The effect of long-term tillage practices on selected soil properties in the Swartland wheat production area of the Western Cape

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Dissertation presented for the degree of
Master of Soil Science in the Faculty of AgriSciences at Stellenbosch University

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March 2013

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ABSTRACT

The effect of long-term tillage on basic soil properties with respect to sustainability was investigated in this dissertation. Over the last three decades soil conservation has become an important prerequisite for sustainable agriculture. The primary aim of this study was to evaluate the effect of different tillage practices on the physical and some of the chemical properties of soil after 37 years of continuous application.

This study was conducted on the Langgewens experimental farm, 18 km north of Malmesbury in the Western Cape. The experiment was initiated in 1975 on a Glenrosa (Haploxeralf) soil form with a gravelly sandy-loam texture. It was treated with four main tillage methods, namely conventional, tine, minimum and no-tillage. Important basic soil properties studied were the electrical conductivity (EC) and total carbon percentage, water stable aggregate percentage, bulk density and hydraulic conductivity. Most of the properties were analysed for the 0-100 mm and 100-200 mm depths. Seasonal bulk density variation for the 0-100 mm soil depth was determined by a Troxler surface gamma-neutron meter for in situ measurement. ANOVA's and Tukey's LSD posthoc tests were computed to assess whether significant statistical differences existed between tillage treatments.

No-tillage proved to be beneficial in terms of salinity and had the lowest electrical conductivity, indicating that salts leeched out of the profile. Total carbon content was in general very low and in the 0-100 mm soil depth it decreased in the order of: no (0.92%), minimum (0.86%), tine (0.83%) and conventional tillage (0.51%). Aggregate stability was significantly the lowest under conventional (47.82%) and tine tillage (45.02%) compared to minimum (61.43%) and no-tillage (78.40%) at 0-100 mm depth. This can be explained by the relatively low amount of total carbon in the soil combined with the tillage intensity. The same trend was observed for the 100-200 mm depth. Significant correlation between total carbon content and aggregate stability for the 0-100 mm confirmed that an increase in total carbon in the soil would lead to an increase in aggregate stability. Significant, increased aggregate stability under the no-tillage treatment would therefore indicate that there may be some stable structure present in the soil. Seasonal bulk density variation was the lowest

in no-tillage, which supports the manifestations of stable soil structure. More intensive tillage treatments such as conventional and tine tillage initially showed lower bulk densities, but only for the first month. Thereafter it increased to significantly higher values as the season progressed. This was mainly as a result of hardsetting of the soil which is driven by natural processes and rainfall. It is also due to the sandy loam texture that is particularly prone to compaction. Hydraulic conductivity studied for conventional and no-tillage showed significant differences. No-tillage (41 $mm.h^{-1}$) showed a noticeably higher conductivity, which remained constant compared to conventional tillage (20 $mm.h^{-1}$) that decreased over time. The main reasons for this increased hydraulic conductivity under no-tillage was higher water stable aggregates and lower bulk density.

In the long term no-tillage thus stimulated structure formation of a Glenrosa soil form that significantly improved soil properties studied. These properties may influence processes such as water infiltration, water storage, run-off and drainage positively, due to soil property interaction. No-tillage, in terms of sustainability, quantified by the soil properties studied, thus proved to be superior compared to conventional and tine tillage but to a lesser extent if compared to minimum tillage.

OPSOMMING

In hierdie tesis word die effek van langtermynbewerking op basiese grondeienskappe met betrekking tot volhoubaarheid ondersoek. Oor die afgelope drie dekades het grondbewaring 'n belangrike aspek in landbou geword, ten einde volhoubaarheid te verseker. Die primêre doel van hierdie studie was om die effek van verskillende bewerkingspraktyke op die fisiese en chemiese eienskappe van grond na 37 jaar van deurlopende bewerking te ondersoek.

Die studie is uitgevoer op die Langgewens eksperimentele plaas, 18 km noord van Malmesbury in die Wes-Kaap. Die eksperiment is in 1975 geïnisieer op 'n Glenrosa (Haploxeralf) grondvorm met 'n klipperige sandleem-tekstuur. Dit bestaan uit vier hoof-bewerkingsbehandelings, naamlik konvensionele, tand-, minimum en geenbewerking. Belangrike basiese grondeienskappe wat bestudeer is, is die elektriese geleidingsvermoë (EG) en die totale persentasie koolstof, persentasie waterstabiele aggregate, bulkdigtheid en hidrouliese geleiding. Die meeste van die eienskappe is ontleed op die 0-100 mm en 100-200 mm diepte. Seisoenale bulkdigtheidsvariasie vir die 0-100 mm gronddiepte is bepaal deur 'n Troxler oppervlak gamma-neutron meter deur middel van in situ meting. ANOVA en Tukey se LSD posthoc-toetse is bereken om te bepaal of daar statisties-beduidende verskille tussen die bewerkingsmetodes is.

Geenbewerking het geblyk voordelig te wees in terme van die soutgehalte en het die laagste elektriese geleidingsvermoë gehad, wat daarop dui dat die soute uit die profiel loog. Die totale koolstofinhoud was oor die algemeen baie laag en in die 0-100 mm gronddiepte het dit afgeneem in die volgorde geen- (0.92%), minimum- (0.86%), tand- (0.83%) en konvensionele bewerking (0.51%). Aggregaatstabiliteit was betekenisvol die laagste onder konvensionele (47.82%) en tandbewerking (45.02%) in vergelyking met die minimum (61.43%) en geenbewerking (78.40%) by die 0-100 mm diepte en kan verduidelik word deur die relatief lae totale koolstofinhoud in die grond gekombineer met die bewerkings-intensiteit. Dieselfde tendens is waargeneem vir die 100-200 mm diepte. 'n Beduidende korrelasie tussen totale koolstofinhoud en aggregaatstabiliteit is vir die 0-100 mm diepte gevind en dit bevestig dat 'n toename in totale koolstof in die grond sal lei tot 'n toename in

aggregaatstabiliteit. Betekenisvolle verhoogde aggregaatstabiliteit onder die geenbewerking-behandeling sal dus aandui dat die grond 'n meer stabiele struktuur vertoon. Seisoenale bulkdigtsheidsvariasie was die laagste in geenbewerking en ondersteun die manifestasies van 'n stabiele grondstruktuur. Meer intensiewe bewerkingsbehandelings, konvensionele en tandbewerking het vir die eerste maand ‘n laer bulkdigtheid getoon, waarna dit tot aansienlik hoër waardes gestyg het soos die seisoen verloop het. Dit was hoofsaaklik as gevolg van grondkonsolidering wat gedryf word deur natuurlike prosesse soos reënval en ook as gevolg van die sandleemtekstuur wat veral geneig is tot verdigting. Hidrouliese geleiding is bestudeer vir konvensionele en geenbewerking en het beduidende verskille getoon. Geenbewerking (41 $mm.h^{-1}$) het 'n merkbare hoër geleidingsvermoë gehad wat konstant gebly het, in vergelyking met konvensionele bewerking (20 $mm.h^{-1}$) wat met die verloop van tyd afgeneem het. Die vernaamste redes vir hierdie verhoogde hidrouliese geleiding onder geenbewerking is hoër waterstabiele aggregate en ‘n laer bulkdigtheid.

Op die langtermyn het geenbewerking dus struktuurvorming van 'n Glenrosa-grondvorm gestimuleer, wat die grondeienskappe wat bestudeer is, aansienlik verbeter het. Hierdie eienskappe kan prosesse soos waterinfiltrasie, waterretensie, -afloop en -dreinering positief beïnvloed as gevolg van grondeienskapinteraksie. Geenbewerking, in terme van volhoubaarheid, gekwantifiseer deur die grondeienskappe wat bestudeer is, is dus bewys as superieur in vergelyking met konvensionele en tandbewerking, maar tot 'n mindere mate in vergelyking met minimumbewerking.

ACKNOWLEDGEMENTS

The Lord is my light and my salvation

Psalm 27:1

- To the Lord God Almighty, for giving me the strength and determination through my studies, making it such a pleasure to complete this project, also for his blessing on all the experiments, field tips and writing up of the thesis.
- To my father and mother supporting me each day and also giving me the opportunity to study at the University.
- My study leader, **Dr de Clercq**, for your inspiration and guidance for the last two years. You always pointed me in the right direction, although still allowing me to follow my own ideas.
- To all my **fellow students** from 2011, 2012 in the Soil Science department. I will always remember the good times we had, academic or not!
- To all the department lecturers, **Dr Ellis**, **Prof Jan Lambrechts, Dr Hardie, Dr Hoffman** and **Dr Rozanov** for all the additional inputs and education at the Department of Soil Science.
- To the people keeping the department up and running, also helping and assisting where they can. Thank you **Nigel**, **Tannie Annetjie** and **Delphine.**
- To family and friends who always had the time for my passion and excitement over soil and its management.
- To the Water Research Commission for funding of the project.
- To ACCESS for additional funding.

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CHAPTER 1: INTRODUCTION

1.1 Background

This study focuses on soil tillage and its effects on basic soil properties. Soil tillage plays a vital role in the production of cereal crops. A tillage practice has mainly four objectives: to create a favourable environment for seed germination and growth, to break physical soil barriers like a hardpan, to incorporate fertilizer and to control weeds (Gajri *et al*., 2002). Over the last three decades, an additional objective has emerged, known as soil conservation. Soil conservation has become an important aspect in agriculture and is a new objective that must be achieved in order to enhance agricultural sustainability. The reason for soil conservation is to prevent soil from degrading and becoming unproductive. Due to poor soil management and extensive tillage, about 1.2 billion hectares of productive soil in the world have degraded to such an extent that it cannot be reclaimed (Smit, 2002). An additional reason for soil conservation is to minimize input costs (fuel, fertilizer, soil preparation) and to help sustain natural resources. Soil can be regarded as a natural resource and must be utilized efficiently to make agriculture more sustainable.

A soil's long-term physical, chemical and biological properties can be measured to determine the sustainability of specific agricultural practices such as soil tillage. Soil physical properties are the most important of the three fundamental soil properties. In most cases the chemical and biological properties will also improve if the physical properties have improved. A good example is that if soil drainage improves, more effective leaching of salt will occur and the soil will become less saline and thus with less free water and a lower salinity index (chemical property). Biological properties will then also improve. Managing soil's physical properties is an important part of soil conservation because physical properties cannot be created and manipulated in the short term. For example to create a well-structured soil from an apedal structure would take millions of years at the right climatic and soil conditions, although breaking down of soil structure may be possible in a few years' time through extensive tillage. It would therefore be impossible to reverse the effect of ploughing. The soil's main physical properties directly affects bulk density, aggregate stability and porosity, and properties like for instance water movement and water storage. These properties in turn affect root growth and biological activity. These factors all relate to sustainability as well as soil productivity.

The influence of soil tillage on the soil properties, especially the soil physical properties, can be described as tillage effects or responses. These tillage effects can be positive or negative for soil conservation depending on the type of tillage and management strategy, the type of soil and the climatic conditions. In order to promote sustainability, tillage effects or responses must be optimized to improve the soil properties and the soil's productivity.

Presently four main tillage practices are used in the Western Cape: conventional , tine, no-tillage (Agenbag, 1987) and relative new, minimum tillage. These four tillage practices can be described in terms of the intensity of disturbing the soil and the amount of residue left on the soil surface after the tillage operation. Mouldboard tillage, which is the secondary tillage operation (after tine tillage) of the conventional tillage practice, has a high intensity and no-tillage a low intensity. Mouldboard tillage involves the tilling and mixing of soil. Common problems that arise from conventional tillage in stony, Mediterranean soils are low organic matter content and poor water infiltration and a higher susceptibility to erosion. Therefore soil degradation is high (Agenbag and Maree, 1991; Hernanz *et al*., 2002). Tine and minimum tillage are in between conventional and no-tillage relative to intensity and the amount of residue left on the field after planting and generally used where soil compaction is a problem. Minimum and no-tillage are conservation tillage methods which focus on less soil disturbance and leave more organic material on the soil surface, in other words improving the soil organic matter content. The majority of farmers in semi-arid and Mediterranean climates are thus moving from conventional tillage to minimum or no-tillage. The main reason is to enhance sustainability not only for the environment but also for the farmer, because minimum and no-tillage have less input costs.

Extensive research has been conducted on soil tillage in the last four decades, especially in America and Europe. Most of this research states that no-tillage is a proven sustainable tillage practice in the semi-arid and Mediterranean climates that improves the soil organic matter content, soil water infiltration and water storage capacity (Agenbag and Maree, 1991; Hernanz *et al*., 2002; Bescansa *et al*., 2006; Moussa-Machraoui *et al*., 2010). Although very little documented physical research has recently been conducted on soil in South

Africa's Mediterranean climate, many farmers consider no-tillage as the new norm for crop production in the Western Cape. Insufficient research, however, is still a problem. Long-term tillage research is especially needed in the Western Cape.

1.2 Previous research

In the preliminary literature study, research on the effect of different tillage practices on soil properties are seldom longer than 15 years. The first and only internationally published tillage research conducted in the Western Cape was from 1978 to 1991 by G.A. Agenbag and P.C.J. Maree. Their main focus was from an agronomist's point of view and not from a soil scientist's point of view. They looked specifically at yield-limiting soil factors. Various research studies was also conducted in the other climates of South Africa that also focused on the effect of tillage on soil properties (Agenbag and Stander, 1988; Du Toit *et al*., 1993; Du Preez *et al*., 2001) but not all of these studies can be related directly to the Mediterranean climate. In the summer rainfall region of South Africa water is stored in the soil during the fallow period in summer when it rains and the crop is grown in the winter after the rainfall season whereas in the winter rainfall region of South Africa the crop is planted just before the winter and thus grown in the rain season. This is one of the main reasons why cereal crops can be grown in the shallow soils of the Western Cape.

A few studies have been done in the stony soils of Spain's Mediterranean climate which is a similar soil type encountered in our experimental site (Pelegrin *et al*., 1990; Moreno *et al*., 1997; Cunha Medeiros, 1997; Hernanz *et al*., 2002). These studies focused on the effect of different tillage practices on the main physical properties of soil, organic carbon and the water balance in the soil. Badalucco *et al*., (2010) studied the reversing from intensive to sustainable, no-tillage manage agriculture and focused on the soil's physical, chemical and microbial properties. Other tillage studies in the Mediterranean climate included Argentina, Italy and Australia. In the other climate zones (humid and subtropical) of the world, literature on tillage is plenty and extensive.

1.3 Focus of the study

Tillage is a vital management step in crop production and influences the soil, crop growth and the yield significantly. Selecting tillage practices which improves soil physical properties is not just important to increase yields but also to reduce the impact of agriculture on the environment, promoting sustainability. Improved soil physical properties will also increase water storage in the winter (rainy season) and it's availability to crops, further increasing crop growth and yields. This is important when looking at climate change and water becoming scarcer, especially in the Western Cape. The increasing world population and food demand would impose on effective long-term tillage practices that improve or sustain soil physical properties, constantly delivering high yields. The focus of the study was thus on tillage practices and it's effect on soil physical properties in the long term.

1.3.1 Rationale

Tillage is a vital management step in crop production and has a significant influence on the soil, crop growth and also the yield. Selecting tillage practices which improve the physical properties of soil is not just important to increase yield but also to reduce the impact of agriculture on the environment, promoting sustainability. Improved soil physical properties will also increase water storage in the winter (rain season) and availability to crops, further increasing crop growth and yields. This is important when considering climate change and water becoming scarcer, especially in the Western Cape. The increasing world population and food demand would impose on effective long-term tillage practices that improve or sustain soil's physical properties, constantly delivering high yields. The focus of the study is thus on tillage practices and the effect on soil's physical and some chemical properties in the long term.

