	< 0.001
	10	0.360 A	0.301 B	0.004	0.010	249.8	< 0.001
	30	0.332 A	0.261 B	0.004	0.010	390.82	< 0.001
	100	0.302 A	0.240 B	0.004	0.010	281.27	< 0.001
320	1	0.422 A	0.395 B	0.003	0.010	58.72	0.002
	5	0.395 A	0.370 B	0.003	0.008	78.37	< 0.001
	10	0.369 A	0.349 B	0.003	0.007	60.00	0.001
	30	0.334 A	0.312 B	0.003	0.008	60.36	0.001
	100	0.282	0.272	0.006	NS	2.71	0.175

NB. T1: NT (Site 7); T2: CT (Site 8)   Degree of freedom for each matric potential = 5

Appendix 3. (Continued)

E. Sites 9 and 10: Cedara Agricultural Research Station

Soil depth (mm)	Matric potentials (- kPa)	Treatments - means				S.E of means	LSD	F	P
		T1	T2	T3	T4				
50	1	0.494	0.490	0.484	0.476	0.010	NS	1.26	0.351
	5	0.452	0.460	0.443	0.467	0.009	NS	2.56	0.128
	10	0.426	0.436	0.406	0.435	0.012	NS	2.70	0.116
	30	0.386 AB	0.386 AB	0.345 C	0.391 A	0.011	0.025	7.95	0.009
	100	0.340 AB	0.340 AB	0.313 C	0.351 A	0.010	0.023	5.26	0.027
150	1	0.489	0.483	0.478	0.490	0.008	NS	0.97	0.453
	5	0.432 CD	0.429 BD	0.440 BC	0.462 A	0.006	0.014	11.53	0.003
	10	0.400 BD	0.402 CD	0.408 BC	0.434 A	0.004	0.010	27.20	< 0.001
	30	0.360	0.367	0.372	0.373	0.005	NS	3.13	0.087
	100	0.317 C	0.331 AB	0.335 AB	0.340 A	0.005	0.011	8.80	0.006
320	1	0.491 AB	0.471 BC	0.500 A	0.471 BC	0.005	0.011	19.38	< 0.001
	5	0.446 CD	0.434 BD	0.477 A	0.450 BC	0.007	0.017	12.89	0.002
	10	0.418 BC	0.406 C	0.436 A	0.427 AB	0.009	0.020	4.56	0.038
	30	0.384	0.358	0.358	0.366	0.011	NS	2.50	0.133
	100	0.341	0.318	0.320	0.329	0.009	NS	3.11	0.089

NB. T1: NT-LIR (9A); T2: NT-CIR (9B); T3: CT-LIR (10A); T4: CT-CIR (10B)

Degree of freedom for each matric potential = 11

Appendix 3. (Continued)

F. Sites 11 and 12: Cedara Agricultural Research Station

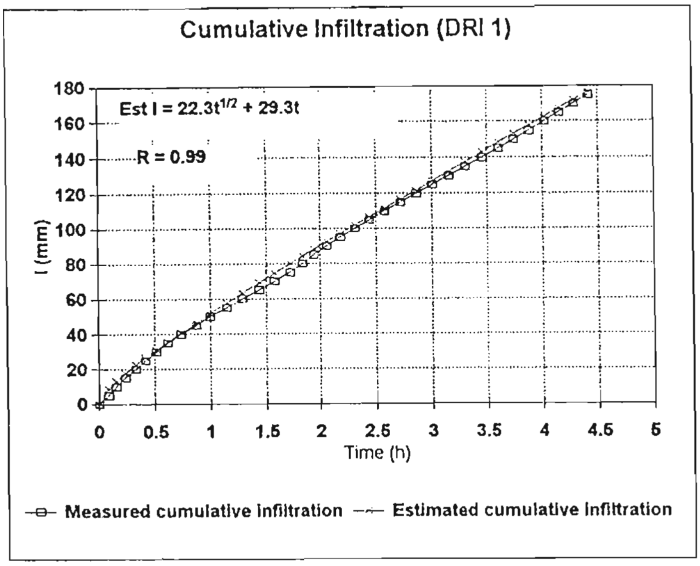
Soil depth (mm)	Matric potentials (- kPa)	Treatments				S.E of means	LSD	F	P
		T1	T2	T3	T4				
50	1	0.473 AB	0.460 C	0.472 BC	0.488 A	0.006	0.015	6.37	0.016
	5	0.436 ABC	0.443 AB	0.390 C	0.452 A	0.008	0.018	25.09	< 0.001
	10	0.413 B	0.426 AB	0.363 C	0.431 A	0.007	0.016	39.68	< 0.001
	30	0.372 B	0.390 A	0.329 C	0.396 A	0.005	0.012	68.58	< 0.001
	100	0.317 BC	0.350 A	0.300 C	0.353 A	0.012	0.028	8.80	0.006
150	1	0.472 C	0.493 A	0.485 B	0.491 AB	0.005	0.011	8.07	0.008
	5	0.428 C	0.459 A	0.441 BC	0.454 AB	0.007	0.016	8.04	0.008
	10	0.396	0.416	0.405	0.417	0.007	NS	3.82	0.058
	30	0.358	0.359	0.363	0.369	0.007	NS	1.12	0.398
	100	0.322 CD	0.335 BC	0.321 D	0.355 A	0.008	0.018	8.58	0.007
320	1	0.478 C	0.496 ABC	0.505 AB	0.523 A	0.012	0.029	4.58	0.0038
	5	0.430 C	0.438 ABC	0.450 A	0.446 AB	0.005	0.018	6.08	0.018
	10	0.395	0.396	0.410	0.394	0.009	NS	1.27	0.348
	30	0.348	0.342	0.366	0.344	0.013	NS	1.33	0.330
	100	0.318	0.301	0.316	0.304	0.013	NS	0.83	0.515

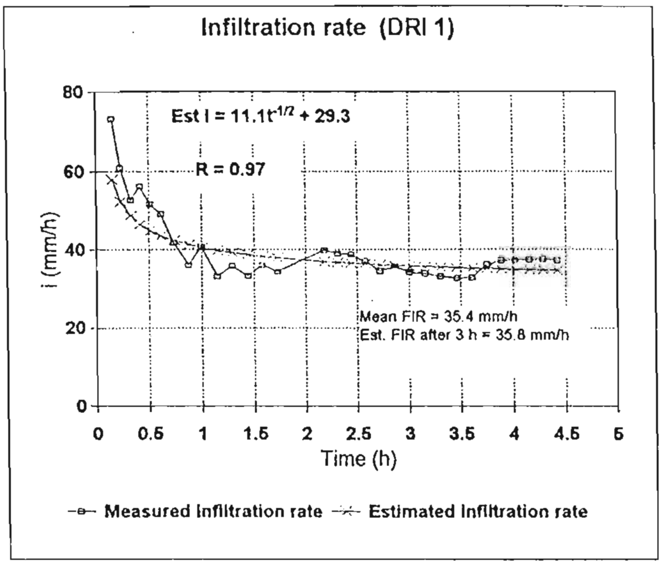
NB. T1: NT-LIR (11A); T2: NT-CIR (11B); T3: CT-LIR (12A); T4: CT-CIR (12B)

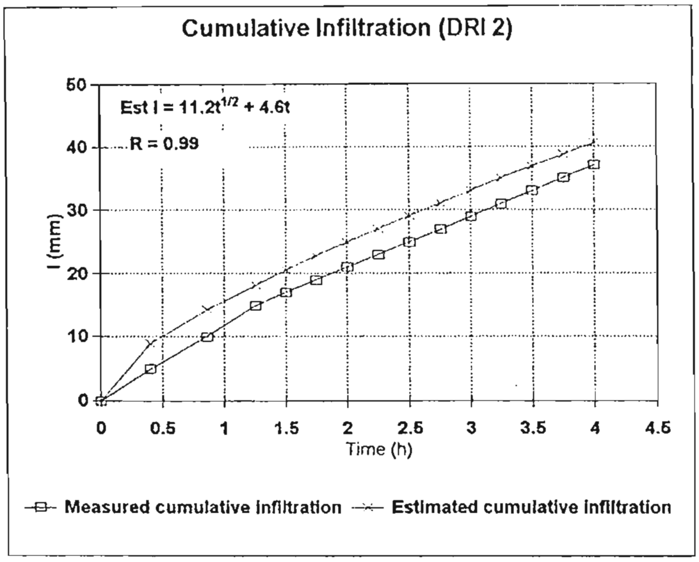
Degree of freedom for each matric potential = 11

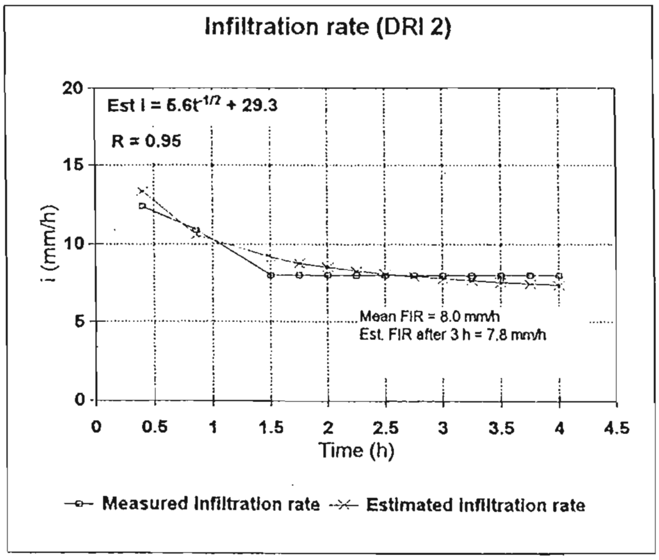
Appendix 4. Mean measured and predicted infiltration rates (using Philip equation), as affected by tillage system for the studied sites

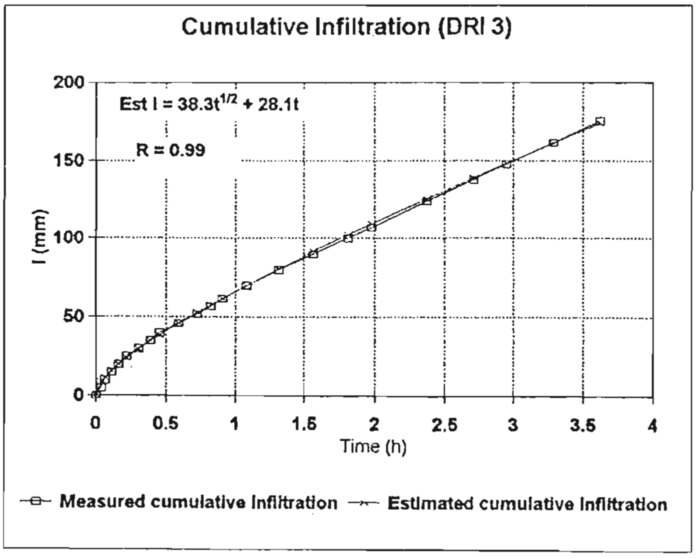
Site 1 (NT, irrigated maize): Mr R. Lund's farm

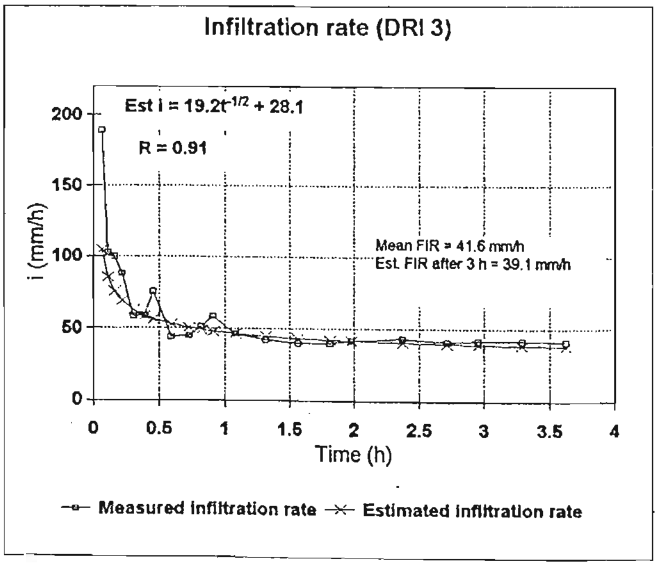












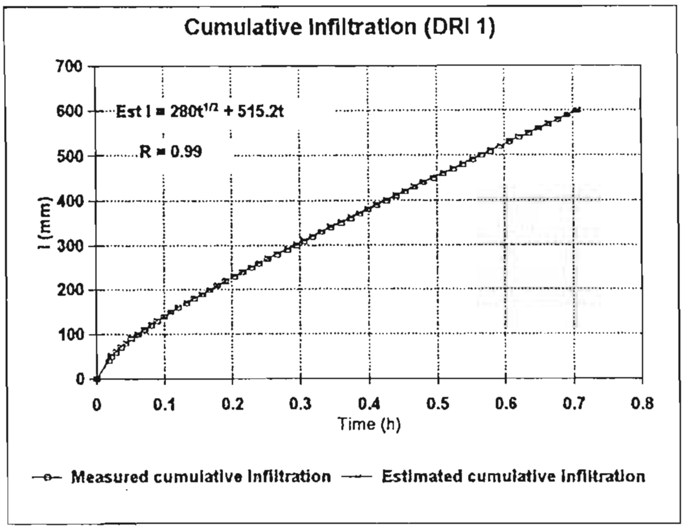
NT: No tillage
CT: Conventional tillage
DRI: Double ring infiltrometer

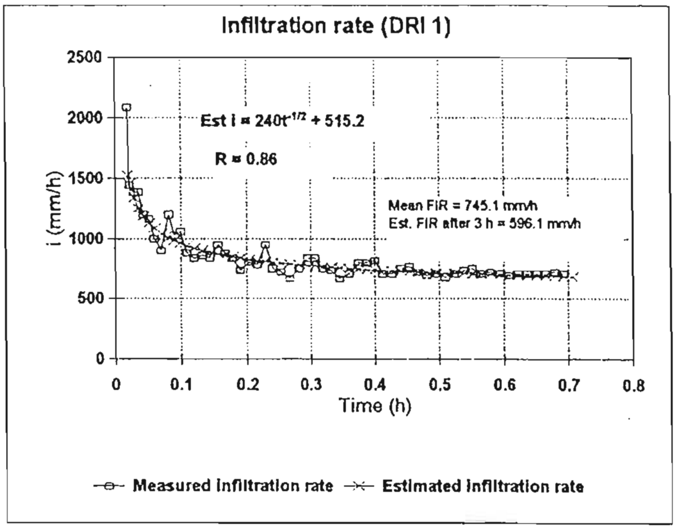
FIR: Final infiltration rate

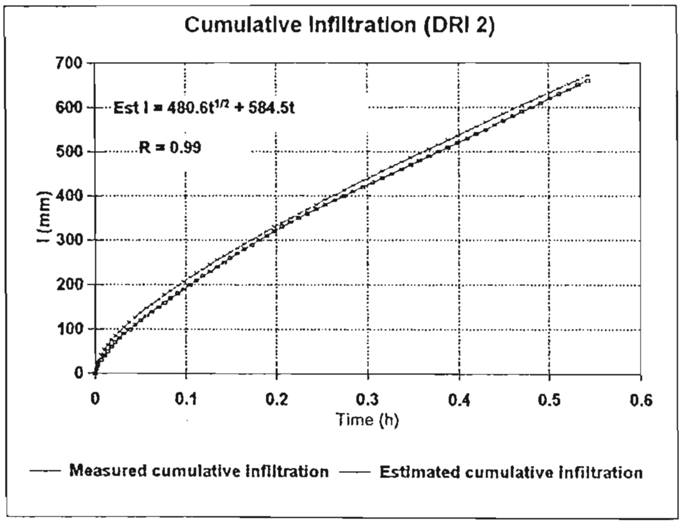
Est FIR: Estimated final infiltration rate

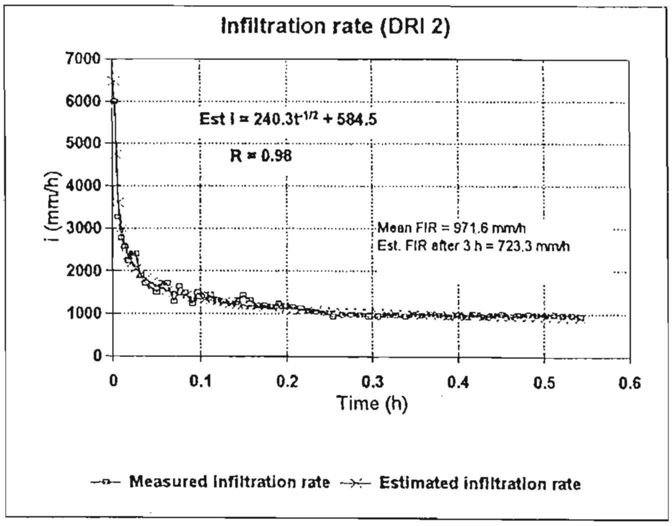
Appendix 4 (Continued)

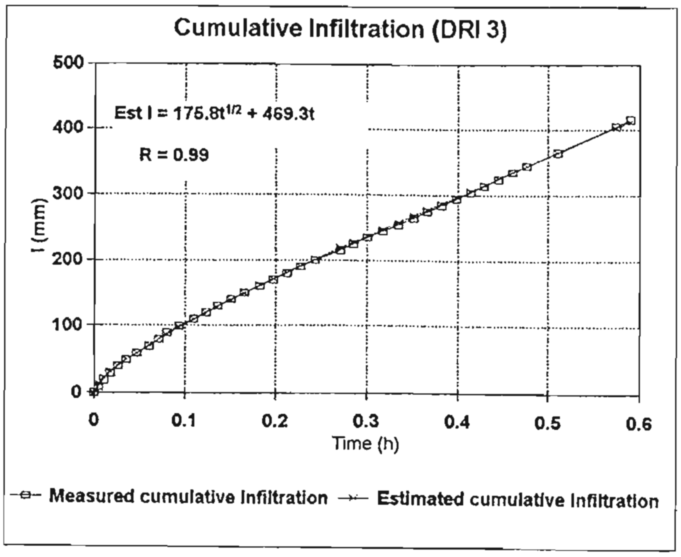
Site 2 (CT, dryland soybean): Mr Boschoff's farm

