A COMPARISON OF THE EFFECTS OF TILLAGE ON SOIL PHYSICAL PROPERTIES AND MICROBIAL ACTIVITY AT DIFFERENT LEVELS OF NITROGEN FERTILIZER AT GOURTON FARM, LOSKOP, KWAZULU-NATAL

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FACULTY OF SCIENCE AND AGRICULTURE

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Abstract

Long-term food security and environmental quality are closely linked to maintaining soil quality. Therefore, the assessment of the effect of agricultural management practices on soil chemical, physical and biological parameters provide fundamental information about sustainability. An agricultural management practice which has received much attention in the last decade is tillage. The loss of topsoil due to erosion and a reduction of soil organic matter under conventional tillage practices, together with escalating fuel prices, have lead to the increased implementation of conservation tillage practices. However, the response of soil to a reduction in tillage is dependent on the inherent soil properties, environmental conditions, crop type and the land management practices. The successful implementation of conservation tillage practices is thus site specific. Furthermore, the effect of fertilizer application on soil quality is affected by tillage regime and therefore has important implications for recommendations of fertilizer application rates. The objectives of this study were to investigate the effect of tillage regime at three rates of nitrogen fertilization on soil microbial activity and selected soil physical properties in the Loskop area of KwaZulu-Natal, South Africa. Based on the outcomes of these investigations, recommendations regarding sustainable tillage practice and nitrogen fertilizer application rate are made.

A field trial was initiated in 2003 on Gourton Farm in the Loskop area of KwaZulu-Natal on an area that was previously under annual conventional tillage and is currently planted to dry-land maize. The trial was arranged as a split plot experimental design with tillage regime (whole plots) replicated three times, and fertilizer type and application rate forming randomized sub-plots within the whole plots. The trial was on a clay loam soil type (Hutton soil form). The effects of annual conventional tillage (CT1) and no-till (NT) at three rates of nitrogen (N) fertilizer (as limestone ammonium nitrate (LAN)) applied at rates of 0 kg N ha^{-1} $annum^{-1}$ (0N), 100 kg N ha^{-1} $annum^{-1}$ (100N) and 200 kg N ha^{-1} $annum^{-1}$ (200N) were evaluated for their effects on soil organic carbon (SOC), microbial activity, bulk density (ρ_b), water retention characteristics, saturated hydraulic conductivity (K_s), micro-aggregate stability and soil penetration resistance.

Undisturbed soil cores were taken from three inter-rows in triplicate from each sub-plot for the A horizon (0 to 20 cm) and from three inter-rows in duplicate for the B horizon (20 to 40 cm). These undisturbed soil cores were used to determine the ρ_b, water retention characteristics and

K_s. Bulk soil samples were collected from three inter-rows in triplicate from each sub-plot for the A (0 to 20 cm) and B (20 to 40 cm) horizons. The bulk samples from each horizon in each sub-plot were thoroughly mixed and halved. One half was used to determine microbial activity as measured by the hydrolytic and cellulolytic activity and the other half was used to determine SOC content, particle size distribution and aggregate stability. Penetration resistance was taken in duplicate in three rows in each sub-plot at 1 cm increments to a depth of 50 cm or until an instrument limiting penetration resistance of 5000 kPa was reached.

Tillage regime and N application rate considerably affected soil microbial and physical properties in the A horizon (0 to 20 cm). The SOC, hydrolytic activity and ρ_b are significantly greater ($P < 0.05$) under NT than under CT1. Cellulolytic activity, aggregate stability and penetration resistance show a similar trend. Water content at saturation and K_s were considerably lower under NT than under CT1 and greater plant available water was retained under NT. In the A horizon, the amount of SOC, the hydrolytic and cellulolytic activity, ρ_b and water retention for the 200N treatment are significantly lower than at the lower rates of N application, especially under NT. A similar trend exists for K_s and aggregate stability. In the B horizon, the effect of tillage had no significant ($P > 0.05$) effect on the soil microbial activity and physical properties except for K_s, where the K_s is significantly ($P < 0.05$) higher under NT than under CT1. Similarly, fertilizer rate had no significant effect ($P > 0.05$) in the B horizon on the measured soil microbial activity and physical properties except for the penetration resistance. Increasing levels of fertilizer resulted in increased penetration resistance throughout the soil profile under NT. Under CT1, this same trend is evident from below the plough layer.

These results indicate that the microbial activity, as measured by hydrolytic and cellulolytic activity, is improved under NT compared to CT1. Furthermore, the soil under NT retains more plant available water (PAW) and although the ρ_b and penetration resistance are greater there was no obvious adverse effect on maize growth. In addition, a high rate of LAN fertilizer adversely affected soil microbial and physical properties, especially under NT. Therefore, it is proposed that NT is the preferred tillage practice in providing long-term sustainability and soil health without causing negative soil structural properties for crop productivity in the short-term. In addition, it is recommended that although increased levels of nitrogen fertilizer results in higher yielding maize plants it is unsustainable to apply high applications of LAN due to the negative effect on the soil microbial and physical properties and thus there is a need to re-evaluate the sustainability of using high rates of LAN to increase crop yields, especially under NT systems.

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List of Abbreviations and Symbols

ACT	African Conservation Tillage Network
AMF	Arbuscular mycorrhizal fungi
ANOVA	Analysis of variance
C	Carbon
CO_2	Carbon dioxide
CT	Conventional tillage
CT1	Annual conventional tillage
FDA	Fluorescein diacetate
LAN	Limestone ammonium nitrate
LSD	Least squares differences
MBC	Microbial biomass carbon
MBN	Microbial biomass nitrogen
MT	Minimum tillage
N	Nitrogen
N_2O	Nitrous oxide
NSW	New South Wales
NT	No-till
PAW	Plant available water
SE	Standard error
SMB	Soil microbial biomass
SOC	Soil organic carbon
SOM	Soil organic matter
USA	United States of America
WFP	Water-filled porosity
ZT	Zero tillage
0N	Nitrogen fertiliser application rate of 0 kg N ha^{-1} $annum^{-1}$

100N	Nitrogen fertiliser application rate of 0 kg N ha^{-1} $annum^{-1}$
200N	Nitrogen fertiliser application rate of 0 kg N ha^{-1} $annum^{-1}$
ρ_b	Bulk density
K_s	Saturated hydraulic conductivity

Chapter 1

Introduction

Global human population expansion and the associated increase in environmental degradation have led to the need for agricultural practices that promote food security and, at the same time, ensure that the quality of the environment does not deteriorate (Fowler and Rockstrom, 2001). Consequently, a large body of literature has accumulated on the sustainability of various agricultural practices and their long-term effects on soil and environmental quality (*inter alia*: Jackson *et al*., 2003; Spedding *et al*., 2004; Riley *et al*., 2008; Fuentes *et al*., 2009). Much of the published literature focuses on the role of different tillage systems, with the emphasis placed on conservation tillage in commercial farming systems in developed countries. However, there is a deficit of similar research on the African continent, where agro-ecological and socio-economic conditions differ markedly from those experienced in developed countries (Fowler and Rockstrom, 2001).

The effects of tillage on soil physical, chemical and biological properties are a function of soil properties, environmental conditions and the type and intensity of the tillage system (Ishaq *et al*., 2002). Ishaq *et al*. (2002) state that the contradictory results of tillage effects on soil properties found in the literature "may be due to differences in crop species, soil properties, climatic characteristics and their complex interactions". Therefore, it is necessary to examine the long-term effects of tillage at different locations and under various environmental and soil conditions so that more accurate generalizations can be made regarding the conditions required for sustainable tillage systems (Ishaq *et al*., 2002).

Much of South Africa has a semi-arid climate, where approximately 60 % of the country receives less than 600 mm of rainfall per annum (Food and Agricultural Organization, 2009). Consequently, inadequate moisture is the major factor limiting crop growth. This, coupled with increasing soil degradation under conventional agricultural systems, has resulted in the recognition that agricultural practices which conserve water and promote soil quality need to be employed (Fowler, 1999). These practices include conservation tillage, residue retention, crop rotation, correct inorganic and organic fertilizer use and appropriate land-use (*inter alia*: Bescansa *et al*., 2006; Govaerts *et al*., 2007; Fuentes *et al*., 2009; Riley *et al*., 2008).

Doctor J.B. Mallet initiated the first no-till research at Cedara in KwaZulu-Natal in the early 1970's and found that crop yield under no-till was greater than that under conventional tillage in the seasons when soil moisture was limiting. His studies also showed that the production cost under no-till was lower than under conventional tillage. Despite these benefits, many farmers remained reluctant to adopt no-till as there was concern over the carry-over of diseases to the following seasons crop. After this initial research, escalating fuel prices encouraged further investigation of tillage practices and led to the establishment of the Conservation Farming Committee in the Western Cape and the No-Till Club in KwaZulu-Natal. With the help of the Department of Agriculture, universities, non-government organizations and some commercial companies, these two organizations are providing the information, through research, to promote sustainable agriculture in South Africa (African Conservation Tillage Network (ACT), 2001).

The benefits of conservation agriculture have not only received attention in South Africa but there is increasing awareness in the whole of Africa for the need to adopt sustainable agricultural practices (Fowler and Rockstrom, 2001). In response to this need the ACT network was established in 1998 at the international workshop on “Conservation Tillage for Sustainable Agriculture” in Harare, Zimbabwe. This network aims to promote successful adoption of agricultural practices and principles in Africa which conserve water and soil, produce higher and more stable yields, promote food security and improve the livelihood of rural communities (ACT, 2001). To achieve these objectives, ACT recognizes the unique understanding that farmers have of their specific circumstances and works directly with farmers by conducting on-farm research on the various agricultural management practices. In so doing, practices which are sustainable and acceptable can be implemented (Fowler and Rockstrom, 2001).

In line with the aim of increasing the knowledge base of tillage effects on South African soils, a field based tillage trial was initiated on Gourton farm, in the Loskop area of KwaZulu-Natal in the 2003/2004 season. The Winterton/Bergville area, of which the Loskop area forms a part, is the most important annual cropping area in KwaZulu-Natal (Lamprecht *et al*., 2008). This trial is used by the Soil Fertility and Analytical Services Division (Department of Agriculture, Cedara) to assess the effects of tillage and nitrogen fertilizer application on soil fertility, maize productivity and quality, and crop diseases. However, no consideration has been given to the effects of tillage and nitrogen fertilizer application on the physical and biological properties of the soil. In view of this, an additional investigation was initiated that considers the effects of tillage practice and nitrogen fertilizer application on selected soil microbial and soil physical properties.

Thus, the specific objectives of this study are to assess the effects of no-till and annual conventional tillage at three difference application rates of nitrogen fertilizer, applied as limestone ammonium nitrate (LAN) on:

- soil organic carbon content;
- soil microbial activity assessed by hydrolytic and cellulolytic activity; and
- soil bulk density, water retention characteristics, saturated hydraulic conductivity, aggregate stability and penetration resistance.

Additional soil fertility parameters (such as soil fertility analyses) and plant growth measures for this trial will be obtained from the Soil Fertility and Analytical Services Division (Department of Agriculture, Cedara) and these data will be related to the properties measured in this study to develop a better overall understanding of the causes and consequences of the different management practices investigated in the trial.

- The document is structured as follows:
- Chapter 2 presents a review of current literature on the effect of tillage regime on soil quality as measured by soil physical and microbiological properties.
- Chapter 3 gives an overall description of the methods and materials used.
- Chapter 4 reports and discusses the effects of tillage and nitrogen fertilization on microbial activity as measured by hydrolytic and cellulolytic activity.
- Chapter 5 reports and discusses the effects of tillage and nitrogen fertilization on selected soil physical properties which include bulk density, water retention characteristics, saturated hydraulic conductivity, aggregate stability and soil penetration resistance.
- Chapter 6 presents a general discussion, draws overall conclusions and provides recommendations for future research.

Chapter 2

The effect of tillage regime on soil physical and microbiological properties

2.1 Introduction

Soil quality, also commonly referred to as soil health, is linked to human health and environmental sustainability. As such, there is a need to evaluate the effect of agroecosystems, and the practices employed, on soil quality (Janke and Papendick, 1994). Soil quality is difficult to define and quantify as it is a function of physical, chemical and biological properties of the soil (Jackson *et al*., 2003; Fuentes *et al*., 2009), which are influenced by environmental conditions and soil management (So *et al*., 2009; Fuentes *et al*., 2009). It is important to assess soil quality by using an approach that is holistic and by determining soil properties which are easily measurable and sensitive to changes in management (Doran and Parkin, 1994). Govaerts *et al*. (2008) define a healthy soil, which is able to support a sustainable production system, as "…the continued capacity of the soil to sustain biological productivity, maintain quality of air and water environments and promote plant, animal and human health".

Tillage alters the physical, chemical and biological properties of soil ecosystems (Doran, 1980) and thus it is an agricultural practice of particular interest in its effect on soil quality. The increasing cost of fossil fuel, loss of topsoil due to erosion, and increasing environmental pollution has led to the need for agricultural management to be more focused on less intensive and more sustainable soil-cultivation practices (Köller, 2003). The motivating factors encouraging farmers to convert from conventional tillage to conservation tillage include savings in time and fuel, reduced machinery and labour costs, and erosion mitigation (Throckmorton, 1986; Beauchamp and Hume, 1997). Further benefits associated with conservation tillage are improved soil physical properties and consequent increases in crop productivity. Generally, the increased amount of crop residues remaining on the surface under conservation tillage improves the soil's physical and biological characteristics which results in increased soil fertility and soil quality (Andrade *et al*., 2003; Köller, 2003).

2.2 Conventional and conservation tillage systems

2.2.1 Conventional tillage

Conventional tillage (CT) is the loosening of soil using a moldboard plough, followed by disking and harrowing for the final seedbed preparation (Beauchamp and Hume, 1997). Conventional tillage generally incorporates crop residues into the soil to a depth of between 10 and 20 cm (Beauchamp and Hume, 1997) and typically results in less than 15 % of the crop residues being left on the soil surface (Hendrix *et al*., 1986). Conventional tillage allows the incorporation of lime and fertilizers into the soil, limits weed and pest infestations, alleviates compaction and loosens the soil structure for the promotion of crop growth (Throckmorton, 1986). However, ploughing the soil continuously may lead to decreased soil quality as there is a loss of soil organic matter (SOM) and structural deterioration (Simmons and Coleman, 2008). This can lead to the formation of surface crusts and sealing, hoe or plough pans (Steiner, 2002), decreased biological activity, increased compaction (Atlas and Bartha, 1998), decreased porosity and reduced infiltration which promotes soil erosion (Hendrix *et al*., 1986; Köller, 2003).

2.2.2 Conservation tillage

Conservation tillage is used to conserve soil and water (Sturz *et al*., 1997; Fowler and Rockstrom, 2001), and encompasses the concept of minimal or no disturbance to the soil. Minimum tillage (MT) and zero tillage (ZT; or no-till (NT)) are commonly practised forms of conservation tillage (Hendrix *et al*., 1986). In MT the intensity and depth of soil inversion for seedbed preparation is reduced, whereas in NT systems ploughing is completely eliminated and planting is done with direct-drill seeding machines (Beauchamp and Hume, 1997). Conservation tillage usually leaves between 15 and 30 % of crop residues on the soil surface as a mulch layer (Hendrix *et al*., 1986). Large amounts of crop residue on the soil surface protect the soil from wind and water erosion, decrease compaction susceptibility, increase aggregate stability (Griffith *et al*., 1986; Köller, 2003), increase infiltration, reduce evaporation losses, improve moisture retention (Bescansa *et al*., 2006), improve aeration (Griffith *et al*., 1986; Riley *et al*., 2008) and regulate soil temperatures (Spedding *et al*., 2004). A greater quantity of plant residues on the soil surface increases the level of SOM and, consequently, conservation tillage results in better soil structure, fertility and biological activity (Andrade *et al*., 2003).

2.2.3 Role of residue retention

In many parts of the world, a common agricultural practice is the removal of crop residues after harvest through burning, grazing or their utilization as fodder. This may result in the soil surface remaining exposed for up to six months each year during the fallow periods (Govaerts *et al*., 2008). Many authors stress the importance of residue retention under NT as the major contributor that improves soil physical and biological properties. For example, Fuentes *et al*. (2009) report that residue retention increased aggregation, improved infiltration and reduced evaporation, which resulted in lower resistance to penetration, higher moisture retention and increased aggregate stability, regardless of tillage system or crop rotation. No-till, without residue retention, resulted in the poorest soil quality (low soil organic carbon (SOC) and moisture content, low aggregate stability, low pH and high salt concentrations), which led to the lowest wheat and maize yields. These results suggest that it is the greater retention of crop residues on the soil surface under NT as compared with CT which results in improved soil physical properties and not the reduction in soil disturbance. Govaerts *et al*. (2007) found that retaining residues from wheat and maize under both conventional and conservation tillage yielded higher microbial populations than when residues were removed. This was attributed to the residue providing a continued supply of carbon (C) as an energy source and the mulch cover improving the environment for microbial growth. They concluded that NT with residue retention was a sustainable practice as there is increased soil aeration, cooler conditions, increased soil moisture, smaller temperature and moisture fluctuations and higher organic-C content in the surface soil.

2.2.4 Limitations of conservation tillage

Although there are distinct benefits of conservation tillage over CT there is reluctance from many farmers to change to conservation tillage. This reluctance is due to the delay in soil response after the adoption of MT or NT practices, (Bescansa *et al*., 2006; Simmons and Coleman, 2008), and that conservation tillage systems usually increase the need for herbicides to control weeds and require higher applications of insecticides and fertilizers (Crosson, 1981; Huwe, 2003). One of the major limitations of NT is that the increased percentage of organic matter in the surface soil may promote pathogen survival due to an increased energy source and more favourable environmental conditions. However, Sturz *et al*. (1997) and Govaerts *et al*. (2008) have shown that increased organic matter under NT may result in decreased pathogen activity due to competition from non-pathogenic organisms. Furthermore, increased macroporosity and pore connectivity under conservation tillage can lead to increased risk of groundwater pollution due to the increased leaching of herbicides, pesticides and fertilizers (Huwe, 2003).

2.3 Effect of tillage on soil physical properties

2.3.1 Aggregate stability

Ploughing the soil increases the mineralisation rate and consequently, continuous tillage results in a loss of SOM which leads to a decrease in soil aggregation and structural stability (Simmons and Coleman, 2008). Conversely, NT allows the build-up of SOM which increases the soils' ability to bind aggregates (So *et al*., 2009). In addition, SOM increases the microbiological and earthworm activity, which further acts to stabilize soil aggregates (Johnson-Maynard *et al*., 2007; D'Haene *et al*., 2008; So *et al*., 2009). In a study by Fuentes *et al*. (2009) the aggregate stability of a soil rotated between maize and wheat in central Mexico was greater under NT when the residue was retained than under NT when residue was removed and greater than under CT when the residue was retained or removed (Table 2.1).

Table 2.1 Aggregate stability (wet sieving) of soils under no-till (NT) or conventional tillage (CT), with residue retention (r+) or residue removal (r-) (modified from Fuentes *et al*., 2009)

Treatment	Aggregate stability, mean weight diameter (mm)
NT +r	1.69
NT -r	1.00
CT +r	0.54
CT -r	0.35

In a similar study, So *et al*. (2009) found that in the upper 20 cm of the soil profile after 14 years of NT the amount of dispersible clay and silt was lower and the mean weight diameter was larger under NT than under CT, and that these results were consistent with an increase in SOM under NT. Conversely, Johnson-Maynard *et al*. (2007) report that micro-aggregate stability (0.5 to 1 mm size fraction) under NT and CT was similar at a soil depth of between 0 and 20 cm and argued that this could be due to the short duration of their experiment (i.e. < 3 years). They suspected that measures of macro-aggregate stability would indicate higher stability under NT than under CT. Improved structural stability under NT reduces the formation of crusts and surface sealing and thus there is less surface run-off and erosion. It is important to note that the time it takes for soil to rebuild its structure after the adoption of NT is dependent on soil texture and climate and thus it may take a number of years before the structural benefits of conservation tillage are seen (Steiner, 2002).

2.3.2 Bulk density (ρ_b)

Tillage influences the total porosity and pore size distribution of the soil by affecting the soil structure. This results in changes in soil hydraulic properties and soil strength, both of which are important determinants of soil quality. Due to its relationship with soil porosity, bulk density (ρ_b) is a useful measure for assessing tillage effects on the structural characteristics of the soil (Huwe, 2003; Simmons and Coleman, 2008) and the consequent effects on the water and aeration status of the soil (Linn and Doran, 1984), hydraulic conductivity, infiltration rate, water retention characteristics, and soil strength (Simmons and Coleman, 2008).

Tillage loosens the soil structure and causes an immediate increase in the percentage of macropores, resulting in a lower ρ_b and greater total porosity (So *et al*., 2009) which can benefit seedling establishment and crop growth (Throckmorton, 1986; Sturz *et al*., 1997). Generally, converting from a CT system to a conservation tillage system results in a higher ρ_b and a lower total porosity (Linn and Doran, 1984; Fabrizzi *et al*., 2005; Johnson-Maynard *et al*., 2007) as macropores are not created as is the case during ploughing (Table 2.2) (Sturz *et al*., 1997; Bescansa *et al*., 2006).

Table 2.2 Bulk density and total porosity (at soil depths of between 3 and 8 cm and between 13 and 18 cm) after 2 years under minimum tillage (chisel plough to a depth of 10 cm followed by two disking operations to a depth of between 8 and 10 cm) and no-till (modified from Fabrizzi *et al*., 2005)

Treatments	Bulk density (g cm^{-3})		Total porosity (%)	
Depth	3 to 8 cm	13 to 18 cm	3 to 8 cm	13 to 18 cm
Minimum tillage	1.19	1.28	56	52
No-tillage	1.26	1.32	53	50

However, as a result of reduced aggregate stability in CT soils, the soil is more susceptible to compaction which, in the long-term, can result in reduced soil quality and lower crop yields (So *et al*., 2009). Osunbitan *et al*. (2005) compared the ρ_b in the surface 5 cm of a NT soil with soils ploughed at three different tillage intensities. They concluded that the ρ_b of the NT soil was significantly higher than the other tillage treatments directly after tillage. However, the percentage increase in ρ_b eight weeks after tillage was lowest under NT as natural resettlement of particles into a more compact arrangement is greater for the more intensive tillage treatments (Figure 2.1).