1.3.2 Objectives

The main objective of this study will be to investigate the different tillage practices currently being used in the Western Cape and understand the different influences on selected soil properties and also the interaction between these properties. From here tillage practices could be evaluated and long-term sustainable tillage practices can be identified. Sustainable tillage practices currently used in the Western Cape-region of South Africa can thus be confirmed or questioned.

1.3.3 Aim

The first aim of this study is to quantify and qualify the soil's physical and chemical properties after more than 30 years of continuous application of four different tillage practices. The second aim is to establish if no-tillage is the most sustainable tillage practice, if it has a significant advantage over other tillage practices and to what extent. The third aim is to generate soil physical data for hydrological modelling.

Hypothesis: A range of tillage practices will have diverse effects on soil properties and agricultural soil sustainability.

1.4 Scope of the study

The study will be presented through an introduction in Chapter 1, the literature study in Chapter 2, the material and methods in Chapter 3, the results in Chapter 4, a discussion in Chapter 5 and a conclusion in Chapter 6.

CHAPTER 2: LITERATURE STUDY

2.1 Introduction

After extensive literature research on tillage, one critical fact came to mind: No agricultural tillage system is fully sustainable. Every tillage practice or system, even no-tillage, has a negative effect on the environment and decreases soil quality. Soil quality is generally considered on physical, chemical and biological grounds and is important for the assessment of the extent of land degradation or amelioration and to identify management practices for sustainable land use (Ling-ling *et al*., 2011). Physical quality, the physical properties of the soil, has pronounced effects on the chemical and biological properties and processes in the soil and therefore plays a central role in studies evaluating soil quality (Dexter, 2004). It can be concluded that tillage practices with the least impact on soil physical properties and which are still economic for the farmer are the most sustainable for crop production and the environment.

Current concerns about environmental quality have questioned the sustainability of the conventional tillage practices which mainly accelerates soil organic matter breakdown (Gajri *et al*., 2002) and destroys soil structure. Exposure of the soil surface and destruction of the soil structure in conventional tillage also increase the susceptibility of the soil to erosion, especially with heavy rainfall just after planting (Agenbag and Stander, 1988). Soils in the semi-arid Mediterranean region typically have low organic matter content and thus in most cases weak structure because organic matter content is one of the important factors influencing soil structure. For this reason, intensive tillage systems for rain-fed crops lead to soil quality deterioration (López-Bellido *et al*., 1997; Hernanz *et al*., 2002). Badalucco *et al.* (2010) pointed out that low soil organic matter content in a Mediterranean climate seems to make soil functions and total biological fertility vulnerable to intensive farming. Thus can be concluded that in most cases conventional tillage affects soil structure negatively and causes excessive breakdown of aggregates and soil structure, thus increasing the soil's potential for erosion and also inducing carbon loss, thereby decreasing the soil's production capacity (Cox *et al*., 1990) and stability. These concerns gave rise to invention of conservation tillage practices that improve soil physical and biological properties and also especially conserve water. For this reason conservation tillage practices are particularly successful in semi-arid and Mediterranean climates with low carbon contents where water availability is the most limiting factor for rain-fed crop production (Morin *et al*., 1984; Moreno *et al*., 1997).

In some cases in the literature, the effects of no-tillage or conservation tillage on soil's physical properties vary. These variable effects depend mainly on the different climates and soil type. Martinez *et al*., (2008) confirm this statement and point out that the effects of conservation tillage on soil properties depend on the soil type, climate and the time since implementation. These variable effects can sometimes be reflected in yield being lower for fields with conservation and no-tillage practices (Pidgeon and Ragg, 1979; Hardgrove and Hardcastle, 1984; Agenbag and Stander, 1988; Bennie and Hensley, 2001) and thus in some climates and certain soil types conservation tillage may not be as successful.

A limiting factor in some circumstances to the conservation and no-tillage practices in die semi-arid regions is the possibility of soil densification by increasing bulk density, penetrometer resistance and reducing porosity through altering the soil structure due to the lack of tillage (Unger *et al*., 1991; Lopezfando *et al*., 2007; Fernández-Ugalde *et al*., 2009), which would be investigated in the following sections. Conservation tillage systems are useful in improving soil quality and control soil degradation, but in many cases lead to increased soil compaction and sometimes have a negative impact on crop growth and finally on yield (Lal, 1997; Ferreras *et al*., 2000). It might even lead to over-compaction of the soil and have negative effects on seed establishment (Agenbag and Stander, 1988) and root growth (Cavalieri *et al*., 2009). Other concerns like increased weed infestation due to the lack of mechanical weed control also have negative effects on crop yield (Bennie and Hensley, 2001). Ultimately the problem arises of whether to plough to counter compaction, aerate the soil and control weeds or to persist with no-tillage and suffer yield losses (López-Garrido *et al.,* 2011). Once again soil type, climate and soil management play an important role in determining the extent to which these undesirable effects may occur. In general, where soil compaction occurs in conservation tillage practices, it does not have a significant effect on soil water and crop dynamics in influencing crop yield (Agenbag and Maree, 1991). The success of conservation tillage depends therefore on the combination of mainly four factors: climatic conditions, tillage type, crop management (Lopezfando *et al*., 2007) and soil type.

Conservation tillage practices mainly affect only the soil's physical properties in the top 0-100 mm of the soil profile (Martinez *et al*., 2008). Buschiazzo *et al*. (1998) showed that the soil's physical, chemical and biological properties were improved by conservation tillage systems due to higher amounts of organic matter accumulation at the soil surface. It could thus be argued that the increase in organic matter is the main factor that improves the physical properties in the upper (0-100 mm) soil profile depth. Improvement of soil physical properties is not always visible in the first few years after switching from conventional tillage to conservation tillage. As already mentioned, tillage effects on soil properties is related to soil type, tillage, crop management and climate, but the effects or responses manifest themselves over a long period of time (Lal, 1997; He et al., 2011). Conservation tillage is thus a long-term investment for the farmer.

One of the important reasons for changing to conservation tillage is to reduce the run-off of fertilizer, sediment and pesticides through surface erosion (Shipitalo *et al*., 2000; Huggins and Reganold, 2008). Conservation tillage practices are also superior to conventional tillage practices because soil preparation is shorter and energy consumption is lower (Hernanz *et al*., 1995), thus reducing production costs and the time and amount of fieldwork that has to be done before planting (Cavalieri *et al.,* 2009; He *et al.,* 2011; Moussa-Machraoui *et al.,* 2010). No-till on average requires 50 to 80% less fuel and 30 to 50% less labour compared to conventional tillage and thus significantly lowers the production cost per hectare (Huggins and Reganold, 2008). Globally conservation and no-tillage practices are accepted as effective alternatives to conventional tillage because it improves the soil environment, sustains natural resources and reduces soil erosion (Huggins and Reganold, 2008; Gwenzi *et al*., 2008; Cavalieri *et al*., 2009; Moussa-Machraoui *et al*., 2010; Morell *et al*., 2011). Thus, conservation tillage is a more sustainable tillage practice for the environment and the farmer (Huggins and Reganold, 2008). Especially for winter cereals, no-tillage has a higher probability than conventional tillage, although minimum tillage is the practice that showed the most stable results in the long term (Hernanz *et al*., 1995). It must be said that chemical herbicides costs and weed resistance is factors that can negatively influence no-tillage sustainability.

The aim of the following sections is to look in depth at the effect of different tillage practices on a few selected physical soil properties. Secondly one would be able to compare these different tillage practices based on each property. This would clarify the strengths and weaknesses of each tillage practice. The following main physical properties of soil will be discussed, viz. particle size distribution, coarse fragment content, organic matter content, bulk density, porosity, aggregate stability, penetrometer resistance and soil water dynamics. First the different main tillage practices would be described and defined.

2.2 Different tillage practices

Soil tillage started as early as ten to twelve millennia ago and is an ancient art of creating a better soil environment for plants to grow in. It started with simple wooden, animal-drawn tillage implements, evolved through various designs of cultivation implements, and lead to the invention of the well-known Roman plough (El Titi, 2003). Charles Newbold invented the first cast-iron plough in 1797. From 1837 steel ploughs were commercially manufactured by John Deere. Many different tillage implements and modifications arose hereafter, according to the tillage objective required. Subsequently agriculture became increasingly mechanized and commercialized. Soil tillage is therefore a historically standard practice for preparing the soil before planting or sowing.

Soil tillage refers to the mechanical modification of soil conditions for crop production. Tillage is performed to kill weeds, manage crop residues, incorporate amendments and fertilizers and improve the soil's physical conditions in order to provide a good seed- and root bed. The main aims of tillage are to create an environment favourable for seedling germination, seedling emergence, root growth and crop development (Klute, 1982; Gajri *et al.,* 2002; El Titi, 2003). Today key outcomes for tillage are optimization of crop production while simultaneously conserving production resources (Gajri *et al*., 2002). Due to the great variation in tillage implements and the different tillage practices, tillage systems are categorized into certain groups according to the intensity of the operation and the amount of residue left on the surface after the operation.

2.2.1 Residues on

Tillage practices that are focused on leaving residues on the field after planting, mainly do so because of its positive effects on the soil's physical properties and the improvement of the organic matter content of the soil (Gajri *et al*., 2002), but also to limit soil degradation (Huggins and Reganold, 2008). These systems are categorized in the 'residue on' group. Generally 'residue on' tillage practices that leave residues on the field are increasingly being used in agriculture. The main reason for this is to limit soil degradation and pursue sustainable agriculture. This group is divided into conservation tillage, reduced tillage and conventional tillage and will each be discussed individually.

2.2.1.1 Conservation tillage

The key definition for conservation tillage systems is leaving the soil surface covered with residues (crop stubble) after planting, but also reducing the number of trips over the field (Huggins and Reganold, 2008). Conservation tillage is thus a system that leaves enough crop residues on the field to protect the soil from erosion (degradation) and also to increase to organic material to new levels in the soil. Long-term conservation tillage includes the reduction of the number of passes over the field with tillage implements as already said, but also reducing the intensity of the tillage operations and the total elimination of ploughing. The Conservation Technology Information Centre (1996) describes the conservation tillage definitions most commonly used. These tillage systems maintain at least 30% of the soil surface covered by crop or plant residues after planting and must reduce wind and water erosion (El Titi, 2003; Gajri *et al.,* 2002). Conservation tillage includes the following tillage practices, namely mulch tillage, ridge tillage and no-tillage.

In mulch tillage the soil surface is disturbed prior to planting, by implements such as chisels, field cultivators, disks, sweeps or blades. Thereafter weed control is accomplished by herbicides and/or cultivation with the implements already named. Lal (1986) specified that mulch tillage is based on the principle of causing limited soil disturbance and leaving the maximum amount of crop residue on the soil surface, while at the same time obtaining a quick germination, an adequate stand and a satisfactory yield. Gajri *et al.* (2002) stated that these tillage practices retain adequate residues to control erosion and conserve water by enhancing infiltration and suppressing evaporation. In some cases, it can also lead to a diminishing of surface crusts and sealing which could reduce water infiltration.

In ridge tillage the soil is left undisturbed from harvest to planting but nutrient injections are allowed. Weed control is accomplished by herbicides and/or cultivation. This system involves the lifting of the seedbed's surface level from the surrounding soil. The ridges are generally 10 to 15 cm higher than the rows between the ridges. Planting is completed after the seedbeds are prepared on ridges with sweeps, disk openers, coulters or row-cleaners. This system reduces erosion and also helps to improve drainage (Gajri *et al*., 2002).

In the no-tillage-method the soil is also left undisturbed from harvest to planting but nutrient injections are allowed. Planting or drilling is accomplished in a narrow seedbed or slot created by coulters, row cleaners, disc openers, in-row chisels, tin openers or rototillers. Weed control is only accomplished by herbicides. Parr *et al*., (1990) defined no-tillage as a specialized type of conservation tillage consisting of a one-pass planting and fertilizer operation in which the soil and the surface residues are minimally disturbed. In this tillage system, all crop residues are retained on the soil surface. Gajri *et al.* (2002) stated that no-tillage systems are suited to well-drained soils and that it helps to control soil erosion, conserve water, reduce energy and lower labour needs, while reducing equipment inventories and their repair needs.

2.2.1.2 Minimum or reduced tillage

This system requires that 15-30% of the soil surface must be covered by crop residues after planting. Before planting the whole soil surface is disturbed for seedbed preparation or crop sowing. Weed control is accomplished by herbicides or cultivation. Reduction in tillage is accomplished by reducing the frequency or intensity of operations. This system is largely aimed at decreasing or shifting the crop residue to facilitate planting or accelerate soil warming (Gajri *et al*., 2002). This system is often used as an intermediate between switching from conventional to no-tillage.

2.2.1.3 Conventional tillage

These tillage systems are generally performed over long periods for production of a given crop. Seedbeds are well prepared by clearing surface residues and interrupting weeds, insect and disease cycles and breaking root-limiting soil layers. Germination and seedling growth take place in a weed-free seedbed, given optimum conditions, but leaves the soil bare for a considerable period. Usually conventional tillage consists of three distinct operations (Gajri *et al*., 2002). Primary tillage is an initial major operation and includes operations like mouldboard ploughing, chisel ploughing and/or subsoiling. Mouldboard ploughing breaks and partially or completely inverts the soil whereas chiseling can break the soil as deep as 300 mm but not invert it. Sub soiling breaks and loosens the subsoil below the working depth of mouldboard ploughing or chiselling. Secondary tillage includes disking or disk harrowing, which pulverizes and firms the soil to a depth of 10-15 cm for seedbed preparation. The main aim of primary and secondary tillage operations in conventional tillage systems is to incorporate residues and to alter the soil's physical state (Gajri *et al*., 2002). Tertiary tillage systems are mainly performed as an inter-culture operation for weed control and crust breaking.

There are mainly two categories of conventional tillage, namely plough tillage, where the soil is extensively inverted and surface tillage, where there is 15% or less crop residue cover at planting. Surface tillage generally only makes use of disks and chisel cultivators or sweeps for primary and secondary tillage operations. Conventional tillage practices is still being used as a tillage option for soils with poor internal drainage, such as heavy clay soil or soil with poor structure, like very sandy soils (El Titi, 2003), especially in summer rainfall areas. This is not true for Mediterranean and semi-arid climates.

2.2.2 Residues off

This is tillage practices that burn or mechanically remove crop residue and are categorized in the ‘residue off’ group, where just small amounts of the stubbles are retained. This group is divided into conventional tillage and no-tillage without containing residues (not used in South Africa). In these tillage practices, the aboveground biomass is burned in situ or harvested mechanically or manually prior to field operations. Burning of crop residues is an excellent method to control weeds and disease cycles but restricts the build-up of carbon in the soil. Conventional tillage is mainly performed to prepare the seedbed, control weeds and to conserve water by improving infiltration and reducing evaporation from the soil surface (Gajri *et al*., 2002). No-tillage in this category consists of seeding a crop directly with a drill after the residues are removed (Gajri *et al*., 2002). It must be noted that these tillage systems, especially the burning of crop residues, are used to a much lesser extent after the 1990's.

Figure 2-1 shows a flow diagram of the different tillage systems broadly divided into categories. It is important to notice that within each tillage practice the operation and implement choice can vary substantially to achieve the tillage system definition. This is mainly due to the wide variability in soil, climatic, crop and socio-economic conditions across different ecoregions (Gajri *et al*., 2002).