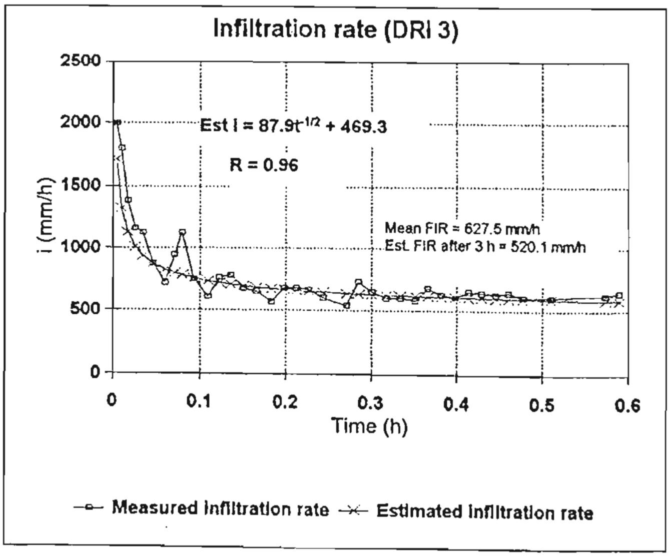

Cumulative Infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative Infiltration (DRI 2)

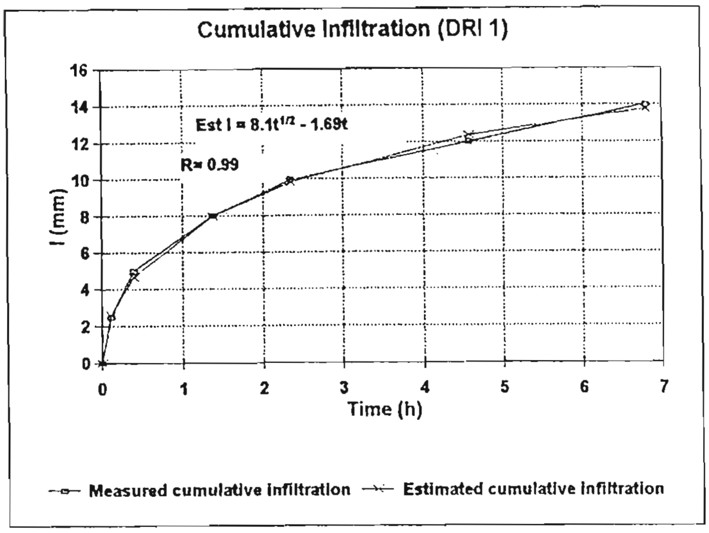

Infiltration rate (DRI 2)

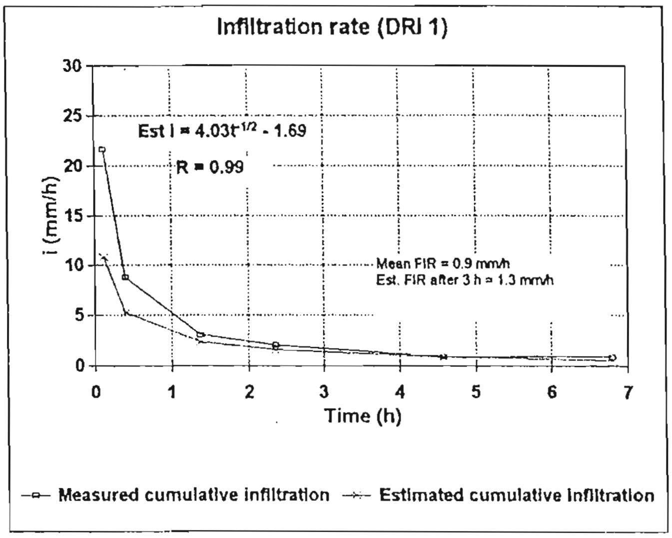

Cumulative Infiltration (DRI 3)

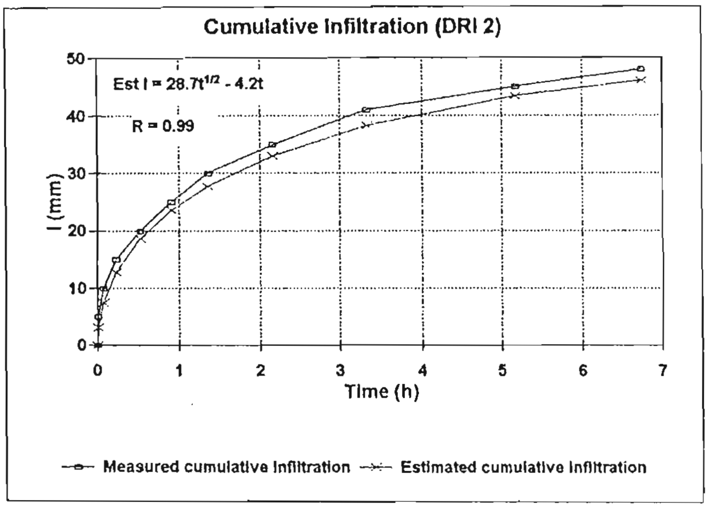

Infiltration rate (DRI 3)

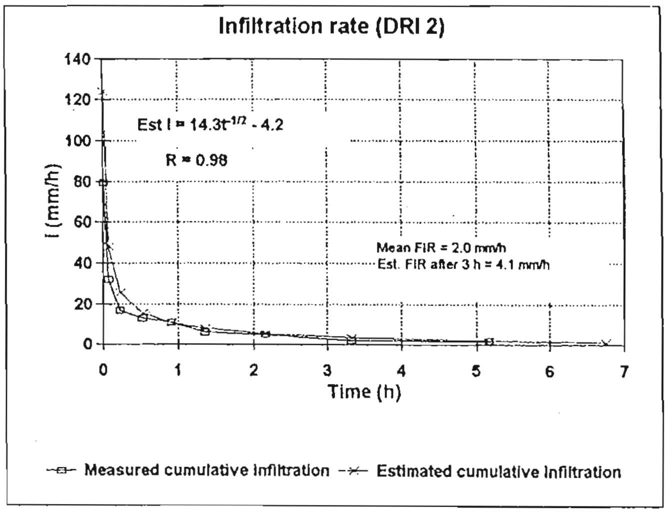
Appendix 4 (Continued)

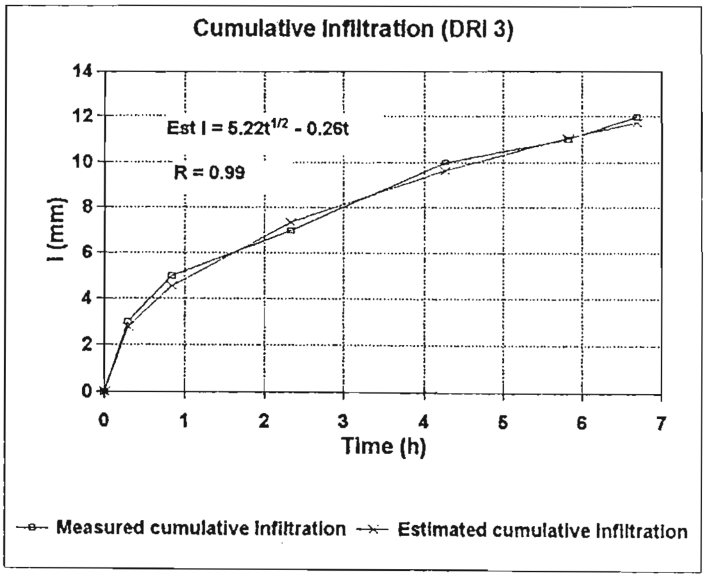
Site 3 (NT, dryland maize): Mr van Der Aardwerg

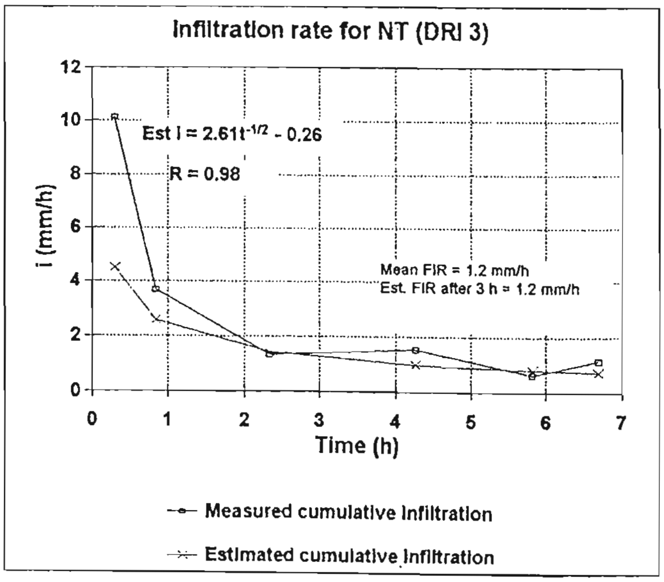

Cumulative Infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative Infiltration (DRI 2)

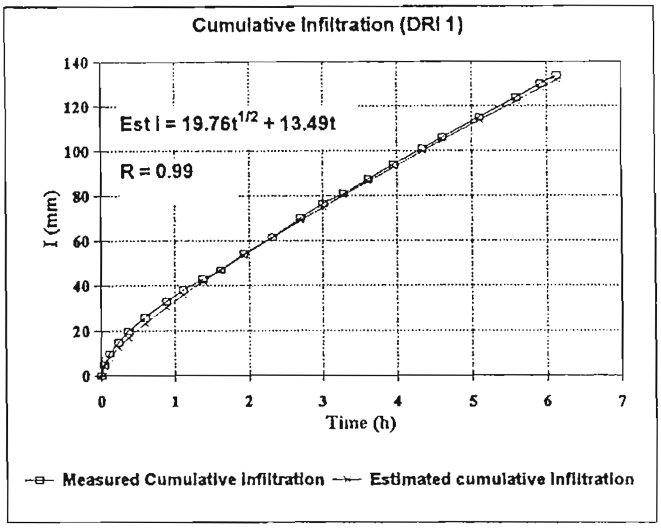

Infiltration rate (DRI 2)

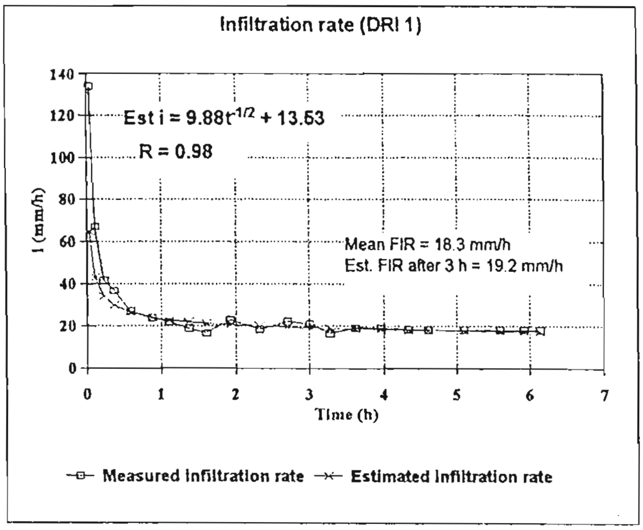

Cumulative Infiltration (DRI 3)

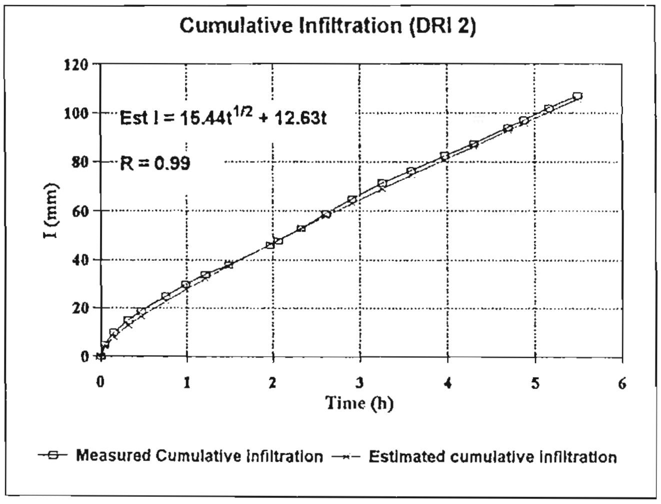

Infiltration rate for NT (DRI 3)

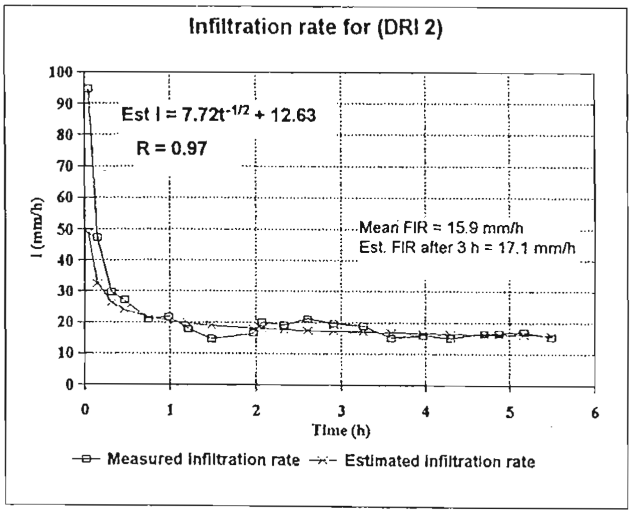
Appendix 4 (Continued)

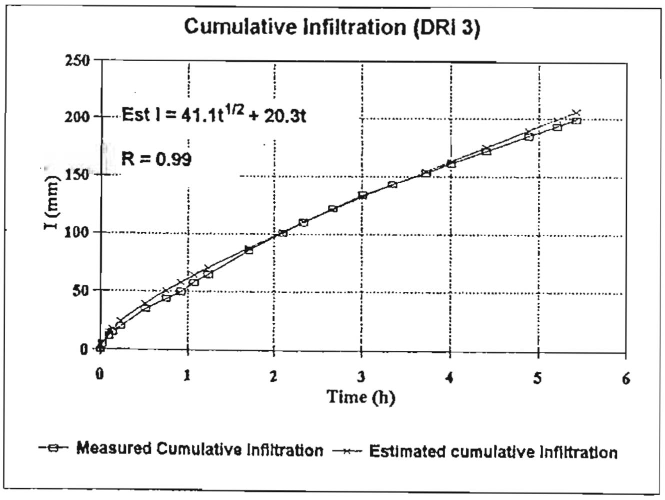
Site 4 (CT dryland maize): Mr Van Vuuven's farm

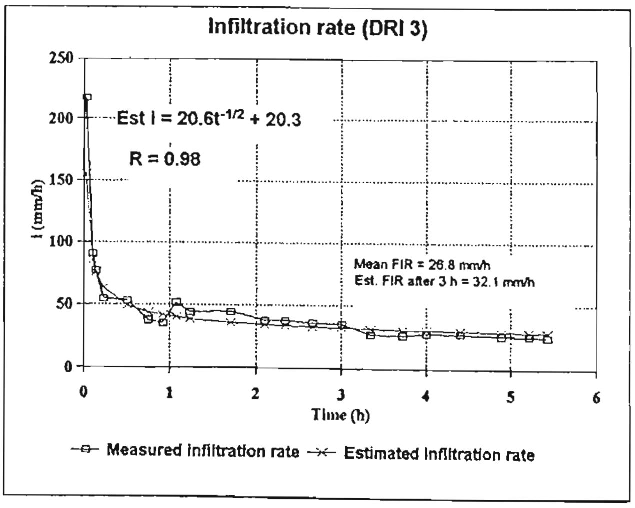






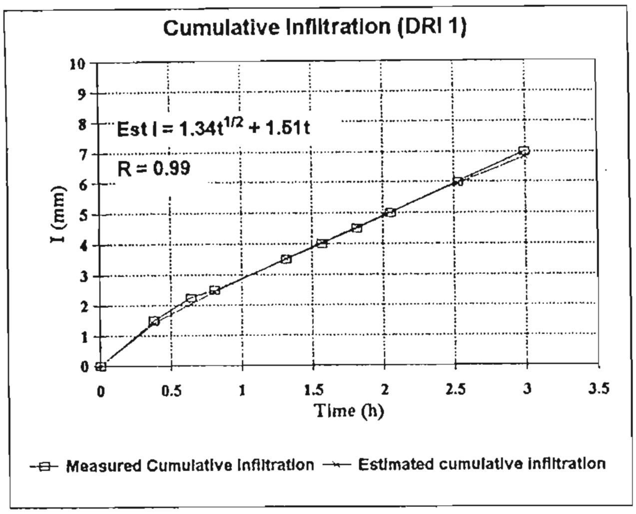


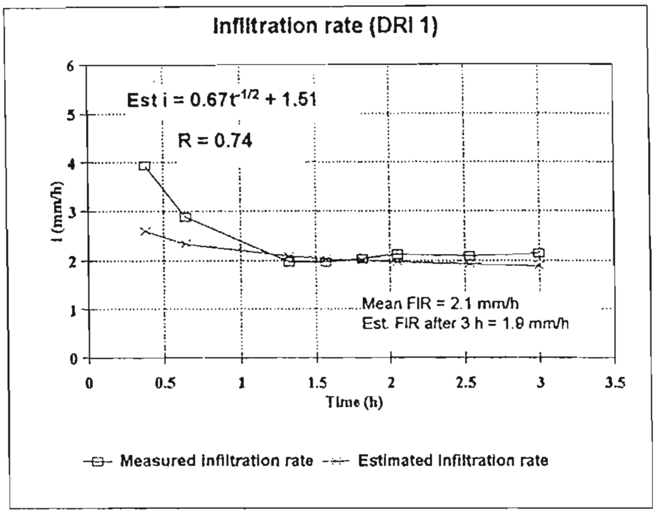


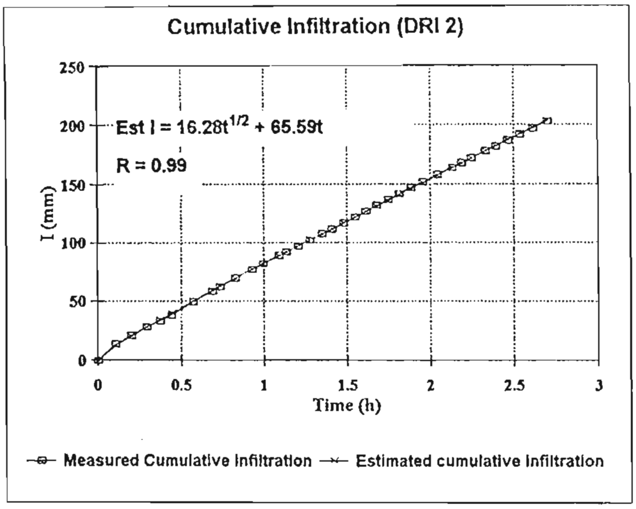


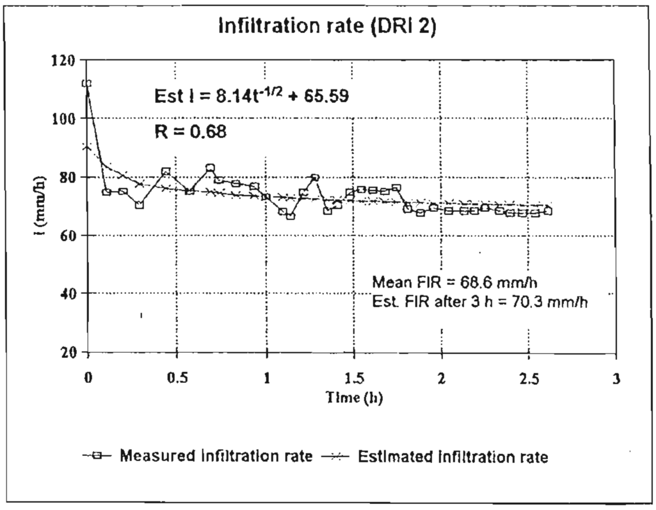
Appendix 4 (Continued)