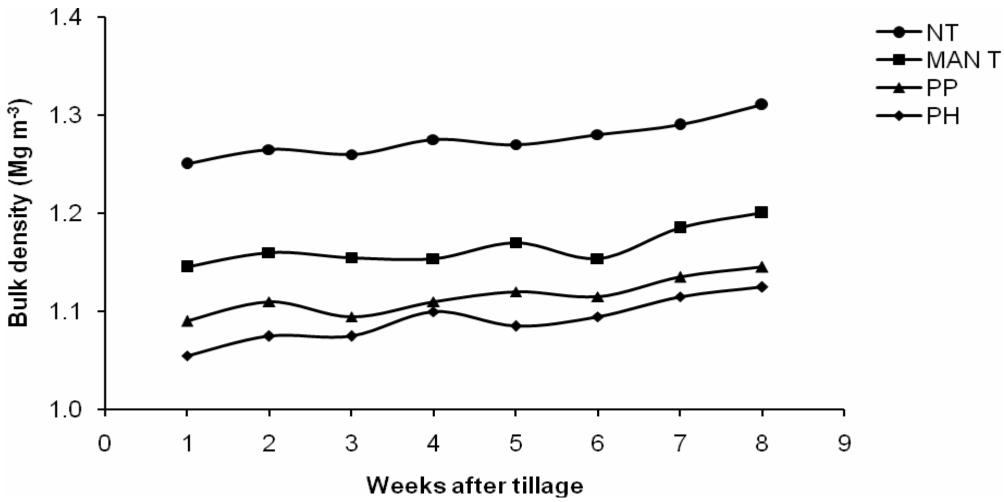

Figure 2.1 Change of mean bulk density (g cm^{-3}) of soil surface (0 to 5 cm) with time after no-till (NT), manual tillage (MAN T), plough-plough tillage (PP) and plough-harrow tillage (PH) (n = 2) (modified from Osunbitan *et al.*, 2005).

Similarly, the study by Fabrizzi *et al.* (2005) shows that under NT there was a significantly ($p < 0.05$) lower total porosity and higher ρ_b than under CT up to a depth of 18 cm in the first two years after the conversion from CT to NT (Table 2.2). However, in the third year the ρ_b under NT had decreased and was attributed to the re-establishment of the inherent soil structure.

Increased susceptibility to soil compaction under CT compared to NT can result in similar bulk densities between CT and NT. Azooz *et al.* (1996); Ishaq *et al.* (2002) and Bhattacharyya *et al.* (2006) found little difference in ρ_b between tillage treatments and attributed this to the long delay between the tillage event and sampling which allowed the CT soil sufficient time to naturally consolidate and compact. Over time the ρ_b under NT is lowered by the development of soil pores created by earthworm activity and root growth (Bescansa *et al.*, 2006), while the decreased aggregate stability and increased susceptibility to compaction of CT soils (So *et al.*, 2009), often results in lower bulk densities under NT soils in the long-term. So *et al.* (2009) found that after 14 years of NT a weakly structured silty loam soil in New South Wales (NSW), Australia had a significantly lower ρ_b in the top 20 cm of the NT soil compared to the CT soil.

Similarly, D'Haene *et al*. (2008) report that silt loam soils in Belgium have a lower ρb in the top 5 cm under NT compared to CT.

2.3.3 Soil strength

Soil strength can be measured indirectly by measuring the soil penetration resistance (Osunbitan *et al*., 2005). Soil penetration resistance is useful to determine the effects of tillage on soil strength and indicates the ability of roots to explore the soil volume. Values over 2000 kPa generally limit root exploration (So *et al*., 2009) and so restricts nutrient and water uptake by crops (Fabrizzi *et al*., 2005), thereby reducing yield (Chan, 1995). Ishaq *et al*. (2002) found that penetration resistance was negatively correlated to grain yield of wheat (r^2 = -0.49, p = 0.01). Similarly, in the study by Materechera and Mloza-Banda (1996) the penetration resistance was negatively correlated to the root length density of maize (r^2 = -0.66, $p < 0.05$) which affected overall plant growth. Ploughing loosens the soil and thus decreases soil strength within the plough layer. For instance, Fabrizzi *et al*. (2005) found that although penetration resistance in the top 30 cm of the soil profile is less than 2000 kPa under both MT and NT the soils under NT have a consistently higher penetration resistance to a depth of 30 cm than soils under MT (Figure 2.2).

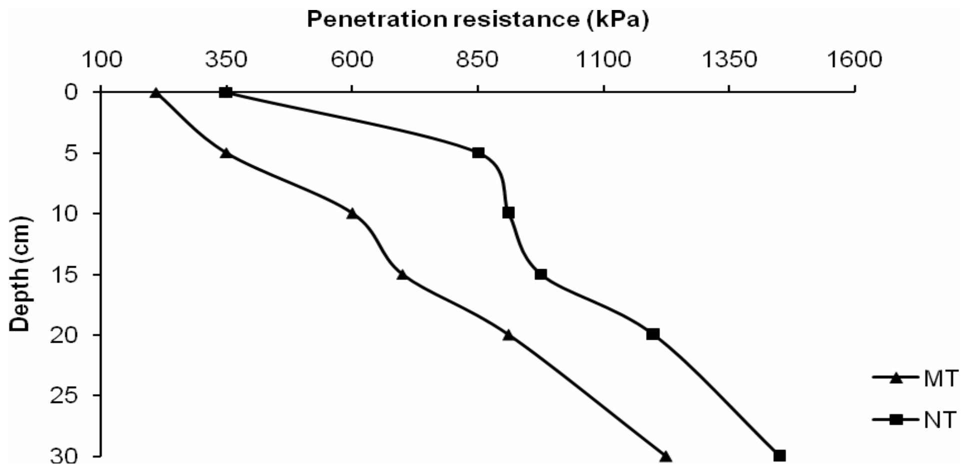

Figure 2.2 The effect of minimum tillage (MT) and no-till (NT) on penetration resistance after wheat harvest, after two years of no-till (modified from Fabrizzi *et al*., 2005).

A comparable study by Materechera and Mloza-Banda (1996) in Malawi showed that penetration resistance was greater when maize was planted on ridges made the previous season (MT) compared to newly constructed ridges (CT), and that root density was lower under MT. Ridges made the previous season were considered MT as there had been less soil disturbance than on the newly constructed ridges during the last season. Although tillage may initially lower the penetration resistance, ploughing decreases the SOM. This increases the likelihood of slaking and dispersion of soil particles and thereby increases the soil's susceptibility to become hardsetting. Upon drying, the soil compacts and hardens, which increases the soil strength and penetration resistance (Chan, 1995). Chan (1995) report that CT of a sandy loam soil in NSW, Australia led to greater soil strength in the top 30 cm of the soil upon drying, whereas the soil strength remained similar at all water contents under undisturbed pasture. Similarly, So *et al.* (2009) found that the upper 20 cm of the soil surface under CT had greater soil strength than NT and exceeded 2000 kPa at a matric potential of -1500 kPa (Table 2.3).

Table 2.3 Soil strength under conventional tillage (CT) and no-till (NT) at a matric potential of -1500 kPa after 14 years of tillage treatments (modified from So *et al.*, 2009)

	Soil strength (kPa)	
Depth (cm)	CT	NT
0 to 5	1874	1236
5 to 10	2898	1927
10 to 20	3709	2234
Average	2827	1799

The decrease in SOM under CT may result in compaction problems if the soil is not ploughed annually. Materechera and Mloza-Banda (1996) showed that by the third season of reduced tillage the soil had compacted sufficiently to adversely affect maize grain yield and that the penetration resistance was significantly higher ($p < 0.05$) than the soil which is tilled annually.

As with ρ_b, soil strength may be greater under CT than NT in the long-term. Osunbitan *et al.* (2005) found that eight weeks after tillage the penetration resistance in the 0 to 5 cm soil layer decreased for NT and increased in the soils which were ploughed (Figure 2.3).

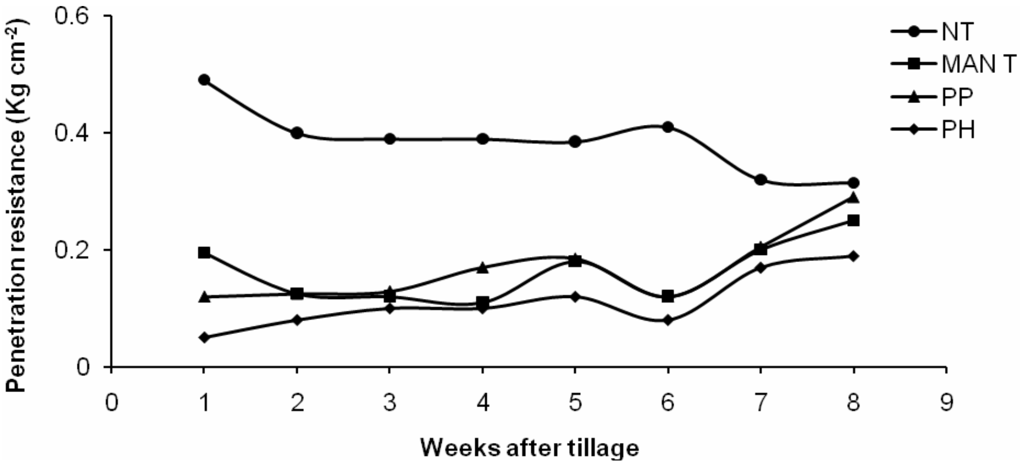

Figure 2.3 Change of soil cone penetration resistance (kg cm^{-2}) of soil surface (0 to 5 cm) with time under no-till (NT), manual tillage (MAN T), plough-plough tillage (PP) and plough-harrow tillage (PH) (n = 2) (modified from Osunbitan *et al.*, 2005).

Furthermore, a common occurrence under CT is the development of a dense, compacted layer of increased soil strength below the plough layer, referred to as a plough-pan (Materechera and Mloza-Banda, 1996; Munkholm *et al.*, 2001). The penetration resistance results of Munkholm *et al.* (2001) show that non-inversion tillage was marginally less effective in loosening the top 15 cm of the soil when compared to CT. However, under CT the penetration resistance increases below the plough layer, indicating the presence of a plough pan (Figure 2.4).

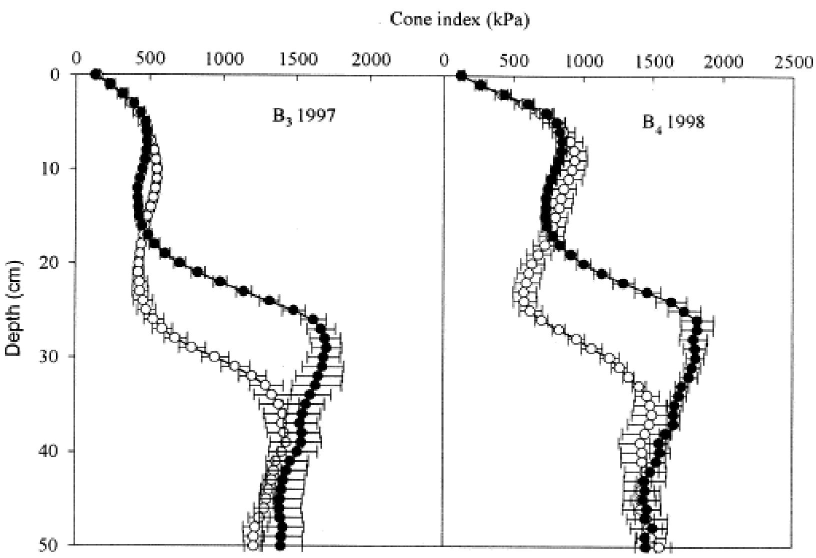

Figure 2.4 Cone penetration measured shortly after tillage operations in spring 1997 (B_3 field) and spring 1998 (B_4 field). (–○–) non-inversion, (–•–) conventional. Horizontal bars indicate ±1 standard error of mean (Munkholm *et al.*, 2001).

2.3.4 Soil water retention

The amount of water retained in the soil at a matric potential of between 0 and -1500 kPa is a function of a soil's pore size distribution (Bhattacharyya *et al*., 2006) and is therefore influenced by the type and intensity of tillage. Under NT the improved aggregation and pore continuity allows the soil to receive more water due to better infiltration and higher hydraulic conductivity. In addition, NT soils lose less water through evaporation due to residue retention on the soil surface. Consequently, NT soils usually maintain a higher moisture content than soils which are ploughed (Fabrizzi *et al*., 2005; Bescansa *et al*., 2006). Furthermore, ploughing the soil increases the number of macropores and thus at saturation the volumetric water content, (or water-filled porosity; WFP), is greater than that under NT. However, macropores drain quickly and the greater number of micropores and mesopores under NT allow the soils to retain more moisture within the plant available range, thus the WFP at field capacity is greater under NT (Linn and Doran, 1984). This is confirmed in the study by Bescansa *et al*. (2006) who found that in the upper 15 cm of a soil in semi-arid northern Spain the water retention at saturation was 13 % greater under CT than NT but at -33 kPa the water retained was 11 % lower under CT than NT.

As mentioned previously, soils which are continuously ploughed are more susceptible to compaction and may reach high bulk densities over time. If ploughed soils compact over time it is likely that micropores constitute the majority of the total porosity and water is therefore held at lower matric potentials making it less available to plants (Bescansa *et al*., 2006). When ploughed soils compact and are dominated by micropores they often hold less moisture than NT soils within the plant available range and at saturation. NT soils are able to retain more moisture than ploughed soils which have compacted as macropores are created by earthworm activity and mesopores are maintained due to better soil structure. The study by So *et al*. (2009) showed that in the top 10 cm of the soil, the water content at field capacity and saturation were greater under NT than CT. Similarly, D'Haene *et al*. (2008) investigated the top 5 cm of a silt loam soil in Belgium and report the water content at saturation to be higher under NT. However, there were no significant differences ($p < 0.05$) in water retention characteristics (measured by the amount of volumetric water content held at different matric potentials) found between NT and CT at the 25 to 30 cm depth. These data suggest that the soil can store and transmit more water in the upper soil layer which benefits crop growth under NT. Increased water retention under reduced tillage is a result of improved infiltration, reduced evaporation and protection of the soil surface from mechanical impact of precipitation (Fabrizzi *et al*., 2005). This has particular relevance in

South Africa, where the semi-arid climate and water scarcity are limiting factors for crop production. Implementing conservation tillage practices can therefore improve yields and sustainability. Studies conducted in the semi-arid region of northern China found that crop yields were higher under NT than under CT in years when annual precipitation was low and was attributed to greater moisture retention under NT (Wang *et al.*, 2007).

Although initial conversion from CT to NT usually results in higher bulk densities it is unlikely that plant growth will suffer markedly as a consequence of insufficient moisture and poor aeration status. Improved aggregation and pore connectivity under NT allows the soil to maintain an adequate supply of moisture and air (Cavalieri *et al.*, 2009).

2.3.5 Saturated hydraulic conductivity (K_s)

The number, continuity and stability of macropores influence the saturated hydraulic conductivity (K_s) of a soil and the percentage of total pores open to infiltration (Bhattacharyya *et al.*, 2006). Under NT the increased percentage of SOM in the soil surface stimulates root growth and mesofaunal activity which leads to the creation of channels (Osunbitan *et al.*, 2005) and the continuity of these channels are then maintained due to the lack of soil disturbance (Griffith *et al.*, 1986; Angers *et al.*, 1992). This results in higher saturated hydraulic conductivities than under CT (Bhattacharyya *et al.*, 2006; So *et al.*, 2009). Osunbitan *et al.* (2005) found that the surface soil had a higher K_s under NT compared with CT (Figure 2.5).

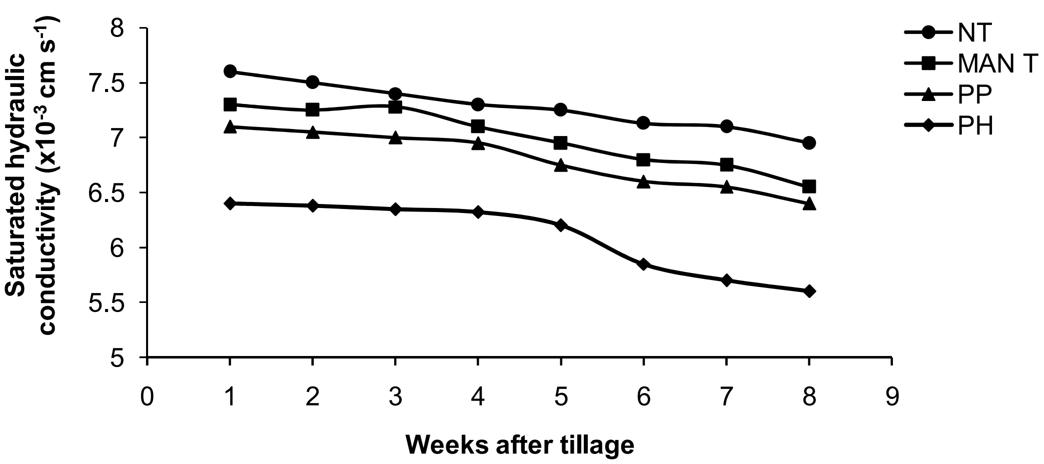

Figure 2.5 Change in time of mean saturated hydraulic conductivity ($\times 10^{-3}$ cm s^{-1}) at a depth of 0 to 15 cm after no-till (NT), manual tillage (MAN T), plough-plough tillage (PP) and plough-harrow tillage (PH) (n = 2) (modified from Osunbitan *et al.*, 2005).

2.4 Effect of tillage on soil microbiological properties

2.4.1 Introduction

The microbial community in soil can contain up to 10 000 different species per gram (Turco *et al*., 1994) and is comprised of viruses, bacteria, fungi, algae and protozoa (Atlas and Bartha, 1998). Microorganisms perform a number of roles in the soil which are essential for maintaining environmental quality and are necessary for sustaining life (Atlas and Bartha, 1998). Soil microorganisms are responsible for the decomposition of organic matter and the mineralisation of nutrients, converting organically bound nutrients into plant available forms as well as producing stable organic compounds (humus) (Zuberer, 2008). Soil microorganisms further stimulate plant growth by synthesising vitamins, amino acids, auxins, cytokinins and gibberellins, and by producing plant hormones such as indoleacetic acid (Atlas and Bartha, 1998). Some soil bacteria, such as rhizobium, form symbiotic relationships with leguminous plants and promote nitrogen (N) assimilation and uptake as they are able to fix N gas (Zuberer, 2008). Furthermore, many fungi and bacteria species contribute towards soil health by being antagonistic to potential plant pathogens (via competition and/or production of antibiotics) (Atlas and Bartha, 1998; Govaerts *et al*., 2007). Microorganisms are also important contributors to soil stability by producing polysaccharides and mucilages which promote the cementation of soil aggregates. The filamentous strands (hyphae) produced by fungi growing in the soil allows for the entanglement of soil particles (Zuberer, 2008). The roles carried out by soil microbes are fundamental in plant growth. However, soil microbes may also reduce productivity by causing a number of crop diseases (Andrade *et al*., 2003). Therefore, it is important to understand the relationship between soil management practices and microbial activity and community composition (Govaerts *et al*., 2007; Bausenwein *et al*., 2008).

2.4.2 Tillage effects on the environment of soil microorganisms

The number and activity of soil microorganisms are influenced by the macro and micro-climate, the plant species grown on the soil in terms of species composition, percentage plant cover, root penetration and litter properties, as well as soil management (e.g. fertilizer and lime application), and cultivation procedures (Schinner, 1996). For optimal growth and activity the majority of soil microorganisms require abundant organic substrates, adequate supplies of inorganic nutrients, sufficient air-filled and water-filled pore space, a near neutral pH and a soil temperature of between 15 and 30 ^{o}C (Zuberer, 2008). Soil tillage has a marked influence on all these properties.

2.4.2.1 Organic matter

Most microbes are organotrophs, meaning they require organic-C compounds as a food source. Only a few are autotrophs, which receive their C requirement from carbon dioxide (CO_2) in the atmosphere. Therefore, the microbial biomass and activity is positively correlated to the amount of SOM (Hamel *et al*., 2006; Bausenwein *et al*., 2008; Nyamadzawo *et al*., 2009). Asuming-Brempong *et al*. (2008) investigated the effect of SOC content on soil microbial biomass (SMB) and activity in Ghana, and found a positive correlation (r^2 = 0.63, p = 0.05) between SOC and the microbial biomass carbon (MBC) (Figure 2.6).

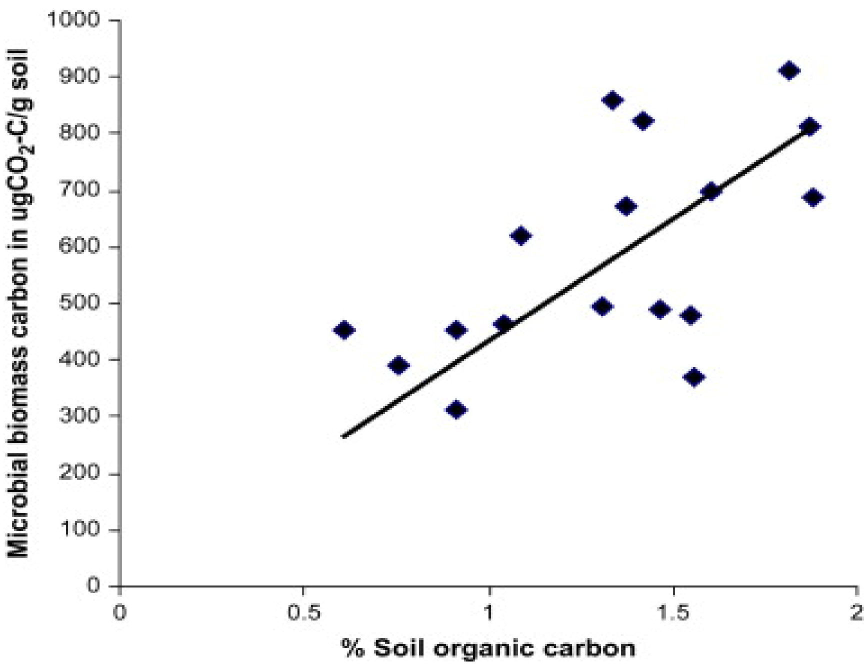

Figure 2.6 Relationship between the microbial biomass carbon and soil organic carbon of soils under different fallow management treatments (Asuming-Brempong *et al*., 2008).

Due to a higher percentage of crop residues remaining on the soil surface under NT when compared to CT, there is greater organic matter build-up in the surface layers of the soil under NT (Spedding *et al*., 2004; Nyamadzawo *et al*., 2009), whereas CT results in a more even distribution of organic matter within the plough layer (Spedding *et al*., 2004). Fuentes *et al*. (2009) report that the 0 to 5 cm depth of soil had higher total N and SOC content under NT when residues were retained as compared with CT (Table 2.4).