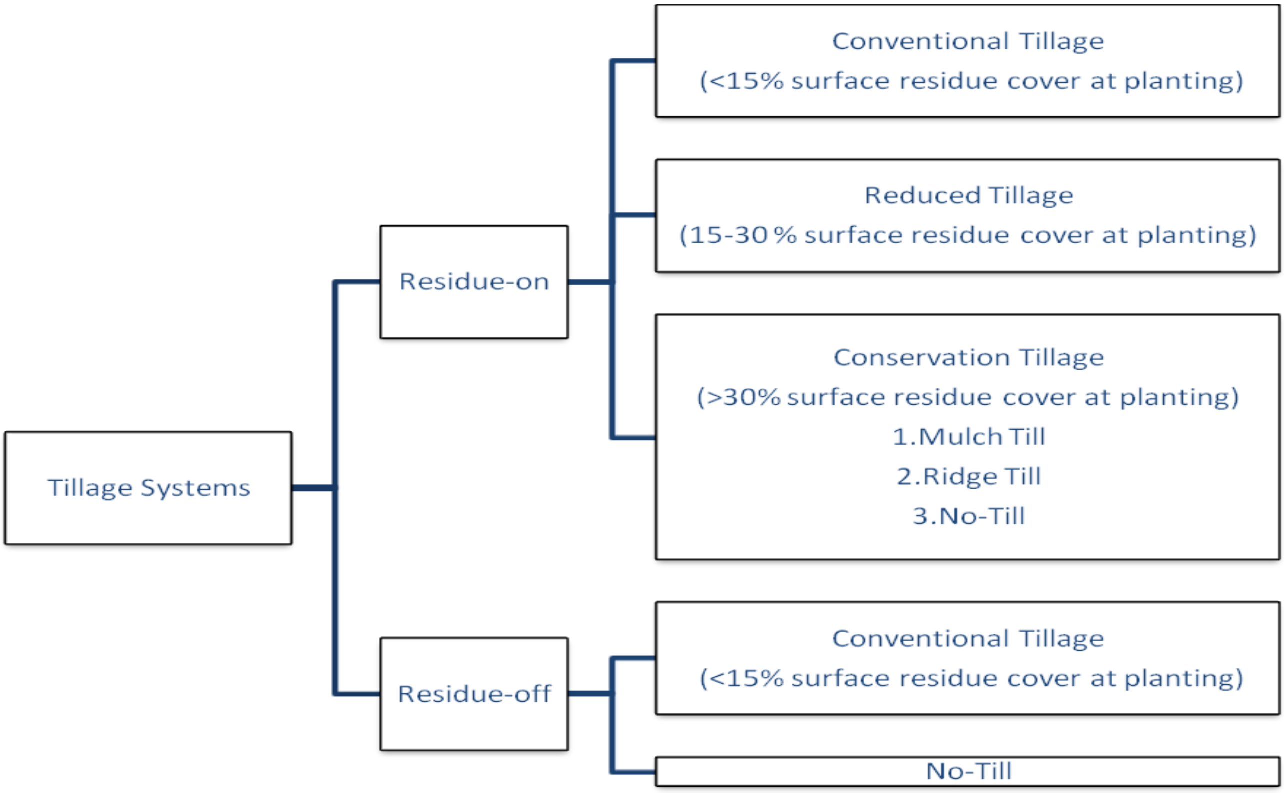


Figure 2-1: Flowchart of the different tillage practices (Gajri *et al*., 2002)

Today appropriate tillage practices are those that avoid degradation of soil properties but also maintain economic crop yields, as well as ecosystem stability (Lal, 1985). Since the late

1960s, many studies on the effect of conservation tillage systems on soil properties and crop yield have been conducted in many parts of the world. These studies focused on soil parameters under the physical, chemical and biological properties.

2.3 Basic soil parameters

The following section focus on selected basic soil properties studied in tillage and the effects of different tillage practices. This will help to form an idea of the way each property is influenced: positively, negatively or not significantly.

2.3.1 Particle size distribution and coarse fragments

Particle size distribution determines the texture class of a soil and consists of seven size classes (Hillel, 1980); coarse sand (0.5-2 mm), medium sand (0.25-0.5 mm), fine sand (0.106-0.25 mm), very fine sand (0.05-0.106 mm), coarse silt (0.02-0.05 mm), fine silt (0.002-0.02 mm) and clay (< 0.002 mm). This property is one of the fundamental physical soil properties that describes and classifies a certain soil type or form. Soil particle-size distribution, also known as the texture, influences many other soil properties. It mainly determines the mechanical, hydrological and chemical behaviours of the soil (Gui *et al*., 2010; Paz-Ferreiro *et al*., 2010) and to some extent also the biological processes. It thus controls soil water processes like hydraulic conductivity, infiltration and the soil's ability to store water. The sand and silt fractions are relatively inert, whereas the clay fraction constitutes the reactive fraction of the soil. Although this property is important in soil tillage it is not extensively studied, like, for instance, bulk density and organic carbon content. This is mainly because tillage generally has a minor effect on the soil particle-size distribution and is especially true for the short term. In long-term tillage studies some authors have found that tillage significantly effected soil texture, but the opposite is mostly common.

Arnold *et al*. (1990) stated that soil texture is the most stable physical property of soil and that changes in soil particle distribution as a result of different tillage practices is unlikely to be found, although Paz-Ferreiro *et al.* (2010) stated that changes in particle-size distribution may respond to long-term time dynamics. Long-term tillage (20 years and more) may thus alter soil texture. In the results from some studies, this statement is true. Lal's (1997) study on an Alfisol in Nigeria showed that after 8 years of tillage, sand content was significantly lower and clay content significantly higher in the 0-100 mm soil profile of no-tillage compared to the conventional tillage treatments. Changes in particle size distribution in the upper soil profile depth as a result of long-term continuous annual cultivation was also found by Brye (2003). In his studies, the sand fraction decreased and the clay fraction increased after 44 years of annual cultivation comparing to shorter times of cultivation. Long-term tillage thus causes the sand and silt fractions to decrease significantly, and the clay sized fractions to increase significantly as the years under continuous annual cultivation increased (Brye, 2003). The higher clay-sized particles give an indication of break down of the larger particles to smaller ones.

Gui *et al.* (2010) found in their study in China on oasis farmlands that cultivation time had an important impact on the soil particle size distribution. Farmlands which were cultivated for more than 30 years, showed to have the most stable and heterogeneous particle-size distribution. This indicates again that tillage breaks down soil partials to a uniform particle-size distribution where equilibrium is reached between tillage and texture stability causing no further breakdown of the particles. K. Brye (2003) said that: *"One rationale is that particles of smaller size fractions could be produced from particles of larger size fractions as the coarser sized particles are physically broken down from repeated mechanical disturbance … However, this explanation does not suggest that more actual clay was formed, because true clay formation is a chemical process, but rather that more clay-sized material developed as a result of decades of mechanical disturbance by cultivation*". Changes in particle-size distribution as a result of tillage are thus physical processes which takes place over many years.

In most cases in the literature, tillage had no effect on textural properties. One study compared the particle size fractions of a deep cultivated soil and natural forest vegetation in the same area. The results did not show significant differences, although a minor clay increase was observed under the deep cultivated soil (Vieira *et al*., 2000). The findings of Paz-Ferreiro *et al.* (2010) showed that particle-size fractions were not significantly different if no-tillage is compared to conventional tillage in two different crop rotations. The small differences that where observed was only due to natural variation of the soil in the experimental field. **Table 2-1** shows their results, using the traditional sieve-pipette method and a laser diffraction method. The laser diffraction results showed that the soil had a silt loam texture class, where in the sieve-pipette method, a loam texture class. The main difference between these methods is that the sieve-pipette method work on mass basis and the laser diffraction work on a volume basis. Concluding on the effect of tillage on particle-size distribution is seems if long-term tillage may to some extent alter the size fractions, especially the sand fraction which can decrease, although other cases show that even after 35 years of tillage it had no effect on the particle-size distribution.

Table 2-1: Mean values of sand, silt and clay contents (percentage) determined by laser diffraction and sieve-pipette methods. RM and RS, ryegrass-maize and ryegrass-sorghum rotations; NT and CT, no-tillage and conventional tillage respectively (Paz-Ferreiro *et al.*, 2010)

	Laser diffraction			**Sieve-pipette**		
Treatment	Sand	Silt	Clay	Sand	Silt	Clay
RMNT	21.86	67.67	10.47	39.95	40.95	19.10
RMCT	20.00	67.35	11.65	40.82	38.52	20.66
RSNT	21.50	68.09	10.41	39.47	38.75	21.78
RSNCT	22.19	67.20	10.61	40.38	38.15	21.27

Coarse fragments are all the particles in the soil larger than 2 mm in diameter. Coarse fragments play a role by influencing the soil volume, soil surface roughness and the ease of tillage operations. **Table 2-2** shows the different coarse fragment classes. Generally it is the larger fragments that are influenced by tillage through moving them vertically, horizontally and laterally. Tillage can also break lager coarse fragments into smaller ones, especially when deep-ripping shale soils.

Tillage has an effect on coarse fragments by influencing their size and distribution in the soil. Oostwoud Wijdenes and Poesen (1999) described one of the vertical processes that occur during tillage, namely segregation. Segregation takes place when different particles with different sizes in one medium such as soil are disturbed causing the largest particles to accumulate at the surface and the smallest at the bottom. Tillage practices such as mouldboard ploughing and deep chiselling are particularly prone to segregation, especially when the soil has low moisture content. Segregation occurs because the smaller particles have more chance to move or slide deeper down through the openings than the larger ones. This process is also known as kinetic filtering, kinetic sieving or inter-particle percolation.

Table 2-2: Different soil coarse fragment classes (Krumbein and Sloss, 1963)

Size range	Fragment name
256 mm <	Boulder
64–256 mm	Cobble
32–64 mm	Very coarse gravel
16–32 mm	Coarse gravel
8–16 mm	Medium gravel
4–8 mm	Fine gravel
2–4 mm	Very fine gravel

Oostwoud Wijdenes and Poesen (1999) experimented in the laboratory to determine the vertical movement of rock fragments by using two types of fine earth as a soil matrix in which rock fragments were embedded. **Figure 2-2** and **Figure 2-3** show the results of the effect of chisel tillage on coarse fragments in two different soil textures. From these figures it is clear that tine tillage causes the vertical upward movement of coarse fragments to the surface. The amount of coarse fragments also increases as the number of tillage passes increased. Soil water content also affected kinetic sieving. Lower water contents tended to increase vertical movement of coarse fragments to the soil surface. These results indicate that coarse soil texture and water content influence kinetic sieving.

Another study showed that gravel content (rock fragments) at the soil surface increased with cultivation because of mixing through deep ploughing (Vieira *et al*., 2000). Cultivated soil in this study was more homogenous than adjacent natural vegetation soil, with a rock layer at the deeper profile layers (beneath the plough layer). Ploughing must therefore have incorporated this rock layer into the cultivated soil after a few years of tillage. Oostwoud Wijdenes and Poesen (1999) showed that kinetic sieving is approximately two times faster under field conditions. Other factors that may influence the rate of kinetic sieving in the field may be the type of tillage implement and the velocity at which the tillage operation takes place.

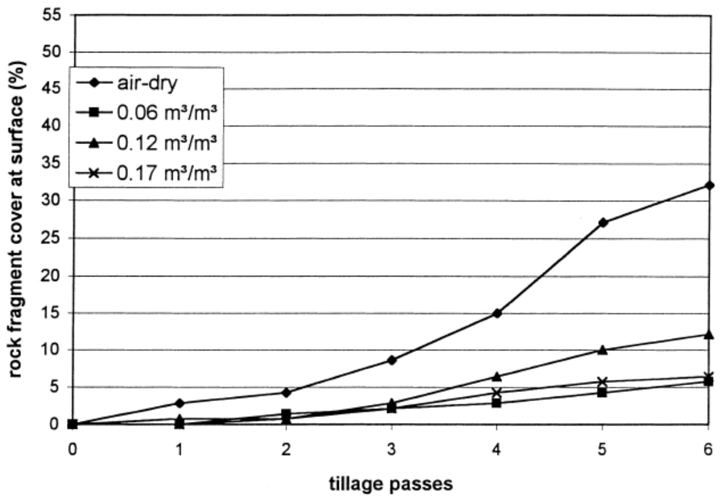


Figure 2-2: Changes of rock fragment cover with number of tillage passes for different moisture content in a sandy soil matrix (Oostwoud Wijdenes and Poesen, 1999)

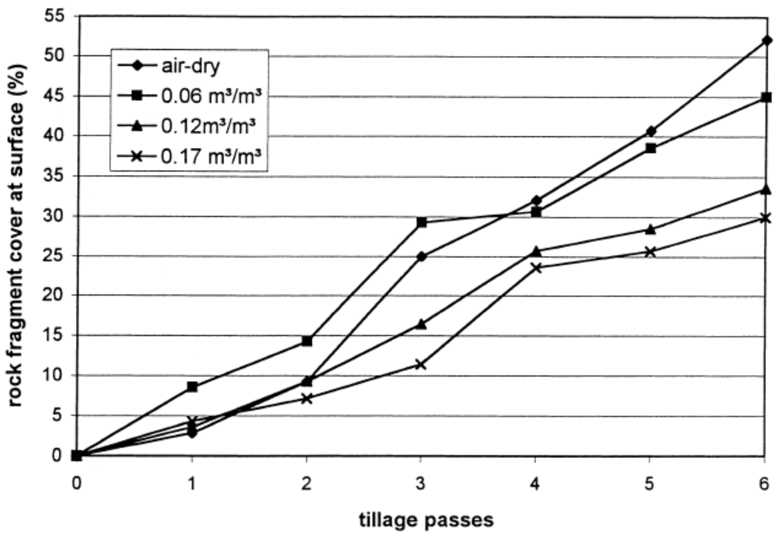


Figure 2-3: Changes of rock fragment cover with number of tillage passes for different moisture content in a silt-loam soil matrix (Oostwoud Wijdenes and Poesen, 1999)

Tillage practices that would increase the coarse fragment content at the soil surface would affect the soil properties. The presence of more coarse fragments in the soil modifies (1) the soil's physical properties: for example: water infiltration and run-off susceptibility; (2) the soil's chemical properties: carbon content or nitrogen content; and potentially also (3) crop yields (Cousin *et al*., 2003).

In some cases it may have a positive effect, for instance high amounts of rock fragments at the soil surface in the Mediterranean climate, can reduce erosion and increase water infiltration (Poesen *et al*., 1996) and also alter the soil temperature. Coarse fragments in the soil can also influence the plant available water content (Cousin *et al*., 2003; Tetegan *et al*., 2011). It can also cause deeper penetration of the wetting front into the soil compared to soils with no coarse fragments. Therefore it reduces evaporation losses (Wesemaep *et al*., 1996) and enhances groundwater recharge (Wesemaela *et al*., 1995).

Although very high amounts of coarse fragments could hamper planting operations especially if a disc planter is used, seed germination could also be negatively influenced if seeds don’t make sufficient contact with the soil. This is mainly because the increase of coarse fragments in the soil surface directly influences the soil volume by lowering it. Less soil means that seeds that are not covered completely with soil will not have an effective water supply through the soil matrix, may not germinate and may decrease the yield. The coarse fragment content distribution in the soil would thus also play a role in the selection of a tillage practice. Next the effect of tillage on total and organic carbon content will be discussed.