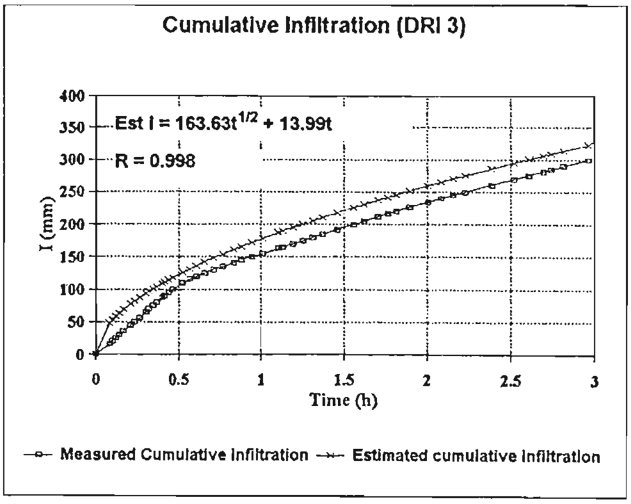
Site 5A (NT, irrigated maize): Mr Muirhead's farm

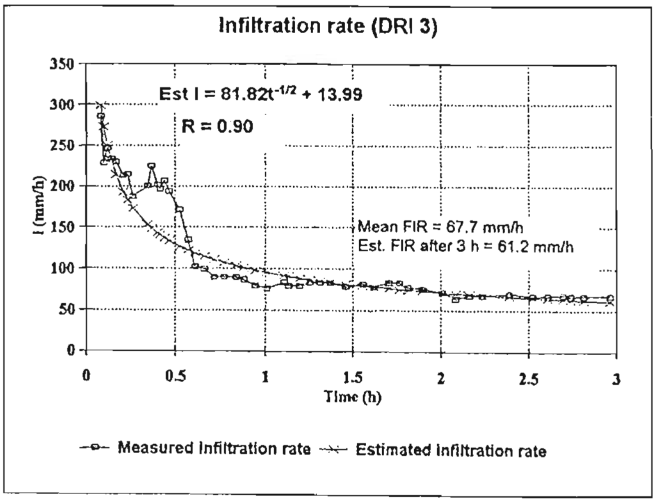






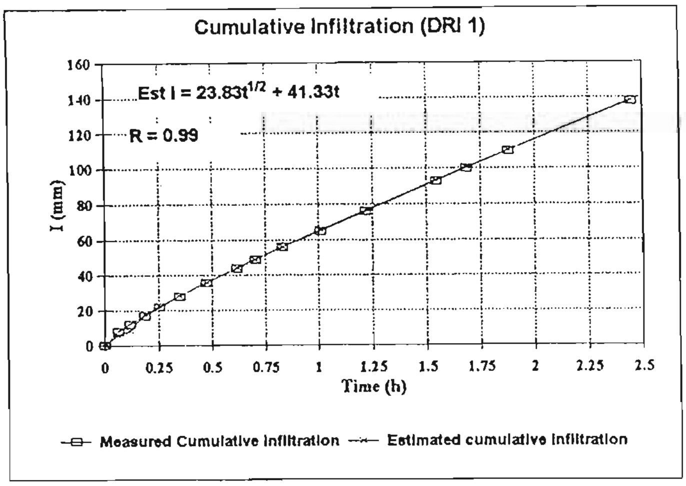


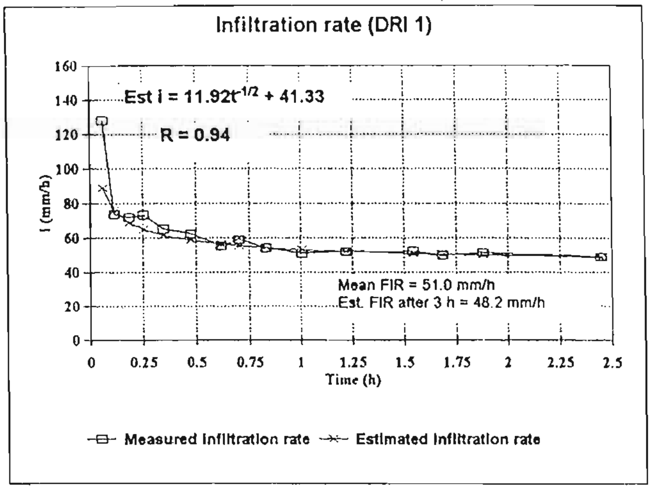


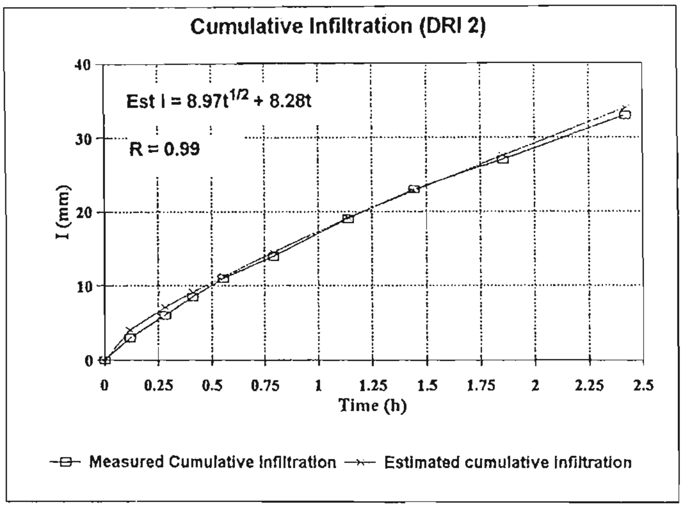


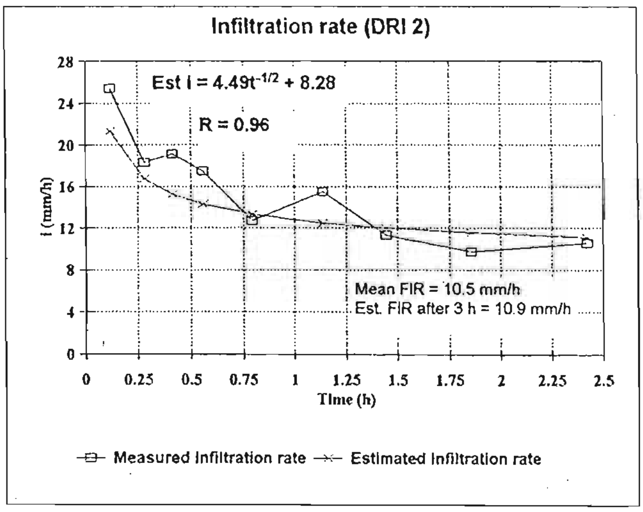
Appendix 4 (Continued)

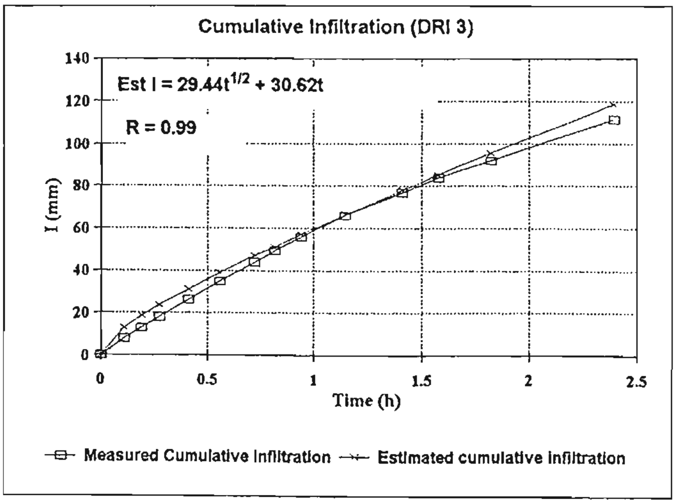
Site 5B (NT, dryland maize): Mr Muirhead's farm

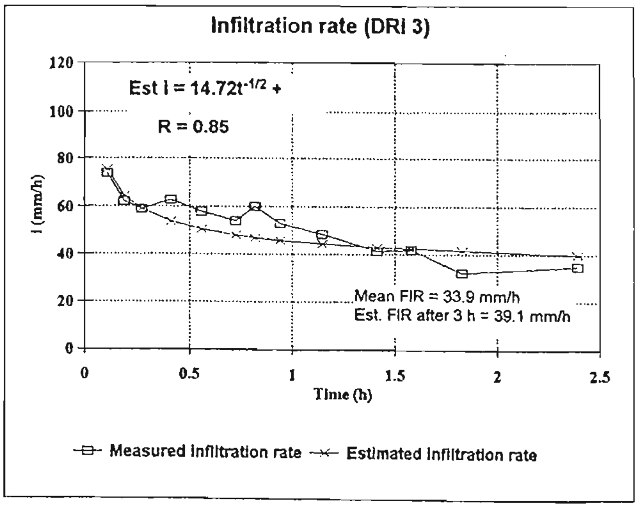

Cumulative Infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative Infiltration (DRI 2)

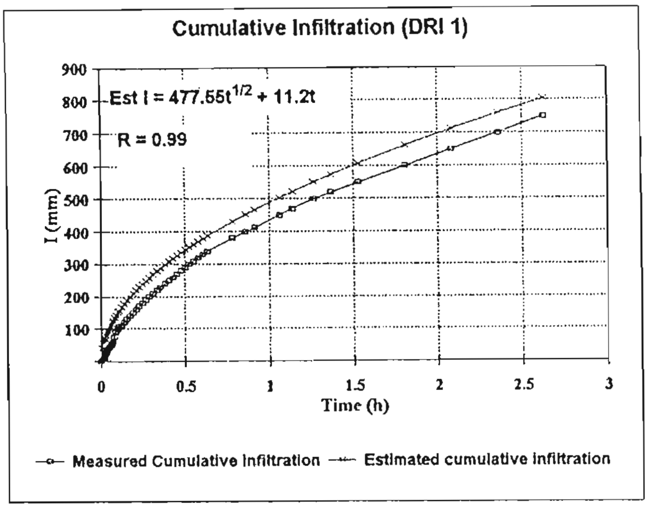

Infiltration rate (DRI 2)

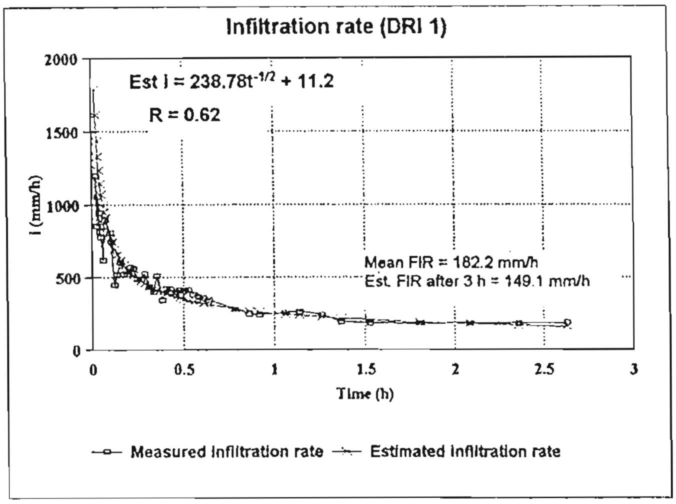

Cumulative Infiltration (DRI 3)

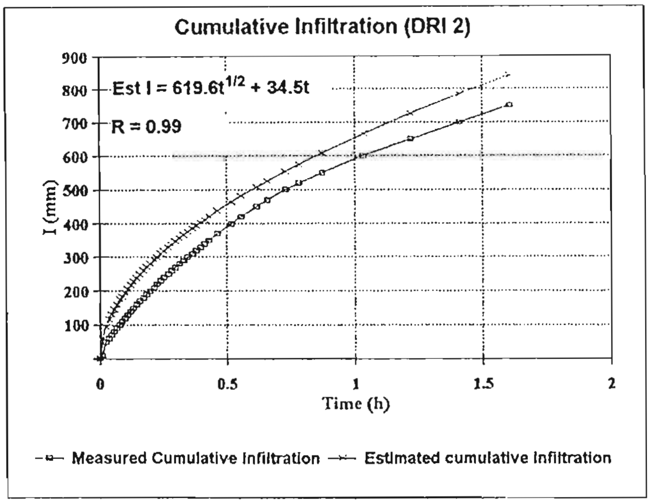

Infiltration rate (DRI 3)

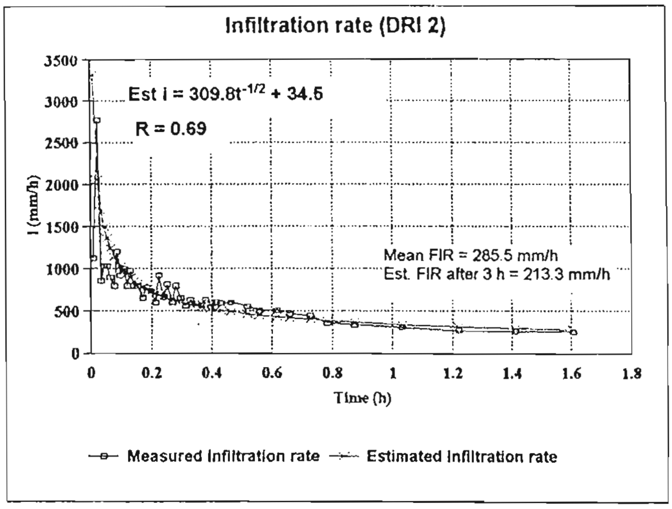
Appendix 4 (Continued)

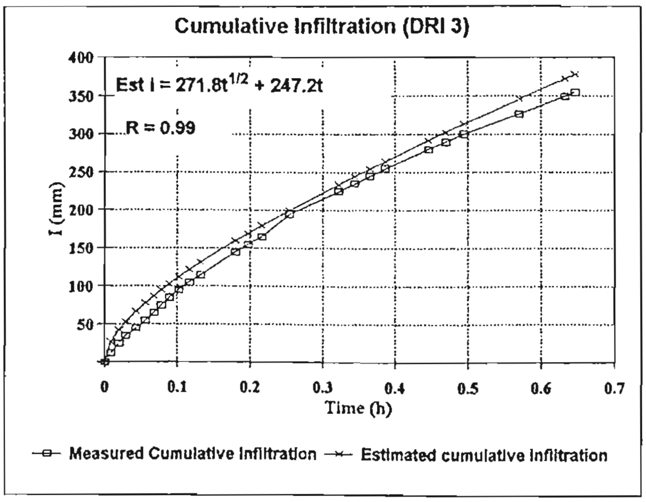
Site 6A (CT, dryland maize, loose interrow): Mr Mostert's farm