Table 2.4 Total nitrogen and organic carbon (0 to 5 cm depth) under zero tillage (ZT) or conventional tillage (CT), with rotation (R) or monoculture (M), and with residue retention (+r) or without residue retention (-r) (modified from Fuentes *et al*., 2009)

Treatment	Total nitrogen content (g kg^{-1})		Soil organic carbon content (g kg^{-1})	
	Maize	Wheat	Maize	Wheat
ZTM + r	1.60	1.40	23.20	21.90
ZTR + r	1.60	1.45	22.75	22.95
CTM + r	1.25	1.10	16.55	15.50
CTR + r	1.20	1.24	15.85	16.70
ZTM - r	1.00	1.30	13.80	19.30
ZTR - r	1.20	1.15	15.80	13.95
CTM + r	1.00	1.10	12.55	14.60
CTR + r	1.10	1.00	14.00	12.90
LSD*	0.21	0.44	2.04	1.97

*$p < 0.05$ level based on least square difference grouping (LSD).

As soil microorganisms are closely related to the SOM, the effect of the tillage system on their distribution within the soil profile follows the same pattern as that for SOM. Blume *et al*. (2002) found that SMB decreased with soil depth and attributed this to the higher quantities of available C closer to the soil surface. Carter (1986) found little difference between CT and NT for the MBC, microbial biomass nitrogen (MBN) and microbial activity in the upper 10 cm of the soil, however in the top 5 cm of soil the MBC, MBN and microbial activity under NT was greater than under CT, whereas in the 5 to 10 cm depth the MBC, MBN and activity were greater under conventional tillage due to the ploughing-in of residues to a greater depth (Table 2.5).

Table 2.5 Changes in microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and activity (CO_2 – C respired) under conventional tillage and zero tillage practices for a cereal grain crop at two soil depths on Prince Edward Island (Carter, 1986)

	Conventional tillage			Zero tillage		
Soil depth (cm)	Activity (CO_2 – C respired)	MBC (kg ha^{-1})	MBN (kg ha^{-1})	Activity (CO_2 – C respired)	MBC (kg ha^{-1})	MBN (kg ha^{-1})
0 to 5	35	111	23	68	182	35
5 to 10	41	247	46	20	164	32

Similarly, Spedding *et al*. (2004) showed higher MBC and MBN in the 0 to 10 cm of soil under NT than under CT. Angers *et al*. (1992) report that ploughing reduced the SOC and the MBC by an average of 40 to 50 % between the 0 and 6 cm soil depth but when the entire depth (0 to 24 cm) was considered there was little difference in SOC and MBC (Table 2.6).

Table 2.6 Soil organic carbon (SOC) and microbial biomass carbon (MBC) as affected by tillage treatment at different soil depths (modified from Angers *et al*., 1992)

	SOC (kg ha^{-1})		MBC (kg ha^{-1})	
Depth (cm)	Meadow (undisturbed)	Ploughed	Meadow (undisturbed)	Ploughed
0 to 6	22.3	13.8	484	245
6 to 12	15.0	18.7	279	414
12 to 18	12.2	13.7	177	275
18 to 24	9.8	7.1	212	133
0 to 24	59.2	53.3	1152	1067

Although NT systems generally have more organic-N in the surface soil, many studies have found that the initial conversion from a CT to a NT system leads to a reduction in the amount of N available to plants. This can be attributed to NT soils having more organic matter, cooler temperatures, higher moisture contents, and greater K_s due to improved pore connectivity. The higher percentage of SOM increases the soils cation exchange capacity which may cause temporary immobilisation of nutrients. The cooler temperatures and higher moisture content of NT soils may provide a more optimal environment for soil microbes and thus the rate of denitrification increases, facilitating N loss as N_2 gas and as NO_3-N leaching. Leaching is further facilitated by the increased pore connectivity (Andrade *et al*., 2003). Generally, under CT, N mineralisation increases as the previously protected SOM becomes available to microbial attack (Beauchamp and Hume, 1997; Jackson *et al*., 2003). However, this may be dependent on the soil texture rather than tillage effects. Spedding *et al*. (2004) found that tillage had little effect on the soil microbial dynamics and attributed similar SMB between tillage treatments to the sandy texture of the soil used in their study. Spedding *et al*. (2004) and Melero *et al*. (2009) suggested that soils with higher clay content would contain a larger amount of protected SOM which is released during tillage and therefore tillage on clay soils will have a more marked effect. Although there may be more N lost through denitrification processes and leaching under NT when compared to CT, there is less N lost due to erosion. Once the NT system has reached equilibrium, the larger organic-N pool provides sufficient N to the plant despite slower mineralisation rates (Fox and Bandel, 1986). Over time, ploughing the soil reduces the percentage of organic matter in the soil until the level of mineralisation achieves a balance with the amount of organic matter being added to the soil. This is typically much less than in a NT system (Beauchamp and Hume, 1997).

2.4.2.2 Soil pH

Due to slower rates of mineralisation, potentially more denitrification and leaching, and greater temporary immobilisation at the soil surface in NT soils (Spedding *et al*., 2004) there is often a greater requirement for N fertilization (Fox and Bandel, 1986). The addition of fertilizer may increase the SMB and activity due to increased crop yields and root biomass (i.e. greater organic matter returns to soil) (Beauchamp and Hume, 1997; Spedding *et al*., 2004). However, the addition of fertilizer in NT systems can be problematic. Under NT the fertilizer that is applied is not incorporated into the soil and therefore remains on the soil surface for longer. This is a particular problem when fertilizers containing NH_4^+ are used as there is greater NH_3 loss due to volatilization. Another problem associated with the use of NH_4^+ fertilizers under NT is the potential for the surface soil to acidify (Fox and Bandel, 1986). The nitrification of the greater quantity of applied NH_4^+ fertilizers results in a release of H^+ ions which are not mechanically incorporated into the soil by way of ploughing, thereby causing surface acidity (Fox and Bandel, 1986). Generally, microbes are intolerant of extreme pH values. Under highly acidic or alkaline conditions, some microbial cell components may be hydrolysed or enzymes denatured. The pH also affects microorganisms indirectly as it affects the solubility and bioavailability of many nutrients that influence microorganism activity and function (Atlas and Bartha, 1998). It is important to note that in a well established NT soil which has a high biologically activity, the fertilizer may be incorporated by the soil organisms, as well as by rain and irrigation water which wash the fertilizer granules deeper into the profile due to better pore connectivity and continuity.

The addition of chemical fertilizers may harm microorganisms temporarily in the vicinity of the fertilizer granule due to changing pH levels, increasing nitrite concentrations and by causing an imbalance of nutrients (Beauchamp and Hume, 1997). However, these adverse conditions eventually dissipate through chemical and biochemical reactions, transformations and diffusion and there is no reported evidence that chemical fertilizers permanently harm the soil microbial population or community structure (Beauchamp and Hume, 1997).

2.4.2.3 Temperature

Temperature affects survival, growth and metabolic activities of microorganisms. Generally, a higher temperature results in an increased activity, where for every 10 ^{o}C increase in temperature, there is a doubling in microbial activity up to an optimum level (Atlas and Bartha, 1998). This increase in activity causes an increase in C mineralisation (Jackson *et al*., 2003). Under reduced tillage the residue remaining on the soil surface decreases the soil temperature due to the absorption of less heat (due to higher reflectance of insolation) and lower thermal conductivity of the residue (Fabrizzi *et al*., 2005) as the residue is generally a lighter colour than the soil, and is filled with air (Thomas, 1986).

2.4.2.4 Aeration and water content

Soil water content significantly affects soil microbial numbers and activity (Zuberer, 2008). As the percentage of water-filled pores increases, the activity of aerobic microorganisms (respiration, nitrification and mineralisation) increases until the amount of oxygen (air-filled porosity) becomes limiting. The air-filled porosity becomes limiting at approximately 60 % of the soil's water holding capacity, at which point the respiration rate decreases and denitrification increases (Linn and Doran, 1984; Figure 2.7).

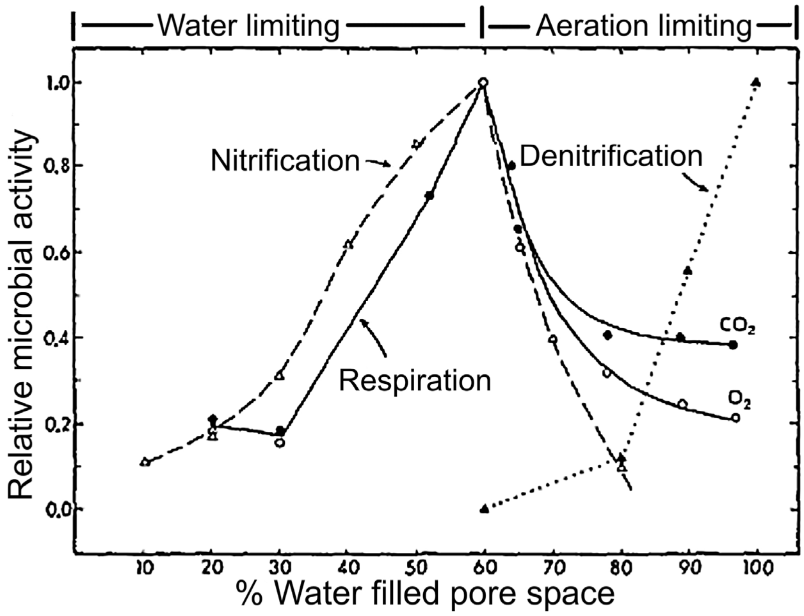

Figure 2.7 The relationship between water-filled pore space in soil and relative microbial activity with respect to nitrification, denitrification, and respiration (O_2 uptake and CO_2 production) (Linn and Doran, 1984).

The soil water content determines the composition of the microbial community as under waterlogged conditions the microbial community will shift from aerobic to anaerobic species (Atlas and Bartha, 1998). Linn and Doran (1984) found that in the top 7.5 cm of four soils in the United States of America (USA) WFP (i.e. volumetric water content) under NT averaged 62 % whereas under CT the WFP averaged 44 %. These results suggest that the topsoil under NT favours aerobic microbial activity and this was confirmed by greater N_2O (nitrous oxide) and CO_2 production from the NT soils as compared to the ploughed soils. At a depth of between 7.5 and 15 cm the ploughed soil had a WFP nearer 60 % whereas the NT soils had a WFP of about 70 %. This suggests that there will be more aerobic microorganism activity in ploughed soils at this depth and this is indicated by higher levels of CO_2 production (Table 2.7). The greater WFP of NT soils is a reflection of a greater soil water holding capacity and higher bulk densities when compared to ploughed soils (Linn and Doran, 1984).

Table 2.7 Soil bulk density, water-filled porosity (WFP), carbon dioxide (CO_2) and nitrous oxide (N_2O) production, with the addition of nitrogen fertilizer, under no-till and ploughed soils at four locations in America (modified from Linn and Doran, 1984)

Depth, location	Tillage treatment	Bulk density (g cm^{-3})	WFP (%)	CO_2 (mg L^{-1})	N_2O (µg L^{-1})
0 to 7.5 cm					
Illinois	no-till	1.46	65.4	33.2	35.0
	plough	1.35	36.5	6.9	1.1
Kentucky	no-till	1.26	66.4	27.3	27.3
	plough	1.36	54.6	21.4	61.4
Nebraska	no-till	1.26	57.1	14.5	79.6
	plough	1.04	40.9	3.7	7.1
Minnesota	no-till	1.00	56.6	15.3	72.7
	plough	0.89	49.2	8.3	14.9
7.5 to 15 cm					
Illinois	no-till	1.50	69.2	15.7	9.0
	plough	1.39	50.6	18.5	12.1
Kentucky	no-till	1.42	68.2	20.2	41.1
	plough	1.33	51.2	23.4	5.4
Nebraska	no-till	1.31	60.3	5.1	73.4
	plough	1.18	53.6	5.3	39.3
Minnesota	no-till	1.19	70.7	8.3	70.0
	plough	0.99	60.3	12.2	49.8

2.4.3 Tillage effects on the composition of the soil microbial community

Many studies indicate that NT results in a greater microbial diversity and fungi-dominated soil, whereas CT leads to bacteria-dominated soil (Spedding *et al.*, 2004; Govaerts *et al.*, 2007; Simmons and Coleman, 2008). This is due to fungi, especially arbuscular mycorrhizal fungi (AMF), being sensitive to tillage (Simmons and Coleman, 2008), as well as the incorporation of residues into the plough layer of the soil which usually promotes bacterial growth (Govaerts *et al.*, 2007). Where the crop residue is buried or labile substrates are abundant, bacteria dominate due to their ability to break down labile carbon sources more efficiently than saprophytic fungi. This results in faster rates of decomposition and N mineralisation. Where crop residue is left on the surface and the C/N ratio is high, saprophytic fungi tend to dominate, slowly breaking down the more resistant substrates (Simmons and Coleman, 2008). Another reason for the dominance of fungi in NT soils is the increase in acidity under NT as fungi generally perform better under acidic conditions when compared to bacteria (Schinner, 1996). Ploughing the soil damages the mycorrhizal hyphae of fungi and therefore decreases the surface area in contact with the soil which reduces nutrient uptake. In undisturbed soil, the network of hyphae in soil remains intact and therefore nutrient uptake by fungi is increased (Beauchamp and Hume, 1997).

Damage caused by tillage to fungal hyphae can significantly reduce the microbial biomass of the soil and/or change the community composition as mycorrhizal fungi make up approximately 25% of the SMB (Spedding *et al.*, 2004). The consequential change in the number and composition of soil fauna further influences the physical and chemical properties of the soil through organic matter decomposition, nutrient cycling, influence of soil structure, etc. (Govaerts *et al.*, 2007). Jackson *et al.* (2003) evaluated the effect of tillage on microbial biomass and community structure. They concluded that tillage causes immediate changes to the community composition but little change to the overall SMB. This change in the community composition leads to a reduced soil quality due to an increase in the amount of greenhouse gases emitted and the increased potential for nitrate leaching. Tillage causes temporary stress conditions for soil microbes and alters their community structure. This weakens their ability to assimilate nutrients and the potential for C and N loss from the soil increases (Jackson *et al.*, 2003).

2.5 Conclusion

Soil tillage has been a popular agricultural practise throughout the world due to the initial improvement of crop productivity, control of weeds and ease with which crops can be planted. However, it has been recognised in many regions that this improved productivity is temporary and overall, SOM content decreases under CT. This decrease in SOM results in a decline of soil quality as SOM plays a major role in the soils structural and pore characteristics by influencing aggregate stability. Although many authors report greater porosity, lower ρ_b and reduced soil strength under CT than under NT due to the creation of macropores during ploughing, less structural stability under CT can lead to lower porosity, higher bulk densities and greater soil strength with time, as tillage-induced pores readily collapse. In turn, lower porosity, greater soil strength and increased ρ_b influence the soils' ability to retain and transmit water. Under NT the pore continuity and pore size distribution are improved due to greater structural stability and biological activity and thus saturated hydraulic conductivity and the plant available water are greater under NT than under CT. Soil organic matter has important effects on the biological component of agricultural soils. As SOM levels decline in continuously ploughed systems the available substrate for soil faunal activity decreases and the beneficial roles carried out by these organisms are greatly reduced. Many authors report lower SMB, MBC, MBN, functional diversity and microbial activity under CT compared to NT. It is important to note the link between soil physical properties and soil biological properties. A change in the soil physical environment impacts on the biological activity as it influences the water and aeration status, temperature and available substrate in the soil. Likewise, changes in the soil biological component affect the soils' porosity, pore size distribution and aggregate stability (Melero *et al*., 2009) and thus both parameters are important measures in determining the sustainability of agricultural management practices. Converting to a conservation tillage system ensures that SOM is maintained and therefore soil physical and biological properties are improved. This ensures long-term productivity of the soils and thus a more sustainable system. As conservation tillage practices become more popular and more necessary, the technology for overcoming planting through residues without seedbed preparation and combating weed and pest infestations without tillage is improving, and the limitations of conservation tillage are slowly being overcome.

It is important to recognise that although conservation tillage is becoming more feasible and is beneficial to soil and overall environmental health, its feasibility is dependent on a number of factors. The effects of tillage on soil properties is site specific and depends on soil texture, cropping systems, climate, fertilizer applications and management practices (Ishaq *et al*., 2002). More research is needed into how best to promote sustainable agricultural under all soil, environmental and agricultural management conditions to ensure global food security and long-term soil and environmental quality. There is a particular need to carry out this research in South Africa, where socio-economic conditions, soil management and environmental conditions differ markedly from other parts of the world where much of the research carried out has been done.

Chapter 3

Methods and materials

3.1 Site description

A field experiment was established by the Soil Fertility and Analytical Services Division (Department of Agriculture, Cedara) to investigate the combined effects of cultivation methods (no-till vs. conventional till) and nitrogen application (urea and limestone ammonium nitrate (LAN)) on maize yield and soil fertility. The trial was established in the 2003/2004 season on Gourton Farm (28°55'26.83"S, 29°33'38.64"E), near Loskop (KwaZulu-Natal Province, South Africa). The site had previously been planted to dry-land maize and soyabeans in rotation and had been managed under no-till since 1990 (*pers. comm., G.* Thibaud[1]). The soil is classified as a Hutton with a clay-loam texture (Soil Classification Working Group, 1991) (Appendix 1). The soil was assumed to be non-swelling as no visible signs of swelling were apparent. Selected physical and chemical properties of selected plots are presented in Appendix 2. The area receives approximately 643 mm of rainfall per annum which occurs mostly during summer and has a mean average midday temperature ranging between 19.3 ^{o}C in June and 27.9 ^{o}C in January (SA Explorer, 2009). The trial is cropped to dry-land maize in the summer and stands fallow in the winter.

The field trial includes three tillage treatments, namely; no-till (NT; which consists of direct seeding into undisturbed soil), annual conventional tillage (CT1; which consists of annual ploughing with a moldboard plough to a depth of 30 cm, followed by disking to a depth of 10 cm) and conventional tillage (CT5; which consists of conventional tillage after every four seasons of no-till). Nitrogen (N) is applied at five rates to each tillage treatment as either urea or LAN. Sampling was done in the 2008/2009 season approximately 12 weeks after planting. Prior to the 2008/2009 season the N was applied at rates of 0, 40, 80, 120, and 160 kg ha^{-1}. In the 2008/2009 season N was applied at application rates of 0, 50, 100, 150, and 200 kg ha^{-1} due to a linear response in maize production to the fertilizer application rate used in the 2007/2008 season (*pers. comm., G.* Thibaud[1]). Lime is applied at a rate of 2 Mg ha^{-1} every second season to the entire trial. Lime is surface applied to the NT plots and incorporated during ploughing in the CT plots. The trial is arranged as a split plot design; with randomized tillage strips forming whole plots and N source and rate of application forming sub-plots which are randomized within the whole plots (Appendix 3). Each treatment is replicated three times (three blocks).

[1] Thibaud G., 2009. Senior Researcher, Soil Fertility and Analytical Services Division, Department of Agriculture, Cedara, South Africa.

Each sub-plot has 12 rows by 9.5 m of maize at a density of 70 000 plants per hectare. Wheels from mechanized equipment were restricted to the inter-rows 1, 3, 5, 7, 9 and 11. The inter-rows 2, 4, 6, 8 and 10 did not have any traffic and it was assumed that these inter-rows were not artificially compacted (Appendix 4). To avoid possible compounding effects of mechanically induced soil compaction on the soil physical and microbial properties, all samples and measurements were taken from inter-rows 4, 8 and 10.

Due to equipment and logistical constraints, only the plots under no-till (NT) and annual conventional tillage (CT) were investigated with LAN fertilizer rates of 0 kg N ha^{-1} (0N), 100 kg N ha^{-1} (100N) and 200 kg N ha^{-1} (200N) (6 treatments) (Appendix 3). A randomly chosen plot for annual conventional tillage and no-till is shown in Plate 3.1.

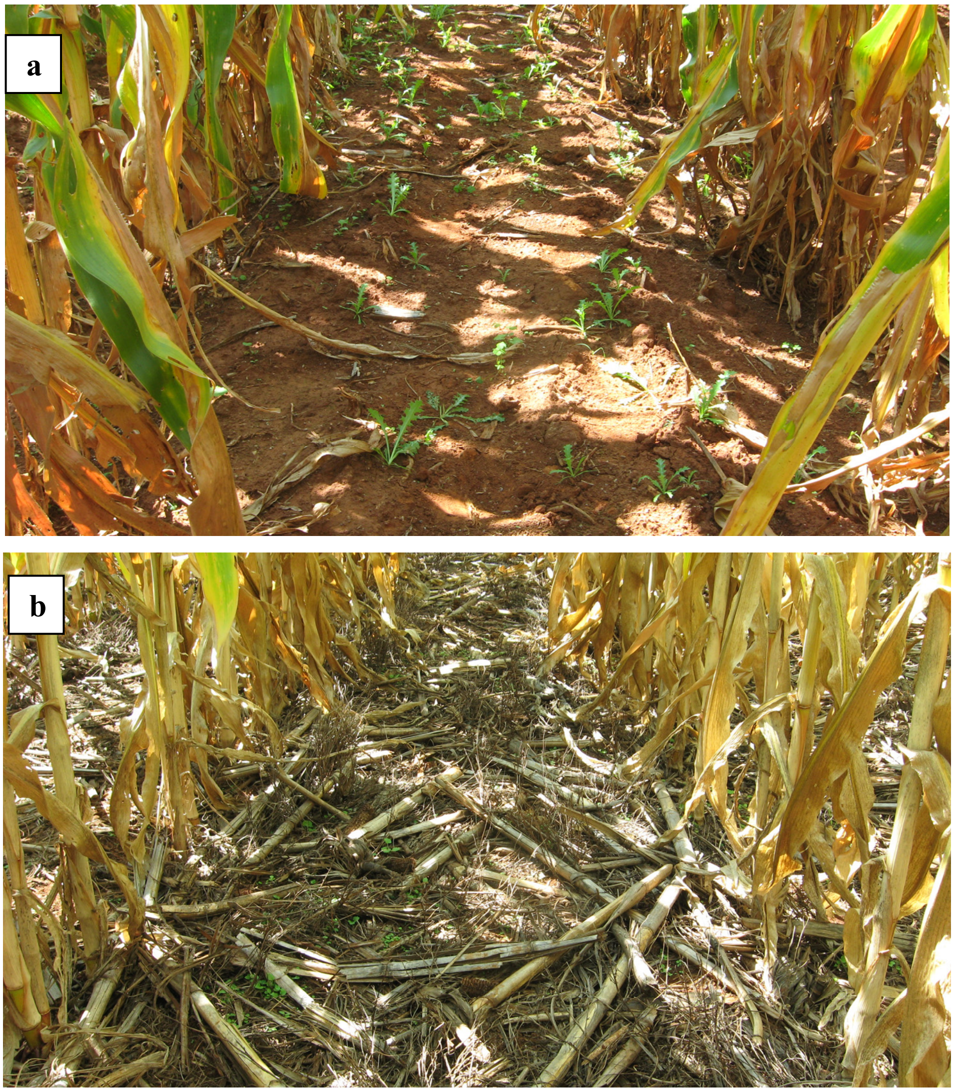

Plate 3.1 A plot from the tillage trial on Gourton Farm representing a) annual conventional tillage and b) no-till.