2.3.2 Organic matter

Soil organic matter content is one of the most important soil quality and productivity indicators in agriculture, especially after the 20th century when sustainable agriculture became more important. Higher organic matter in the soil results in higher organic carbon and total carbon content and is controlled by mineralization. Organic carbon content is one of the key factors influencing soil stability (Ekwue, 1990) because it influence the soil's physical and chemical properties directly. It is thus a vital soil property essential to erosion control, water infiltration, soil structure stabilization and conservation of soil nutrients (Franzluebbers *et al*., 2004).

Crop production and tillage usually lowers the organic matter content in soils (Rasmussen and Collins, 1991). Prinsloo *et al*. (1990) found that in South Africa soil cultivation caused a decrease of 68% in organic carbon in some Free State soil where the initial content was 5 g kg^{-1} 70 years earlier. Du Toit *et al.* (1993) concluded that cultivation also resulted in a significant decrease of soil organic matter and amounted up to 10-75% on South Africa's dry land soils in the summer rainfall areas. One of the main reasons being that soil mixing and crushing (by conventional tillage) promote the decomposition and oxidation of organic matter (Rasmussen and Collins, 1991; Du Toit *et al*., 1993; Cannell and Hawes, 1994). The main factors that influence organic matter stratification by tillage were summarized by Hernanz *et al.* (2002). They are: (1) type of implement, depth and speed of tillage, sequence of operations (2) soil texture, soil moisture conditions when tillage is performed and (3) amount, type and size of crop residues and distribution on soil surface. The climate is certainly also a main factor. Sustainable agriculture would thus also require tillage practices that increase the organic carbon content of the soil or at least maintain it close to the natural occurring contents.

Maintaining soil organic material content (soil carbon stocks) at desirable levels is a major task in agriculture because intensive farming practices generally reduce it (Du Toit *et al*., 1993; Badalucco *et al*., 2010). This problem is even greater in the Mediterranean and semi-arid regions of the world with low organic matter contents, because of historical exploitation, high mean temperatures, low rainfall and high evaporative demand promoting extensive and rapid mineralization of organic matter (Imaz *et al*., 2010; Badalucco *et al*., 2010). Accumulation of organic matter in these climates is thus difficult. For this reason total organic carbon may not be the key indication of soil quality in the Mediterranean climate because a high concentration is not expected at the surface (Franzluebbers *et al*., 2004). Rasmussen and Collins (1991) stated that significant changes in soil organic carbon can only be detected in the long term (20-30 years) displaying that those long-term studies were important. The potential of different ecosystems of the world sequester carbon (organic matter) is climatically dependent with tropical and temperate regions having more favourable conditions for carbon accumulation, comparing to the arid and semi-arid regions (Buschiazzo *et al*., 1998; Pardo *et al*., 2011). The difference is mainly because of higher amount of rainfall for the summer season occurring in the tropical and temperate regions.

Agenbag and Maree (1989) looked at the effect of three different tillage practices on organic carbon content. The study was conducted in the Mediterranean climate (Western Cape) of South Africa on a stony Alfisol (Haploxeralf). They found that soil organic carbon stabilized at significant higher levels in the 0-100 mm soil profile in the no-tillage and tine tillage practice compared to the conventional tillage practice. This effect was first significant after four years of experiments in the case of monoculture. They stated that after a new less intensive tillage practice is introduced to a conventional tilled field an average of 5 years are needed for organic carbon to stabilize at new levels. Organic carbon will only increase to a new optimum level in equilibrium with the climate, soil and water properties and the type of tillage practice being used (Agenbag and Maree, 1989; Du Toit *et al*., 1993). **Table 2-3** shows the results of Agenbag and Maree (1989).

Table 2-3: The effect of tillage method on the organic carbon content of the 0-100 mm soil profile in a wheat-mono-culture (A) and wheat-after-pasture system (B), 1978-1985 (Agenbag and Maree, 1989)

Tillage treatment		Organic carbon content (%) over years							
		1987	1979	1980	1981	1982	1983	1984	1985
(A)	MDT	1.21	1.38	1.25	0.79[a]	0.99[b]	1.17	1.01[b]	1.07[b]
	TT	1.38	1.34	1.24	1.83[a]	1.49[a]	1.38	1.42[a]	1.33[ab]
	NT	1.36	1.36	1.37	1.83[a]	1.32[a]	1.27	1.28[a]	1.41[a]
	LSD_T (P = 0.05)	NS	NS	NS	0.32	0.30	NS	0.17	0.31
	CV (%)	9.9	13.9	10.1	9.9	10.0	13.0	6.4	11.1
(B)	MDT	-	1.19[b]	1.09	0.99[b]	0.37[b]	1.09[b]	0.98[b]	0.68[c]
	TT	-	1.45[a]	1.17	1.26[a]	0.83[ab]	1.49[a]	1.31[a]	1.51[b]
	NT	-	1.28[ab]	1.17	1.18[ab]	0.93[a]	1.33[a]	1.41[b]	2.02[a]
	LSD_T (P = 0.05)	-	0.20	NS	0.22	0.53	0.27	0.29	0.45
	CV (%)		6.9	13.8	8.8	34.3	9.7	10.8	14.8

[1] Values in a column followed by the same subscripts do not differ significantly at *P* = 0.05

MDT - Vonventional mouldboard tillage, TT - Tine tillage, NT - No-tillage

From the table it is also clear that crop rotation leads to a higher and faster increase of soil organic carbon compared to mono culture and that the values of tine and no-tillage are more or less the same. In 2008 similar results were obtained in the 0-150 mm soil depth. For the wheat mono culture, organic carbon content significantly differed between tillage treatments. It increased in the order, conventional, tine, minimum and no-tillage, 0.43%, 0.60%, 0.68% and 0.80%, respectively (Agenbag, 2012). For the crop rotation system (still the same as in 1987) the organic carbon content increased in the following order:

conventional (0.53%) minimum (0.82%), tine (0.93%) and no-tillage (0.97%). This means that among the cropping systems content also differed significantly and the organic carbon content were 0.63% for the wheat monoculture and 0.75% for the crop rotation system. From these results it is clear that there is a decrease in organic carbon content of about 44.5% from 1985 till 2008. This can be due to a few reasons regarding this particular study that will be discussed in later chapters. Comparing a similar study conducted in the Southern Cape of South Africa on a Alfisol with legume pastures, soil organic carbon content in the no-tillage treatment was also significantly higher than conventional tillage in the 0-100 mm soil depth (Agenbag and Stander, 1988). The minimum tillage treatment also had higher soil organic carbon content but was not significant for all of the study years. Sasal *et al*. (2006) also found that no-tillage showed a higher organic matter content compared to tine tillage in the 0-50 mm soil depth.

In some cases, organic matter increases even deeper down the soil profile. In Tunisia, soil organic carbon content was greater in the 0-200 mm soil profile for the no-tillage treatment, compared to conventional tillage in a four year experiment (Moussa-Machraoui *et al*., 2010). Filho *et al*. (2002) made a similar finding and reported that after 21 years of tillage, no-tillage had significantly higher organic carbon than conventional tillage comparing differed aggregate classes of Typic Haplorthox soil. Another study concluded that organic carbon stocks of the no-tillage treatment was the highest concentration in the 0-100 mm and 0-200 mm depths if comparisons were made on a mass basis after 16 years of tillage (Hernanz *et al*., 2002), although soil organic carbon was most uniformly spread in the 0-400 mm soil profile depth of conventional tillage. This is mainly as a result of mouldboard ploughing. Mrabet *et al*. (2001) conducted a long-term tillage experiment in a semi-arid area of Morocco, and found a 14% increase of soil organic matter in the 0-200 mm deep soil layer over a period of 11 years under no-tillage compared to conventional tillage. Similar results were found by Bescansa *et al*. (2006), indicating a 13% increase of organic matter content in the 0-150 mm soil profile due to conservation tillage practices (no-tillage and chisel tillage).

Contradiction is also found in the literature. No-tillage after four years in Mediterranean Vertisols under rain-fed crop production did not increase organic matter content in the 0-300 mm tillage depth compared to conventional tillage (López-Bellido *et al*., 1997). This was ascribed to be mainly due to a small amount of residue that was produced indicating that a longer time is needed for organic matter to accumulate. No increase in organic matter can also be due to deeper sampling depths or because carbon loss is less significant in soils with a higher clay content (López-Bellido *et al*., 1997). Conventional tillage did therefore not significantly decrease the organic matter content in this particular study. Another study showed that after 10 years of no-tillage, soil organic carbon was significantly higher in the 0-50 mm soil surface (2.15%) than conventional tillage (1.25%), but no differences were found in the 50-150 mm and the 150-300 mm soil layer (Blevins *et al*., 1983).

Comparing the different sampling depths of conventional and no-tillage, a study showed that organic carbon content was significantly higher for no-tillage in the 0-50 mm and 150-300 mm than for the 50-150 mm depth. Conventional tillage in this case showed more or less the same amount of organic carbon in the 50-150 mm depth and then gradually decreased to the 150-300 mm sampling depth, indicating a uniform distribution of organic carbon as a result of conventional tillage (Fernández-Ugalde *et al*., 2009). Agenbag (2012) found that conventional tillage inverted organic matter evenly into the soil with the mouldboard ploughing to the working depth of the implement. In a similar study, no-tillage increased soil organic matter content in the 0-50 mm soil surface but in die whole 0-600 mm soil profile there were no significant differences between conventional tillage and no-tillage (Chatterjee and Lal, 2009). Filho, *et al.* (2002) also found no significat differences between no-tillage and conventional tillage at the 200-400 mm soil depth. Chatterjee and Lal (2009) thus suggested that when evaluating the potential of no-tillage to accumulate organic matter, it is necessary to consider the whole soil profile, not just the surface, when looking at soil organic matter concentration, although it can be argued that higher organic matter contents at the surface is more preferential for crop production due to the positive effects after accumulating to new levels.

Lower organic carbon content in more intensive conventional tillage practices is mainly due to higher mineralization rates. Tillage aerates the soil surface and mixes the organic matter uniformly, making it more available to microorganisms. Higher oxygen levels and the supply of organic matter deeper in the soil profile cause an increase in mineralization and thus a decrease of organic carbon content. Importantly organic matter takes years to accumulate, especially in semi-arid regions where the climate refuses it. The potential of no-tillage to sequester soil organic matter and improve soil physical properties varies widely (Chatterjee and Lal, 2009). It is therefore a sensitive property and can be altered within short periods. This is confirmed by a study conducted on an Inceptisol. Conventional mouldboard tillage significantly decreased total organic carbon content in the 0-50 mm soil layer after the first year of ploughing soil that was previously managed under conservation tillage. It also decreased the 50-100 mm content, but the difference was not significantly lower (Lopez-Garrido *et al*., 2011). Organic matter can thus be depleted very easily through cultivation (Vieira *et al*., 2000). Depletion is especially fast in the first years of tillage. Thereafter the rate decreases to a new equilibrium where little or no organic carbon loss occurs (Du Toit *et al*., 1993).

All these studies confirms that no-tillage only increases the upper (0-100 mm) soil organic carbon content, but if the whole sampling depth of profile depth is compared there are generally no differences between conventional tillage and no-tillage. From the literature it is known that organic matter is linked to the soil structure and thus to aggregates. Increasing the organic matter content (organic carbon content) would thus increase the amount of stable aggregates and then also the soil's structure. A linear relationship between water stable aggregates and soil organic carbon is shown in **Figure 2-4** (Abid and Lal, 2008). This figure illustrates the accumulation of organic matter in the top soil because of no-tillage which improves the aggregate stability. In the top 100-200 mm soil profile an increase of organic matter content led to an improvement of water stable aggregates. Although the r^2 is only 0.42 the effect is clearly visible on the graph but suggest that there are also other factors which play a role in aggregate stability. The deeper soil profiles do not show a trend and has a very low r^2 value confirming that organic carbon is not the only parameter controlling aggregate stability.

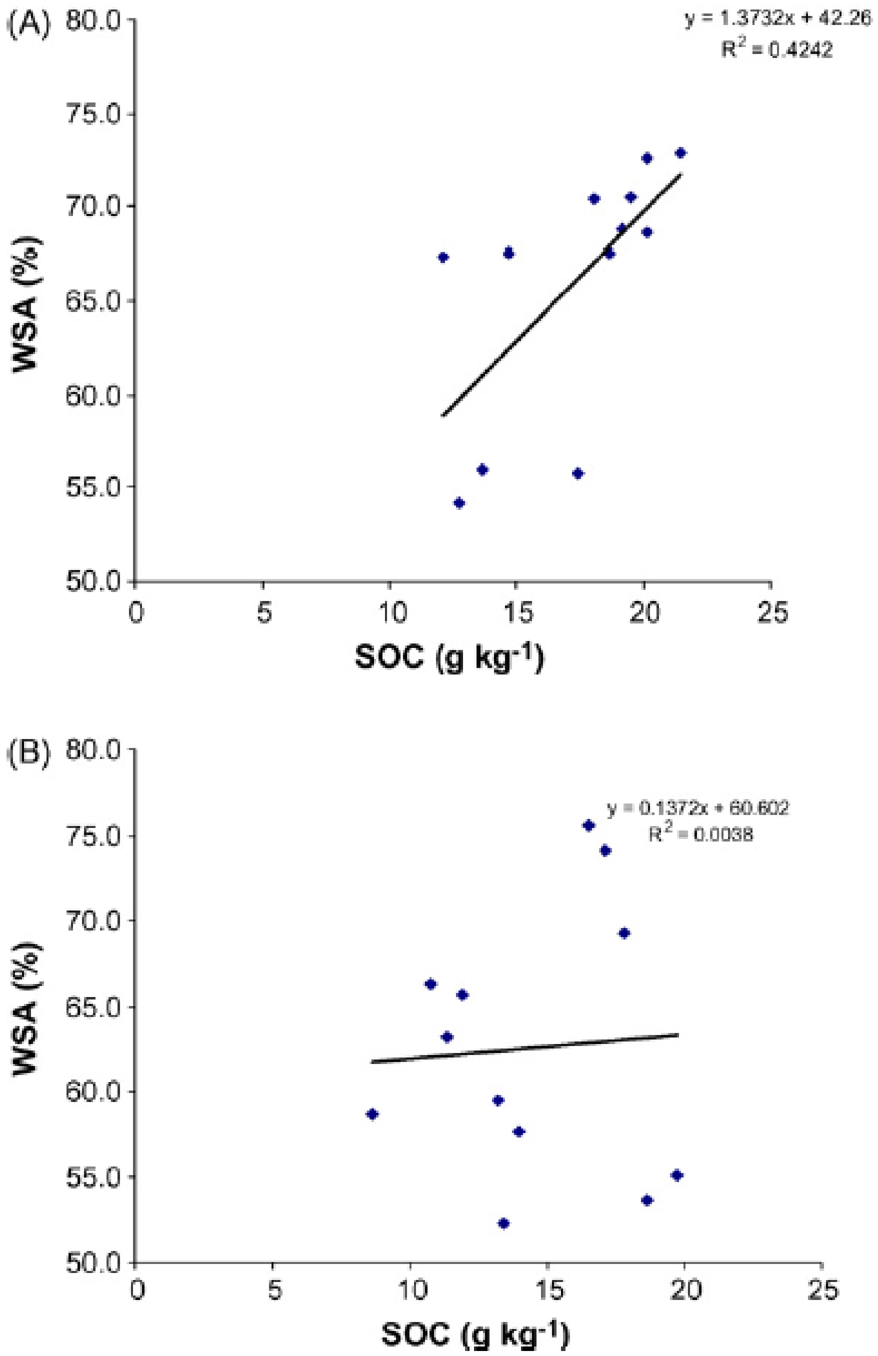


Figure 2-4: Relationship between water stable aggregates (WSA) and soil organic carbon (SOC) (A), 10-20 cm depth and (B) 20-30 cm depth (Abid and Lal, 2008)

No-tillage thus promotes surface accumulation of soil organic carbon (Hamblin, 1987; Lopezfando *et al*., 2007; Agenbag, 2012). Soil organic carbon (g/kg, Mg/ha and%) is thus mainly effected in the 0-50 mm depth of soils and generally significantly greater under no-tillage (Fernández-Ugalde *et al*., 2009). Higher content can reduce soil strength (Agenbag and Maree, 1989) and improve the amount of stable aggregates that are formed. Aggregate stability is a quality directly related to soil organic carbon content (Hernanz, *et al.,* 2002; Abid and Lal, 2008). Higher amounts of organic matter in the soil can also improve biological activity and aggregate stability and promote soil structure formation. Higher biological activity due to more available organic matter can promote more biopore formation (preferential flow paths), which in turn can improve water infiltration (Benjamin, 1993). Improved structure can influence the water dynamics of the soil, increasing water infiltration and water storage. Martinez *et al,*. (2008) stated that accumulation of organic soil carbon could also buffer problems of compaction in the long run. Tillage effects on bulk density will be discussed in the next section.