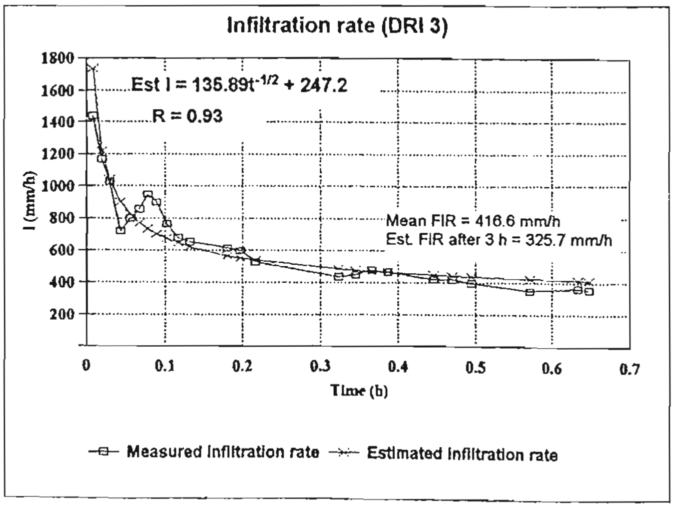






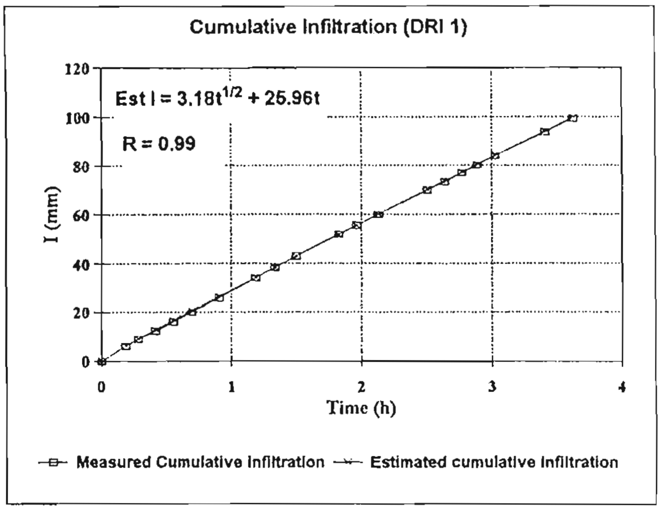


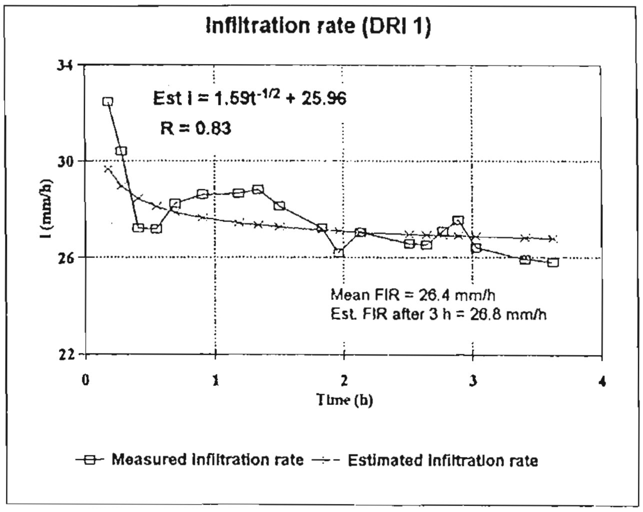


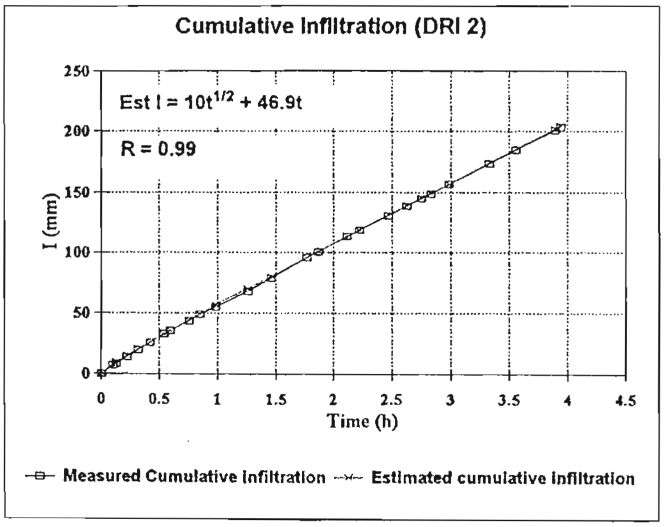


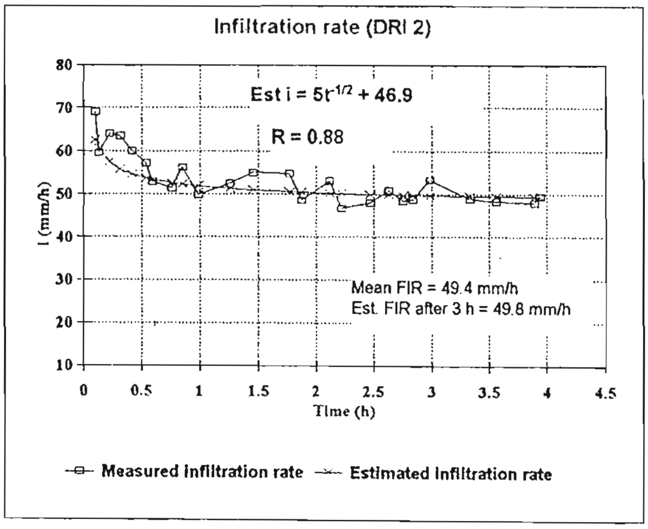
Appendix 4 (Continued)

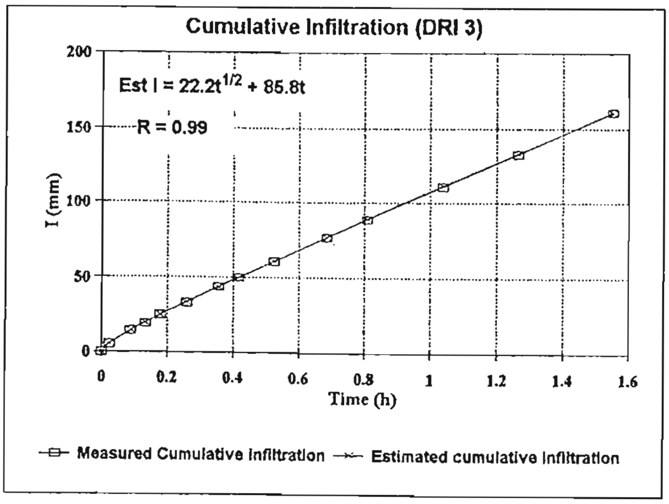
Site 6B (CT, dryland maize, compacted interrow): Mr Mostert's farm

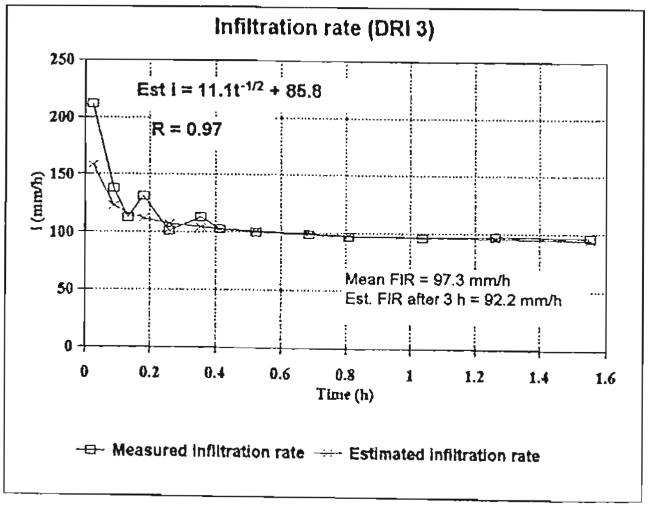

Cumulative Infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative Infiltration (DRI 2)

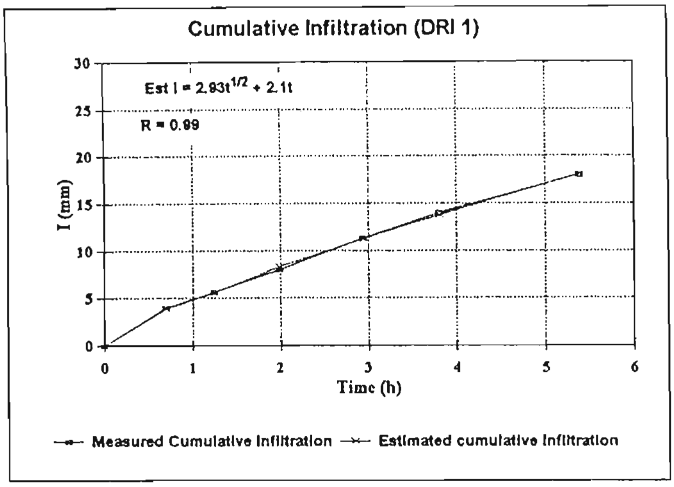

Infiltration rate (DRI 2)

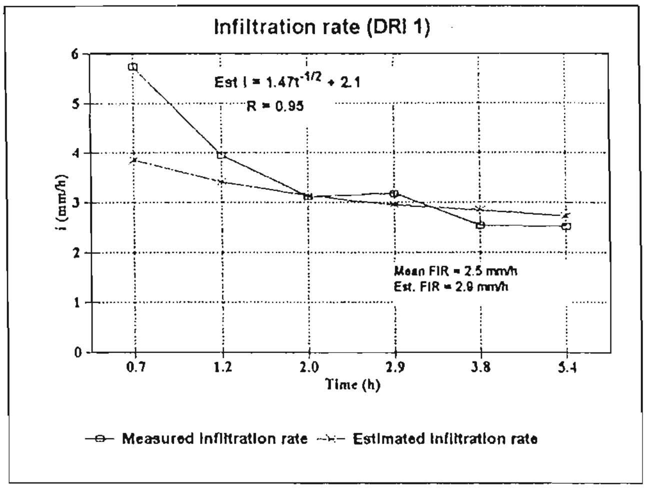

Cumulative Infiltration (DRI 3)

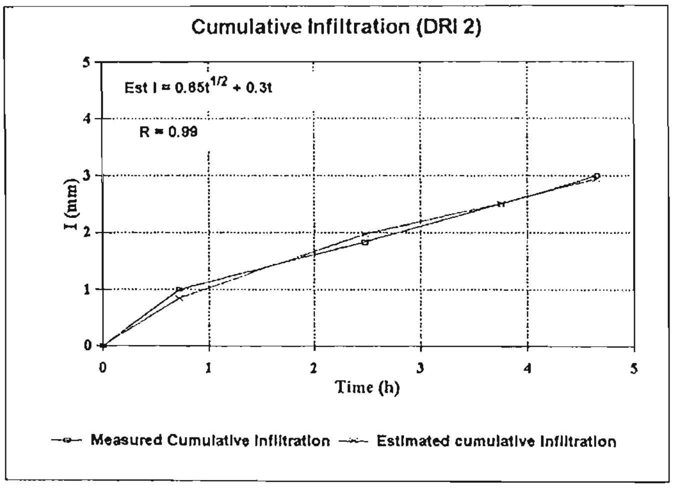

Infiltration rate (DRI 3)

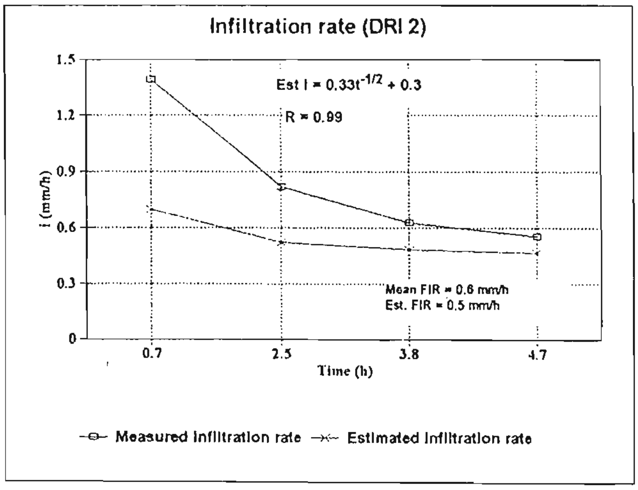
Appendix 4 (Continued)

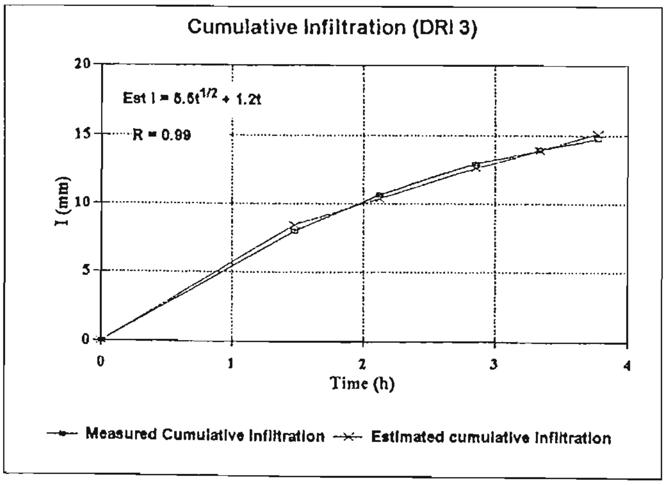
Site 7 (NT, irrigated soybean): Mr J. Jackson's farm

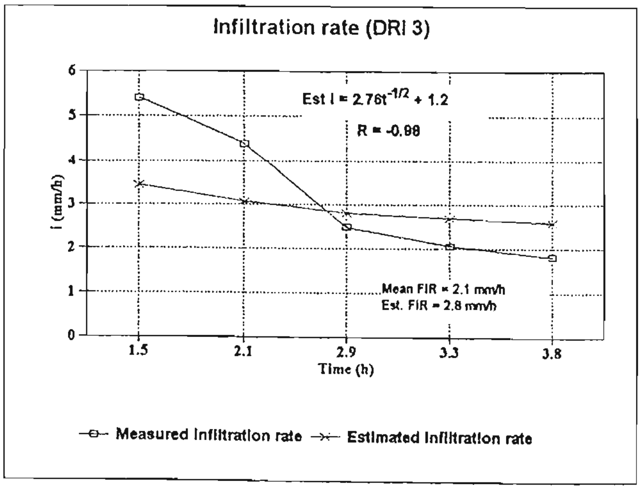






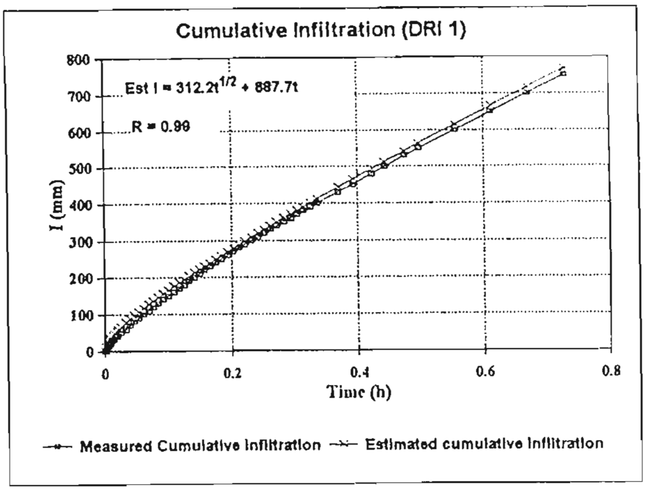


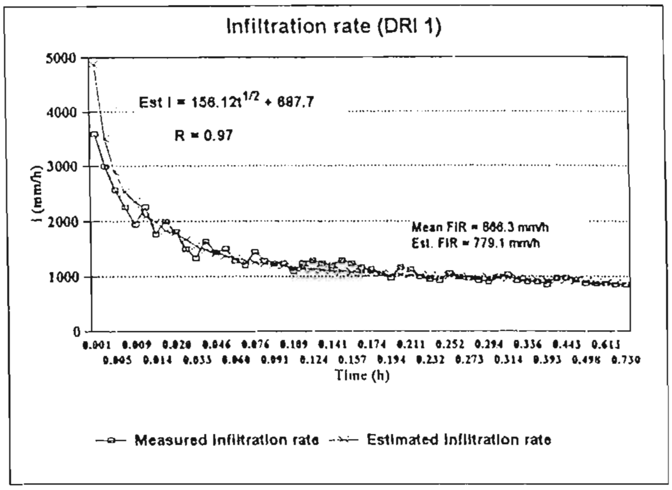


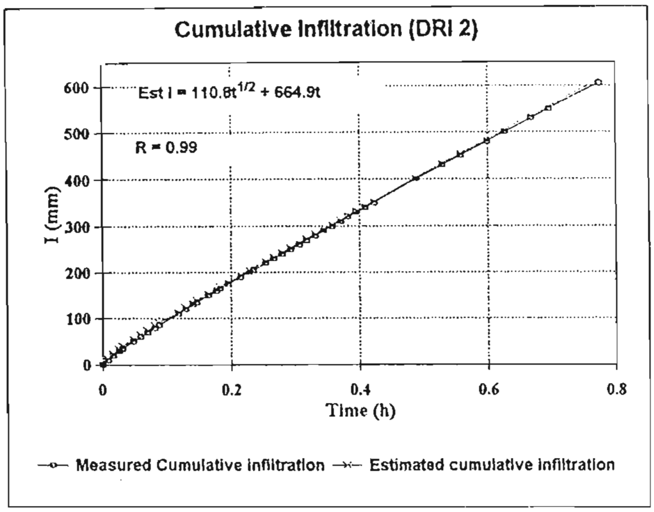


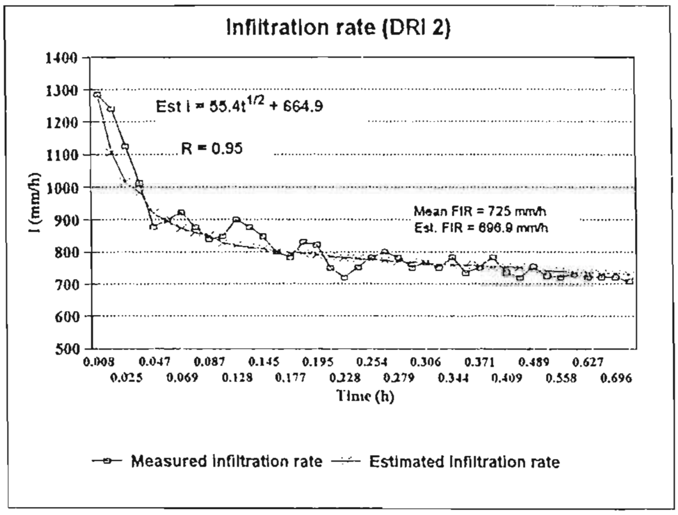
Appendix 4 (Continued)