3.2 Field sampling

3.2.1 Bulk soil samples

Bulk soil samples were collected from each plot at a depth of between 0 to 20 cm (A horizon) and 20 to 40 cm (B horizon). A spade was used to collect the soil samples to minimize the shearing effects of a soil auger. To account for plot variability a sample was collected from each of the three inter-rows, bulked and thoroughly mixed. The sample was then split in two, with half being placed into plastic bags and stored at 4 ^{o}C for microbial activity analysis. The other half of the bulk soil samples were air-dried, gently milled by mortar and pestle and passed through a 2 mm sieve for the analysis of soil organic carbon (SOC) content, particle size and micro-aggregate stability.

3.2.2 Soil cores

Undisturbed soil cores were taken by inserting the labeled stainless steel core (50 mm in height and 75 mm in diameter) into the soil using the core sleeve guide. A hammer is used to insert the core to the correct depth. Three undisturbed soil cores were collected from the topsoil in each plot, where a single core was collected from inter-rows 4, 8 and 10 at a depth of 0 to 5 cm. Undisturbed soil cores were collected in the subsoil after excavating a pit to a depth of 30 cm in inter-row 8 of each plot. Two cores were collected from each pit at a depth of 30 to 35 cm. Only two cores were collected from the subsoil due to practical difficulties in excavating pits and collecting cores. The high clay content of the subsoil limited the number of pits that could be opened for the more comprehensive approach used to sample the topsoil.

3.2.3 Soil penetration resistance

Soil penetration resistance was measured in every plot using a Geotron P5 penetrometer (Geotron Systems, Potchefstroom). All readings were taken within the same day at the same antecedent rainfall so that differences in penetration resistance would not be a result of soil moisture differences resulting from differences in the amount of rainfall received. The instrument was set to measure the penetration resistance at 1 cm increments to a depth of 50 cm. The penetrometer was equipped with a load cell capable of detecting pressure up to 5000 kPa. Six penetrometer profiles were taken in each plot, with two readings from inter-rows 4, 8 and 10.

3.3 Laboratory analysis

3.3.1 Microbial activity

3.3.1.1 Hydrolytic activity

Bulk soil samples collected from the field and stored at 4 ^{o}C were sieved through a 2 mm sieve prior to analysis. The analyses were conducted within 72 hours of collecting the samples from the field. Each sample was then analysed in duplicate for hydrolytic activity using the fluorescein diacetate (FDA) method (Alef, 1995).

3.3.1.2 Cellulolytic activity

The same bulk soil samples as used for hydrolytic activity were analysed in duplicate for cellulolytic using the method of Smith and Hughes (2001). In brief, a pre-weighed circular sheet of Whatman 1 filter paper was placed in a petri-dish between two layers of 2 mm nylon gauze and covered on both sides by approximately 20 grams of soil. Distilled water was added to bring the soil to approximate field capacity as determined visually (i.e. until soil was moist). The petri dish was placed in an incubator at 30 ^{o}C for 14 days. After 14 days the petri dish was taken from the incubator and the filter paper was removed, rinsed of adhering soil, dried at 105 ^{o}C for 12 hours, cooled in a desiccator and weighed. The difference in the mass of the filter paper from before and after incubation was used to estimate the mass of microbially degraded cellulose, where cellulolytic activity is expressed as a percentage of the cellulose degraded after 14 days.

3.3.2 Soil organic carbon, particle size analysis and aggregate stability

Bulk soil samples were air-dried, milled and passed through a 2 mm sieve for further analysis. Soil organic carbon content was determined in duplicate for each plot for both the A and B horizon by dichromate oxidation (Walkley, 1947). Particle size distribution (dispersed) was determined by the pipette method (Gee and Bauder, 1986) on six randomly chosen plots representing each treatment being investigated for both the A and B horizon. The unbound silt and clay (undispersed) was also measured using the pipette method and was determined for each plot in both the A and B horizon. From the results of dispersed and undispersed particle size distribution the micro-aggregate stability could be determined as follows (Richards, 1954):

$$\frac{[(\text{Total silt + clay after complete dispersion}) - (\text{unbound silt + clay})] \times 100}{\text{Total silt + clay after complete dispersion}} \quad (\%) \qquad \text{(equation 1)}$$

3.3.3 Water retention characteristic, saturated hydraulic conductivity and bulk density

Soil cores collected in the field were prepared and analysed for water retentivity characteristics, saturated hydraulic conductivity (K_s) and bulk density (ρb) using the method of Moodley *et al.* (2004). In brief, the method involves placing a pre-weighed piece of nylon cloth and elastic band onto the lower end of a soil core that has been trimmed level with the upper and lower surface of the ring. The core is then slowly saturated by capillary water movement to saturate the micropores and then by flooding to saturate the larger pores. Immediately after complete saturation the cores are weighed for saturated water content. The cores were then placed on a tension table (sand bath construction; Avery and Bascomb, 1974) using a hanging water column to achieve a matric potential of -1.0 kPa. The cores were allowed to equilibrate to constant mass before being reweighed and returned to the tension table. The hanging water column was then lowered to achieve a matric potential of -2 kPa. This process was repeated for matric potentials of -4, -6 and -8 kPa. The cores were then transferred to ceramic pressure plates in a pressure chamber apparatus. The cores were equilibrated at matric pressures equivalent to -33 and -100 kPa and weighed at each respective pressure once constant mass was reached. The moisture content at -33 kPa was used to represent field capacity (Givi *et al*., 2004). The cores were then oven-dried at 105 ^{o}C for 48 hours and this was used to determine ρb and mass moisture content of the soil for each respective matric potential. The mass moisture content was converted to volumetric water content as follows:

$$\frac{\text{Gravimetric water content x Bulk density}}{\text{Water density}} \quad (m^3\ m^{-3}) \qquad \text{(equation 2)}$$

where the density of water is taken as 998 kg m^{-3}.

Wilting point moisture content was determined at -1500 kPa in a high pressure chamber apparatus. Rings (10 mm height x 50 mm diameter) were filled with loosely packed soil (< 2 mm) and saturated by capillary wetting overnight. The rings were then placed in the pressure chamber and allowed to equilibrate for about 2 weeks constant mass was reached. After removal from the pressure chamber the mass moisture content of the soil was determined by oven drying at 105 ^{o}C for 24 hours. The mass moisture content of the soil was converted to volumetric water content using equation 2, where bulk density used was calculated from repacked rings.

Prior to oven-drying the soil cores (and directly after the soil retentivity measurements), the K_s was determined using the method of Moodley *et al*. (2004). This required taping a second empty core to the soil core to increase the length and re-saturating the core. The core was then placed on a steel mesh held inside a funnel and K_s was measured by the constant head method (Klute and Dirksen, 1986). The K_s was calculated using Darcy's equation for saturated flow under constant head conditions as follows:

$$K_s = ((V / (A \times t)) \times (L / \Delta H)) \times 10 \text{ (mm hr}^{-1}\text{)} \qquad \text{(equation 3)}$$

where
V = Volume of water in cm^3 collected for a time period of t (hours)
A = cross sectional area of the core (cm^2)
L = Length of soil column (cm)
ΔH = total hydraulic head (cm)

3.4 Statistical Analysis

Correlation matrices were produced, using Microsoft Excel, between air-dried soil moisture content, field soil moisture content, hydrolytic activity, cellulolytic activity, ρ_b, SOC content, K_s, and the volumetric water content at 0 kPa (assumed to be total porosity), at -33 kPa (field capacity) and at -1500 kPa (wilting point). The replicates within a plot were averaged and correlations were carried out between the measured plots (n = 3).

Overall differences between treatment means were assessed using analysis of variance (ANOVA) for a split plot experimental design. This was done for SOC content (%), hydrolytic activity (µg fluorescein g^{-1} h^{-1}), cellulolytic activity (% cellulose degraded over 14 days), ρ_b (g cm^{-3}), K_s (mm hr^{-1}), and the volumetric water content at 0 kPa (i.e. total porosity), -33 kPa (field capacity) and -1500 kPa (wilting point) using GENSTAT, (12th edition). Where overall significant differences between treatment means were found, treatment means were compared by least square difference (LSD) comparisons at the 5 % level of significance (GENSTAT).

Chapter 4

The effect of tillage and nitrogen fertilizer on soil organic carbon and microbial activity

4.1 Introduction

Soil organic matter (SOM) is a key indicator of soil quality as it affects soil structure which influences soil stability, friability and moisture retention (Riley *et al*., 2008). In addition, SOM has an effect on nutrient storage, biological activity (Melero *et al*., 2009), and filtration and buffer capacity of soil. Soil organic matter has no definite composition and therefore total soil organic carbon (SOC), which is the main component of SOM, is usually determined (Melero *et al*., 2009). Fuentes *et al*. (2009) propose that SOC is the most sensitive chemical property in determining sustainability due to its positive relationship with crop productivity and thus maintaining SOM is an important objective of soil management practices (Bausenwein *et al*., 2008).

Soil microbial activity is responsible for nutrient cycling and organic matter decomposition (Turco *et al*., 1994) where approximately 90 % of energy in the soil environment flows through microbial decomposers (Adam and Duncan, 2001; Green *et al*., 2006). The enzymes responsible for the metabolic activity in soils are responsive to changes in the soil chemical and physical environment, such as changes in organic substrates, pH, temperature, and moisture status (Schinner *et al*., 1996) and are therefore affected by land management practices such as tillage and fertilizer application. As such, measuring the metabolic activity of the soil gives an indication of soil health and acts as a sensitive parameter in monitoring the effects of land management on the sustainability of soil as a resource (Melero *et al*., 2009).

A common method of measuring total soil microbial activity involves determining the hydrolytic activity of a soil using the fluorescein diacetate (FDA) method. Schnürer and Rosswall (1982) found a positive correlation between soil basal respiration and FDA hydrolytic activity. Similarly, Swisher and Carroll (1980) found that microbial biomass was directly proportional to FDA hydrolytic activity. Fluorescein diacetate is a colourless substrate which is hydrolysed by both exo-enzymes (free) and membrane bound enzymes in the soil environment (Adam and Duncan, 2001), including proteases, lipases and esterases (Green *et al*., 2006). The by-product of enzymatic decomposition of FDA is fluorescein, a yellow-green substance which can be detected spectrophotometrically or by fluorescence microscopy (Green *et al*., 2006).

Another measure of microbial activity is cellulase activity. Cellulose is a structural polysaccharide of the plant cell wall and thus its degradation by cellulases is important in breaking down plant debris. Cellulases found in the soil are produced mainly by fungi and thus determination of cellulolytic activity is a good measure of fungal activity in soils. Cellulase activity is affected by type of litter, amount of substrate, pH, temperature and water content (Alef and Nannipieri, 1995), all of which are influenced by agricultural management practices.

In order to promote the most sustainable agricultural mangement practices in terms of nitrogen (N) fertilizer application and tillage regime on the clay-loam soils of the Loskop area; this chapter aims at identifying the effects that annual conventional tillage (CT1) and no-till (NT, i.e. direct seeding) have on SOC, hydrolytic activity and cellulolytic activity at three rates of limestone ammonuim nitrate (LAN) fertilizer application.

4.2 Results and discussion

4.2.1 Soil organic carbon

The effect of tillage by fertilizer on SOC is highly significant ($p < 0.001$) in the A horizon but not significant ($p = 0.24$) in the B horizon (Appendix 5). Comparisons by least squares differences at the 5 % level of significance ($LSD_{5\%}$) indicate that this difference in the A horizon is due to the NT 0N treatment being significantly higher than the other treatments and NT 100N and NT 200N being significantly higher than the SOC content at all N fertilizer application rates under CT (Appendix 6). There is a highly significant ($p < 0.001$) tillage effect, averaged across fertilizer treatments, on SOC in the A horizon but not in the B horizon ($p = 0.076$) (Appendix 5). At each N fertilizer application rate the SOC is higher under NT than under CT1 in the A horizon, whereas in the B horizon the SOC is higher under CT1 than under NT (Figure 4.1).

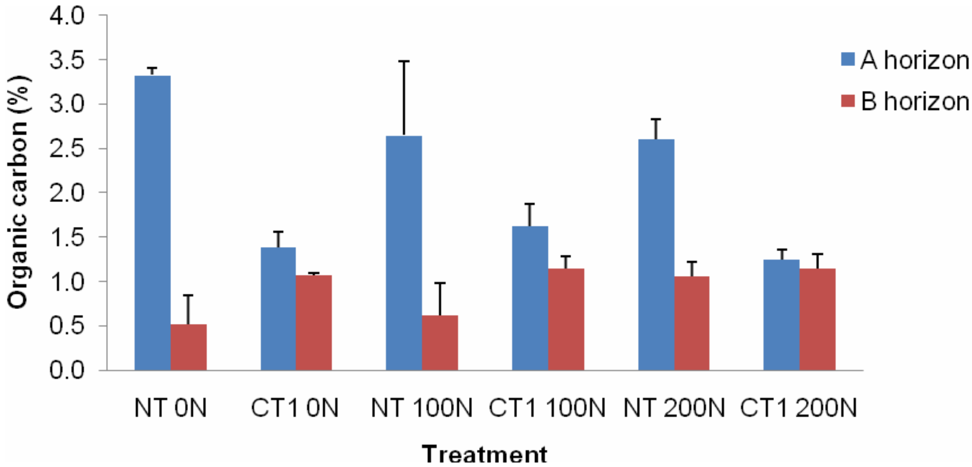

Figure 4.1 The effect of no-till (NT) and annual conventional till (CT1) at N application rates of 0, 100 and 200 kg ha^{-1} $annum^{-1}$ (0N, 100N and 200N, respectively), on soil organic carbon in the A horizon (0 to 20 cm) and the B horizon (20 to 40 cm) (n = 3, +SE).

These results confirm the study by Bescansa *et al*. (2006) who found that conservation tillage systems resulted in 13 % more organic matter than CT systems in the 0 to 15 cm soil depth. Under NT organic matter builds up on the soil surface, whereas under CT organic matter is incorporated within the plough layer and mineralisation rates are promoted. Incorporation of crop residues into the soil accelerates microbial decomposition by providing more direct contact between the residues and the soil decomposers (Fuentes *et al*., 2009; Melero *et al*., 2009). Furthermore, the ploughing action mechanically reduces the size of organic residue fragments, increasing their specific surface area which increases microbial activity. Consequently, there is generally a lower amount of SOC under CT than under NT in the soil surface. The higher SOC in the B horizon under CT1 is attributed to soil samples that were collected from the B horizon including the lower portion of the plough layer and thus surface incorporated residues contributed to the higher SOC. This was not the case for NT as residues remain on the soil surface.

There is a highly significant ($p < 0.001$) difference in SOC content between the fertilizer treatments (averaged over tillage treatments) for the A horizon but no significant ($p = 0.261$) difference was found for the B horizon (Appendix 5). Comparions by least squares differences at the 5 % level of significance ($LSD_{5\%}$) indicate that the SOC content at each N application rate in the A horizon is significantly different (Appendix 6).

It is expected that a higher rate of fertilizer would increase the amount of plant biomass and thus increase the amount of SOC. It is proposed that the lower SOC with increasing nitrogen is a function of the C:N ratio. As the amount of nitrogen increases more residues are decomposed due to an increase in the microbial activity and thus the SOC percentage decreases (i.e. microbial activity is not nutrient limited). Given that the method used to determine SOC (dichromate oxidation) only extracts readily oxidisable carbon, any carbon assimilated (i.e. incoporated into microbial cellular strucutures) or respired (i.e. lost as CO_2) by microorganisms would not be included in the estimate of SOC. Sarathchandra *et al*. (2001) report similar results, where the organic carbon content is lower in fertilized plots than in unfertilized plots. In the A horizon under CT1 the highest SOC content was found at a N application rate of 100N. It is suspected that this result is a function of variability due to the ploughing in of residues.

There is a marked difference in SOC content between the A and B horizon under NT, though this difference is less marked between the A and B horizon under CT1. Regardless of treatment the SOC is higher in the A horizon than in the B horizon (Figure 4.1). This is in agreement with Angers *et al*. (1992), who found that SOC decreased with depth in two loamy soils and that repeated cultivation resulted in homogenisation of SOC within the plough layer. Under NT the organic matter builds-up and remains on the soil surface and thus stratification of SOC within the soil profile occurs (Cavalieri *et al*., 2009; Melero *et al*., 2009).

4.2.2 Hydrolytic activity

No significant interactive effect of tillage and fertilizer were found for the A or B horizons ($P > 0.05$), however there were significant ($p = 0.002$) differences between means of tillage treatment when averaged across fertilizer treatment in the A horizon, though no significant ($P = 0.420$) differences were found in the B horizon (Appendix 7). For each N application rate the microbial activity is higher under NT than under CT1 in both the A and B horizons (Figure 4.2)

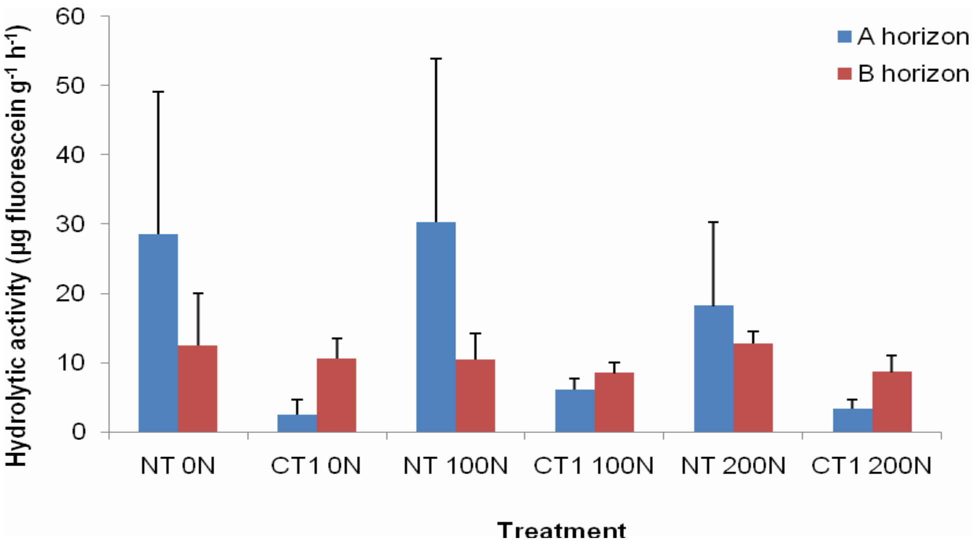

Figure 4.2 The effect of no-till (NT) and annual conventional till (CT1) at N application rates of 0, 100 and 200 kg ha^{-1} annum^{-1} (0N, 100N and 200N, respectively), on soil hydrolytic activity in the A horizon (0 to 20 cm) and the B horizon (20 to 40 cm) as measured by the fluorescein diacetate (FDA) method (n = 3, +SE).

These results suggest that NT provides a more favourable environment for increased microbial activity. Carter (1986) also found that microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) are closely related to microbial activity (r^2 = 0.84 and 0.86, respectively) and that MBC and MBN increased by between 10 and 23 % under NT when compared to shallow tillage over a four year period in the 0 to 5 cm soil depth. Similarly, Melero *et al.* (2009) found higher MBC and enzyme activity in the top 20 cm of soil under NT when compared to CT. This concurs with Govaerts *et al.* (2007) who found greater microbial activity and functional diversity in soils under NT when compared to CT and attributed these findings to improved aeration, a cooler and more moist soil environment, less temperature fluctuations and higher SOC content under NT. While ploughing promotes microbial activity immediately after soil tillage (mineralisation "flush") (Spedding *et al.*, 2004), long-term tillage reduces the amount of organic matter in the soil due to increased mineralisation (Acosta-Martínez *et al.*, 2008). Angers *et al.* (1992) found that MBC decreased by 6 % in the top 6 cm of soil due to ploughing. Under NT the accumulation of crop residues promote the microbial and enzyme activity, particularly at the soil surface (Martens *et al.*, 1992). Melero *et al.* (2009) found that microbial activity increased with increased organic matter. Acosta-Martínez *et al.* (2008) found a significant relationship between dehydrogenase activity and SOC (r^2 = 0.683), and that intensive tillage caused a 30 to 50 % reduction in C content compared to undisturbed pastures. This resulted in a community structure with fewer fungal populations and lower enzyme activity in < 10 years after conversion to ploughing. The lack of a positive correlation (r = 0.499) between SOC and hydrolytic activity (Appendix 8) is possibly a function of sample depth and the high variability in hydrolytic activity measurements in the A horizon under NT (Figure 4.2). It is expected that microbial activity and SOC under NT would be greatest in the 0 to 5 cm depth, and decrease with increasing depth. In this study the soil was sampled at 0 to 20 cm leading to a dilution effect of organic matter and microbial activity and thus the relationship between the two parameters is less marked. It is expected that the correlation would be stronger if the soil was sampled at a higher resolution (i.e. smaller depth increments). Carter (1986) and Angers *et al.* (1992) found that MBC under NT was higher in the top 5 cm compared to CT but when the entire plough layer (0 to 30 cm) is considered there was no difference in MBC between tillage treatments. Furthermore, the lack of homogenisation of the SOC into the soil under NT is likely to create localised areas of high microbial activity, leading to high variability in measures of microbial activity.

There are no significant differences in the A horizon (p = 0.474) or B horizon (p = 0.707) between fertilizer application rate treatment means (Appendix 7). However, in the A horizon under both NT and CT1 there is higher hydrolytic activity for the 100N treatment compared to the 0N and 200N treatments. This suggests that an intermediate N rate is preferable for microbial activity. Increased N fertilizer application results in increased grain yield (Appendix 9), suggesting higher plant biomass and consequently greater SOM content which increases microbial activity. Linn and Doran (1984) found that plots fertilized under both NT and CT had greater N_2O production. However, fertilizer affects soil chemical properties and at high rates of application may act as an irritant to soil microorganisms (Fuentes *et al.*, 2009). Tanyolac *et al.* (2001) cite a number of studies which indicate that the high levels of the ammonium ion has an adverse effect on microbial activity (*inter alia*: Krylova *et al.*, 1997; Lay *et al.*, 1997; Lay *et al.*, 1998; Princic *et al.*, 1998).