2.3.3 Bulk density

Bulk density is the measurement of the mass of soil per unit volume. This property traditionally describes soil porosity and aeration, but can also give an indication of the degree of compaction. In the case of soil tillage, bulk density is not a constant value and may vary through the season (Rousseva *et al*., 1988; Pelegrin *et al*., 1990; Osunbitan *et al*., 2005). This variation is primarily due to tillage, natural compaction, and the fluctuation of soil water content through the cropping season and through the influence of ants, termites and earthworms. Tillage effects on bulk density are well documented in the literature.

Bulk density is an important soil property because it can be used to describe other properties like porosity, water infiltration rate, water storage capacity and compaction. Lower bulk densities is preferred in agriculture because it promotes root growth, increases water infiltration, improves soil aeration and air exchange and also increases the ease of tillage operations. High bulk densities resulting in over-compaction of the soil can have a detrimental effect on other soil properties and crop yield. Densities ranging from 1500 to 1980 kg.m^{-3} can be harmful to plant growth, especially during wet years (Pollard and Elliott, 1978). Jones (1983) found that bulk density ranging from 1600 to 1700 kg.m^{-3} limited root growth that could have a negative effect on crop yield. The results from Pabin *et al*. (1998) showed that bulk densities of 1500 kg.m^{-3} at 30% and 1770 kg.m^{-3} at 60% field water capacity restricted root growth. This indicates that water content plays an important role determining critical wet bulk density values. Critical bulk density values are also affected by clay content and decrease as the clay content increases (Reichert *et al*., 2009) in the soil. They showed that clay contents of 60% decreased the critical bulk density to 1400 $kg.m^{-3}$. Higher soil clay content thus lower critical bulk density values in most cases one must remember that clay type also play a role (swelling vs. non-swelling). Bulk density and different soil types are therefore interrelated.

Tillage also effects bulk density and selecting a sustainable tillage practice that would prevent the soil from compacting and reaching its critical bulk density, is an important task mainly because it is directly related to water infiltration, soil water storage, run-off, erosion (Rousseva *et al*., 1988) and some other properties. Tillage practices variable in intensity, like conventional tillage and no-tillage have different effects on bulk density and in turn on the other factors as already mentioned. Determining bulk density is thus an important part in evaluating tillage practice sustainability. Long-term studies for bulk density determination are more accurate because different tillage practices reach different 'soil' equilibriums, which are established in a few years after a new practice is introduced to the soil. Generally a minimum of three years is required for bulk density to stabilize at a new equilibrium as a result of tillage (Pidgeon and Soane, 1977). Voorhees and Lindstrom (1984) had similar findings, displaying that after a new tillage practice is introduced, it takes about three to five years for the new equilibrium to be reached. Hernanz *et al.* (2002) did a long-term tillage trial in the Mediterranean area of Spain on an Alfisol (Calcic Haploxeralf). There were two cropping systems and three different tillage treatments, viz. conventional, minimum and no-tillage. They found that in the 0-100 mm depth no-tillage had a significant higher bulk density in comparison with minimum and conventional tillage at the end of crop growth, although from 150 mm deeper, no differences between tillage treatments were found. **Figure 2-5** shows the results of the effect the three different tillage practices and two cropping systems had on bulk density.

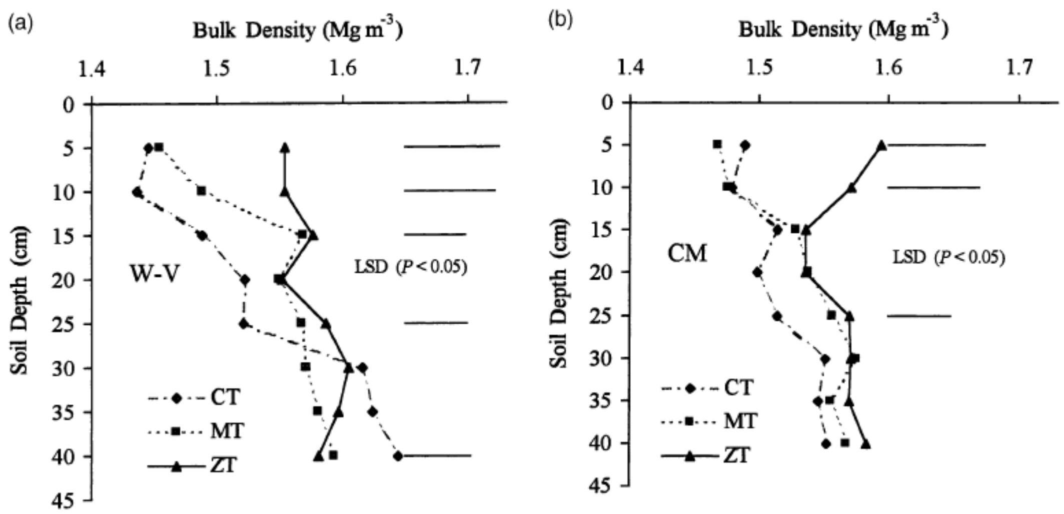


Figure 2-5: Soil bulk density profiles measured on each crop rotation at the end of crop growth season 1995/1996. CT, conventional tillage; MT, minimum tillage; ZT, zero tillage; W-V, wheat-vetch rotation (a); CM, cereal monoculture (b) (Hernanz *et al.,* 2002)

From the graph it is clear that mostly the top 150 mm of the soil profile is affected. Another study done on the same soil (Haploxeralf) and climate also concluded that no-tillage had the highest bulk density in the 0-200 mm surface layer in comparison with conventional tillage and other less intensive tillage practices (Pelegrin *et al.*, 1990). They also observed that bulk density increased with time in the arable layer, which was most noticeable in the no-tillage practice due to natural soil consolidation and compaction by traffic.

Several other studies in the Mediterranean climate also found similar results in different soils. Bescansa *et al.* (2006) found on an Inceptisol that bulk density in the 0-150 mm soil profile was greater under no-tillage (1620 $kg.m^{-3}$) than under chisel (1500 $kg.m^{-3}$) or conventional tillage (1520 $kg.m^{-3}$) after 5 years. On the same soil type Fernández-Ugalde *et al.* (2009) made similar findings for the 0-50 mm depth, bulk density was significantly greater for the no-tillage compared to conventional tillage, although there were also no differences found in the deeper soil profile between tillage treatments. In Mollisols no differences in soil bulk density was found between conventional and no-tillage treatments (Ferreras *et al.*, 2000; Martinez *et al.*, 2008), although in the one study bulk density increased from tillage to harvest (Ferreras *et al.*, 2000). In a study done on an Entisol

(Xerofluvent), results showed that bulk density in die 0-200 mm layer was significantly higher in the conservation tillage treatment than in the conventional tillage treatment after direct tillage operations (Moreno *et al*., 1997). These results show that the lack of tillage causes an increase in bulk density in these specific studies.

Some studies found different results. Blevins *et al.* (1983) showed that on a Typic Paleudalfs (Alfisol), no difference in the 0-150 mm soil depth was observed among tillage treatments. Agenbag (1987) also found no differences between tillage practices in the 0-90 mm soil depth of an Alfisol (Haploxeralf). Gwenzi *et al.* (2008) found no difference between tillage treatments even after 6 year of tillage. Lal (1997) also concluded that different tillage practices had no significant effect on bulk density in the 0-100 mm soil depth in an 8-year tillage experiment in Nigeria. Although the bulk density increased in general due to crop production in the 0-100 mm soil depth from 1300 kg.m^{-3} to 1500 kg.m^{-3} over the years, the soil was classified as an Alfisol.

Some studies found results in contradiction with high bulk densities encountered in no-tillage. Lal *et al*. (1994) found that after 28 years of tillage mean bulk densities of three different crop rotations measured prior to application and planting were 1180 for no-tillage, 1240 for tine tillage, and 1280 kg.m^{-3} for conventional tillage conducted on a Typic Fragiudalf. Another study conducted on an Alfisol showed that no-tillage also had a significant lower bulk density (1460 kg.m^{-3}) compared to conventional tillage (1560 kg.m^{-3}) for the 0-100 mm soil depth (Abid and Lal, 2008). In the humid climate of North China Plain no-tillage also had a significantly lower bulk density in the 0-300 mm soil depth compared to conventional tillage in a long-term experiment (He *et al*., 2011). Lower bulk densities in the more humid areas with higher rainfall might be due to organic matter accumulating, which improves the soil structure and buffers compaction. This could also be true for other climates when carbon is built up to significant levels to increase aggregate formation and stability which can lower the bulk density. Lower bulk densities encountered for no-tillage in these study's less intensive tillage caused the formation of stable soil structure (Cameron *et al*., 1987; Singh *et al*., 1994; Hernanz *et al*., 2002; Birkás *et al*., 2004; Bronick and Lal, 2005) that lowers bulk density.

No-tillage in the Mediterranean and semi-arid climates tend to increase bulk density, especially in the upper soil profile for the sort-term. Higher bulk densities are mainly due to a reduction of tillage and compaction by the weight of the planter. This can be a problem because a surface compacted layer can affect seedling development, root growth and water infiltration (Martinez *et al*., 2008). An increased bulk density causes porosity to decrease, which can have a negative impact on water dynamics and thus crop growth. Gradual compaction (severe compaction in some cases) is due to increasing bulk density of no-tillage that occur in the first few years as a result of reduction of macro pore volume (Bescansa *et al*., 2006) as the new equilibrium is formed. In the long term biological activity would be less disturbed in conservation tillage practices and may thus increase porosity due to biological activity and in the end decrease bulk density. Porosity is directly related to bulk density and will be disused next.

2.3.4 Porosity

Lower bulk density would thus result in higher soil porosity. As already discussed, tillage affects bulk density and it would thus also in turn affect total pore volume. Tillage thus alters the pore size and distribution of the soil (Fernández-Ugalde *et al*., 2009), especially in the short term. Conventional tillage generally has a greater areal porosity directly after tillage operation compared to no-tillage, because in no-tillage the surface layer is disturbed minimally (Lipiec and Kus, 2006; Sasal *et al.,* 2006). Different tillage practices also stimulate different pore formation processes resulting in unique pore characteristics for each type of tillage practice (Benjamin 1993; Lipiec and Kus, 2006).

The pore formation processes in the soil can be biotic (natural by soil organisms and roots) and/or abiotic (mechanical by tillage). In conventional tillage practices pores are formed by rearrangement of the solid phase because of the tillage implement action, the formation process is thus abiotic. In no-tillage practices pores are primarily formed through biological activity as a result of soil organisms (soil fauna) and old root channels (Benjamin, 1993), but also due to other natural soil processes like consolidation and swelling/shrinking, here the formation process is biotic. These different methods of pore creation, formation and stabilization cause the great variation in pore size, pore distribution and pore continuity and pore stability between no-tillage and conventional tillage practices (Benjamin, 1993).

In the Mediterranean zones no-tillage in general reduces total pore volume and alters pore size distribution, with larger pores disappearing and smaller ones predominating (Carter, 1992; Martinez *et al,* 2008), but also the creation of preferential flow paths (Singh *et al.*, 1994; Osunbitan *et al.*, 2005). The effect can be attributed to the more compacted surface layer generally formed in no-tillage that seems to reduce the number of macro pores (Pelegrin *et al.,* 1990). Conventional tillage thus promotes the establishment of macro pores that increase the water infiltration rate directly after ploughing (Martinez *et al.,* 2008) but these macro pores are not always stable and bulk densities might increase drastically through the growing season. Ferreras *et al.* (2000) showed that the volume of pores with diameter larger than 20 µm was higher under conventional tillage compared to the no-tillage treatment. Bescansa *et al.* (2006) found that large pores (> 9 µm) occupied more than 50% of the total pore volume of chisel and conventional tillage treatment, whereas small pores (0.2-6µm) occupied about 60% of the pore volume of no-tillage treatments. A similar study showed that no-tillage had more small pores. The small pores (0.2-9 µm) occupied most of the total soil pore volume (79%, 0-50 mm depth and 52% for the 50-300 mm depth), but at the same time large pores (> 9 µm) was more abundant (57%, 0-50 mm depth and 59% for the 50-300 mm depth) in conventional tillage (Fernández-Ugalde *et al*., 2009) two months before harvest.

Lipiec and Kus (2006) conducted a tillage study in Poland on a Typic Xerofluvent (Entisol). The soil had 25% clay (<2 mm), 62% silt (2-50 mm) and 13% sand (50-2000 mm) at the 0-300 mm depth. Comparing the pore size distribution between tillage treatments, no-tillage had the most small pores corresponding with the matric pore system and conventional tillage had more large pores corresponding to transmitting pores (Lipiec and Kus, 2006). Their results of pore size distribution are shown in **Figure 2-6**. This figure shows that in the 0-100 mm soil depth macro pores are more abundant in more intensive tillage practices (conventional tillage) and micro pores in less intensive practices although in the 100-200 mm depth pore size distribution were more or less the same among tillage treatments. In deeper soil layers macropores are thus also created by biological activity.

Contradiction of the findings on pore size distribution is also found in literature. He *et al.* (2011) showed that no-tillage significantly increased macro- and meso porosity in the 0-300 mm soil depth compared to conventional tillage. In an Australian Alfisol macropore density and continuity in the 0-100 mm soil depth were significantly lower in conventional tillage compared to no-tillage (Chan and Mead, 1989). Another study also concluded that conservation tillage increased macro porosity and improved preferential flow paths (Shipitalo *et al*., 2000).