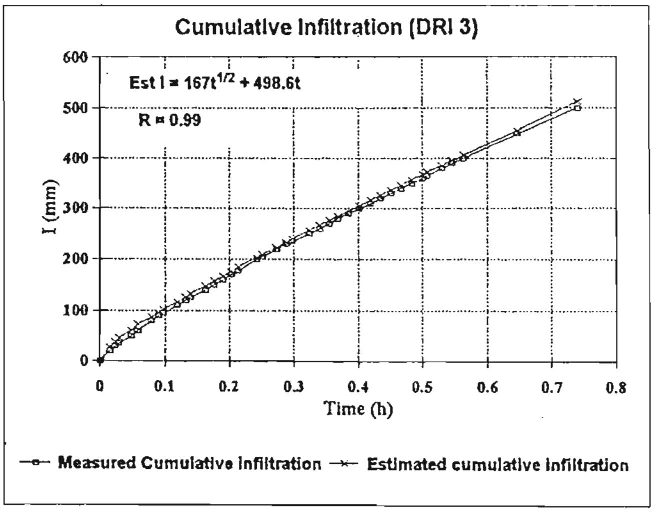
Site 8 (CT, Irrigated soybean): Mr Joubert's farm

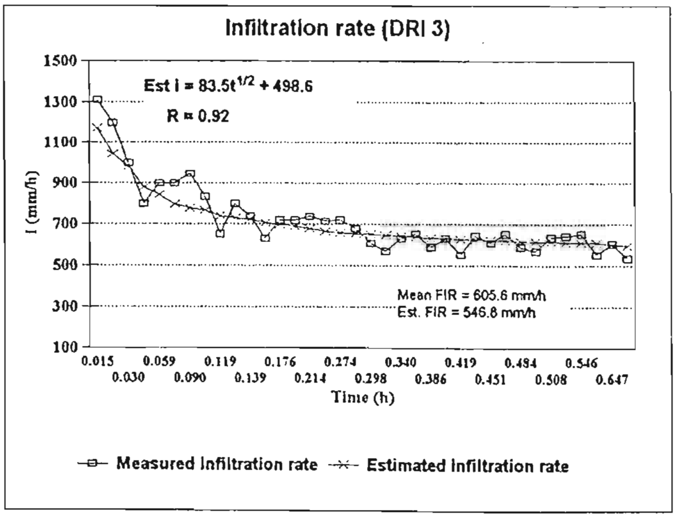






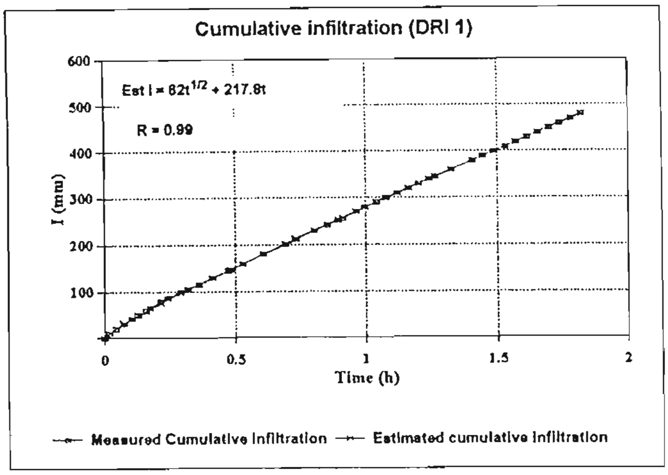


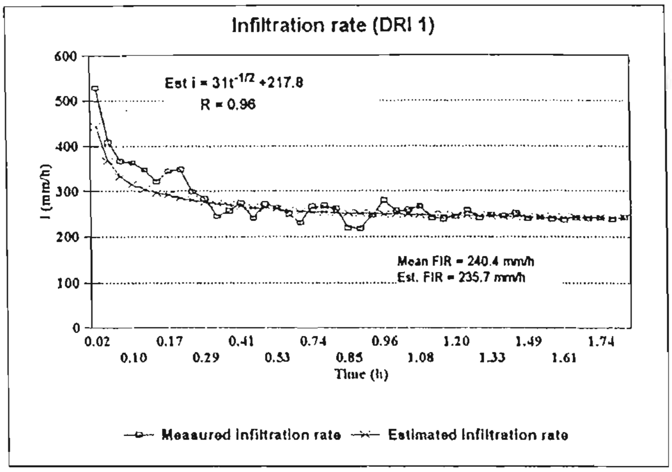


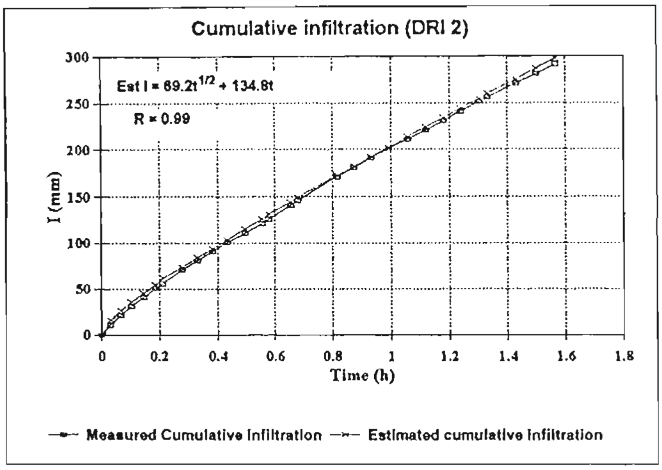


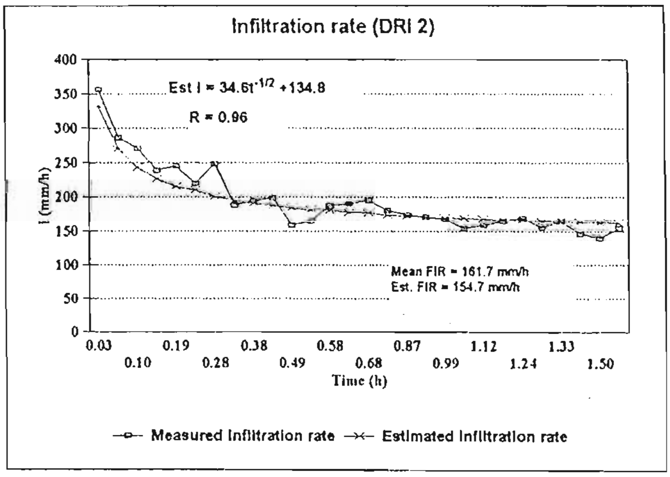
Appendix 4 (Continued)

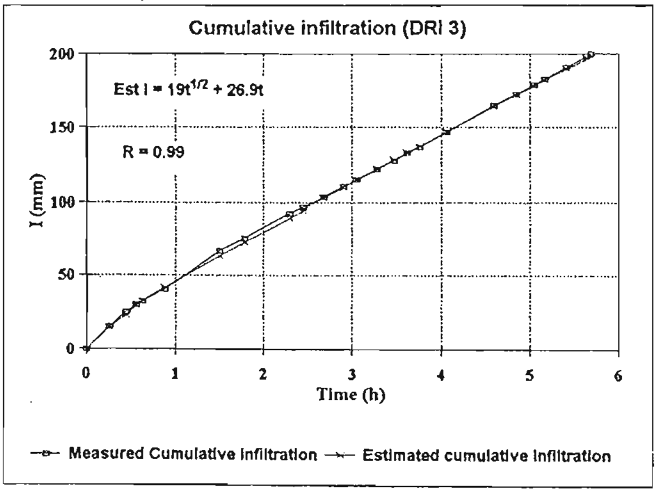
Site 9A (NT, dryland maize, loose inter-row): Cedara's field

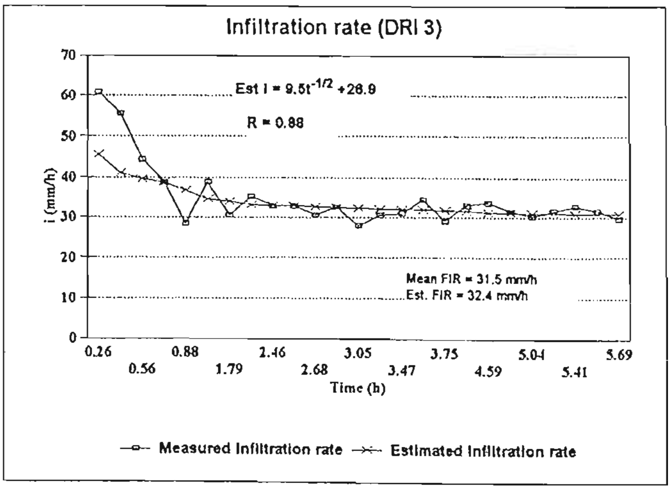

Cumulative infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative infiltration (DRI 2)

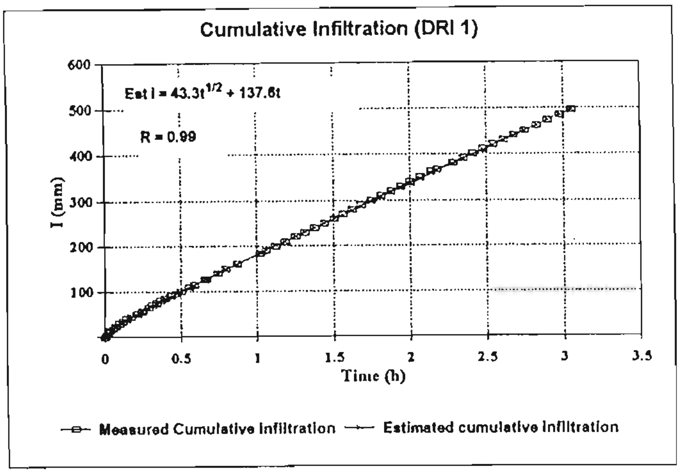

Infiltration rate (DRI 2)

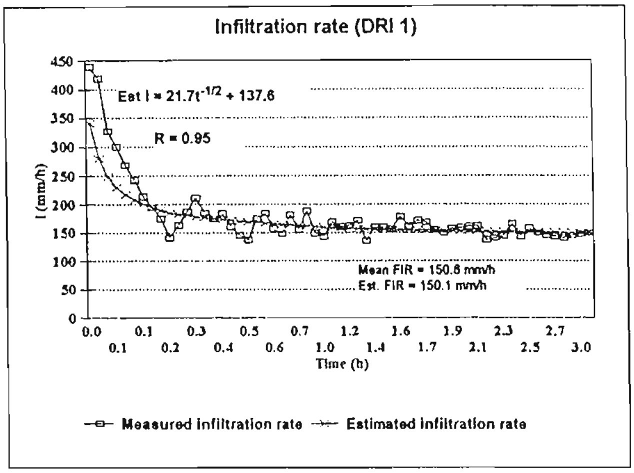

Cumulative infiltration (DRI 3)

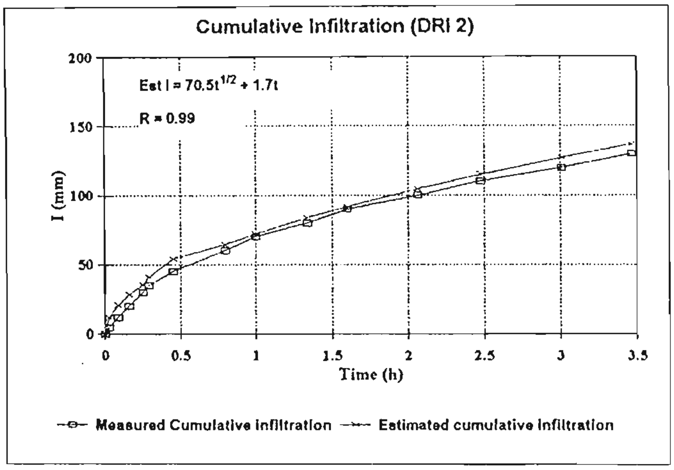

Infiltration rate (DRI 3)

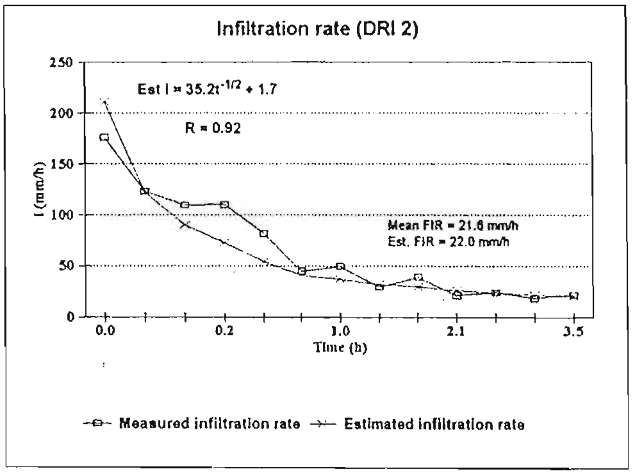
Appendix 4 (Continued)

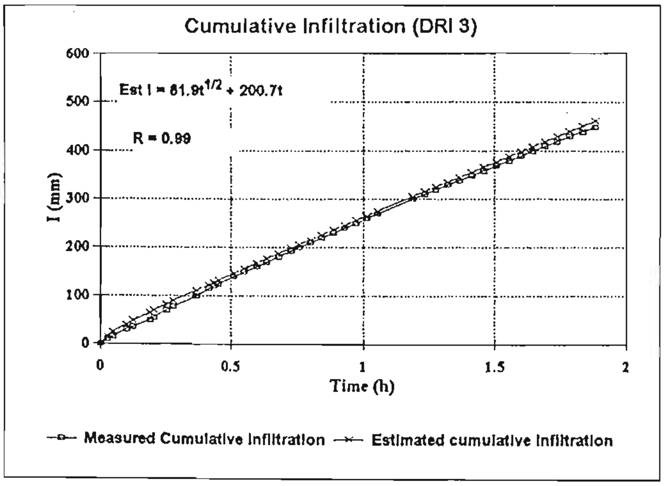
Site 9B (NT, dryland maize, compacted inter-row): Cedara's field

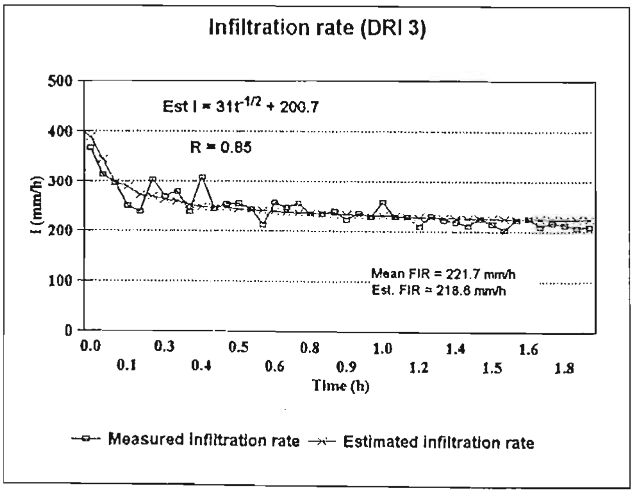

Cumulative Infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative Infiltration (DRI 2)

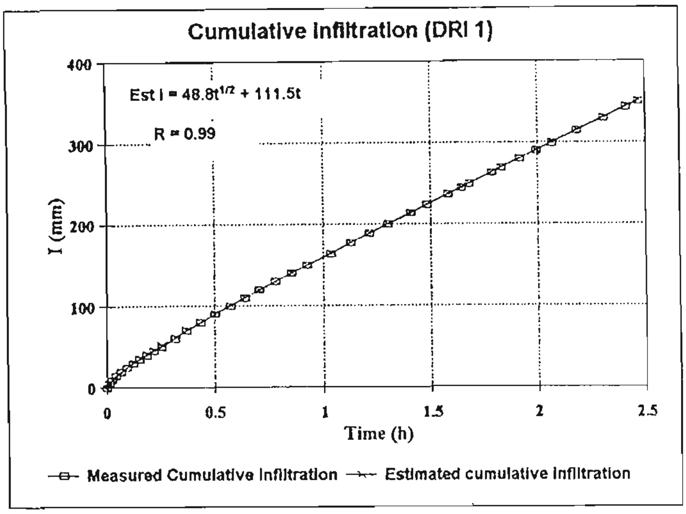

Infiltration rate (DRI 2)

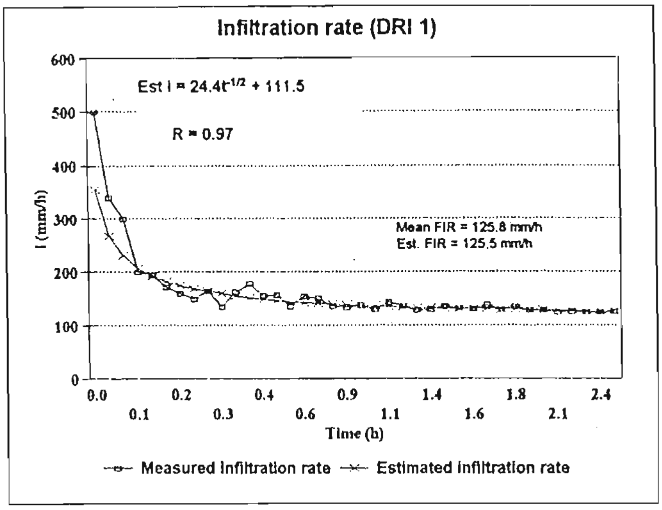

Cumulative Infiltration (DRI 3)

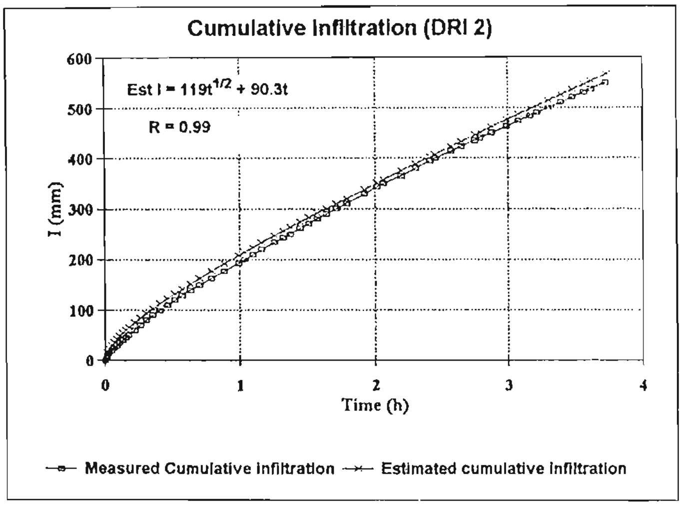

Infiltration rate (DRI 3)