At all rates of N fertilizer the hydrolytic activity under NT in the A horizon is notably higher than the B horizon, whereas under CT1 the hydrolytic activity is only slightly higher in the B horizon as compared to the A horizon (Figure 4.2). Many studies indicate that with increasing soil depth there is a decrease in SOC and microbial activity (Bausenwein *et al.*, 2008; Nyamadzawo *et al.*, 2009; Melero *et al.*, 2009). However, ploughing of the soil results in a more even distribution of plant residues within the plough layer and thus the stratification of SOC and microbial activity that exists in NT soils is not present in CT soils. Doran (1980) found higher phosphatase and dehydrogenase enzyme activities, and greater aerobic microbial numbers under

NT in the 0 to 7.5 cm soil depth, whereas at the 7.5 to 15 cm soil depth the aerobic microbial activity was higher under CT. This was attributed to a higher percentage of mineralisable N in the surface soil under NT and to NT soils retaining more water. At depth, NT soils experience a less oxidative environment and as such the biomass and activity of aerobic soil microbes decrease as the community structure changes. In a related study, Linn and Doran (1984) found higher CO_2 and N_2O production in the CT soils compared to NT soils at a depth of 7.5 to 15 cm. They attribute a decline in microbial respiration, nitrification and mineralisation at this depth to NT soils containing more than the optimal WFP (i.e. 60 %) for aerobic microbial activity. These results suggest that soil microbial biomass and activity is strongly influenced by both SOM and soil moisture content. However, a weak correlation ($r = 0.182$) was found between hydrolytic activity and field moisture water content, (Appendix 8) suggesting that moisture was not a limiting factor to microorganisms. This result may be a function of sampling time, as at the time of sampling, the WFP of the A horizon averaged 19.66 % whereas the B horizon averaged 18.76 %. Thus samples were taken at a time when moisture content between the A and B horizons were similar. However, variations in moisture content over time are likely to play a more prominent role. However, at the time of sampling it appears that SOM content had a stronger influence on microbial activity. Under CT1 the crop residues are incorporated into the soil and distributed throughout the plough layer which results in a more readily available food source for microorganisms in the 20 to 40 cm soil depth and thus the microbial activity in the B horizon is greater under CT than NT.

4.2.3 Cellulolytic activity

There is higher cellulolytic activity in the A horizon under NT compared to CT1, except for the CT1 0N treatment (Figure 4.3). Although there are no significant differences in cellulolytic activity in the A horizon ($p = 0.897$) or B horizon ($p = 0.065$) between tillage treatment means (Appendix 10).

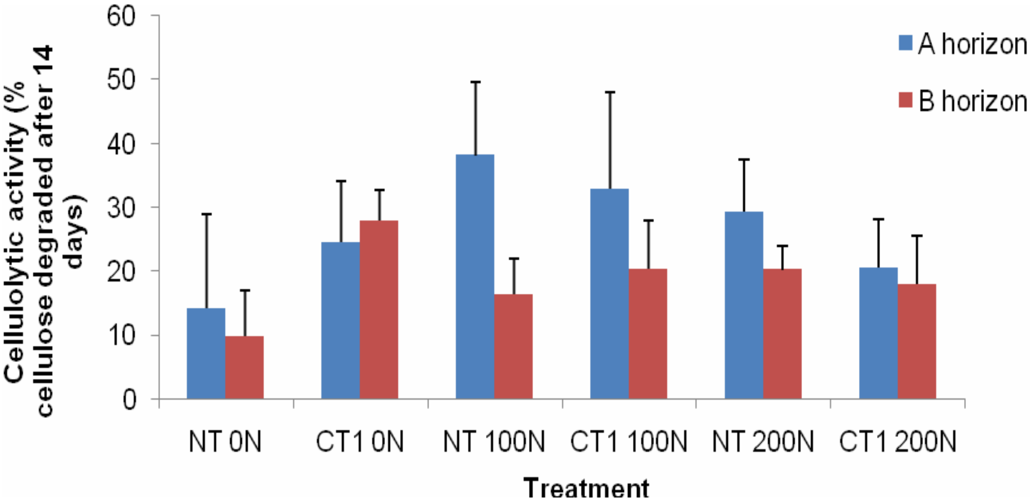

Figure 4.3 The effect of no-till (NT) and annual conventional till (CT1) at N application rates of 0, 100 and 200 kg ha^{-1} $annum^{-1}$ (0N, 100N and 200N, respectively), on soil cellulolytic activity in the A horizon (0 to 20 cm) and the B horizon (20 to 40 cm) as measured by amount of cellulose degraded over 14 days (n = 3, +SE).

The generally higher cellulolytic activity in the A horizon is attributed to more residue on the soil surface under NT which provides more substrate for cellulose degraders. In addition, fungal hyphae remain intact under NT while under CT1 fungal hyphae are damaged by ploughing. Smith and Hughes (2004) found that frequent turning of compost lowered the cellulolytic activity. They suggested that turning the compost resulted in the disruption of fungal hyphae, the major contributor to cellulose degradation, and thus the cellulolytic activity was reduced. Spedding *et al.* (2004) also suggested that tillage disrupts fungal mycelium. There is no apparent reason for the higher cellulolytic activity under CT1 0N compared to NT 0N in the A horizon and is possibly due to the high variability of the NT 0N treatment (Figure 4.3).

There is no significant difference in the A horizon or B horizon (p = 0.071 and 0.896, respectively) between fertilizer application rate treatment means (Appendix 10). However, in the A horizon under both NT and CT1 there is a strong trend indicating higher cellulolytic activity for the 100N treatment compared to the 0N and 200N treatments (Figure 4.3). This corresponds with the trend seen for hydrolytic activity.

For all treatments the amount of cellulose degraded in the A horizon is higher than the B horizon, except for the CT1 0N treatment. This was attributed to more residues on the soil surface under NT and thus a greater food supply for microorganisms in the topsoil. Under CT1 this effect is less marked as residues are incorportaed into the soil resulting in a more homogenised food supply in the plough layer. The likely reason of the slightly higher cellulolytic activity in the B horizon campared to the A horizon under CT1 at 0N is variability. A high level of variability in measured cellulolytic activity may be due to the method used. After incubation of the filter paper a washing procedure is required. This required very careful removal of the partially decomposed filter paper from the soil and then washing of this filter paper to remove adhering soil particles. It is likely that small errors during these steps are a source of error that may lead to high variability in the estimation of cellulytic activity. It is suspected that this, along with heterogeneity in microbial populations and depth of sampling, are the causes of the high variability and some of the anomalous trends found.

4.3 Conclusions

The amount of SOC in the upper 20 cm of the soil is higher under NT compared to CT1 due to the build-up of organic matter on the soil surface and the slower mineralisation rate which allows SOM to accumulate. Under both tillage regimes the amount of SOC decreases with depth, though this is more marked under NT than under CT1. This is attributed to the statification of SOM under NT, whereas under CT1 the SOM is incorporated into the plough layer. The close relationship between SOC and microbial activity is illustrated by measures of both hydrolytic activity and cellulolytic activity. In both measures the microbial activity in the A horizon is higher under NT compared to CT1 and is attributed to more SOM which provides more substrates for microbes. Similarly to SOC content, the hydrolytic and cellulolytic activity is higher in the A horizon than in the B horizon and this difference is more marked under NT than under CT1.

In terms of nitrogen fertilizer, the effects on SOC and microbial activity appear contradictory. Increasing N application under NT in the A horizon results in a lower percentage of SOC. It is presumed that increasing levels of nitrogen increase the rate of SOM decomposition due to a more favourable C:N ratio coinciding with greater plant biomass. However, under both NT and CT1 the hydrolytic and cellulolytic activity increases from 0N to 100N but is lowest at a fertilizer application rate of 200N. This suggests that microbes preform at an optimal nitrogen level and that 200N negatively affects their activity. The lower SOC at 200N suggests increased microbial activity resulting in faster decomposition of SOM. These contradictory results may be due to dehydrogenase and cellulase activity contributing only a small proportion of the total enzymes responsible for degradation. In the study by Sarathchandra *et al*. (2001) the soil functional diversity decreased with increased N application although the microbial community remained similar. These results suggest that N application affects the soil microbial community structure. Therefore, a high application of N may have adverse affects on some soil microbes while others are promoted. Consequently, SOM is still decomposed although the soils functionality is reduced.

Overall, it is proposed that NT is the preferred tillage practice in providing long-term sustainability and soil health by promoting increased leves of SOM and greater enzyme activity. Furthermore, it is recommended that, although increased levels of N fertilizer results in higher yielding maize plants, it is unsustainable to apply high applications of N due to the negative effect on measured microbial activity.

Chapter 5

The effect of tillage and nitrogen fertilizer on soil physical properties

5.1 Introduction

Agricultural management practices, such as fertilizer application and tillage, impact on soil physical properties by influencing the quantity and quality of soil organic matter (SOM) and mechanically altering soil physical properties. Fertilization generally increases plant biomass and results in more SOM, whereas continuous ploughing of soil results in a net loss of SOM due to increased mineralisation (Ishaq *et al*., 2002). Changes in SOM influence the soil structural properties and impact on bulk density (ρ_b), water retention, saturated hydraulic conductivity (K_s), aggregate stability and soil penetration resistance, as well as other soil chemical, physical and biological properties. Tillage also directly influences soil physical properties by creating temporary unstable macropores and altering overall soil porosity (Osunbitan *et al*., 2005).

Bulk density is directly related to soil porosity and indicates the degree of soil compaction (Assouline, 2006). Consequently, ρ_b is considered a good measure of soil quality as it affects other soil physical parameters such as water retentivity, K_s and ease at which roots can penetrate the soil. Other important physical measures of soil quality include the soil water retention characteristics and K_s, both of which are a function of soil pore characteristics (shape, volume and continuity) and are important determinants of the water and aeration status of the soil. When all soil pores are saturated with water the soil matric potential is considered to be 0 kPa and the volumetric water content represents the total soil porosity (Linn and Doran, 1984). Between -10 kPa and -33 kPa the soil water is held at field capacity, which represents the amount of water remaining in the soil pores after readily available water has drained under the influence of gravity. The water available for plant use is usually retained by the soils mesopores at a matric potential of between -10 kPa and -1500 kPa, whereas the wilting point of the plant is taken as the moisture content at -1500 kPa and represents the water that is strongly adsorbed to pore surfaces and is generally not available for plant uptake (Schulze *et al*., 1985). In addition to the water and aeration status of the soil, crop productivity is also affected by the ease at which roots can penetrate the soil (i.e. soil strength), which is frequently estimated by determining the soil penetration resistance (Osunbitan *et al*., 2005).

The aim of this chapter is to identify the effects that annual conventional tillage (CT1) and no-till (NT, i.e. direct seeding) have on soil ρ_b, water retentivity, K_s, aggregate stability and soil penetration resistance at three rates of nitrogen (N) fertilizer applied as limestone ammonuim nitrate (LAN). In so doing, more sustainable agricultural mangement practices, in terms of fertilizer application and tillage regime, on the clay-loam soils of the Loskop area can be proposed.

5.2 Results and discussion

5.2.1 Bulk density (ρ_b)

There was no significant difference found for the tillage by fertilizer effect on ρ_b in the A or B horizons (p = 0.79 and p = 0.178, respectively) (Appendix 11). In the A horizon there is a significantly (p = 0.015) higher ρ_b under NT compared to CT1, though no significant (p = 0.246) difference between tillage means was found in the B horizon (Appendix 11), (Figure 5.1).

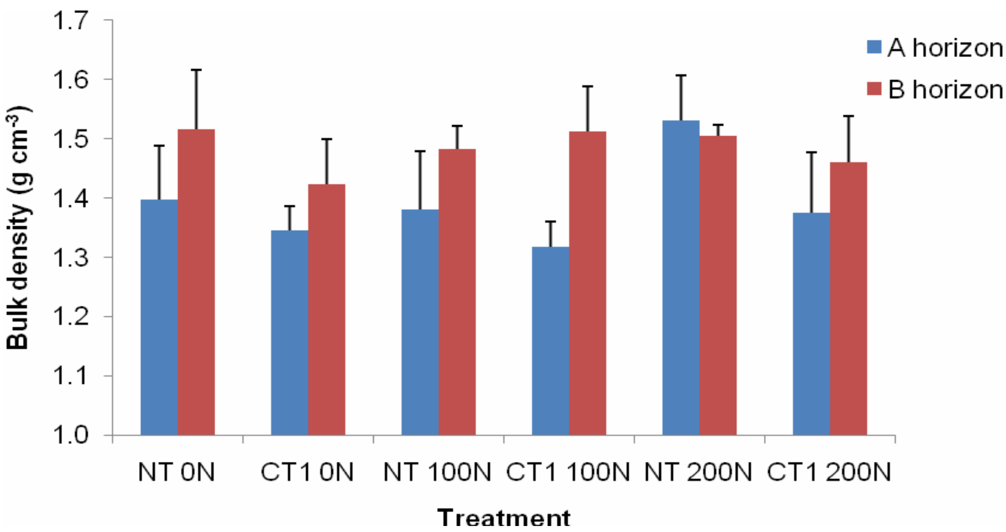

Figure 5.1 The effect of no-till (NT) and annual conventional tillage (CT1) at N application rates of 0, 100 and 200 kg ha^{-1} $annum^{-1}$ (0N, 100N and 200N, respectively), on soil bulk density in the A horizon (0 to 20 cm) and the B horizon (20 to 40 cm) (n = 3, +SE).

Under CT the ρ_b in the plough layer is lowered by the mechanical inversion of the soil during tillage which creates macropores and increases the porosity of the soil. A strong negative correlation (r = -0.917) was found between the ρ_b and total porosity (Appendix 8). Many authors (e.g. Osunbitan *et al*., 2005; Bescansa *et al*., 2006) have found that ρ_b in the top 5 to 20 cm of soil is greater under conservation tillage compared to CT up to 10 years after conversion to conservation tillage. However, in the long-term (> 10 years) the higher ρ_b under NT has been found to be temporary and is reduced as SOM content and biological activity increases (Bescansa *et al*., 2006). This results in similar ρ_b between tillage systems (Angers *et al*., 1992; Johnson-Maynard *et al*., 2007) or a slightly lower ρ_b under conservation tillage systems (D'Haene *et al*., 2008; Riley *et al*., 2008). Soils which are continuously ploughed lose SOM which leads to the degradation of soil aggregation. As a result, pores created during ploughing are unstable and readily collapse (Osunbitan *et al*., 2005) due to greater slaking and dispersion of soil aggregates and consequently ρ_b increases (So *et al*., 2009). Osunbitan *et al*. (2005) found that although ρ_b in the top 5 cm was greater under NT than CT, the increase in ρ_b over eight weeks since the tillage event was greater under CT. This was attributed to the soil particles under CT settling into a more compact arrangement compared to NT. The loss of SOM under CT also leads to a reduction in the soils mesoflora. Earthworms are important for improving and maintaining soil structure and aggregate stability (Riley *et al*., 2008). Tillage adversely affects earthworm populations by impacting on the SOM and moisture retention and also, increasing the exposure of earthworms to predators and adverse climatic conditions by bringing them to the soil surface (Smith *et al*., 2008). Since NT has a positive effect on earthworm populations (Kladivko *et al*., 1997; Johnson-Maynard *et al*., 2007; Riley *et al*., 2008; Smith *et al*., 2008) the soil structural characteristics under NT are gradually improved which leads to better pore size distribution (i.e. a larger range of pore sizes) and a lower ρ_b with time (Kladivko *et al*., 1997; D'Haene *et al*., 2008). It is important to note that ρ_b under CT is strongly affected by sampling time. If ρ_b is measured directly after ploughing then ρ_b under CT is much lower than under NT. However, if measurement of ρ_b is taken well into the growing season and the CT soil has consolidated due to a loss of structure and structural stability then the ρ_b between tillage regimes is likely to be similar or greater under CT. In the current study samples were taken near the end of the growing season and while significant differences were found between treatments, these were less marked than they may have been if samples were taken earlier in the season.

There is a highly significant ($p < 0.001$) difference in bulk densities between fertilizer application rate in the A horizon but no significant ($p = 0.604$) difference in the B horizon, across the mean of tillage treatments (Appendix 11). Comparisons by least squares differences at the 5 % level of significance ($LSD_{5\%}$) indicate that the 200N treatment is significantly higher than the other treatments in the A horizon (Appendix 6). It was found that the high N application rate had a negative impact on microbial activity (Section 4.2.1 and 4.2.2) and it was suspected that earthworm populations were also negatively impacted. This would adversely affect aggregation and soil pore formation, leading to higher ρ_b. Although increased fertilizer may increase the level of plant biomass and provide more food for earthworms, the addition of a high quantity of ammonium containing inorganic fertilizers can negatively affect the earthworm population due to acidifying conditions and changing the availability of nutrients such as Ca^{2+} (Riley *et al*., 2008; Smith *et al*., 2008). This effect was not observed in the CT1 treatment at 200N as the effect of tillage would dominate, where macropores are created by the mechanical inversion of the soil during ploughing.

For all treatments, except NT 200N, the ρ_b is higher in the B horizon compared to the A horizon (Figure 5.1). Under CT1 the ρ_b is expected to be relatively higher in the B horizon than the A horizon due to a reduction in topsoil ρ_b as a consequence of ploughing. Under NT, ρ_b in the A horizon is reduced due to the build-up of organic matter on the soil surface which helps in building and preserving soil structure, and increasing biological activity. Cavalieri *et al.* (2009) found that under NT, SOC decreased with increasing depth and ρ_b increased with decreasing SOC. The high ρ_b value in the A horizon for the NT 200N treatment is possibly due to a high amount of LAN remaining on the soil surface and acting as an irritant to the soils micro and mesofauna. In the B horizon of the NT 200N treatment soil biota are limited by available substrate though they are not exposed to the surface applied fertilizer and thus there may be a small amount of activity which helps to reduce ρ_b in the B horizon.

5.2.2 Water retentivity

There was a significantly ($p = 0.008$) higher (Appendix 12) volumetric water content at saturation under CT1 compared to NT across fertilizer treatment means in the A horizon (Figure 5.2). This is the result of greater macroporosity under CT created by the mechanical inversion of the plough layer during tillage (Lampurlanés and Cantero-Martínez, 2006). The volumetric water content of the CT1 soil remained higher than the NT soil up to a matric potential of -6 kPa, while the water contents were similar between -6 and -10 kPa (Figure 5.2). This was attributed to the lower ρ_b (therefore higher porosity) of the CT1 treatments (Section 5.2.1).

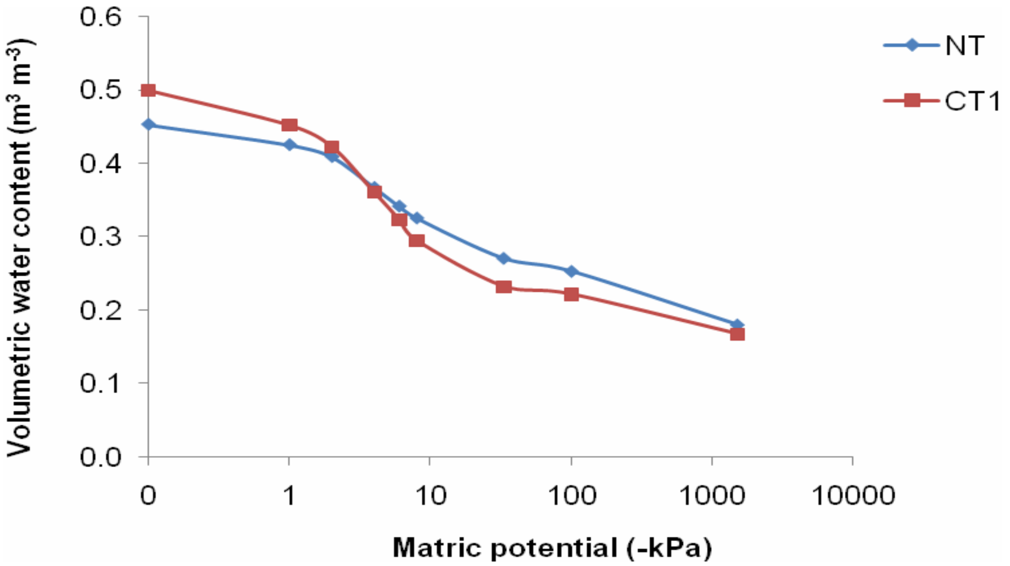

Figure 5.2 The effect of no-till (NT) and annual conventional tillage (CT1) averaged across fertilizer treatments (n = 9) on the water retention characteristics for the A horizon (0 to 20 cm).

The volumetric water content is greater under NT compared to CT1 at matric potentials between -10 and -1500 kPa in the A horizon (Figure 5.2) and there is a significantly ($p = 0.024$) higher volumetric water content for the NT treatments at -33 kPa matric potential (i.e. field capacity) (Appendix 13). These results are consistent with So *et al.* (2009) who report greater plant available water (PAW) under NT than CT in the top 10 cm of weakly structured silt loam soil. Although tillage increases the proportion of macropores, the poor aggregation and weak structure associated with continuously ploughed soils results in a loss of mesoporosity (Osunbitan *et al*., 2005). Conversely, the meso and microporosity of soil under NT increases as greater SOM improves soil aggregation and biological activity and thus NT soils are able to hold more PAW (i.e. -10kPa - wilting point) (Osunbitan *et al*., 2005; Saxton and Rawls, 2006).

In the A horizon, there is a highly significant ($p < 0.001$) effect of N fertilizer on the water content at saturation and -33 kPa (Appendix 12 and 13, respectively). Comparisons by $LSD_{5\%}$ at both 0 kPa and -33 kPa show that the 200N treatment is significantly lower than at 0N and 100N treatments (Appendix 6) (Figure 5.3).

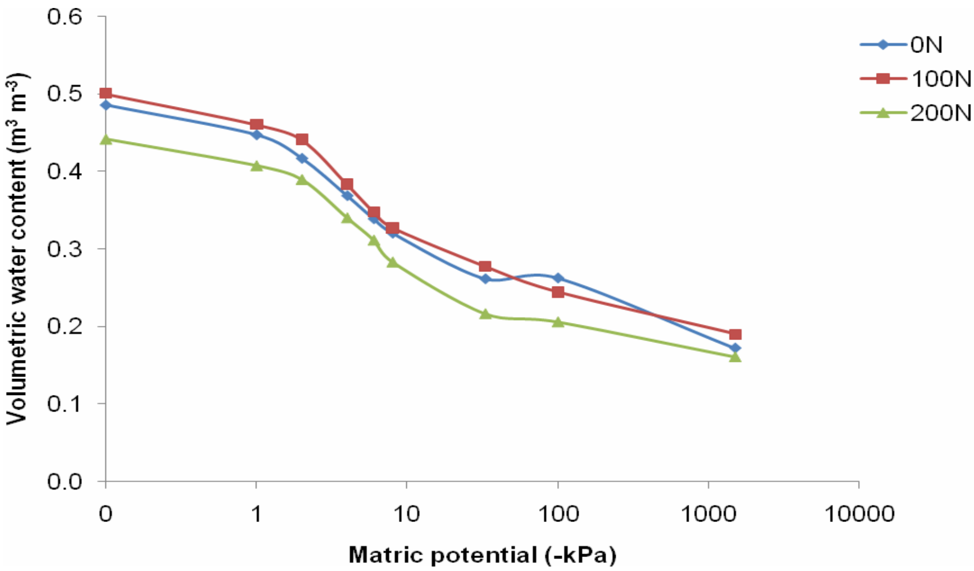

Figure 5.3 The effect of N application rates at 0, 100 and 200 kg ha^{-1} annum^{-1} (0N, 100N and 200N, respectively) averaged across tillage treatments (n = 6) on the water retention characteristics for the A horizon (0 to 20 cm).