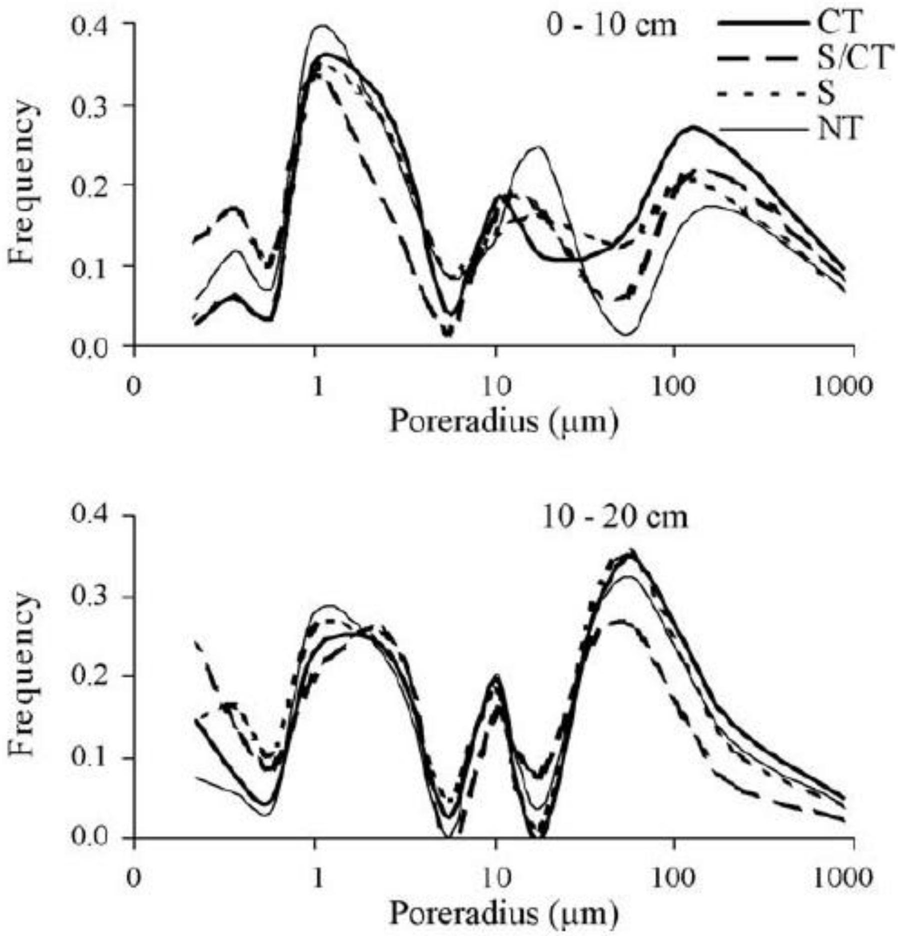


Figure 2-6: Continuous pore size distribution at depths 0-10 and 10-20 cm for the four tillage treatments; ploughing to the depth of 20 cm (CT); ploughing to 20 cm every 6 years and to 5 cm in the remaining years (S/CT);harrowing to 5 cm each year (S); sowing to the uncultivated soil (NT) (Lipiec and Kus, 2006).

Evident from the literature is that no-tillage leads to the development of a new pore system that is more extensive and which could potentially improve water retention and thus the water holding capacity (Bescansa *et al*., 2006), but also hydraulic conductivity. The new pore distribution formed in no-tillage is mainly due to biological porosity, bio-pores that are formed by roots and soil organisms. **Figure 2-7** shows the results of pore size distribution in different tillage treatments of the work done by Sasal *et al.* (2006). Here the pore distribution is not so different between tillage treatments.

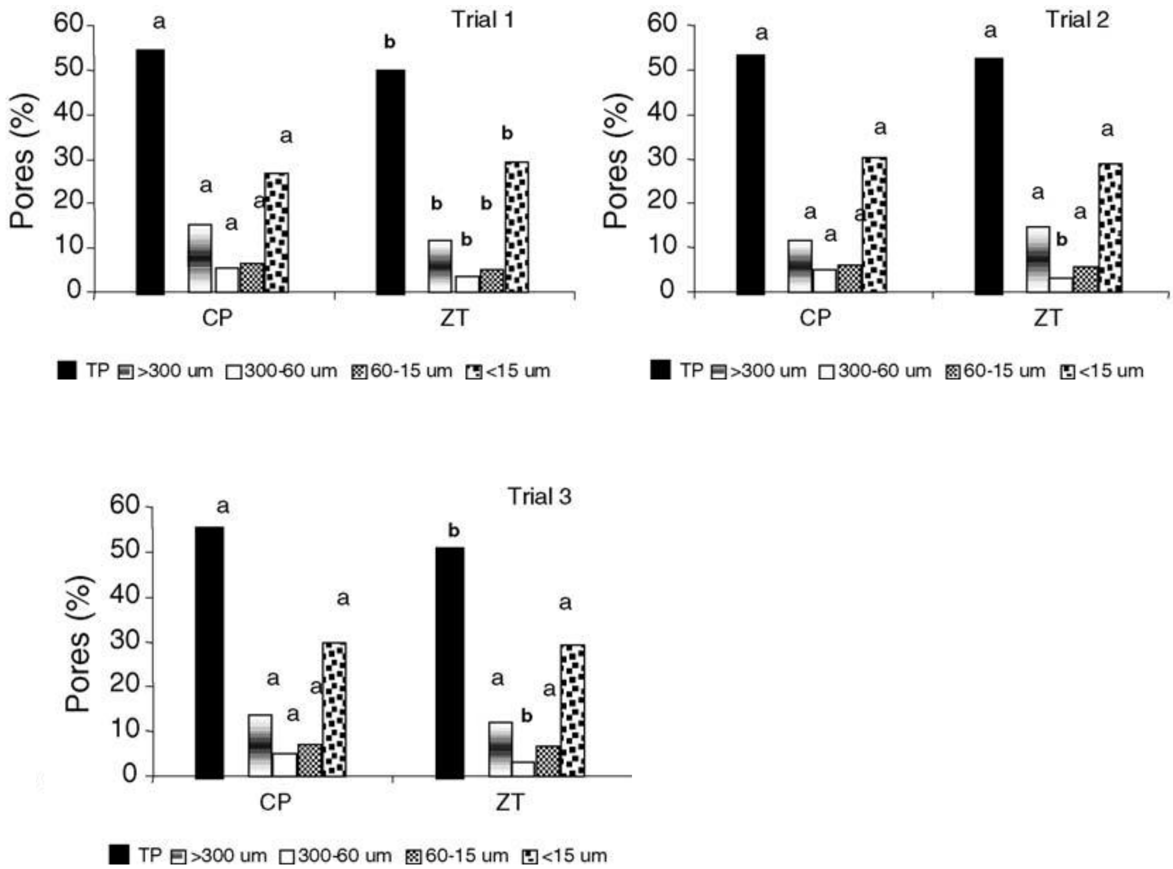


Figure 2-7: Total porosity (TP) and pore distribution (>300, 300-60, 60-15 and <15 µm) under chisel plough (CP) and zero tillage (ZT) of three trials (1,2 and3). Different letters within the treatments for each range of pores mean significant differences ($p < 0.05$) (Sasal *et al.,* 2006)

Soil properties that may influence biological pore generation in no-tillage practices are clay and organic matter content. In soils with high clay content complexes are formed between organic matter and clay. Organic matter is then less accessible to soil organisms and thus lower the soil's biological activity (Sasal *et al*., 2006), limiting pore generation. Pore generation under no-tillage is not always sufficient to increase total porosity of less intensive tillage practices, but in most cases the macro porosity in no-tillage is enough for optimum aeration and water movement (Sasal *et al*., 2006). Biopores are more effective for water and air movement and root growth because they are more continuous, less tortuous, and more stable than macro pores created during conventional tillage practices (Lal and Vandoren, 1990; Sasal *et al.*, 2006). Pore formation is thus influenced by soil organic matter content and tillage and may determine the success of a tillage practice to some extent. Concluding this section on soil porosity, no-tillage practices seem to have less macro pores compared to conventional tillage but the pore-size distribution is stable and still adequate for crop production. In soils with the potential to increase the organic carbon content and/or the biological activity under less disturbance, no-tillage might increase porosity and pore continuity and create preferential flow paths which would improve infiltration and hydraulic conductivity (Benjamin, 1993; Bhattacharyya *et al*., 2009).

2.3.5 Aggregate stability

Aggregate stability is the measurement for the resistance of aggregates against the disintegration into smaller particles when subjected to destructive forces. An aggregate is defined as a group of primary soil particles bound together to form a single primary soil unit. Binding agents in aggregates can be inorganic, such as iron and aluminium oxides, carbonates, amorphous gels and sols. It can also be organic like polysaccharides, hemicellulose, and other natural or manufactured organic polymers. Organic matter is thus considered one of the main binding agents in soil particle aggregation which influences the formation and stabilization of soil aggregates (Filho *et al*., 2002) and tillage practices that would increase the organic matter content of the soil would potentially increase the soil aggregate stability leading to structure development.

In literature, aggregate stability is studied as much as for instance bulk density. Gwenzi *et al.* (2008) conducted research in Zimbabwe in the semi-arid southeastern Lowveld on a Typic Haplustalf under wheat and cotton cropping systems. They found that tillage significantly affected mean weighted diameter aggregates and percentage of water-stable aggregates when the 0-300 mm soil depth was studied. Further the average mean weighted aggregates at the 0-150 mm soil depth decreased in the order: no-tillage (0.22 mm), minimum tillage (0.20 mm) and conventional tillage (0.12 mm). At the 150-300 mm soil depths a similar trend was observed. Water stable aggregates also differed significantly between tillage treatments at the 0-150 mm soil depth, but at the 150-300 mm no differences were observed between minimum and no-tillage but these two treatments were still significantly higher than conventional tillage. In another study by Abid and Lal (2008), results showed that water stable aggregate percentage was significantly more in the no-tillage treatment for all the different aggregate size fractions studied compared to the tine tillage treatment. They also found that the fraction of macro- and micro-aggregates decreased with increased soil depth. **Figure 2-8** shows the results on aggregate size distribution by weight of a study conducted by Martinez *et al.* (2008). They found similar results where mean weighted diameter of all aggregates was greater under no-tillage compared to conventional tillage and also increased with time (years) that the soil was subjected to no-tillage. Interestingly the mean weighted diameter aggregates decreased with depth under no-tillage but increased with depth under conventional tillage. This phenomenon may be linked to soil organic matter concentration and distribution in the soil profile (Martinez *et al*., 2008) and will be discussed next.

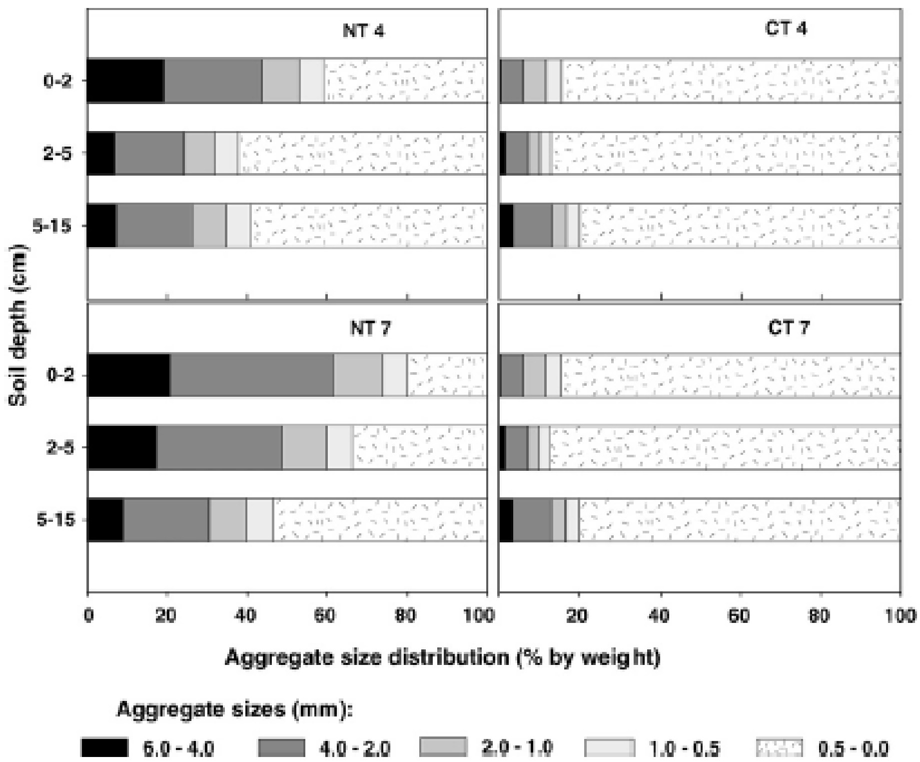


Figure 2-8: Aggregate size distribution under different tillage treatments (Martinez *et al*., 2008) of different aggregate sizes. CT – conventional tillage, NT – no-tillage

Abid and Lal (2008) stated that the effect of tillage on distribution water stable aggregates is manifested through the change in organic carbon concentration. There would therefore be a decrease in water stable aggregates with an increase in soil depth due to the fact that carbon content also decreases. No-tillage, which causes the accumulation of organic carbon at the soil surface, thus leaves more stable aggregates in the soil surface layer. Conventional tillage, which causes a uniform distribution of organic carbon across the tillage depth, could theoretically have more stable aggregates in the deeper soil profile. Interestingly this statement is also confirmed by Filho *et al.* (2002), who found that conventional tillage showed significantly higher numbers of aggregates, although in the smaller aggregate diameters (< 0.25, 0.25 and 0.50 mm) compared to no-tillage. The higher proportion of stable micro aggregates (< 0.5 mm) observed under conventional tillage could be related to the continuous tillage of the soil which inhibits die forming of macro aggregates (Martinez *et al*., 2008) but aggregates do not diminish due to the higher carbon content of conventional tillage in die deeper soil profile. There must therefore be a relationship between aggregate stability and the carbon content of the soil at a specific soil profile depth.

Gwenzi *et al.* (2008) investigated the relationship between soil organic matter and stable aggregates. They found that in the 0-300 mm soil depth both mean weighted diameter aggregates and percentage of water-stable aggregates were highly correlated (linear relationship) with r^2 values of 0.81 and 0.86 respectively. Abid and Lal (2008) also found a linear relationship but just for the 0-100 mm soil depth with an r^2 value of 0.42. Hernanz *et al.* (2002) too, found a linear relationship between water aggregate stability (water stability of 1-2 mm aggregates of the 0-50 mm soil depth) and soil organic carbon with an r^2 of 0.62. This indicates that an increase of soil organic carbon would lead to more stable aggregates and improve soil structure in the long term.

Tillage practices which would thus increase the organic carbon at a certain depth, would have the potential to increase the amount of stable aggregates at that specific depth, which can withstand certain destructive forces (Filho *et al*., 2002; Hernanz *et al*., 2002; Abid and Lal, 2008; Gwenzi *et al*., 2008; Kasper *et al*., 2009), hence the tillage intensity is low. Increases in soil organic matter would also lead to the increase in aggregate size (Yang and Wander, 1998; Kasper *et al*., 2009). The type of tillage practice thus plays an important role because intensive tillage practices like conventional tillage might break down aggregates to micro aggregates as already explained, but it can also increase the carbon content of the deeper soil layer that could in turn lead to aggregate formation and stabilization in the deeper soil layers. Generally the soil surface is the first priority in selecting a sustainable tillage practice such as no-tillage, which is preferred and will promote aggregate formation in the upper soil profile. One of the main reasons is that intensive tillage inhibits the development of larger stable aggregates (Yang and Wander, 1998; Kasper *et al*., 2009). Increased aggregate stability and formation will lead to improved soil structure, which in turn could improve other soil properties. These properties include porosity and water infiltration (Filho *et al*., 2002), but also aeration, water storage potential and drainage. Other factors which contribute to aggregate stability is the crop type, for instance lupines are known to be beneficial in promoting aggregate formation compared to wheat (Chan *et al*., 1994) and also higher amounts of nitrogen in the soil may promote aggregate stability (Filho *et al*., 2002). Tillage practices that increase aggregate stability would thus enhance sustainability.