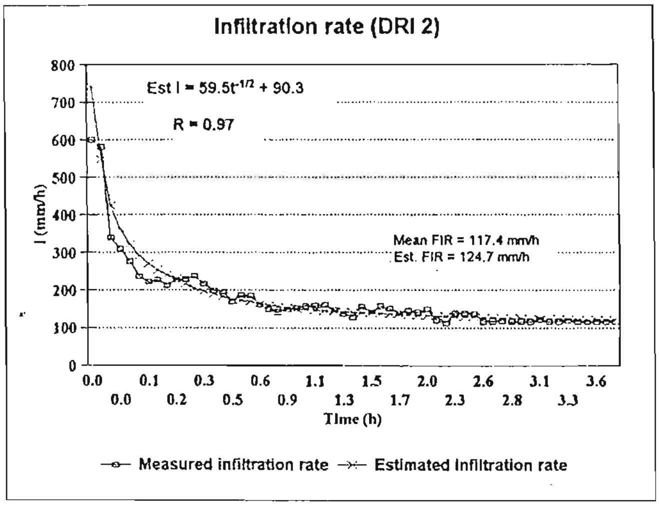
Appendix 4 (Continued)

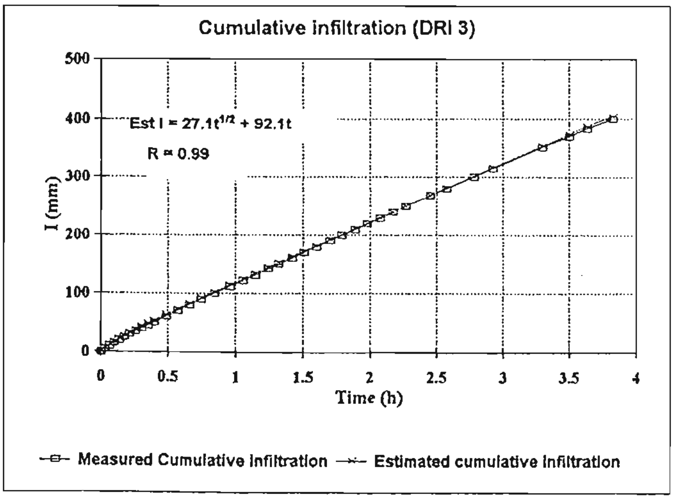
Site 10A (CT, dryland maize, loose inter-row): Cedara's field

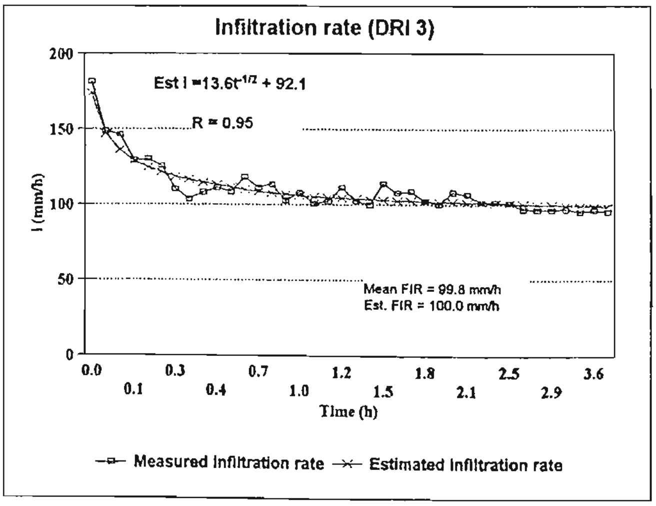






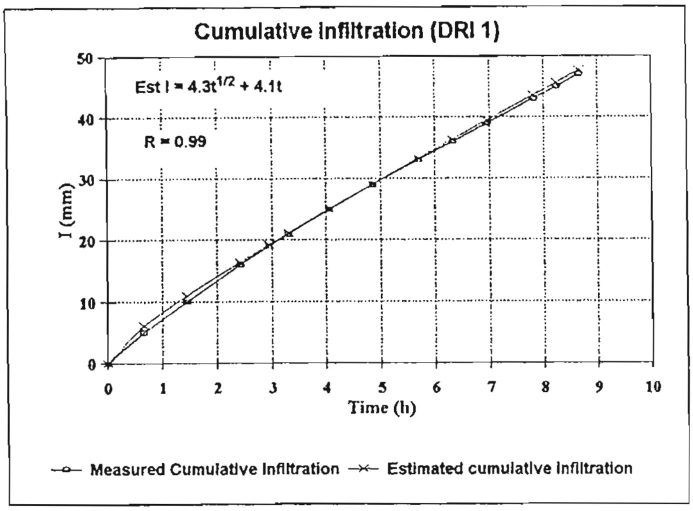


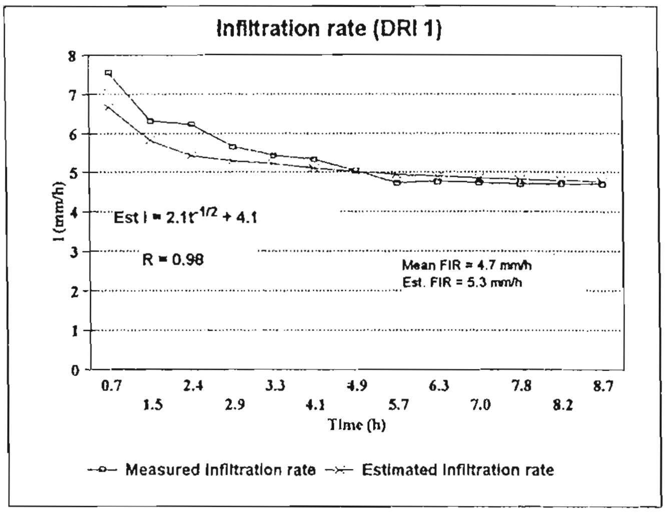


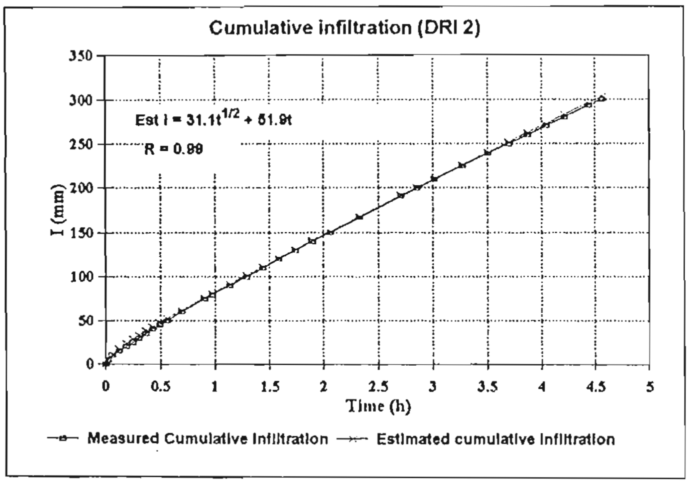


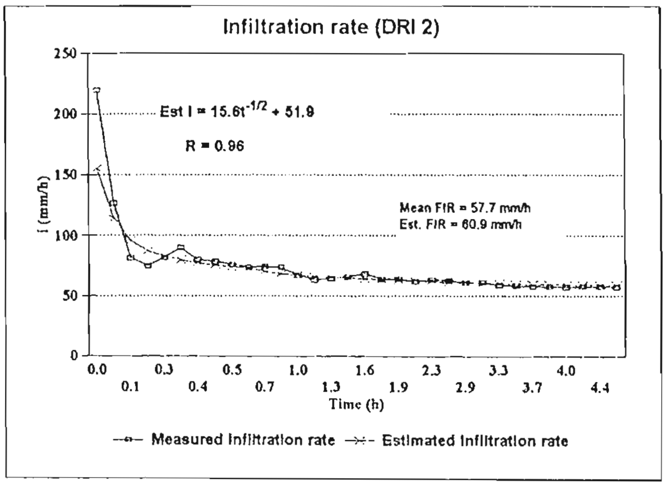
Appendix 4 (Continued)

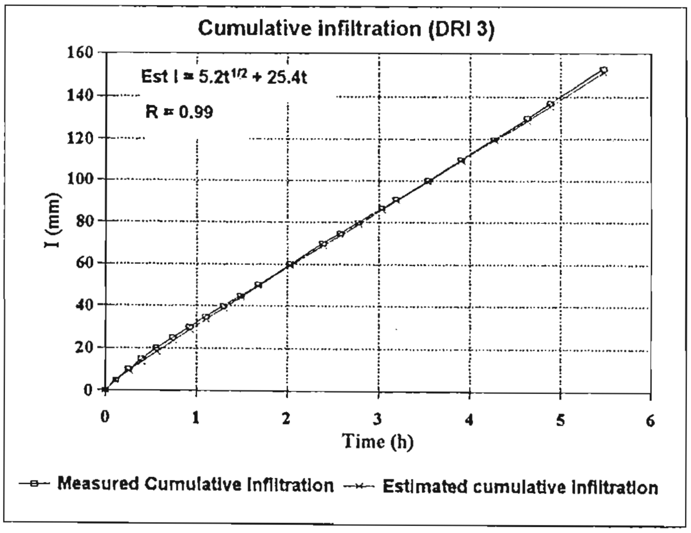
Site 10B (CT, dryland maize, compacted inter-row): Cedara's field

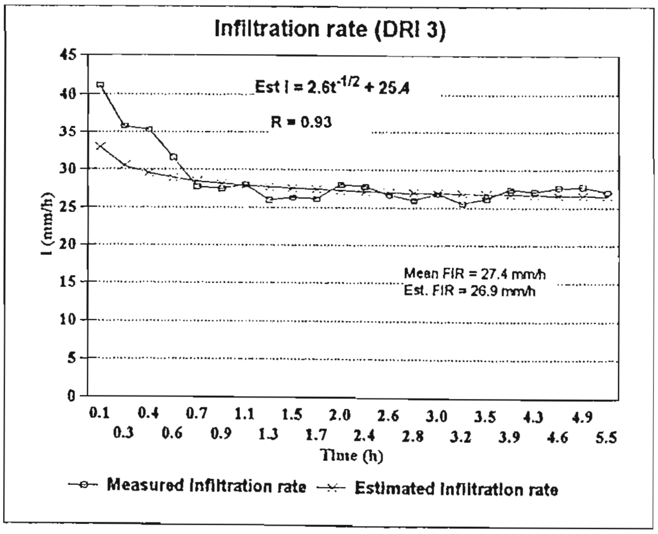

Cumulative infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative infiltration (DRI 2)

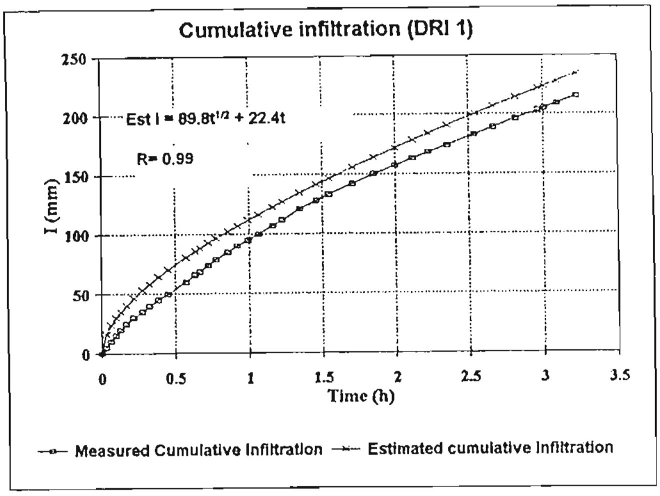

Infiltration rate (DRI 2)

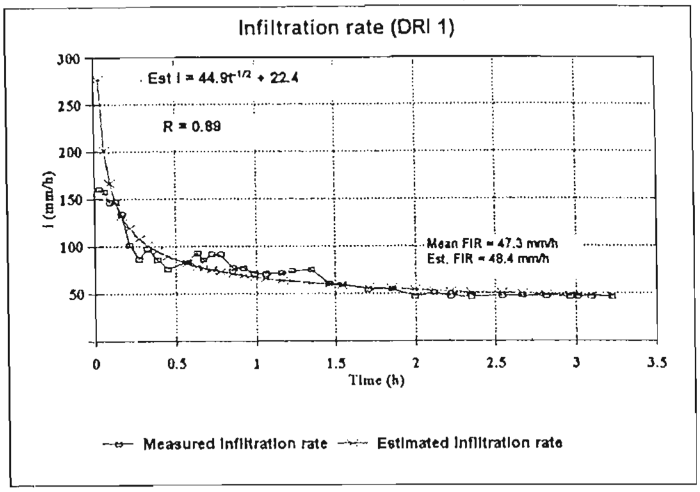

Cumulative infiltration (DRI 3)

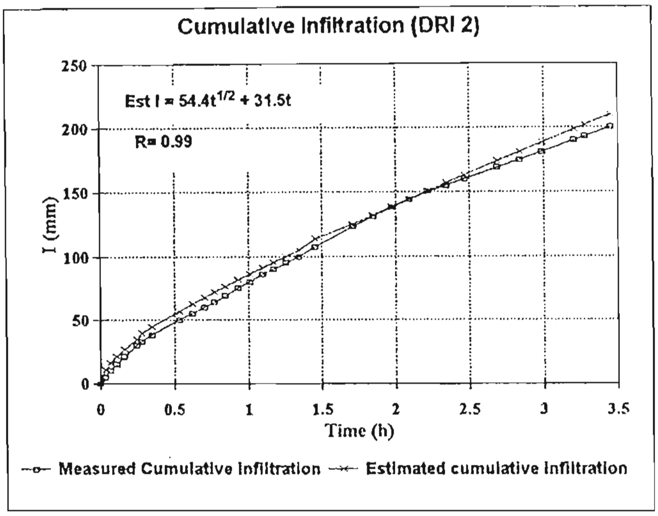

Infiltration rate (DRI 3)

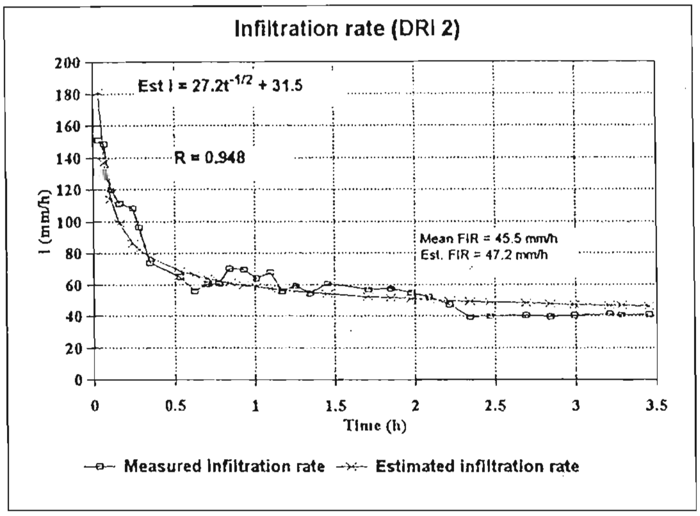
Appendix 4 (Continued)

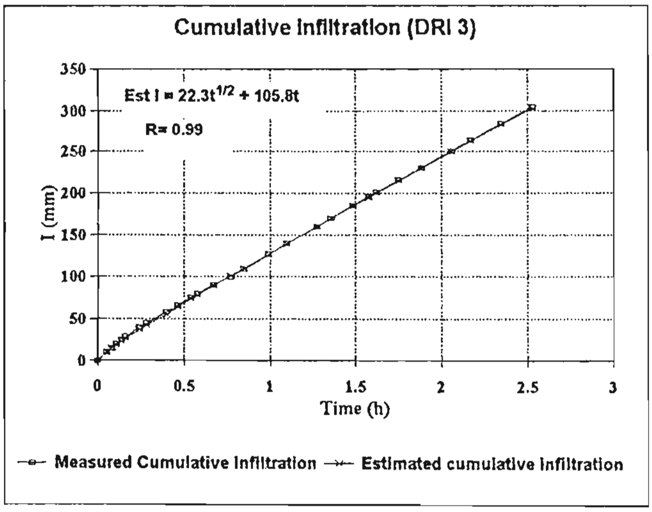
Site 11A (NT, dryland maize, loose inter-row): Cedara's field

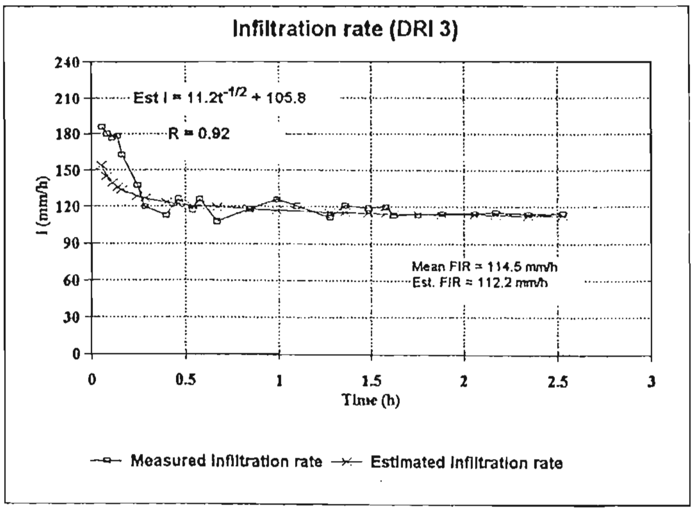

Cumulative infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative infiltration (DRI 2)