These results show that at 200N the water retained at every matric potential is lower compared to 0N and 100N. These results are in agreement with the findings for ρ_b (Section 5.1), where the 200N treatment had the highest ρ_b in the A horizon (Figure 5.1). As proposed earlier, it is suspected that the high fertilizer rate acts as an irritant to the soil biota, decreasing microbial and mesofauna activity, leading to reduced porosity. In the case of microbial activity, these findings correspond to the results found for both hydrolytic and cellulolytic activity (Section 4.2.1 and 4.2.2). A reduction in microorganisms leads to a decrease in soil structural stability and mesoporosity is not maintained (Bossuyt *et al*., 2001).

It is important to note that there is a significant ($p = 0.009$) tillage by fertilizer effect at saturation in the A horizon (Appendix 12). Comparisons by $LSD_{5\%}$ indicate that the lower volumetric water content under NT compared to CT1 when averaged across fertilizer treatments is due to the NT 200N treatment being significantly lower than all other treatments (Appendix 6). The NT 0N and NT 100N treatments have similar volumetric water contents at saturation to all the CT1 treatments (Appendix 14). More organic material in the A horizon under NT can increase the soil mesofauna which results in increased macroporosity (Joschko *et al*., 2009), while macroporosity is maintained by ploughing in the CT treatments. This is not seen for the NT 200N treatment due to the adverse effect fertilizer has on soil organisms. Concurrently, there is a highly significant ($p < 0.001$) tillage by fertilizer effect at -33 kPa (Appendix 13). The highest PAW was measured for the NT 0N treatment in the A horizon, which was almost 2.5 fold higher than the CT 0N treatment. However, this marked difference was not evident for the 100N and 200N treatments in the A horizon, where NT and CT1 had similar PAW contents (Table 5.1).

Table 5.1 The effect of no-till (NT) and annual conventional tillage (CT1) at N application rates of 0, 100 and 200 kg ha^{-1} $annum^{-1}$ (0N, 100N and 200N, respectively), on plant available water in the A horizon (0 to 20 cm) (n = 3).

	Plant available water (m^3 m^{-3})	
	NT	CT1
0N	0.13	0.05
100N	0.09	0.08
200N	0.05	0.06
Average	0.09	0.06

Comparisons by $LSD_{5\%}$ show that the NT 200N has a significantly lower moisture content than the other NT treatments and a similar moisture content to the CT 0N and CT 200N treatments (Appendix 6). Again, this is most likely due to the irritant effect of a high application rate of N on soil organisms, especially under NT where the fertilizer remains on the soil surface and is not diluted through mixing within the plough layer. Slightly higher PAW for CT1 100N compared to other CT1 treatments in the A horizon (Table 5.1) could be a result of (i) increased SOM due to greater plant biomass as compared to the CT1 0N and (ii) that the irritant effect of the N fertilizer on soil biota is not occurring at CT1 100N as it is at CT1 200N. Consequently, mesoporosity created by mesofauna is limited by the amount of available substrate.

In the B horizon, there is no significant ($P < 0.05$) tillage by fertilizer effect at a matric potential of 0 kPa or -33 kPa (Appendix 12 and 13, respectively). There is no significant difference at saturation between tillage means or fertilizer means ($p = 0.063$ and $p = 0.180$, respectively) and only a marginally significant difference between tillage means and fertilizer means ($p = 0.033$ and $p = 0.036$, respectively) at a matric potential of -33 kPa (Appendix 12 and 13, respectively). At all matric potentials the moisture content is similar between tillage regimes (Figure 5.4) and between fertilizer application rates (Figure 5.5)

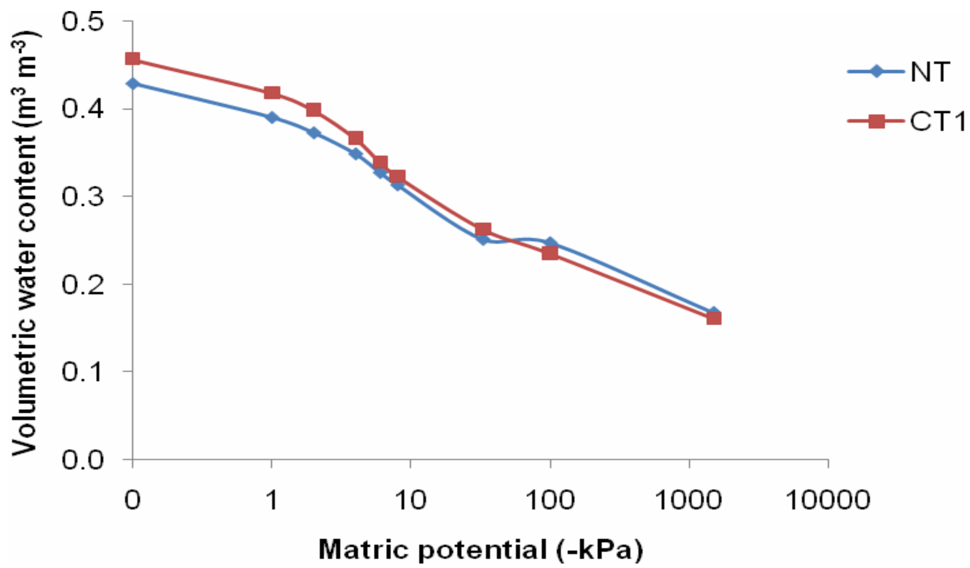

Figure 5.4 The effect of no-till (NT) and annual conventional tillage (CT1) averaged across fertilizer treatments (n = 9) on the water retention characteristics for the B horizon (20 to 40 cm).

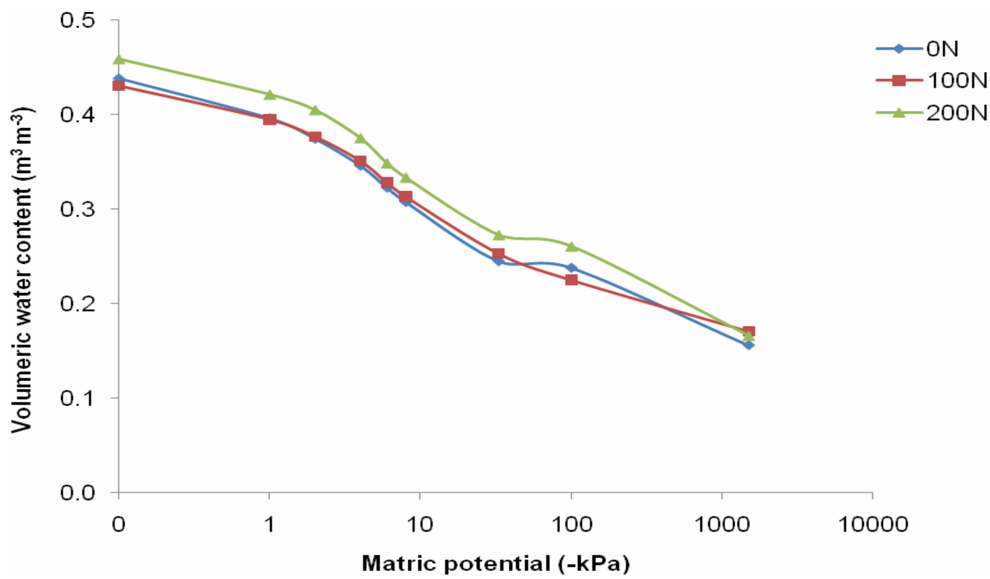

Figure 5.5 The effect of N application rates at 0, 100 and 200 kg ha^{-1} $annum^{-1}$ (0N, 100N and 200N, respectively) averaged across tillage treatments (n = 6) on the water retention characteristics for the B horizon (20 to 40 cm).

At -1500 kPa there was no significant difference in the A or B horizons ($p = 0.089$ and $p = 0.518$, respectively) between tillage means averaged over fertilizer treatments (Figure 5.2 and 5.4; Appendix 15). Soil organic matter and the degree of aggregation have a minimal effect on the water retained at -1500 kPa and soil texture is the dominant factor affecting water retention at very low matric potentials (Saxton and Rawls, 2006). Apart from an anomaly for the CT1 100N treatment, water contents for both the A and B horizon at wilting point are similar across all treatments (Appendix 14). Although significant differences between fertilizer treatments ($p < 0.001$) averaged across tillage regimes were found in the A horizon (Appendix 15), the difference in water contents at wilting point were very small, (Figure 5.3) and unlikely to have a marked impact on plant growth under favourable growing conditions.

5.2.3 Saturated hydraulic conductivity

Tillage has a significant ($p = 0.002$) effect on the K_s averaged across all fertilizer application rates in the A horizon and a significant ($p = 0.011$) effect in the B horizon (Appendix 16). In both the A and B horizon the K_s is notably higher under CT1 compared to NT at all fertilizer application rates (Figure 5.6).

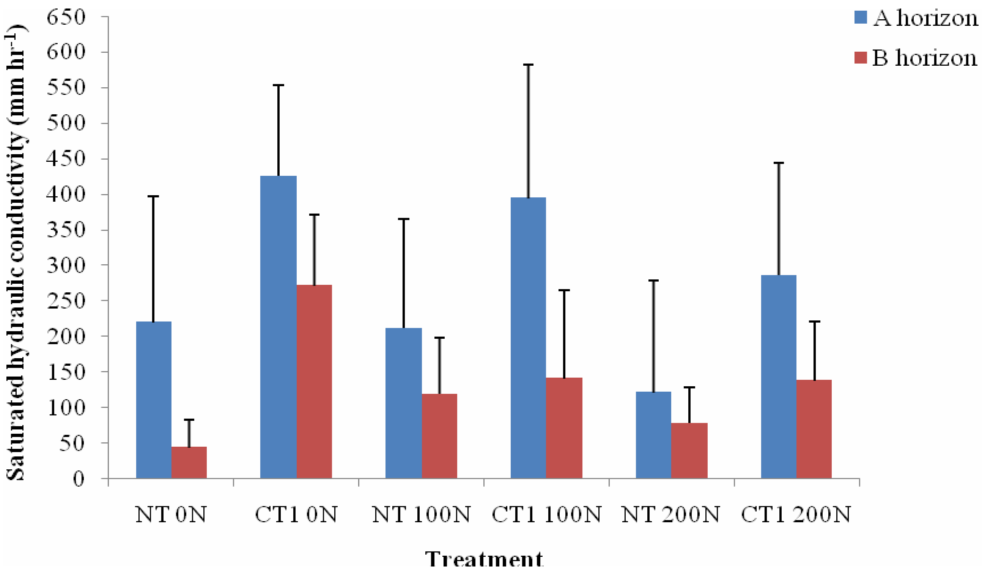

Figure 5.6 The effect of no-till (NT) and annual conventional tillage (CT1) at N application rates of 0, 100 and 200 kg ha^{-1} $annum^{-1}$ (0N, 100N and 200N, respectively), on saturated hydraulic conductivity in the A horizon (0 to 20 cm) and the B horizon (20 to 40 cm) (n = 3, +SE).

Saturated hydraulic conductivity is a function of the soils macroporosity and pore connectivity (Osunbitan *et al*., 2005). Although tillage results in an immediate increase in macroporosity

(Section 5.2.2), CT is likely to decrease pore continuity (Bhattacharyya *et al.*, 2006). In contrast, the build-up of organic matter on the soil surface under NT improves structural stability and leads to increased soil faunal activity and increased growth of plant roots. Consequently, more stable channels are created which leads to better pore connectivity (Saxton and Rawls, 2006) and can also lead to greater macroporosity with time. Accordingly, K_s has been found to be considerably lower under CT than under NT in the soil surface by a number of authors (Osunbitan *et al*., 2005; Bhattacharyya *et al.*, 2006; So *et al*., 2009; Cavalieri *et al*., 2009). In this study the higher K_s measured under CT1 is probably due to the lower ρ_b of the CT1 soils (Section 5.2.1) and is also reflected in the higher saturated water content of CT1 soils (Section 5.2.2). The time it takes for organic matter to build-]up and for a new biological equilibrium to be reached in NT soils is dependent on soil management, soil properties and environmental conditions and therefore differs between locations (Cavalieri *et al*., 2009). Johnson-Maynard *et al*. (2007) found similar K_s between NT and CT, suggesting that the NT soil macroporosity and pore connectivity had improved over time but had not yet improved to a level that exceeded the soil water transmission under CT. It is suspected that this is the case in this study and the long-term improvements in macroporosity are not yet evident in the NT soils.

There is no significant difference in the K_s for the A or B horizons ($p = 0.066$ and $p = 0.422$, respectively) between fertilizer application rates averaged across the tillage treatments (Appendix 16). However, there is a slightly lower K_s for the 200N treatment in the A horizon under both NT and CT1. This may be a consequence of fewer macropores being created by the soil biota as the high rate of fertilizer negatively affects the soils mesofauna, which concurs with the results for ρ_b and water retentivity (Section 5.2.1 and 5.2.2).

Comparisons of K_s by $LSD_{5\%}$ indicates that the significant ($p = 0.028$) effect of the tillage by fertilizer treatment in the B horizon (Appendix 16) is a result of the CT1 0N treatment (Appendix 6). The K_s for CT1 0N is considerably higher than all other treatments in the B horizon (Figure 5.6). There is no clear reason for this result and is suspected that boundary flow in the soil core during K_s measurement or a continuous open channel in one of the cores resulted in a skewing of the data, this reflected in the high error terms.

The K_s is substantially higher in the A horizon than the B horizon under both NT and CT1 at all fertilizer application rates (Figure 5.6). This is expected as under NT the increased SOM in the surface horizon allows for more biological activity and improved soil aggregation and thus water conductivity is improved in the soil surface and decreases with depth. Under CT, large connected pores are a result of tillage and thus below the plough layer the K_s decreases. In this study the B horizon samples were taken partially from the ploughed layer although it is expected that if samples had being taken completely below the plough layer the difference between K_s in the A and B horizon would be more marked under CT1.

5.2.4 Aggregate stability

There was higher micro-aggregate stability under NT than under CT1 in the A horizon and a small difference between the B horizon when averaged over fertilizer treatment means (Figure 5.7).

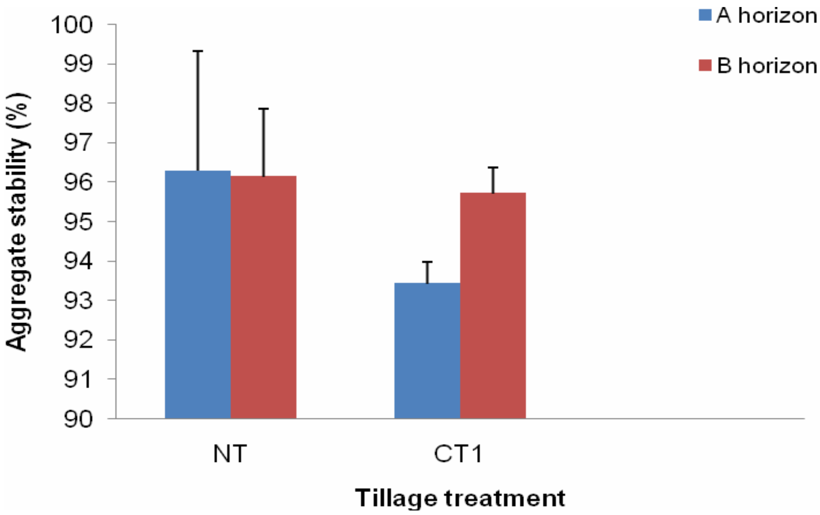

Figure 5.7 The effect of no-till (NT) and annual conventional tillage (CT1) averaged across N application rates on micro-aggregate stability for the A (0 to 20 cm) and B (20 to 40 cm) horizons (n = 3).

There is a strong correlation between SOM, SOC and the structural stability of micro and macro-aggregates (Fuentes *et al*., 2009). It is important to note that this study measured micro-aggregation rather than macro-aggregation. However, it is presumed that as micro-aggregates are the building blocks for macro-aggregates (Bossuyt *et al*., 2001) both are affected by management practices in the same way. Riley *et al*. (2008) found that soil management practices which promoted the accumulation of SOM had higher aggregate stability than soils which are ploughed annually. Nyamadzawo *et al*. (2009) found greater SOM levels and aggregate stability under NT than under CT in the soil surface. Under CT the aggregates are more susceptible to disruptive forces of wetting and drying cycles and raindrop impact as they are not protected by organic matter or held together by organic colloids. Therefore, under CT the macro-aggregation is destroyed due to mechanical disruption (Nyamadzawo *et al.*, 2009). In the B horizon the difference in aggregate stability is smaller between NT and CT1 as there is less SOM under NT with increasing depth, whereas under CT1 the amount of SOM is more evenly distributed within the plough layer (Section 4.2.1).

The micro-aggregate stability in the A horizon was considerably lower at 200N than the other N application rates under NT (Figure 5.8), whereas in the B horizon the aggregate stability between fertilizer treatments is not markedly different (Figure 5.8).

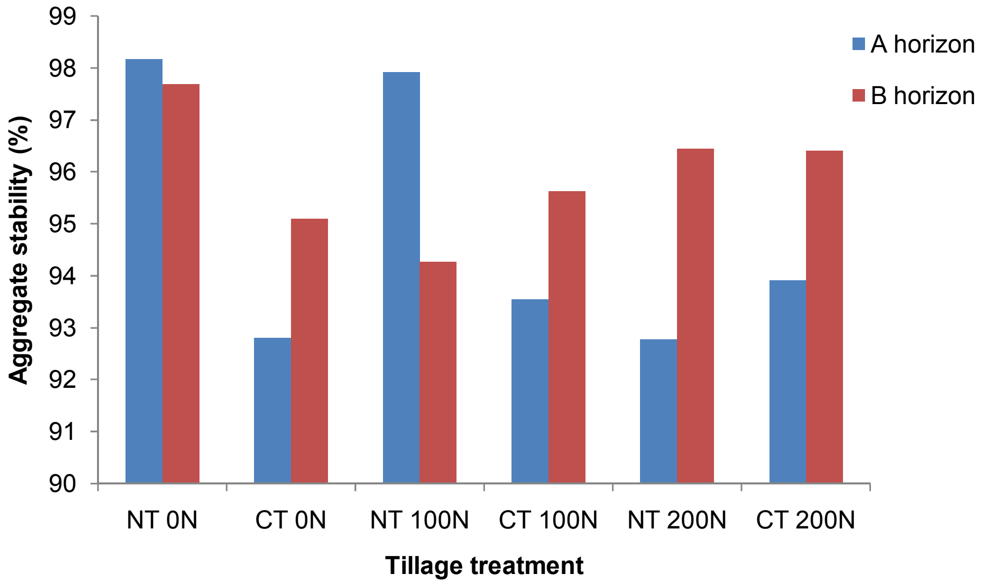

Figure 5.8 The effect of N application rates at 0, 100 and 200 kg ha^{-1} annum^{-1} (0N, 100N and 200N, respectively) averaged across tillage treatments on micro-aggregate stability for the A (0 to 20 cm) and B (20 to 40 cm) horizons (n = 2).

The lower aggregate stability of the 200N treatment may be attributed to the adverse effect of the high fertilizer application rate on soil microorganisms (Section 4.2.2 and 4.2.3). Given that soil microorganisms provide polysaccharides, gels and hyphae which bind soil particles (Bossuyt *et al.*, 2001); a decrease in their activity may lead to a lower production of these binding agents and a subsequent reduction in aggregation.

The similarity in aggregate stability between fertilizer treatments in the B horizon may be a consequence of similar soil microbial activity (Section 4.2.2 and 4.2.3) and similar SOC content (Section 4.2.1) between fertilizer treatments in the B horizon. Under NT the fertilizer remains on the soil surface and thus has minimal influence with increasing soil depth. Under CT the fertilizer is ploughed into the soil and thus although it is likely to influence aggregate stability, its effect is diluted within the plough layer. It is important to note that the aggregate stability for all treatments ranges between approximately 93 and 96 % and therefore, although reasons are given for these slight differences, the difference is negligible in terms of soil management. It is proposed that if aggregate stability had been measured on samples from 0 to 5 or 0 to 10 cm soil depth, as opposed to 0 to 20 cm soil depth used in this study, the difference in aggregate stability would have been more pronounced.

5.2.5 Soil Strength

The penetration resistance, averaged across fertilizer treatments, is greater under NT than under CT1 between a soil depth of 5 and 35 cm (Figure 5.9), indicating greater soil strength at a soil depth of between 0 and 30 cm under NT than under CT1. Below the plough layer the penetration resistance is similar between tillage regimes (Figure 5.9). This corresponds to the results found for ρ_b which showed higher ρ_b in the A horizon (0 to 20 cm) under NT and similar bulk densities between tillage regimes in the B horizon (30 to 40 cm) (Section 5.2.1).

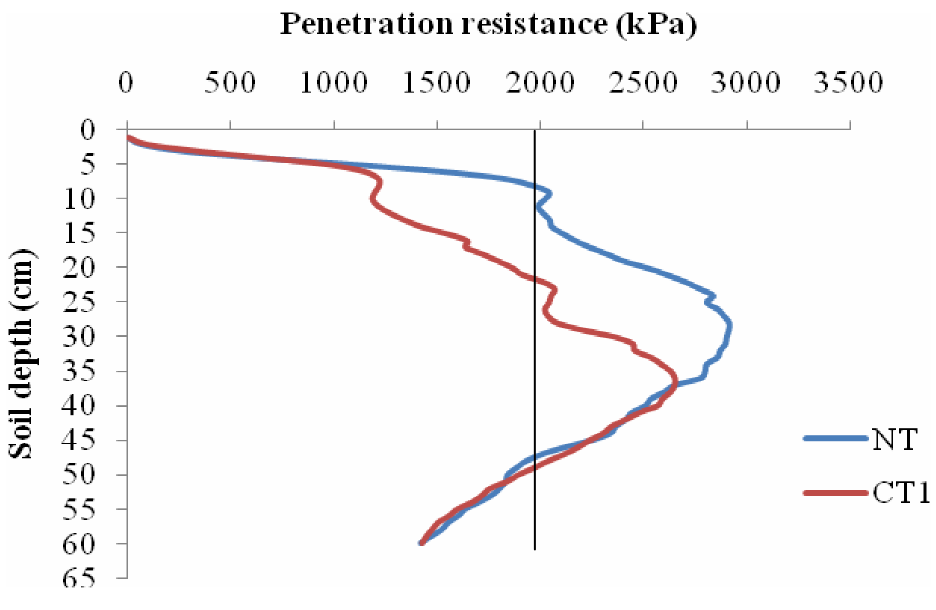

Figure 5.9 The effect of no-till (NT) and annual conventional tillage (CT1) on soil penetration resistance with depth, averaged over N application rate means (n = 9). The line at 2000 kPa represents the accepted soil strength at which root growth is limited (So *et al.*, 2009).