2.3.6 Penetrometer resistance

Penetrometer resistance is simply the force which is required to push a steel rod into the soil and is also known as cone resistance or mechanical resistance. It more or less simulates the resistance that a root must exercise to grow vertically into the soil. This is an in situ measurement and gives a good idea of soil compaction and limiting barriers that may be present in the soil. Penetrometer resistance also correlates well with sheer strength measurements (Bachmann *et al*., 2006).

Penetrometer resistance is a function of soil structure, bulk density, coarse fragment content and also soil water content. It is necessary to know the water content of the soil where the measurements were taken, because penetrometer resistance increases with decreasing water content (Ball and O'Sullivan, 1982). Penetrometer resistance may also in some cases not have a good correlation to root growth, because roots have the ability to grow around or between obstructions like heavy soil structures, rocks and coarse fragments, whereas a penetrometer need to go right through them (Cameron *et al*., 1987). In soils with a weak structure penetrometer resistance correlates well with the growth of crop roots, but correlation is not so good in soils with a well-developed structure (Agenbag, 1987). It is thus important to describe and note the soil properties with penetrometer results. Gooderham (1977) derived critical penetrometer resistance values of 2.0 to 4.2 MPa (mega Pascal) where root growth of most crops is limited. Penetrometer resistance higher than these critical limits may decrease root growth, and reduce dry matter accumulation and wheat yield (Ferreras *et al*., 2000). Penetrometer measurements are therefore a valuable measurement to help determine soil productivity.

A study by Agenbag and Maree (1991) on penetrometer resistance were conducted on a stony Alfisol (Haploxeralf). Measurements were done 30 days after planting. **Figure 2-9** shows their results. From the figure it is evident that no-tillage (NT) treatment causes significantly higher resistance compared to tine tillage (TT) and conventional tillage (MDT) treatments for the surface soil profile. A sharp increase in the measurements was clear when the different tillage depths were reached: tine tillage at 97-113 mm and conventional tillage at 161-193 mm. Another study also encountered a sharp increase in resistance at 105-135 mm depth in the conventional treatment, probably also giving an indication of the tillage depth (Fernández-Ugalde *et al*., 2009). Sharp increases in conventional tillage treatments, including mouldboard ploughing, might also give an indication of a plough pan being present.

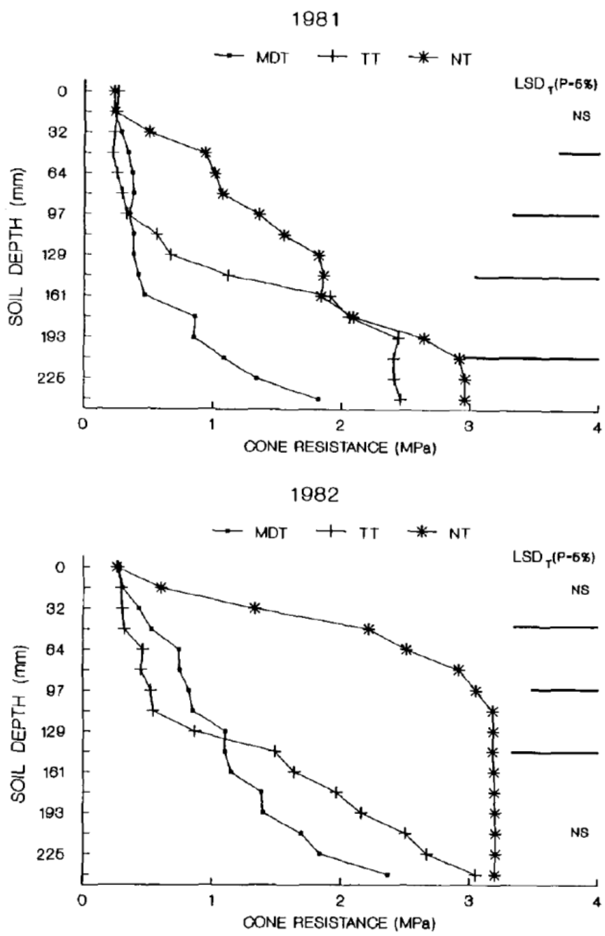


Figure 2-9: Change in cone resistance of a stony soil as a result of different tillage practices (Agenbag and Maree, 1991) MDT - Conventional mouldboard tillage, TT - Tine tillage, NT - No-tillage

Pelegrin *et al.* (1990) also did experiments on an Alfisol (Haploxeralf). Directly after planting there were no differences between tillage treatments to a depth of 150 mm, although in the deeper soil profile conventional tillage had a slightly higher resistance and this was ascribed to a plough pan being present. A few months after planting no-tillage had a significantly higher resistance in the 0-300 mm soil profile, whereas deeper down the soil profile increases and differences were not so prominent. At the end of the growing season the soil was so hard that penetrometer resistance was impossible to measure. In a study conducted in the Southern Cape of South Africa soil penetrometer resistance was significantly higher for the 0-250 mm soil depth in no-tillage compared to conventional tillage practices (Agenbag and Stander, 1988). Moreno *et al.* (1997) found that penetrometer resistance after the first year of planting was also significantly higher in conservation tillage in the 0-

250 mm soil depth compared to conventional tillage. At the third year of planting the same trend were observed only between the 100 to 250 mm soil depths. The 0-100 mm soil surface of no-tillage thus stared to form a loose soil structure displaying the positive effects of the tillage treatment. They also showed that penetrometer resistance increased from planting to flowering stage of the sunflower crop used in their experiments. This increase was only significant in the first year in the conservation tillage treatment. In the third year this increase in conservation tillage was not significant. There was only a tendency for higher penetrometer resistance in the 0-300 mm soil depth. This shows that some sort of equilibrium or soil structure formation is reached after a few years when switching to no-tillage. Martinez *et al.* (2008) made similar findings on penetrometer resistance in a four-year trial in the top 20 mm of the soil. In the 50-150 mm soil depth, conventional tillage had a higher penetrometer resistance compared to no-tillage. After seven years no differences were found between these two tillage treatments. These findings thus emphasizes that no-tillage improves soil structure by decreasing the degree of compaction or consolidation in the long-term.

Ferreras *et al.* (2000) did a study in Argentina on a Mollisol (Petrocalcic Paleudoll). They found that no-tillage increased penetrometer resistance in the top 200 mm soil layer compared to conventional tillage, and stated that the difference is an indication of compaction occurring due to lack of tillage. The increased compaction was only due to tillage practice and not as a combined result of different factors including natural compaction (Ferreras *et al*., 2000). It is interesting that the resistance measured was higher at emergence, which then decreased to harvest time in contradiction to most of the literature. This phenomenon could be due to an intensive root system that developed or fauna activity which might have decreased the bulk density, lowering penetrometer resistance. Their results are shown in **Figure 2-10**. The volumetric water content of the 0-100 mm soil profile was 0.23 for no-tillage and 0.25 for conventional tillage at emergence and corrections were made.

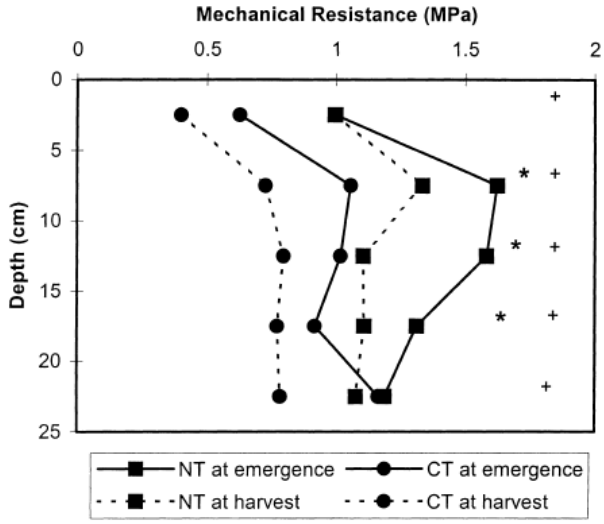


Figure 2-10: Variation of soil mechanical resistance with depth at emergence (August 1994) and at harvest (December 1994), averaged for measurement in the row and in the interrow for no-tillage and conventional tillage. (*) indicates significant differences between treatments at the 0.05 level of probability at emergence. (+) indicates significant differences between treatments at the 0.05 level of probability at harvest (Ferreras *et al.*, 2000)

In most cases no-tillage thus leads to higher penetrometer resistance, which implies that the soil becomes more compacted. A possible reason for higher penetrometer resistance encountered in no-tillage can be as a result of the lack of tillage as was illustrated in the bulk density section. Secondly it can also be the relative heavy weight of no-till, the planter and the combined relative high water content of the soil generally at the time of planting (Martinez *et al.*, 2008) compacting the soil. Although some studies suggested that in the long-term no-tillage may cause a decrease in penetrometer resistance because of the occurrence of soil structure development.

Soil compaction as a result of no-tillage may cause a decrease of restriction in root growth (López-Bellido *et al.*, 1997), dry matter accumulation and finally yield of wheat (*Triticum aestivum L.*) independent of water availability (Ferreras *et al.*, 2000). Although high soil penetrometer resistance in the early stages of the growing season often occur in conservation tillage practices like no-tillage, it does not always have a negative impact on crop growth and yield (Agenbag and Maree, 1991). Importantly long-term studies revealed that penetrometer resistance after more than five years of conservation tillage did not differ from conventional tillage. This might be as a result of increased soil organic carbon content and soil structure which buffered compaction (Martinez *et al*., 2008). Concluding this section, conservation tillage initially leads to higher penetrometer resistance in the upper soil profile but tends to decrease or reach equilibrium relative to conventional tillage. In the next section the effect of tillage on the soil's water dynamics will be discussed.

2.3.7 Water dynamics

The deficiency of water is certainly the most limiting factor in crop production (Bolton, 1981), especially for rain-fed crops in the semi-arid and Mediterranean climates, where rainfall is mostly restricted. Water availability for crops is not only influenced by the climate but also by soil type, crop type, tillage practice and management (Agenbag, 1987) that influence the soil's physical properties. As already known tillage directly affects most of the soil's physical properties and therefore have an indirect impact on the water dynamics (Moreno *et al*., 1997). Knowing that water availability is the most limiting factor in dry land crop production, tillage and crop management practices which would improve water infiltration, storage and availability through the growing season are thus likely to increase crop productivity and yield (Imaz *et al.,* 2010). In this section, the effect of different tillage practices on water infiltration, hydraulic conductivity, soil water retention and storage will be discussed.

2.3.7.1 Infiltration rate

Infiltration is the process by which water enters the soil from the ground surface. The rate of infiltration is the measurement of the rate at which soil is able to absorb water supplied to the surface. The water infiltration decreases as the soil becomes saturated and if the precipitation rate exceeds the infiltration rate, run-off will usually follow. High infiltration rates are essential to areas under dry land crop production to limit run-off where rainfall intensities are high in a short period of time and to facilitate effective water storage. Run-off will also occur if water encounters some physical barrier such as a plough pan which inhibits infiltration. If run-off is a concern in a specific area, it is better to select tillage practices which improve the water infiltration rate.

In a long-term experiment in Nigeria no-tillage had a significantly higher infiltration rate compared to more intensive tillage practices (Lal, 1997), although there were no differences between tillage practices when the equilibrium rate was reached. Moreno *et al.* (1997) made similar findings and showed that infiltration rate was only significantly higher than the tine tillage treatment when compared to no-tillage treatment for the first 30 minutes of infiltration. The results from Sasal *et al.* (2006) confirmed these initial infiltration rate findings, but in one trial there were no differences found between tillage treatments. A study conducted in South Africa on a poor structured soil found that there was no significant difference in final infiltration rate comparing conventional, mulch and no-tillage treatments. The values were 8 $mm.h^{-1}$, 9 $mm.h^{-1}$ and 10 $mm.h^{-1}$ respectively (Hoffman, 1990). No-tillage tended to have a higher infiltration rate.

Contradiction is found in the literature where no-tillage had a lower or no significant higher infiltration rate compared to other tillage practices. Lipiec and Kus (2006) found that conventional tillage had the highest water infiltration rate over 3 hours of water application compared to no-tillage, which was 58% less. Martinez *et al.* (2008) made similar findings. Differences in infiltration rates are mainly due to different pore size distributions with conventional tillage having more macropores.

Infiltration of water is mainly dependent on the number of large pores and biochannels (root channels and fauna tunnels) of the soil profile (Unger, 1990). Higher infiltration rate in more intensive tillage practices can thus be ascribed to more macropores created by intensive tillage but these pores are not stable, as described in previous sections. No-tillage in some cases have higher infiltration rates because it preserves old root- and earthworm-formed channels that are normally disrupted by conventional tillage (Shipitalo *et al*., 2000). No-tillage create a more favourable environment for faunal activity and thus also increase the number of biopores in comparison to a conventional tilled soil (Shipitalo *et al*., 2000). Earthworm burrows and old root channels function as preferential flow paths contributing to 10% of water collected though rain storms (Shipitalo *et al*., 2000). Infiltration rate is thus theoretically higher in no-tillage practices. Morin (1993) stated that in practice conservation tillage in semi-arid regions in Africa eventually leads to improved infiltration rates.

A possible concern of increased infiltration in no-tillage is leaching of salts to the groundwater or the deeper soil profile. Shipitalo *et al.* (2000) stated that with more water infiltration into the soil profile due to conservation tillage, a concern may arise on groundwater quality due to chemical transport of ions. This issue was also highlighted in another study, where no-tillage increases deep drainage and can increase the risk of recharge to saline groundwater, causing a rising of saline water tables (O'Leary, 1996). On the other hand improved leaching of undesirable salts would improve the soil chemical status and have an effect on yield.

2.3.7.2 Saturated hydraulic conductivity

Hydraulic conductivity (K) defines the rate of water movement through a porous medium such as a soil when submitted to a hydraulic gradient and is the ratio of the flux to a hydraulic gradient (Hillel, 1980). Factors that influence hydraulic conductivity in the soil are (1) total porosity (2) permeability (3) tortuosity (4) cracks, wormholes and old root channels in the soil (5) trapped air (6) soil water content (7) soil texture and (8) temperature which is an major determining factor. For instance a clay soil will have a much lower saturated hydraulic conductivity (0.0036-3.6 $mm.h^{-1}$) compared to a sandy soil (36-360 $mm.h^{-1}$) in general (Hillel, 1980). Tillage effects, bulk density and porosity as already discussed in previous sections, would also have an effect on most of the other named factors and will thus indirectly influence hydraulic conductivity.

Benjamin's (1993) tillage study showed that no-tillage had a higher (30-180%) saturated hydraulic conductivity than both conventional and chisel tillage treatments. These findings are confirmed by another study that showed hydraulic conductivity at the surface of a Chromic Vertisol increase about eight times from 12-33 $mm.h^{-1}$ to 145-206 $mm.h^{-1}$ after 10 years of no-tillage compared to conventional tillage (Bissett and O'Leary, 1996). The increase of hydraulic conductivity in the no-tillage practice is mainly due to greater continuity of pores and/or due to flow of water through a few very large pores. These large pores might be created by earthworms and other biological activity due to less disturbance of the soil (Benjamin, 1993) improving hydraulic conductivity. The results of Benjamin (1993) are shown in **Table 2-4**. Another study conducted on a loamy sand soil in Nigeria found that saturated hydraulic conductivity was also the highest under no-tillage, 273.6

mm.h^{-1}, compared to the 230.4 mm.h^{-1} for conventional tillage and stated that total porosity of soil is not the major factor determining hydraulic conductivity (Osunbitan *et al*., 2005). No-tillage thus may have a lower total porosity compared to conventional tillage but a more continuous pore structure and the presence of preferential flow paths will lead to a higher hydraulic conductivity.