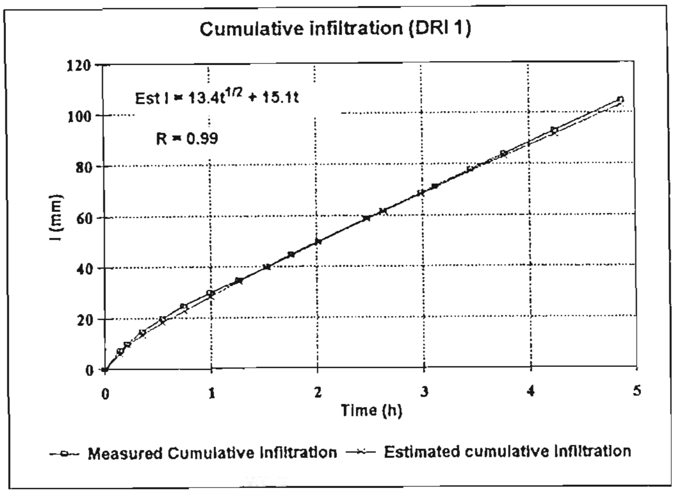

Infiltration rate (DRI 2)

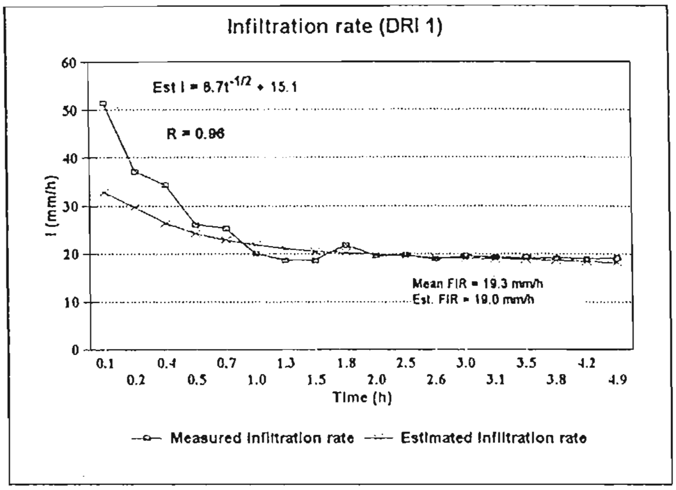

Cumulative infiltration (DRI 3)

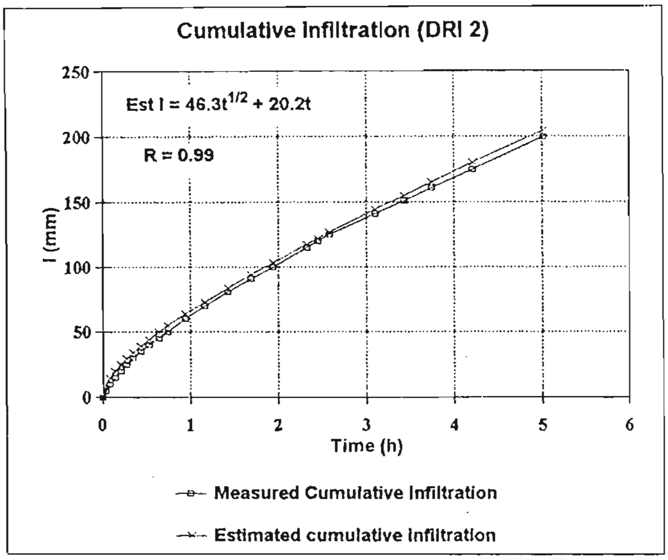

Infiltration rate (DRI 3)

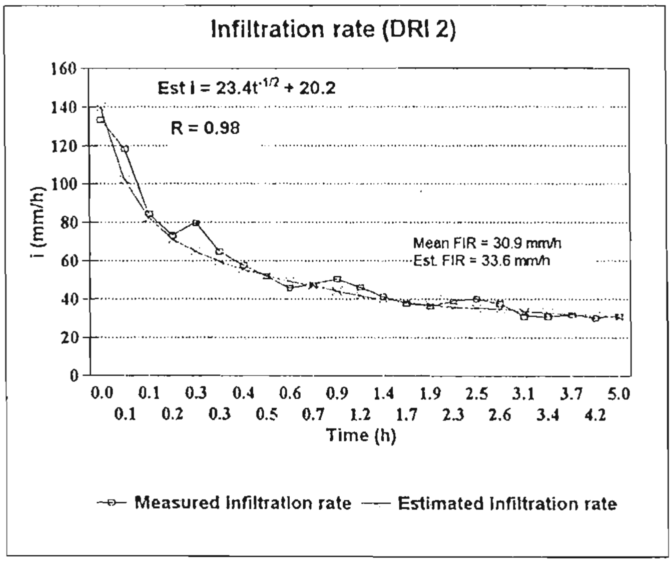
Appendix 4 (Continued)

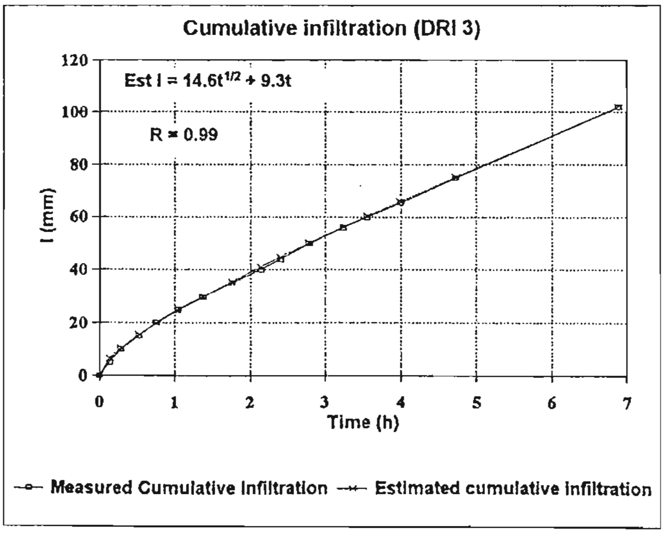
Site 11B (NT, dryland maize, compacted inter-row): Cedara's field

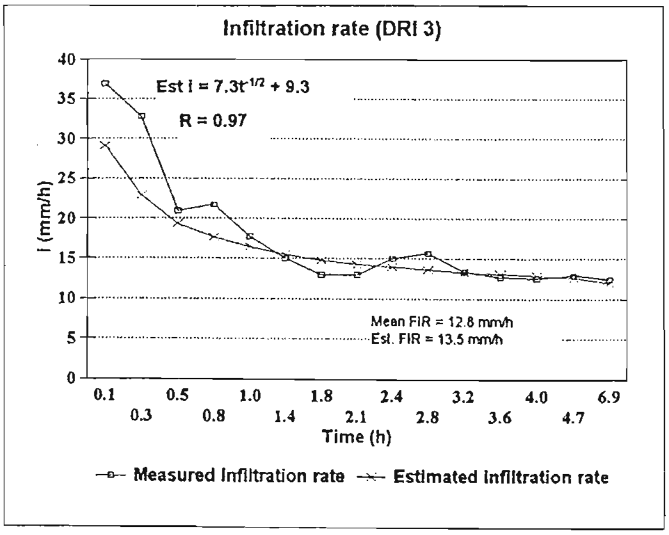






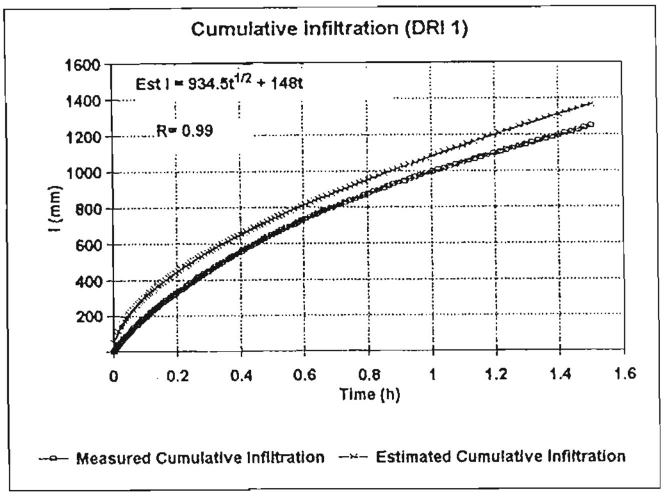


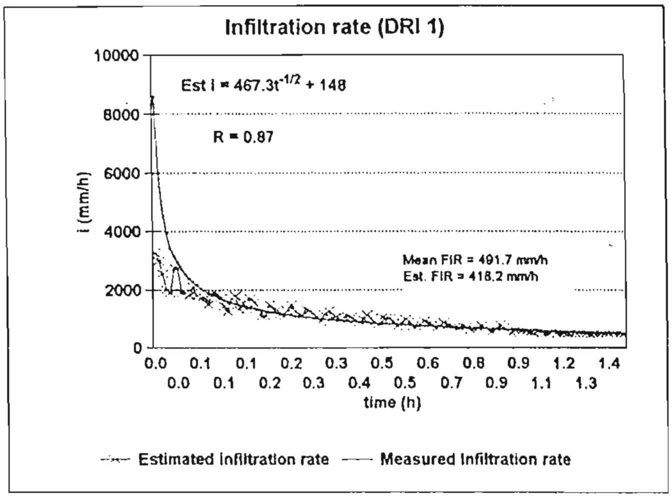


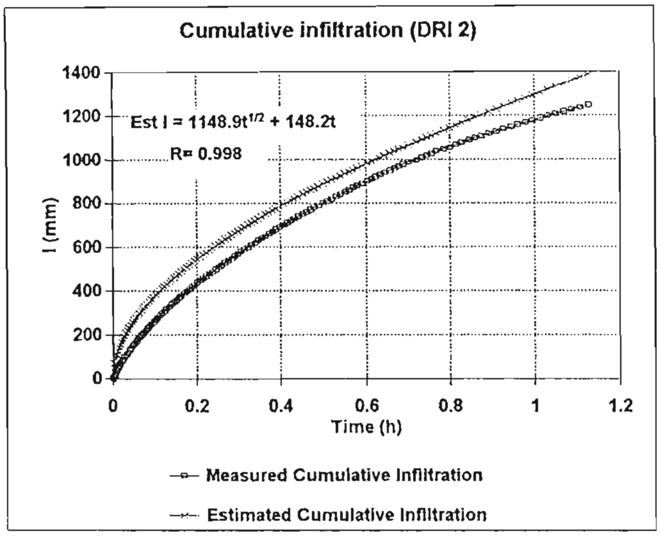


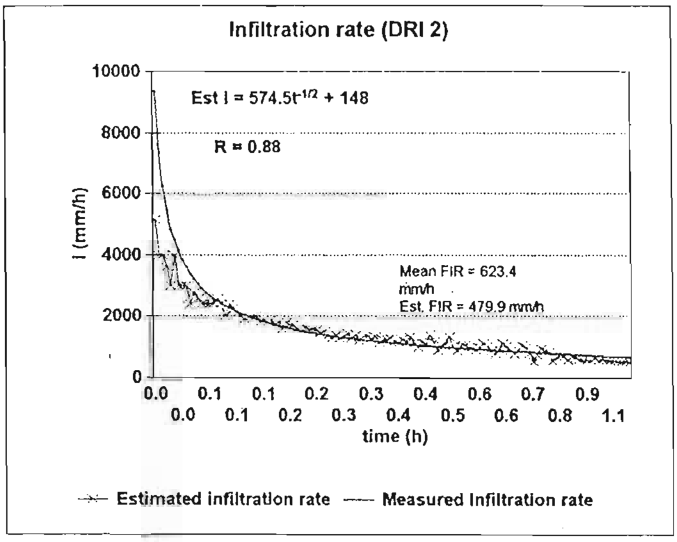
Appendix 4 (Continued)

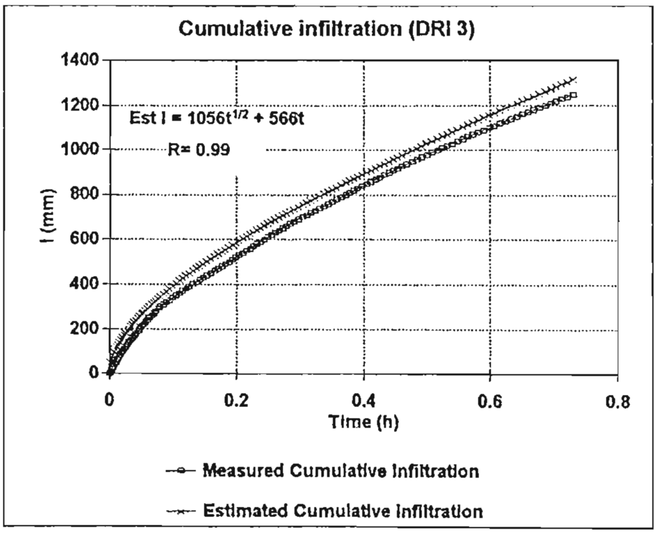
Site 12A (CT, dryland maize, loose inter-row): Cedara's field

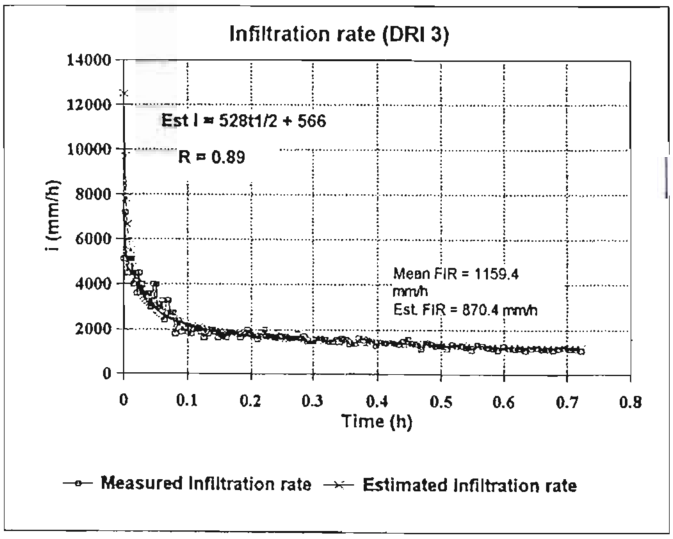






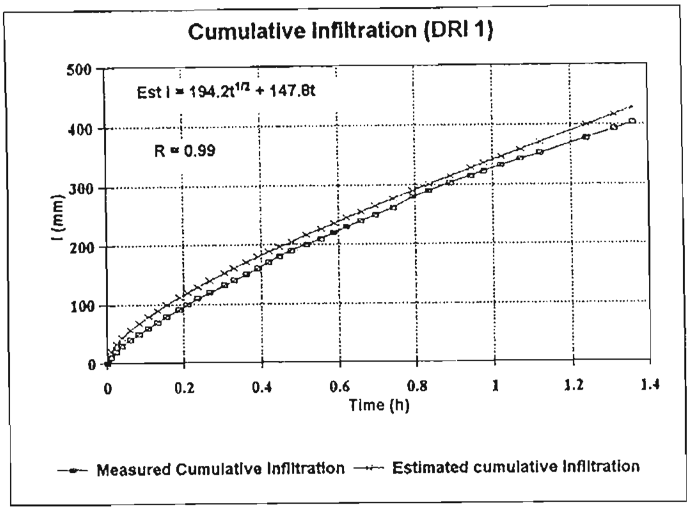


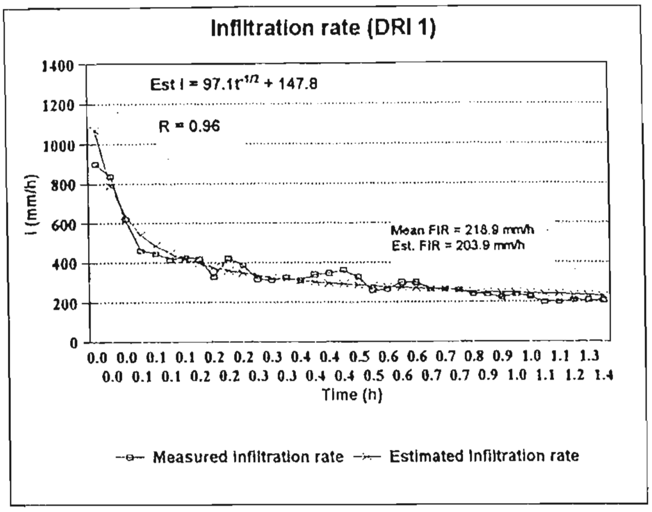


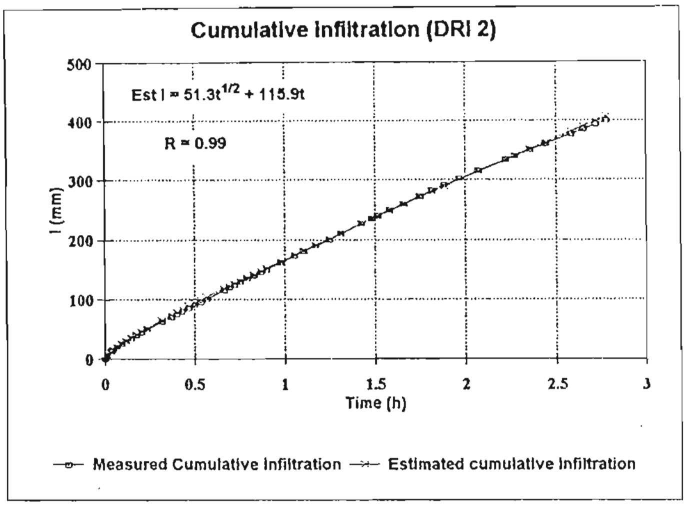


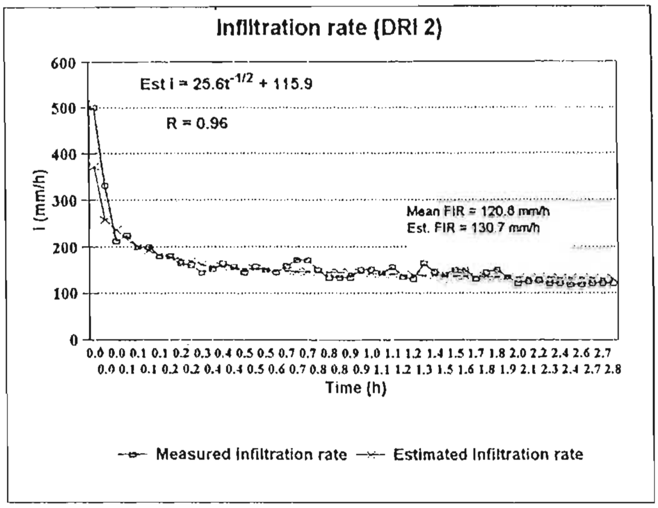
Appendix 4 (Continued)