Soil tillage involves the mechanical loosening of the soil, which in the short-term reduces soil strength. However, the build-up of organic matter on the soil surface under NT results in a decrease in penetration resistance as the mulch layer increases the moisture content of the soil surface and the accumulation of residues promotes the development of macroporosity by improving soil structure and enhancing soil biological activity. For this reason, there was a similar penetration resistance in the top 5 cm of the soil surface in both tillage treatments in this study. A comparable study by Osunbitan *et al*. (2005) found that penetration resistance under NT was greater than under CT up to a depth of 30 cm. However, eight weeks after the tillage event the 0 to 5 cm soil layer under NT and CT had similar bulk densities.

The highest penetration resistance under NT and CT1 occurs at a soil depth of approximately 30 to 35 cm (Figure 5.9). As the penetrometer readings were taken from the inter-rows which are not exposed to vehicular traffic the presence of this layer of increased soil strength under both NT and CT1 may be a residual plough pan created before the initiation of this experiment. Cavalieri *et al*. (2009), working in Brazil on a sandy clay, non-expansive soil, found after 14 years of NT the 20 to 30 cm soil depth had an increased ρ_b, lower total porosity and less macroporosity than the 10 to 20 cm and 30 to 40 cm soil depth, indicating the remains of a plough pan created during CT. After conversion from CT to NT soil compaction occurs as a result of natural reconsolidation of poorly structured aggregates with low stability. Biotic activity, shrink and swell due to wet and dry cycles and channels left by decaying plant roots are more prevalent in the surface soil and thus the compaction in the 0 to 10 cm layer is alleviated faster than the compacted layer at the 20 to 30 cm soil depth (Cavalieri *et al*., 2009). Plant roots may be denser and more abundant at approximately 30 cm and thus more water is being extracted from this layer which results in increased soil strength.

Under NT the fertilizer application rate is influencing the soil penetration resistance. The soil penetration resistance for the 0N and 100N treatments are similar up to a depth of approximately 10 cm but lower than the penetration resistance of the 200N treatment. At a soil depth of between 10 and 60 cm the 200N treatment has the greatest penetration resistance, followed by the 100N and then by the 0N treatments (Figure 5.10).

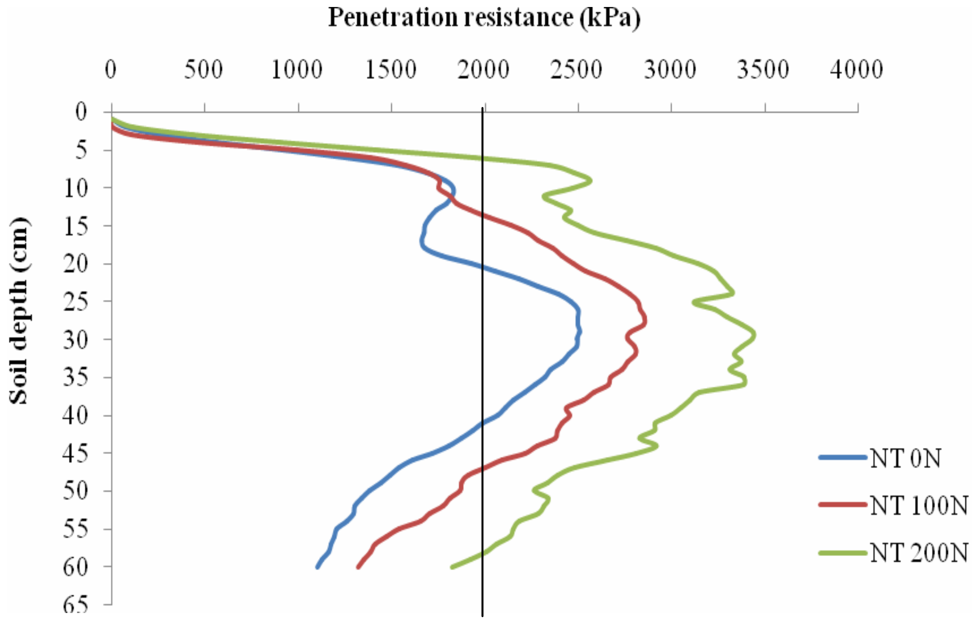

Figure 5.10 The effect of N application at 0, 100 and 200 kg ha^{-1} annum^{-1} (0N, 100N and 200N, respectively) under NT, on soil penetration resistance (n = 3) The line at 2000 kPa represents the accepted soil strength at which root growth is limited (So *et al*., 2009).

The rate of N application to soils is directly related to above ground plant biomass (Appendix 9) and can be correlated with the size of the maize plant. Higher applications of N fertilizer result in bigger plants which will have higher transpiration rates, which will dry the soil. Consequently, soils which receive higher application rates of N are likely to have lower soil moisture contents. This result is similar to Ishaq *et al*. (2002) who found that the penetration resistance of a sandy clay loam soil under reduced tillage was greater in soil which received a high application of NPK fertilizer compared to soil which received a medium and low application. Similarly, Fabrizzi *et al*. (2005) found that 150 kg N ha^{-1} resulted in a significantly higher penetration resistance than 0 kg N ha^{-1}. Fabrizzi *et al*. (2005) attribute higher penetration in the fertilized plot compared to the unfertilized plot to the higher moisture content in the unfertilized plot.

Under CT the penetration resistance for all fertilizer application rates is similar up to a depth of approximately 5 cm. Below 5 cm the penetration resistance is consistently lower at an application rate of 0N compared to the higher application rates. At a soil depth between 5 and 20 cm the 100N treatment has the highest penetration resistance, whereas between 20 and 60 cm the soil which received 200N has the highest penetration resistance (Figure 5.11).

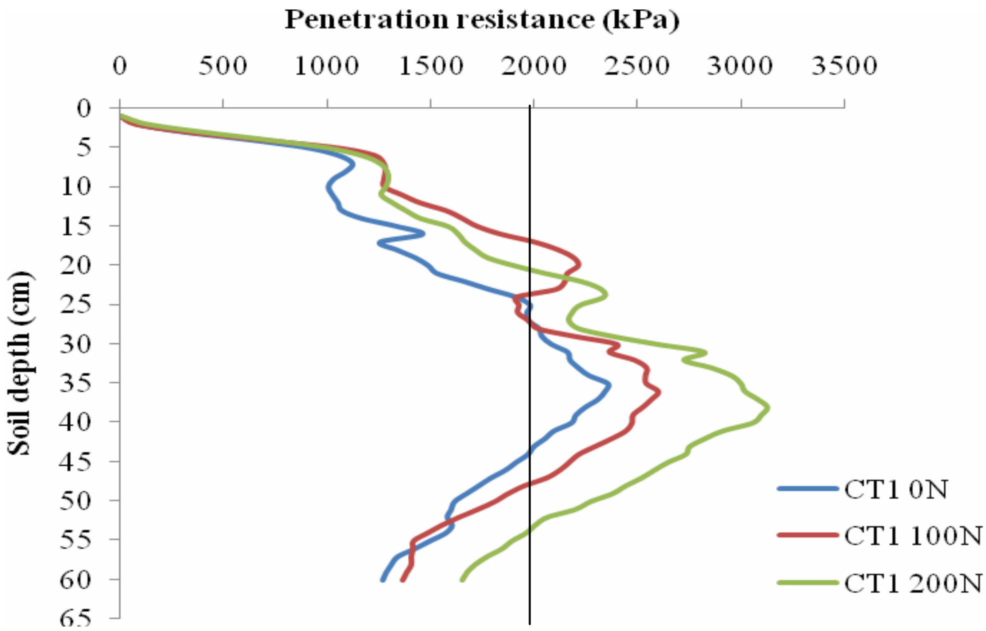

Figure 5.11 The effect of N application at 0, 100 and 200 kg ha^{-1} annum^{-1} (0N, 100N and 200N, respectively) under CT, on soil penetration resistance (n = 3) The line at 2000 kPa represents the accepted soil strength at which root growth is limited (So *et al*., 2009).

Under CT1 the effect of fertilizer on penetration resistance is not as clearly seen as under NT. This result may be due to the disturbance caused by the tillage, especially in the upper layers. At depth, the trend seen for N application rate under NT is similar to that seen under CT1. Under deep tillage, Ishaq *et al*. (2002) also found that the penetration resistance was similar at all fertilizer application rates.

Although the soil strength was found to be above 2000 kPa at most depths under NT and CT1 the maize growth did not show any visual signs of being adversely affected. This may be due to the relationship between penetration resistance and soil moisture content. As the soil dries, the cohesion increases between soil particles and soil strength increases (Materchera and Mloza-Banda, 1996). Thus, the penetration resistance measured at the time of sampling may be higher than what is experienced by the crop for the majority of the growing season if measurements were taken at a drier than usual period.

5.3 Conclusions

Tillage has a considerable impact on the soil physical properties in the upper 20 cm of the soil profile (A horizon). Bulk density is greater under NT than under CT1 which indicates that the porosity created by soil tillage is still greater than NT at the time of sampling. This suggests that after 5 years of annual conventional tillage there is still sufficient SOM to maintain soil structure and structural stability, which allows a lower ρ_b under CT throughout the season or at least up to the time of sampling. Furthermore, the time elapsed between the tillage event and sampling was insufficient to allow for the pores created by the tillage to collapse and result in a higher ρ_b under CT1 than under NT. Higher ρ_b under NT corresponds to the lower saturated water content and K_s under NT compared to CT1. These results also correspond to a greater penetration resistance under NT compared to CT1 at a depth of between 5 and 35 cm. Tillage induced macropores allow more water to be held at saturation. However, PAW is greater under NT than under CT1 due to a higher proportion of micropores and mesopores. A higher percentage of smaller pores under NT is a consequence of increased aggregate stability, which allows for the maintenance of soil structure.

The application of fertilizer also has a considerable effect on the soil physical properties in the upper 20 cm of the soil profile. An application rate of 200 kg N ha^{-1} was found to significantly increase ρ_b and lower the water retention at all matric potentials in the A horizon, especially under NT. Concurrently, there is a trend for lower K_s and aggregate stability for the 200N treatment under both NT and CT1 compared to the lower rates of N fertilization. It was proposed that the accumulation of a high concentration of fertilizer on the soil surface is an irritant to the soil fauna and thus pore formation and aggregate stability is reduced leading to higher ρ_b and an overall reduction in water retention. Under CT1 the negative effect of 200N is less marked as the fertilizer is ploughed into the soil and the concentration is diluted throughout the plough layer.

In the B horizon (20 to 40 cm) the effect of tillage and nitrogen fertilizer on the soil physical properties is reduced. Bulk densities, water retention characteristics and aggregate stability between treatments are similar. Furthermore, the penetration resistance below a soil depth of 35 cm is similar between tillage regimes. Below the plough layer there is less direct structural change caused by tillage implements and the amount of organic matter under NT and CT1 is similar and thus comparable levels of aggregation and biological activity are promoted. Consequently, soil physical properties remain alike regardless of treatment.

The results for penetration resistance indicate a substantial effect of fertilizer application rate on soil strength. Under NT, increasing rates of N application result in increased soil strength throughout the profile. This was attributed to greater plant biomass with increased fertilization leading to great utilization of soil water and consequently penetration resistant increased. The same trend is seen under CT1 from a soil depth of approximately 35 cm. Above 35 cm the soil is disturbed through tillage and the penetration resistance response to fertilizer is disrupted. A further effect of moisture content of the soil on penetration resistance is found under both NT and CT1 at a soil depth of between 30 and 35 cm. The high penetration resistance at this depth is presumed to be a consequence of plant roots at this depth being more abundant and thus utilizing more moisture.

Although soils under CT1 have greater saturated water content, lower ρb and lower soil strength compared to NT soils, the water retention within the plant available range is greater under NT. Furthermore, plant growth under NT does not show any adverse effect to reduced porosity and it is proposed that root growth is not restricted and the soil water and aeration status under NT is satisfactory for crop growth. Therefore, NT is the preferred tillage practice in providing long-term sustainability and soil quality without causing negative soil structural properties for crop productivity in the short-term. In addition, it is recommended that although increased levels of nitrogen fertilizer results in higher yielding maize plants it is unsustainable to apply high applications of LAN due to the negative effect on the soil physical properties.

Chapter 6

General conclusions and recommendations

The results from this study show that five years after the initiation of a tillage trial in the Loskop area of KwaZulu-Natal, South Africa, the effects of NT practices resulted in higher bulk density and penetration resistance and lower saturated water content and saturated hydraulic conductivity. However, greater soil organic carbon content, microbial activity and aggregate stability under NT help maintain soil structure and therefore there is greater moisture retention within the plant available range compared to CT1. These results suggest that although NT may negatively impact some soil physical properties, soil functionality is maintained due to improved structural properties.

The application of N fertilizer was also found to impact on the soil microbiological and physical properties, thus affecting overall soil quality. Although increased application rates of LAN have resulted in a linear growth and yield response of maize, it was found that at 200 kg N ha^{-1} $annum^{-1}$ the microbial activity (as measured by hydrolytic and cellulolytic activity) was negatively affected, especially under NT. In addition, the 200N treatment also resulted in higher bulk densities and penetration resistance and lower saturated water content, saturated hydraulic conductivity and aggregate stability. The negative effect of the 200N treatment on soil microbial and physical properties is more pronounced under NT than under CT1 due to fertilizer being concentrated at the soil surface. It is proposed that the negative effect of high N application rates on microbial activity also implies a general negative effect on other soil biota (most likely earthworms). Consequently, aggregate stability and pore formation are reduced and the soil quality deteriorates. This suggests that in the long-term, applying higher rates of N fertilizer will lead to reduced crop productivity due to degradation of soil quality and thus is unsustainable.

Although soils under CT1 have greater saturated water content and lower bulk density, the water retained within the plant available range (-33 to -1500 kPa) is greater under NT compared to CT1 at 0N and similar at 100N and 200N. Furthermore, plant growth under NT is not adversely affected by reduced porosity and therefore NT is the preferred tillage practice to provide long-term sustainability and soil quality without causing negative soil structural properties for crop productivity in the short-term.

Time and logistical constraints limited intensive sampling and so there may be concerns about the sampling approach used here. As such recommendations for future research are given. Sampling at a higher resolution by taking soil cores and soil bulk samples from smaller depth increments is needed (i.e. 5 cm increments). The build-up of residues on the soil surface under NT means that the beneficial effects of SOM on soil microbiological and physical properties are more pronounced in the surface layers of the soil and by taking samples at smaller depth increments it is possible to assess how deep these beneficial effects are present. It is likely that the sampling at a soil depth of between 0 to 20 and 20 to 40 cm in this study resulted in a dilution effect of measured properties under NT.

Sampling time must also be considered in future research and data collection. Soil microbes and other soil fauna (i.e. earthworms) are sensitive to environmental conditions and are therefore affected by season and time of sampling. Furthermore, sampling directly after ploughing will yield different results to sampling near the end of the growing season. It is suggested that the effect of tillage and fertilizer on soil microbes should be determined in different seasons and that all sampling should be taken near the end of the growing season.

Other measures useful in determining the effect of tillage at different rates of N fertilzation on soil microbiological and physical properties that should be included in further studies is the measurement of earthworm populations and more microbial measurements such as other enzyme activities, microbial biomass nitrogen and carbon, community composition and functional diversity. Measuring *in situ* saturated hydraulic conductivity and unsaturated hydraulic conductivity may also be useful in determing macropore water flow and the water movements through meso and micropores, respectiviely. Including these measurements may further help in understanding the effect of soil agricultural management practices on soil quality, especially where effects may be small or subtle.

In addition to the above recommendations, it is necessary to study the effects of tillage and fertilizer application on soil quality at other locations, under different environmental and soil conditions. The soil in this study is considered a stable soil and thus less stable soils (i.e. a soil with greater shrink/swell capacity) may behave differently under the same soil management practices. Tillage regime and fertilizer application rate have considerable effects on soil quality by impacting on the soil microbial and physical properties and therefore the evaluation of these agricultural management practises is needed to sustain productivity. This study indicates a need to re-evaluate recommended fertilizer rates, especially under NT. In addition, long-term experiments are needed in different locations throughout the farming regions of South Africa to study the site-specific impacts of tillage and fertilizer rates on productivity and environmental quality.

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Appendices

Appendix 1 Particle size analysis using the double pipette method (Gee and Bauder, 1986) on a randomly chosen plot which represents no-till (NT) and annual conventional tillage (CT1) at nitrogen fertilizer rates (applied as limestone ammonium nitrate) of 0, 100 and 200 kg N ha^{-1} (0N, 100N and 200N respectively).

Plot	Treatment	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Very fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)
1A	NT 0N	3	4	18	16	10	10	38
8A	NT 100N	3	3	18	17	8	12	39
10A	NT 200N	3	3	17	17	11	9	39
27A	CT1 0N	1	3	18	20	9	10	39
38A	CT1 100N	1	2	18	20	9	10	40
29A	CT1 200N	1	2	18	18	11	10	40
1B	NT 0N	0	2	18	16	9	12	43
8B	NT 100N	1	3	18	20	6	13	39
10B	NT 200N	1	2	16	21	10	10	40
27B	CT1 0N	1	2	18	20	9	10	41
38B	CT1 100N	1	3	18	18	10	10	42
29B	CT1 200N	1	2	19	18	11	9	39
Average		1	3	18	18	9	10	40
Total		**40**				**20**		**40**

Appendix 2 Selected soil physical and chemical properties of annual conventional tillage (CT1) and no-till (NT) plots at a nitrogen fertilizer application rate (applied as limestone ammonium nitrate) of 0, 100 and 200 kg ha^{-1} (0N, 100N and 200N respectively).

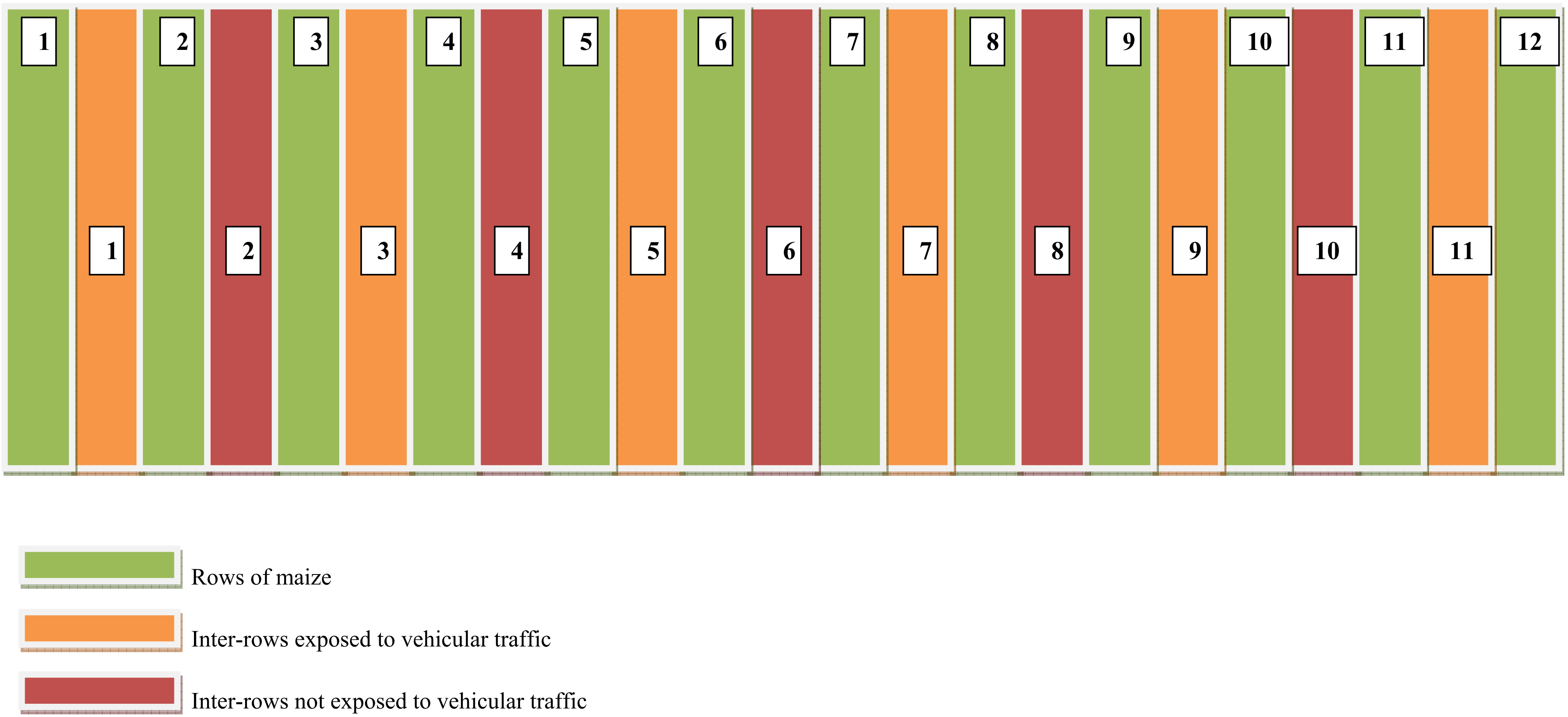
Plot	Rep	Treatment	P (mg kg^{-1})	K (cmolc kg^{-1})	Ca (cmolc kg^{-1})	Mg (cmolc kg^{-1})	Exchangeable acidity (cmol L^{-1})	ECEC	Acid sat. (%)	pH (KCl)	Zn (mg kg^{-1})	Mn (mg kg^{-1})	Cu (mg kg^{-1})	MIR N (%)
1	1	NT 0N	69.80	0.39	2.15	0.51	0.14	10.29	1	5.62	6.54	11.99	3.92	0.19
35	2	NT 0N	115.30	0.35	2.42	0.45	0.02	10.51	0	6.20	11.64	11.30	4.63	0.18
50	3	NT 0N	34.50	0.31	2.46	0.59	0.03	10.54	0	5.58	4.40	9.52	2.14	0.18
8	1	NT 100N	127.70	0.36	2.23	0.57	0.05	10.28	0	6.13	11.19	11.30	4.29	0.19
14	2	NT 100N	57.00	0.35	2.32	0.58	0.06	10.54	1	5.83	6.27	15.96	4.45	0.20
19	3	NT 100N	66.00	0.42	2.27	0.58	0.08	10.85	1	6.00	5.72	15.40	4.18	0.19
10	1	NT 200N	65.90	0.43	2.01	0.52	0.09	9.83	1	5.58	6.80	16.20	3.89	0.20
71	2	NT 200N	64.40	0.30	2.51	0.56	0.03	10.98	0	5.76	7.59	12.65	4.26	0.18
77	3	NT 200N	66.70	0.39	2.19	0.51	0.02	9.77	0	5.51	7.02	12.65	3.11	0.17
27	1	CT1 0N	19.60	0.37	2.00	0.48	0.08	9.02	1	5.56	3.22	11.50	4.26	0.13
56	2	CT1 0N	20.40	0.53	2.02	0.45	0.04	8.70	0	5.23	4.44	24.00	5.28	0.17
76	3	CT1 0N	20.40	0.42	2.00	0.52	0.03	8.77	0	5.43	3.24	12.00	4.08	0.15
13	1	CT1 100N	24.20	0.43	1.87	0.51	0.10	8.75	1	5.35	3.91	20.70	4.37	0.14
38	2	CT1 100N	18.90	0.49	2.07	0.44	0.05	8.96	0	5.59	3.30	18.88	4.96	0.16
45	3	CT1 100N	18.70	0.28	1.97	0.46	0.04	8.59	0	5.38	3.28	18.72	5.15	0.14
29	1	CT1 200N	19.60	0.44	1.97	0.49	0.09	9.03	1	5.54	3.22	17.25	4.37	0.15
40	2	CT1 200N	25.80	0.35	1.94	0.43	0.06	8.04	1	5.30	5.17	17.22	5.17	0.14
63	3	CT1 200N	20.10	0.27	1.84	0.47	0.05	8.10	1	5.17	3.19	16.52	4.72	0.15

*Analysis done by the Soil Fertility and Analytical Services Division (Department of Agriculture, Cedara)

Appendix 3 Field trial layout. Tillage regime (i.e. no-till (NT), annual conventional tillage (CT1), and conventional tillage every five years (CT5)) form whole plots with three replicates. Nitrogen fertilizer source (i.e. urea and limestone ammonium nitrate (LAN)) and rate of nitrogen application (i.e. 0, 50, 100,150 and 200 kg N ha^{-1} $annum^{-1}$ (0N, 50N, 100N, 150N and 200N respectively) form random subplots within the whole plots. Coloured blocks represent sampled treatments.