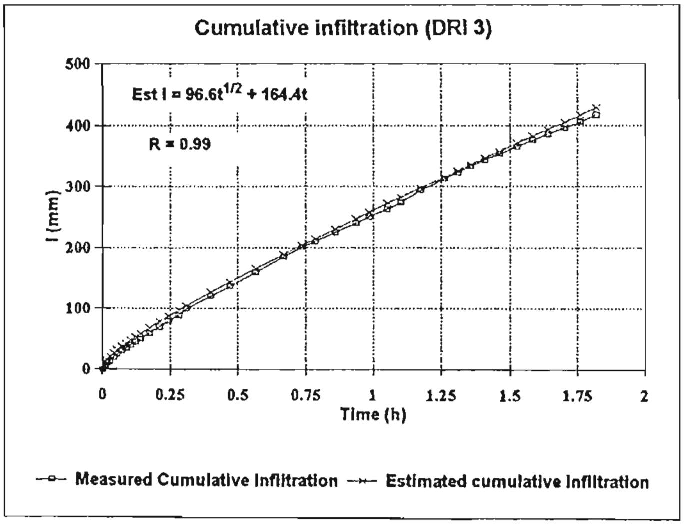
Site 12B (CT, dryland maize, compacted inter-row): Cedara's field

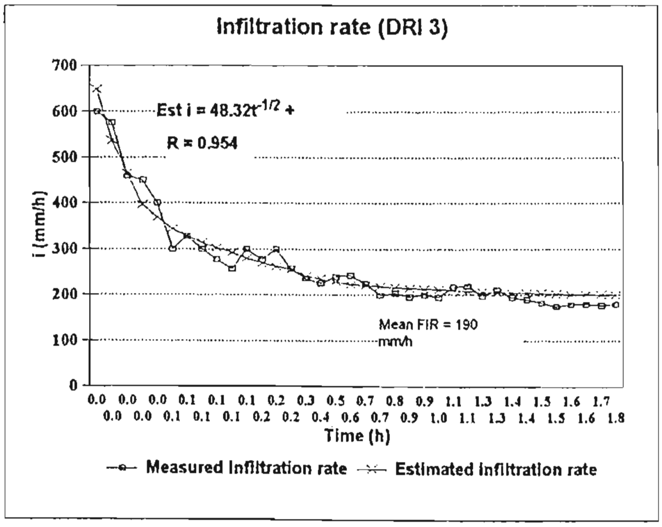

Cumulative infiltration (DRI 1)


Infiltration rate (DRI 1)


Cumulative infiltration (DRI 2)


Infiltration rate (DRI 2)


Cumulative infiltration (DRI 3)


Infiltration rate (DRI 3)

Appendix 5. Summary of analysis of variance for the effect of tillage on K_S at different soil depths. The values quoted are the mean of three replicates (LSD: Least significant difference – means followed by same letter on same row are significantly similar)

A. Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
50	0.119 B	67.54 A	0.166	1.3×10^6	< 0.001
150	0.389 B	16.016 A	0.056	6.0×10^5	< 0.001
320	1.56 B	18.12 A	0.749	3768.5	< 0.001

NB. T1: NT (Site 1); T2: CT (Site 2) Degree of freedom for each soil depth = 5

B. Sites 3 and 4: Mr van Der Aardweg and Mr van Vuuven's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
50	0.200 B	38.50 A	24.34	19.12	0.012
150	0.160 B	3.840 A	2.445	17.37	0.014
320	0.272 B	6.543 A	0.323	2907.75	< 0.001

NB. T1: NT (Site 3); T2: CT (Site 4) Degree of freedom for each soil depth = 5

C. Sites 5A, 5B and 6: Mr Miurhead's and Mr Mostert's farms

Soil depth (mm)	Treatments				LSD	F	P
	T1	T2	T3	T4			
50	35.1 CD	35.4 BC	115.7 A	14.4 CD	25.01	34.12	< 0.001
150	1.0	4.7	26.9	2.0	NS	1.03	0.430
320	10.7	1.4	4.3	6.0	NS	2.43	0.140

NB. T1: NT-IM (Site 5A); T2: NT-DLM (Site 5B); T3: CT-LIR (6A); T4: CT-CIR (6B)
Degree of freedom for each soil depth = 11

D. Sites 7 and 8: Mr J. Jackson's and Mr J. Joubert's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
50	1.1 B	74.9 A	18.96	116.87	< 0.001
150	1.0	27.4	NS	5.08	0.087
320	1.1	2.62	NS	11.27	0.028

NB. T1: NT (Site 7); T2: CT (Site 8) Degree of freedom for each soil depth = 5

E. Sites 9 and 10: Cedara Agricultural Research Station

Soil depth (mm)	Treatments				LSD	F	P
	T1	T2	T3	T4			
50	22.2 AB	16.0 AB	43.0 A	2.8 B	28.95	3.56	0.067
150	59.7 A	27.5 B	8.8 CD	2.6 D	16.76	24.89	< 0.001
320	31.91 A	12.02 B	4.71 CD	2.51 D	4.532	92.66	< 0.001

NB. T1: NT-LIR (9A); T2: NT-CIR (9B); T3: CT-LIR (10A); T4: CT-CIR (10B)
Degree of freedom for each soil depth = 11

F. Sites 11 and 12: Cedara Agricultural Research Station

Soil depth (mm)	Treatments				LSD	F	P
	T1	T2	T3	T4			
50	150.0 AB	3.0 BC	306.0 A	69.0 BC	225.5	3.58	0.0066
150	20.5	19.9	17.7	6.5	NS	1.45	0.300
320	7.7	29.9	26.8	63.7	NS	2.37	0.146

NB. T1: NT-LIR (11A); T2: NT-CIR (11B); T3: CT-LIR (12A); T4: CT-CIR (12B)
Degree of freedom for each soil depth = 11

Appendix 6. Summary of analysis of variance for the effect of tillage on MWD at different soil depths. The values quoted are the mean of three replicates (NS: non-significant; LSD: Least significant difference – means followed by same letter on same row are significantly similar)

A. Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	2.817 A	1.666 B	0.248	165.6	< 0.001
50 - 100	2.526	2.174	NS	4.25	0.108
100 - 150	1.954 B	2.405 A	0.222	31.94	0.005
270 - 450	1.258 B	1.918 A	0.208	77.94	< 0.001

NB. T1: NT (Site 1); T2: CT (Site 2) Degree of freedom for each soil depth = 5

B. Sites 3 and 4: Mr van Der Aardweg and Mr van Vuuven's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	2.552 A	1.840 B	0.199	97.98	< 0.001
50 - 100	2.526	2.174	NS	0.036	0.876
100 - 150	1.954	2.405	NS	0.69	0.451
270 - 440	1.258 B	1.918 A	0.050	128.98	< 0.001

NB. T1: NT (Site 3); T2: CT (Site 4) Degree of freedom for each soil depth = 5

C. Sites 5A, 5B and 6: Mr Miurhead's and Mr Mostert's farms

Soil depth (m)	Treatments			LSD	F	P
	T1	T2	T3			
0 - 50	2.745 A	2.565 B	1.281 C	0.159	300.8	< 0.001
50 - 100	2.185 A	1.959 B	1.234 C	0.200	73.7	< 0.001
100 - 150	1.068 BC	0.998 C	2.009 A	0.143	186.5	< 0.001
200 - 400	1.062 B	0.624 C	1.567 A	0.056	848.3	< 0.001

NB. T1: NT-IM (Site 5A); T2: NT-DLM (Site 5B); T3: CT (Site 6) D.f = 8

D. Sites 7 and 8: Mr J. Jackson's and Mr J. Joubert's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	3.033 A	2.588 B	0.237	27.11	0.006
50 - 100	2.342 A	1.526 B	0.327	48.03	0.002
100 - 150	1.940	2.274	NS	2.96	0.160
270 - 400	0.993 A	0.535 B	0.176	52.32	0.002

NB. T1: NT (Site 7); T2: CT (Site 8) Degree of freedom for each soil depth = 5

E. Sites 9 and 10: Cedara Agricultural Research Station

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	1.860 A	1.118 B	0.078	690.5	< 0.001
50 - 100	1.059	0.900	NS	1.24	0.328
100 - 150	0.704	0.774	NS	1.82	0.249
200 - 300	0.458 B	0.692 A	0.134	23.4	0.008

NB. T1: NT (Site 9); T2: CT (Site 10) Degree of freedom for each soil depth = 5

F. Sites 11 and 12 : Cedara Agricultural Research Station

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	1.848 A	1.651 B	0.068	97.98	0.001
50 - 100	1.325 A	1.221 B	0.067	0.036	0.013
100 - 150	0.780 B	1.340 A	0.291	0.69	0.006
150 - 350	0.750 B	0.960 A	0.069	128.98	0.001

NB. T1: NT (Site 11); T2: CT (Site 12) Degree of freedom for each soil depth = 5

Appendix 7. Summary of analysis of variance for the effect of tillage on OC at different soil depths. The values quoted are the mean of three replicates (LSD: Least significant difference – means with same letter on same row are significantly similar)

A. Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	2.315 A	1.814 B	0.035	1610.8	< 0.001
50 - 100	2.103	2.074	NS	0.81	0.419
100 - 150	1.902 B	2.015 A	0.054	34.24	0.004
270 - 450	1.067 B	1.903 A	0.297	61.11	0.001

NB. T1: NT (Site 1); T2: CT (Site 2)   Degree of freedom for each soil depth = 5

B. Sites 3 and 4: Mr van Der Aardweg and Mr van Vuuven's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	1.948 A	1.647 B	0.073	129.3	< 0.001
50 - 100	1.410 B	1.453 A	0.031	15.29	0.017
100 - 150	1.192 B	1.349 A	0.045	96.03	< 0.001
270 - 440	0.567	0.633	NS	2.00	0.230

NB. T1: NT (Site 3); T2: CT (Site 4)   Degree of freedom for each soil depth = 5

C. Sites 5A, 5B and 6: Mr Miurhead's and Mr Mostert's farms

Soil depth (m)	Treatments			LSD	F	P
	T1	T2	T3			
0 - 50	2.285 A	2.205 B	1.672 C	0.023	2439.5	< 0.001
50 - 100	1.815 A	1.683 C	1.737 B	0.027	73.9	< 0.001
100 - 150	1.507 AB	1.141 B	1.809 A	0.484	5.72	0.041
200 - 400	0.800 C	1.067 B	1.773 A	0.213	67.03	< 0.001

NB. T1: NT-IM (Site 5A); T2: NT-DLM (Site 5B); T3: CT (Site 6)   D.f = 8

D. Sites 7 and 8 : Mr J. Jackson's and Mr J. Joubert's farms

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	2.997 A	2.063 B	0.034	5689.3	0.001
50 - 100	1.623 A	1.341 B	0.051	238.6	< 0.001
100 - 150	1.477 B	2.125 A	0.033	2953.3	< 0.001
270 - 400	0.633	0.500	NS	1.60	0.275

NB. T1: NT (Site 7); T2: CT (Site 8) Degree of freedom for each soil depth = 5

E. Sites 9 and 10: Cedara Agricultural Research Station

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	3.922 A	3.216 B	0.047	1722.7	< 0.001
50 - 100	3.288 A	3.123 B	0.041	124.0	< 0.001
100 - 150	2.665 B	3.083 A	0.023	2453.0	< 0.001
200 - 300	1.000 B	1.600 A	0.227	54.0	0.002

NB. T1: NT (Site 9); T2: CT (Site 10) Degree of freedom for each soil depth = 5

F. Sites 11 and 12: Cedara Agricultural Research Station

Soil depth (mm)	Treatments		LSD	F	P
	T1	T2			
0 - 50	3.432 A	3.083 B	0.022	1955.7	< 0.001
50 - 100	2.992 B	3.043 A	0.030	21.49	0.010
100 - 150	2.786 B	2.946 A	0.056	63.44	0.001
150 - 350	2.500	2.700	NS	6.00	0.070

NB. T1: NT (Site 11); T2: CT (Site 12) Degree of freedom for each soil depth = 5

Appendix 8. Summary of analysis of variance for the effect of tillage on SPR at different soil depths. The values quoted are the mean of ten replicates (NS: non significant; LSD: Least significant difference – means followed by same letter on same row are significantly similar)

Sites 1 and 2: Mr R. Lund's and Mr Boschoff's farms

Soil depth (m)	Treatments				LSD	F	P
	T1	T2	T3	T4			
0.10	2295 AB	2870 A	475 C	2225 AB	658.9	22.19	< 0.001
0.20	2290	2220	1980	2215	NS	0.23	0.872
0.30	3005	2837	2925	3225	NS	0.15	0.930
0.40	4390	4350	4280	4035	NS	0.55	0.653
0.50	4105	4350	4085	3930	NS	0.31	0.821
0.60	4455	5000	4505	5000	NS	0.91	0.457

N.B. T1 (1A): NT loose inter-row (NT-LIR) T3 (2A): CT loose inter-row (CT-LIR)
T2 (1B): NT compacted inter-row (NT-CIR) T4 (2B): CT compacted inter-row (CT-CIR)
Degree of freedom for each depth = 39

Sites 3 and 4: Mr Van Der Aardwrg's and Mr Van Vuuven's farms

Soil depth (m)	Treatments			LSD	F	P
	T1	T2	T3			
0.10	4362	1617	2792	NS	3.24	0.111
0.20	3808	2892	2262	NS	0.80	0.492
0.30	3942	1608	2275	NS	2.69	0.147
0.40	3958	1492	2350	NS	2.97	0.127
0.50	3767	1433	2408	NS	2.53	0.159
0.60	3767	2742	3300	NS	0.22	0.806

N.B. T1 (3): NT T2 (4A): CT loose inter-row (CT-LIR)
Degree of freedom for each depth = 29 T3 (4B): CT compacted inter-row (CT-CIR)

Sites 5A, 5B and and 6: Mr Miurhead's and Mr Mostert's farms

Soil depth (m)	Treatments				LSD	F	P
	T1	T2	T3	T4			
0.10	2950 CD	4840 A	1847 D	2992 BC	1169	12.11	< 0.001
0.20	3000 BC	4632 A	2867 CD	2497 CD	1399.9	4.11	0.024
0.30	3065 CD	4655 A	3165 CD	3437 BC	1144.4	3.69	0.034
0.40	2470 BC	4647 A	2505 BC	3242 AB	1425.4	4.59	0.017
0.50	2142 BC	4450 A	1855 BC	3140 AB	1628.4	4.66	0.016
0.60	4310	500	3395	4435	NS	0.98	0.426

N.B. T1 (5A): NT Irrigated maize (NT-IM)

T2 (5B): NT dryland maize (NT-DLM)

Degree of freedom for each depth = 39

T3 (6A): CT loose inter-row (NT-LIR)

T4 (6B): CT compacted inter-row (NT-CIR)

Sites 7 and 8: Mr J.Jackson's and Mr J. Joubert's farms

Soil depth (m)	Treatments			LSD	F	P
	T1	T2	T3			
0.10	1928 BC	1803 C	3944 A	724.4	23.79	< 0.001
0.20	1472	2156	2636	NS	2.97	0.073
0.30	1580 B	2409 AB	2845 A	986.6	3.67	0.043
0.40	1489 B	2156 AB	2856 A	877.6	5.25	0.014
0.50	1064 B	3466 A	3145 A	1110.1	11.94	< 0.001
0.60	4031	5000	4869	NS	1.97	0.164

N.B. T1 (7) : NT

Degree of freedom for each depth = 29

T2 (8A) : CT loose inter-row (CT-LIR)

T3 (8B) : CT compacted inter-row (CT-CIR)

Sites 9 and 10: Cedara's fields

Soil depth (m)	Treatments				LSD	F	P
	T1	T2	T3	T4			
0.10	3074 A	3042 AB	1944 C	2979 AB	498.4	9.85	< 0.001
0.20	2384 AB	2570 AB	1755 C	2605 A	407.6	7.70	< 0.001
0.30	1852 BC	1795 CD	2361 A	1850 CD	340.5	5.01	0.005
0.40	1570 CD	1361 D	2219 AB	2292 A	280.4	22.63	< 0.001
0.50	1217 CD	1441 CD	1556 BC	2052 A	405	6.25	0.002
0.60	1496 BC	3304 A	2234 AB	1637 BC	1082	4.75	0.007

N.B. T1 (9A): NT loose inter-row (NT-LIR) T3 (10A): CT loose inter-row (CT-LIR)

T2 (9B): NT compacted inter-row (NT-CIR) T4 (10B): CT compacted inter-row (CT-CIR)

Degree of freedom for each depth = 39

Sites 11 and 12: Mrs Cedara's fields

Soil depth (m)	Treatments				LSD	F	P
	T1	T2	T3	T4			
0.10	3751 AB	3792 A	886 D	3018 C	467.3	70.12	< 0.001
0.20	2525 B	3452 A	908 D	1950 C	414	54.50	< 0.001
0.30	1864 BC	2642 A	1834 BD	1851 CD	412.7	7.60	< 0.001
0.40	2119 AB	2165 A	1743 C	1395 D	325.1	10.11	< 0.001
0.50	1908	1784	1730	1410	NS	1.58	0.211
0.60	1747	2020	1808	1834	NS	0.09	0.966

N.B. T1 (11A): NT loose inter-row (NT-LIR) T3 (12A): CT loose inter-row (CT-LIR)

T2 (11B): NT compacted inter-row (NT-CIR) T4 (12B): CT compacted inter-row (CT-CIR)

Degree of freedom for each depth = 39