Rep 1			Rep 2			Rep 3		
NT	CT1	CT5	CT1	NT	CT5	CT5	NT	CT1
50 UREA 73	50 UREA 74	200 LAN 75	0 N 76	200 LAN 77	150 UREA 78	150 UREA 79	200 UREA 80	50 LAN 81
100 UREA 64	150 UREA 65	50 UREA 66	150 UREA 67	200 UREA 68	0 N 69	150 LAN 70	200 LAN 71	50 UREA 72
150 LAN 55	0 N 56	200 UREA 57	100 UREA 58	50 LAN 59	100 LAN 60	200 LAN 61	50 LAN 62	200 LAN 63
50 LAN 46	100 UREA 47	50 LAN 48	50 LAN 49	0 N 50	200 LAN 51	50 LAN 52	50 UREA 53	200 UREA 54
200 UREA 37	100 LAN 38	100 LAN 39	200 LAN 40	150 LAN 41	100 UREA 42	100 LAN 43	100 UREA 44	100 LAN 45
150 UREA 28	200 LAN 29	150 UREA 30	50 UREA 31	100 UREA 32	150 LAN 33	50 UREA 34	0 N 35	150 LAN 36
100 LAN 19	200 UREA 20	150 LAN 21	200 UREA 22	150 UREA 23	50 UREA 24	100 UREA 25	150 LAN 26	0 N 27
200 LAN 10	50 LAN 11	100 UREA 12	100 LAN 13	100 LAN 14	200 UREA 15	200 UREA 16	150 UREA 17	100 UREA 18
0 N 1	150 LAN 2	0 N 3	150 LAN 4	50 UREA 5	50 LAN 6	0 N 7	100 LAN 8	150 UREA 9

Appendix 4 Layout of maize rows and inter-rows exposed to vehicular traffic and inter-rows not exposed to vehicular traffic.



Appendix 5 Analysis of variance tables for soil organic carbon (%) from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no-till and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

a)

Source of variation	**df**	**SS**	**MS**	**VR**	**F Probability**
Block (replicate)	5	1.79	0.36	1.56	
Tillage	1	24.31	24.31	105.52	< 0.001
Residual	5	1.15	0.23	3.84	
Fertilizer	2	3.04	1.52	25.32	< 0.001
Tillage.Fertilizer	2	3.30	1.65	27.49	< 0.001
Residual	14	0.84	0.06		
Total	29	16.91			
Coefficient of variation (%)	10.9				

b)

Source of variation	**df**	**SS**	**MS**	**VR**	**F Probability**
Block (replicate)	5	0.84	0.17	1.51	
Tillage	1	0.56	0.56	5.00	0.076
Residual	5	0.56	0.11	0.19	
Fertilizer	2	1.83	0.92	1.54	0.261
Tillage.Fertilizer	2	1.97	0.98	1.65	0.240
Residual	10	5.95	0.59		
Total	25	10.46			
Coefficient of variation (%)	16.9				

df degrees of freedom .
SS sum of squares.
MS mean sum of squares.
VR variance ratio.

Appendix 6 Comparisons by least significant difference (LSD) at the 5 % level of significance for the **a)** tillage by fertilizer application rate on soil organic carbon in the A horizon **b)** fertilizer application rate on soil organic carbon in the A horizon **c)** fertilizer application rate on soil bulk density in the A horizon **d)** fertilizer application rate on the soil moisture retention at 0 kPa in the A horizon **e)** fertilizer application rate on the soil moisture retention at -33 kPa in the A horizon **f)** tillage by fertilizer application rate on soil moisture retention at 0 kPa in the A horizon **g)** tillage by fertilizer application rate on soil moisture retention at -33 kPa in the A horizon **h)** tillage by fertilizer application rate on saturated hydraulic conductivity in the B horizon.

a)

$P < 0.001$, LSD = 0.4366

Treatment	Tillage by fertilizer mean for average organic carbon content (%) in the A horizon	
NT 0N	3.868	a
NT 100N	2.706	b
NT 200N	2.606	b
CT 100N	1.621	c
CT 0N	1.383	c
CT 200N	1.246	c

b)

P = < 0.001, LSD = 0.2145

Fertilizer application rate	Fertilizer mean averaged across tillage regimes for average organic carbon content (%) in the A horizon	
0N	2.626	a
100N	2.163	b
200N	1.926	c

c)

P = < 0.001, LSD = 0.0503

Fertilizer application rate	Fertilizer mean averaged across tillage regimes for bulk density (g cm^{-3}) in the A horizon	
200N	1.455	a
0N	1.368	a
100N	1.344	b

d)

P = < 0.001, LSD = 0.02294

Fertilizer application rate	Fertilizer mean averaged across tillage regimes for soil moisture content at 0 kPa (m^3 m^{-3}) in the A horizon	
100N	0.5018	a
0N	0.4871	a
200N	0.4410	b

e)

P = < 0.001, LSD = 0.02235

Fertilizer application rate	Fertilizer mean averaged across tillage regimes for soil moisture content at -33 kPa (m^3 m^{-3}) in the A horizon	
100N	0.2782	a
0N	0.2589	a
200N	0.2223	b

f)

P = 0.009, LSD = 0.03734

Treatment	Tillage by fertilizer mean for soil moisture content at 0 kPa (m^3 m^{-3}) in the A horizon	
CT 100N	0.5175	a
CT 0N	0.4946	ab
NT 100N	0.4861	ab
CT 200N	0.4843	ab
NT 0N	0.4795	b
NT 200N	0.3977	c

g)

P = 0.009, LSD = 0.03564

Treatment	Tillage by fertilizer mean for soil moisture content at -33 kPa (m^3 m^{-3}) in the A horizon	
NT 0N	0.2988	a
NT 100N	0.2963	a
CT 100N	0.2602	b
CT 200N	0.2305	bc
CT 0N	0.2190	c
NT 200N	0.2141	c

h)

P = 0.028, LSD = 104.1

Treatment	Tillage by fertilizer mean for saturated hydraulic conductivity (mm hr^{-1}) in the B horizon	
CT 0N	271	a
CT 100N	141	b
CT 200N	138	b
NT 100N	118	b
NT 200N	77	b
NT 0N	44	b

Appendix 7 Analysis of variance tables for soil microbial activity as measured by hydrolytic activity (fluorescein diacetate analysis (FDA)) from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no tillage and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

(a)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	2	0.02	0.01	2.57	
Tillage	1	2.52	2.52	594.97	0.002
Residual	2	0.01	0.00	0.05	
Fertilizer	2	0.14	0.07	0.85	0.474
Tillage.Fertilizer	2	0.20	0.10	1.18	0.369
Residual	6	0.50	0.08		
Total	15	3.03			
Coefficient of variation (%)	4.6				

(b)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	2	40.60	20.3	0.67	
Tillage	1	30.54	30.54	1.01	0.420
Residual	2	60.35	30.17	1.95	
Fertilizer	2	11.33	5.66	0.37	0.707
Tillage.Fertilizer	2	5.47	2.73	0.18	0.842
Residual	7	108.57	15.51		
Total	16	254.60			
Coefficient of variation (%)	17.4				

df degrees of freedom.
SS sum of squares.
MS mean sum of squares.
VR variance ratio.

Appendix 8 Correlation matrix of selected soil physical and microbial properties.

	Air dried moisture content (%)	**Field moisture content (%)**	**Hydrolytic activity (µg fluorescein g^{-1} h^{-1})**	**Cellulolytic activity (% cellulose degraded over 10 days)**	**Bulk density (g cm^{-3})**	**Organic carbon (%)**	**K_s (mm hr^{-1})**	**Moisture content at 0 Kpa (m^3 m^{-3})**	**Moisture content at -33 kPa (m^3 m^{-3})**	**Moisture content at 1500 kPa (m^3 m^{-3})**
Air dried moisture content (%)	1									
Field moisture content (%)	0.137	1								
Hydrolytic activity (µg fluorescein g^{-1} h^{-1})	0.058	0.182	1							
Cellulolytic activity (% cellulose degraded over 10 days)	-0.074	-0.159	0.1	1						
Bulk density (g cm^{-3})	0.077	-0.173	0.101	-0.416	1					
Organic carbon (%)	0.348	-0.026	0.499	0.546	-0.083	1				
K_s (mm hr^{-1})	-0.068	0.249	-0.044	0.394	-0.66	0.147	1			
Moisture content at 0 Kpa (m^3 m^{-3})	-0.075	0.175	-0.101	0.39	-0.917	0.042	0.571	1		
Moisture content at -33 kPa (m^3 m^{-3})	-0.155	-0.073	0.173	0.147	-0.3	0.252	-0.075	0.501	1	
Moisture content at -1500 kPa (m^3 m^{-3})	-0.141	-0.129	0.304	0.459	-0.148	0.208	0.15	0.226	0.504	1

Appendix 9 Total above-ground biomass of maize under a nitrogen fertilizer application rate (applied as limestone ammonium nitrate) of 0, 100 and 200 kg N ha^{-1} $annum^{-1}$ for both no-till (NT) and conventional tillage (CT).

Plot no.	Tillage	Nitrogen (kg ha^{-1} $annum^{-1}$)	Yield (tons ha^{-1})
1	NT	0	5.35
50	NT	0	4.05
35	NT	0	4.60
Average	NT	0	**4.67**
19	NT	100	9.40
14	NT	100	8.30
8	NT	100	9.70
Average			**9.13**
10	NT	200	9.60
77	NT	200	11.60
71	NT	200	10.00
Average			**10.40**
56	CT	0	6.55
76	CT	0	6.20
27	CT	0	4.55
Average			**5.77**
38	CT	100	9.65
13	CT	100	8.05
45	CT	100	8.05
Average			**8.58**
29	CT	200	9.15
40	CT	200	9.60
63	CT	200	8.80
Average			**9.18**

*Analysis done by the Soil Fertility and Analytical Services Division (Department of Agriculture, Cedara)

Appendix 10 Analysis of variance tables for soil microbial activity as measured by cellulolytic activity from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no tillage and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

(a)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	2	236.46	118.23	8.12	
Tillage	1	0.31	0.31	0.02	0.897
Residual	2	29.10	14.55	0.19	
Fertilizer	2	638.70	319.35	4.25	0.071
Tillage.Fertlizer	2	274.48	137.24	1.83	0.240
Residual	6	450.35	75.06		
Total	15	1497.86			
Coefficient of variation (%)	17.0				

(b)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	2	165.03	82.51	6.31	
Tillage	1	182.45	182.45	13.96	0.065
Residual	2	26.14	13.07	0.85	
Fertilizer	2	3.46	1.73	0.11	0.896
Tillage.Fertlizer	2	333.57	166.78	10.80	0.007
Residual	7	108.06	15.44		
Total	16	818.70			
Coefficient of variation (%)	19.9				

df degrees of freedom .
SS sum of squares.
MS mean sum of squares.
VR variance ratio.

Appendix 11 Analysis of variance tables for soil bulk density from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no tillage and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

(a)

Source of variation	**df**	**SS**	**MS**	**VR**	**F Probability**
Block (replicate)	8	0.05	0.01	0.61	
Tillage	1	0.09	0.09	9.40	0.015
Residual	8	0.08	0.01	1.82	
Fertilizer	2	0.12	0.06	11.19	< 0.001
Tillage.Fertlizer	2	0.03	0.02	2.77	0.079
Residual	29	0.16	0.01		
Total	50	0.52			
Coefficient of variation (%)	2.3				

(b)

Source of variation	**df**	**SS**	**MS**	**VR**	**F Probability**
Block (replicate)	5	0.02	0.00	0.90	
Tillage	1	0.01	0.01	1.73	0.246
Residual	5	0.02	0.00	0.63	
Fertilizer	2	0.01	0.00	0.52	0.604
Tillage.Fertlizer	2	0.02	0.01	1.89	0.178
Residual	19	0.12	0.01		
Total	34	0.19			
Coefficient of variation (%)	1.6				

df degrees of freedom.
SS sum of squares.
MS mean sum of squares.
VR variance ratio.

Appendix 12 Analysis of variance tables for soil moisture retention at 0 kPa from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no tillage and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

(a)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	8	0.02	0.00	1.07	
Tillage	1	0.03	0.03	12.15	0.008
Residual	8	0.02	0.00	1.93	
Fertilizer	2	0.04	0.02	15.99	< 0.001
Tillage.Fertilizer	2	0.01	0.01	5.57	0.009
Residual	29	0.03	0.00	29.00	
Total	50	0.14			
Coefficient of variation (%)	4.1				

(b)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	5	0.01	0.00	1.57	
Tillage	1	0.01	0.01	5.66	0.063
Residual	5	0.01	0.00	0.87	
Fertilizer	2	0.01	0.00	1.88	0.180
Tillage.Fertlizer	2	0.00	0.00	1.21	0.321
Residual	19	0.03	0.00		
Total	34	0.06			
Coefficient of variation (%)	4.0				

df degrees of freedom.

SS sum of squares.

MS mean sum of squares.

VR variance ratio.

Appendix 13 Analysis of variance tables for soil moisture retention at -33 kPa from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no tillage and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

(a)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	8	0.01	0.00	0.37	
Tillage	1	0.01	0.01	7.68	0.024
Residual	8	0.02	0.00	1.82	
Fertilizer	2	0.03	0.01	13.70	< 0.001
Tillage.Fertlizer	2	0.02	0.01	9.87	< 0.001
Residual	25	0.03	0.00		
Total	46	0.11			
Coefficient of variation (%)	4.3				

(b)

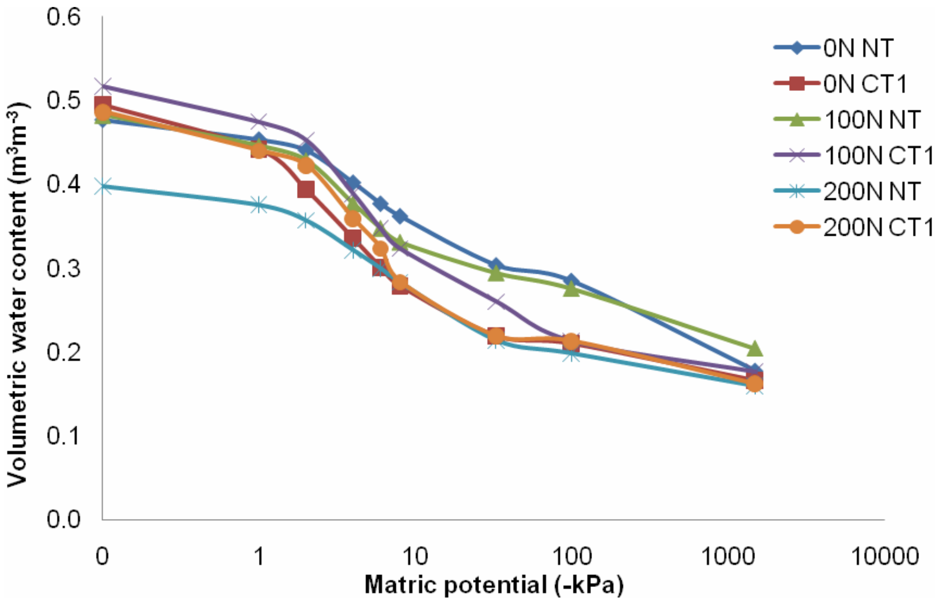
Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	5	0.00	0.00	2.79	
Tillage	1	0.00	0.00	8.54	0.033
Residual	5	0.00	0.00	0.24	
Fertilizer	2	0.00	0.00	3.99	0.036
Tillage.Fertlizer	2	0.00	0.00	1.41	0.268
Residual	19	0.01	0.00		
Total	34	0.22			
Coefficient of variation (%)	3.2				

df degrees of freedom. **SS** sum of squares.

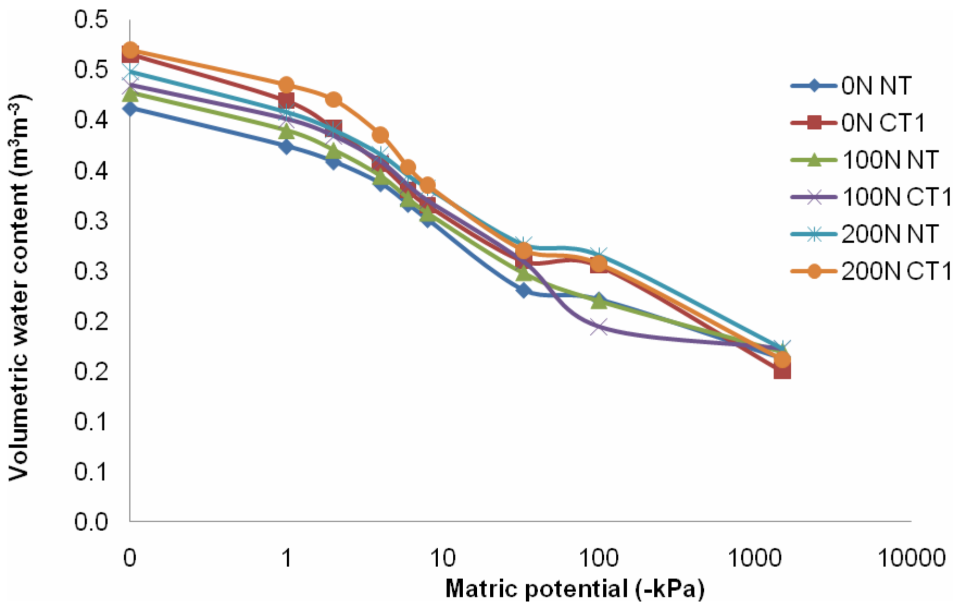
MS mean sum of squares. **VR** variance ratio.

Appendix 14 Effect of no-till (NT) and annual conventional tillage (CT1) at nitrogen application rates (applied as limestone ammonium nitrate) of 0, 100 and 200 kg ha^{-1} annum^{-1} (0N, 100N and 200N, respectively) on the water retention curves for a) A horizon and b) B horizon (n = 6).

a)



b)



Appendix 15 Analysis of variance tables for soil moisture retention at -1500 kPa from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no tillage and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

(a)

Source of variation	**df**	**SS**	**MS**	**VR**	**F Probability**
Block (replicate)	8	0.002	0.000	0.730	
Tillage	1	0.001	0.001	3.730	0.089
Residual	8	0.003	0.000	2.350	
Fertilizer	2	0.009	0.005	29.620	< 0.001
Tillage.Fertilizer	2	0.003	0.001	8.190	0.002
Residual	23	0.004	0.000		
Total	44	0.017			
Coefficient of variation (%)	3.8				

(b)

Source of variation	**df**	**SS**	**MS**	**VR**	**F Probability**
Block (replicate)	5	0.002	0.000	2.290	
Tillage	1	0.000	0.000	0.480	0.518
Residual	5	0.001	0.000	0.870	
Fertilizer	2	0.001	0.001	3.880	0.05
Tillage.Fertlizer	2	0.001	0.000	1.500	0.263
Residual	12	0.002	0.000		
Total	27	0.006			
Coefficient of variation (%)	4.7				

df degrees of freedom. **SS** sum of squares.

MS mean sum of squares. **VR** variance ratio.

Appendix 16 Analysis of variance tables for saturated hydraulic conductivity from the (a) A horizon (0 to 20 cm), (b) B horizon (20 to 40 cm) in a Hutton soil under either annual conventional tillage or no tillage and treated with nitrogen fertilizer (applied as limestone ammonium nitrate) at rates of 0, 100 and 200 kg N ha^{-1}.

(a)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	8	229564	28695	1.24	
Tillage	1	456154	456154	19.76	0.002
Residual	8	184686	23086	0.85	
Fertilizer	2	162387	81193	2.99	0.066
Tillage.Fertilizer	2	8175	4087	0.15	0.861
Residual	30	815636	27188		
Total	51	0.18			
Coefficient of variation (%)	25.5				

(b)

Source of variation	df	SS	MS	VR	F Probability
Block (replicate)	5	15880	3176	0.51	
Tillage	1	95997	95997	15.27	0.011
Residual	5	31432	6286	0.76	
Fertilizer	2	14975	7487	0.90	0.422
Tillage.Fertlizer	2	71453	35727	4.30	0.028
Residual	20	166342	8317		
Total	35	166342			
Coefficient of variation (%)	17.5				

df degrees of freedom.

SS sum of squares.

MS mean sum of squares.

VR variance ratio.