The tillage study of Ferreras *et al.* (2000) showed the opposite. Saturated hydraulic conductivity was significantly lower in no-tillage (1.26 mm.h^{-1}) compared to conventional tillage (3.92 mm.h^{-1}) using the constant head technique. This might be due to compaction and a greater percentage of small pores in no-tillage that may impede water flow, and also the absence of fauna activity to create biopores. Another factor may be that this study was conducted over a period of 3 years and might have been too short for a new equilibrium and soil structure to form in the no-tillage practice. Lampurlanés and Cantero-Martínez (2006) made similar findings and stated that with the adoption of no-tillage practices a decrease in hydraulic conductivity can be expected due to a reduction in soil porosity.

Table 2-4: Tillage effects on hydraulic conductivity (Benjamin, 1993)

Tillage effects on hydraulic conductivity (K)							
Rotation	Tillage	Saturation	ψ (kPa)				
			-1.0	-2.5	-5.0	-10.0	-20.0
			K (mm.h^{-1})				
CC	CP	257^{ab}	101^{a}	24.6	11.9^{b}	3.5	1.1
	MP	212^{a}	166^{b}	36.9	15.4^{c}	3.8	1.1
	NT	395^{b}	162^{b}	29.6	9.5^{a}	2.6	0.8
CS	CP	294^{a}	116	39.9	11.1	3.3	0.9
	MP	263^{a}	143	38.1	9.1	2.8	0.8
	NT	375^{b}	112	34.0	10.4	2.3	0.7
COA	CP	264^{a}	74	11.8	5.0	2.2^{b}	0.7
	MP	223^{a}	87	18.6	7.8	2.7^{b}	0.9
	NT	631^{b}	90	17.5	5.0	1.4^{a}	0.6

Means within rotation followed by a different letter are significantly different at P< 0.05. If no letters follow the means, the F statistic was not significant at P< 0.05.

Continuous corn rotation (CC), corn-soybean rotation (CS) and corn-oats-alfalfa rotation (COA); tine tillage (CP), conventional tillage (MP) and no-tillage (NT)

Biological activity is thus an important factor in no-tillage, mainly to create porosity and preferential flow paths. Hydraulic conductivity is thus improved as a result of no-tillage due to increased pore continuity and water flow through larger biopores and channels.

2.3.7.3 Soil water retension

Soil water retention is the ability of the soil to retain water. Water storage in soil is a result of water retention due to suction (negative pressure potential). Suction is created through the soil's pore distribution and to some extent also the texture of the soil. Dao (1993) stated that the presence of more small pores would increase soil water retention capacity. As we already know that tillage has an effect on soil pore distribution, it would thus also affect soil water retention. Aggregation also affects the water storage capacity of a soil (Unger, 1997).

Bescansa *et al.* (2006) showed that conventional tillage resulted in decreased water retention capacity and thus more soil water loss through drainage. Water retention at 0 kPa (no-suction) was greater for chisel and conventional tillage treatments but at -33, -50 and -1500 water retention was greater for no-tillage in the 0-600 mm soil depth. He *et al.* (2011) obtained similar results, showing that no-tillage also had a higher water retention capacity. No-tillage thus has a greater potential for storing water and indicates that more water may be available to the crop for uptake and growth through the season. Fernández-Ugalde *et al.* (2009) concluded that soil water retention characteristics are improved in no-tillage practices, compared to conventional tillage, and was shown in the yields being twice as high in barley production in the driest year.

Concluding this sub section, no-tillage change the pore size distribution of the upper soils profile (0-200 mm), with small pores being more predominant and thus increasing the water retention capacity, leading to higher available water content (Bescansa *et al*., 2006).

2.3.7.4 Soil water holding capacity

Soil water storage is the ability of a soil to store water that is plant available defines between an upper (field water capacity) and lower limit (permanent wilting point). The storage capacity is largely determined by the retention capacity, the pore size distribution, texture and soil structure or aggregation. The higher the storage capacity of a soil, the higher the soil's crop production potential will be, as already said. Water availability is the most limiting factor in dry land crop production.

Agenbag and Maree (1991) showed that less intensive tillage treatment like tine and no-tillage had higher soil water content through the growing season compared with conventional tillage in the 0-300 mm soil profile. Another study in the same type of climate and soil conditions showed similar findings. Plant-available water content was significantly greater for no-tillage in die 0-300 mm soil depth compared with conventional tillage, but in the deeper depths no differences were observed between encounters (Fernández-Ugalde *et al*., 2009). Fabrizzi, García, Costa and Picone (2005) compared the water storage in the 0-80 mm soil depth of minimum and no-tillage under a corn-wheat rotation on a Typic Argiudoll. No-tillage had significant higher water content for corn from 50 days after planting and for wheat from planting till anthesis, but thereafter differences were not significant. Numerous other studies showed that available water capacity (water storage) was greater under no-tillage than under more intensive, conventional tillage practices (Berry *et al*., 1985; Cameron *et al*., 1988; Buschiazzo *et al*., 1998; Moussa-Machraoui *et al*., 2010). **Figure 2-11** shows the results of Agenbag and Maree (1991).

Ferreras *et al.* (2000) also found that soil water content was only significantly higher under no-tillage practices but only early in the growth season until anthesis of wheat. In the study of Agenbag and Maree (1991), lower water contents in the conventional tillage at the end of the growing season contributed to significantly more water stress days compared to the no-tillage treatment. A stress day was defined as a day when the water potential reached below 1500 kPa. On average, conventional tillage had eleven stress days more than no, and four more than tine tillage. Moreno *et al.* (1997) concluded that *"Under the conservation, tillage applied to the crop saved water early in the season, leaving more water for the seed or grain filling season"*. As a result, yield is generally higher than no-tillage practices in dry years. Conservation tillage thus seems to be more effective in improving soil water recharge and water conservation, especially in years with below average rainfall (Hamblin, 1987; Moreno *et al*., 1997).

Main reasons for increased water storage under conservation tillage practices like no-tillage is improved water infiltration, hydraulic conductivity, water retention capacity and better pore size distribution and continuity as described in the previous subsections.

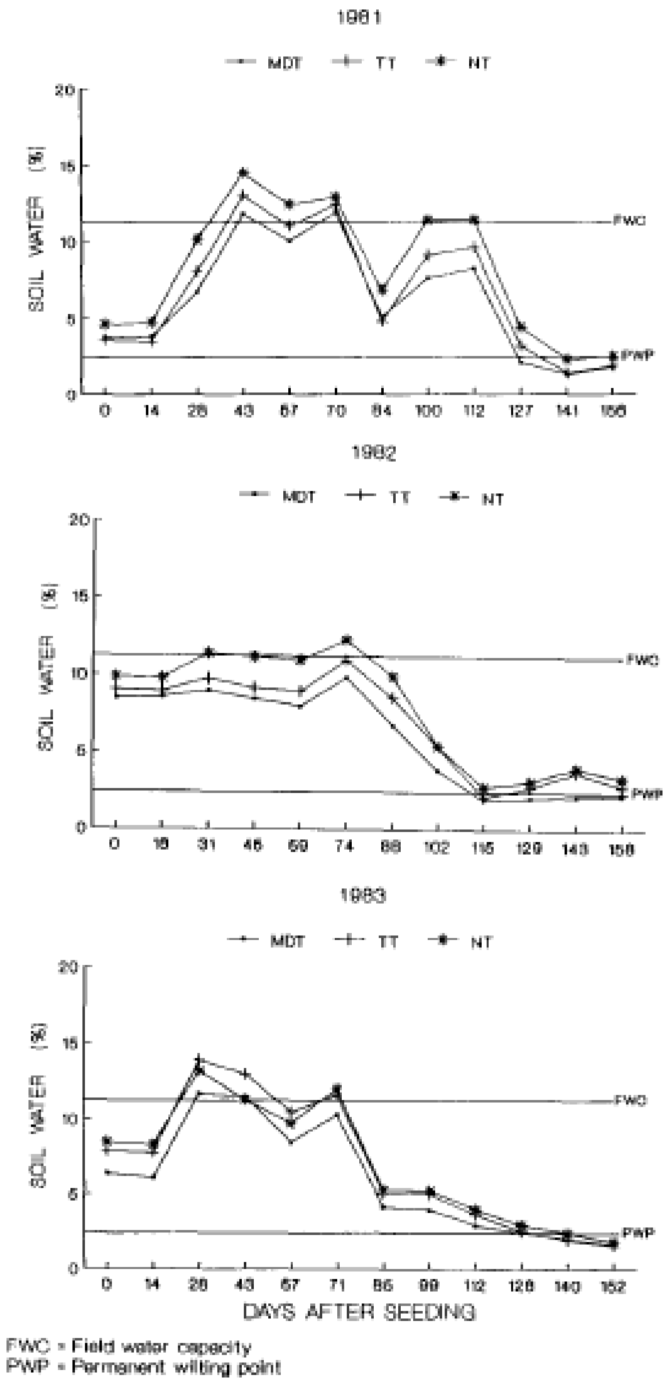


Figure 2-11: Effects of tillage on the soil water content in the 1981-1983 period; conventional tillage (MDT), tine tillage (TT), no-tillage (NT) (Agenbag and Maree, 1991).

There are also additional reasons for increased available water content in no-tillage practices. First, soil water content can also be increased by less soil disturbance and more plant residues on the surface to reduce evapotranspiration (Jones *et al*., 1968; Dao, 1993).

No-tillage have a lower water evaporation rate from the soil surface, thus increasing available water content through the season (Cameron *et al*., 1988; Huggins and Reganold, 2008; Moussa-Machraoui *et al*., 2010). A second reason is explained by Martinez *et al.* (2008). They showed that no-tillage had greater air entry values indicating that more time is needed for the soil profile to drain (unsaturated) and thus help to retain more water through the growing season. Thirdly Abid and Lal (2009) showed a linear relationship between plant available water and soil organic carbon content. **Figure 2-12** shows the relationship with an r^2 value of 0.89. Increasing the carbon content (organic material) of the soil would increase the plant available water content. No-tillage thus has higher water content due to accumulation of organic matter. The main effect of higher organic matter content is that it promotes aggregate formation and structure development which leads to higher storage capacity for plant available water content (Birkás *et al*., 2004; Abid and Lal, 2009).

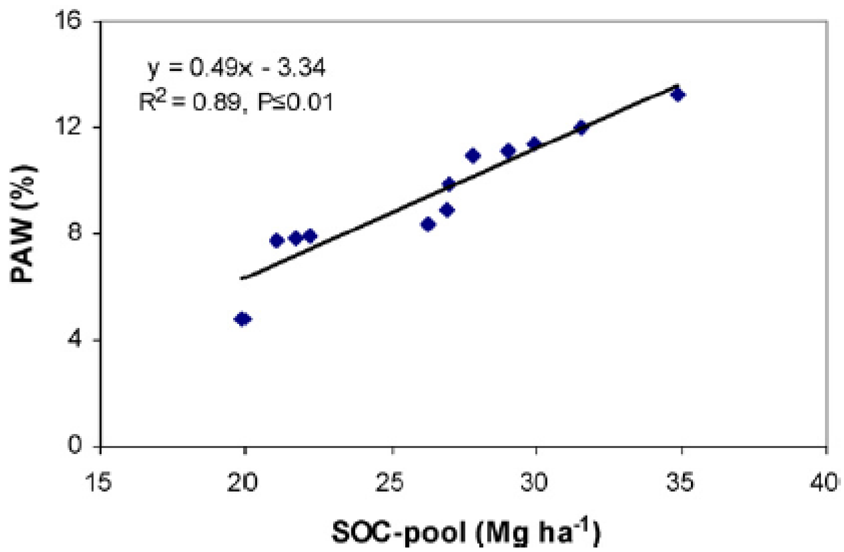


Figure 2-12: The effect of soil organic carbon on plant available water (%) for the 0-100 mm soil depth. SOC Soil organic carbon: PAW: Plant available water (Abid and Lal, 2009)

Conservation tillage practices have higher water contents through the growth season which can potentially lead to high yields, especially in dry seasons with below average rainfall.

2.4 Conclusion

In an extensive study on the effects of common tillage practices on soil properties it becomes clear that agriculture, no matter what type of tillage practice you use, is not completely sustainable towards the soil. There is always some factor which contributes to unsustainability. The tillage practice that would have the least impact on the environment in a certain area and specifically the soil would thus be the most sustainable practice in that area. In most cases no-tillage (a conservation tillage practice) is such a practice because it improves soil quality, especially in the semi-arid Mediterranean climate. Imaz *et al.* (2010) confirmed this statement by using a quality indicator response technique. No-tillage is a more sustainable system for the Mediterranean region (Hernanz *et al*., 2002) but also in semi-arid areas and in some humid areas.

Concluding on the soil properties studied in this section, one can say that in general particle-size distribution is not affected by tillage, although coarse fragment content is affected. Tillage practice, like conventional tillage and any practice with a deep tine application would increase the coarse fragment content in the soil surface layers (Oostwoud Wijdenes and Poesen, 1999). High amounts of coarse fragments at the soil subcase could reduce run-off and evapotranspiration but also hamper the plantning operation and influence seed germination. Organic matter is increased in conservation tillage practices when studying the soil surface. In most cases the organic carbon content is significantly higher comparing to intensive tillage practices like conventional tillage and will have a pronounced effect on other properties. The higher amount of organic carbon in the surface soil profile would directly affect soil properties such as the aggregate stability and indirectly affect water properties like infiltration rate and water storage capacity (Birkás *et al*., 2004; Abid and Lal, 2009). Bulk density and penetrometer resistance are in most cases increased under conservation tillage practices but not to such an extent that root and plant growth are significantly affected. In most cases crop yield is the same or higher, compared to other tillage practices (Agenbag and Maree, 1991). Total porosity is altered by no-tillage, with small pores becoming more dominant and bigger pores decreasing, while the opposite is true for conventional tillage in the short term. This phenomenon leads to higher retention capacities, which increase plant available water content. Increased plant available water content through no-tillage helps to overcome the negative causes, like higher bulk density and penetrometer resistance characteristic of this tillage practice (Fernández-Ugalde *et al*., 2009). A major advantage of conservation tillage is erosion control. Surface run-off can be virtually eliminated with no-tillage due to higher infiltration rates due to preferential flow paths created naturally (Shipitalo *et al*., 2000).

A common problem that arises under no-tillage is increased compaction which cannot be corrected an ounce off tillage treatment, because it would have a negative effect on soil quality, primarily at the soil surface (Lopez-Garrido *et al*., 2011). Although under moderate signs of soil compaction, soil physical properties responsible for the dynamic processes maintaining soil functionality for crop development are generally still intact (Cavalieri *et al*., 2009). Thus water infiltration and soil aeration will still be adequate to allow satisfactory crop yields. No-tillage especially outperforms other tillage practices in dry years because of increased plant available water storage underground. No-tillage is thus less appropriate during wet years in Mediterranean and semi-arid climates or in areas with high rainfall (Lampurlanés *et al*., 2001).

Conservation tillage, such as no-tillage practices is thus potentially better for semi-arid and Mediterranean regions because it maintains greater water content in the soil, especially in years of low rainfall. The main soil-related advantages of no-tillage over conventional tillage, therefore, is increased organic matter content, aggregation and plant available water content through the growing season, showing significantly higher yields than conventional tillage in dry years (Hamblin, 1987; Agenbag and Maree, 1991; Morell *et al*., 2011). Especially in the Swartland wheat production area of the Western Cape, if used in combination with crop rotation and high N fertilizer rates (Agenbag, 2012). No-tillage is thus the a sustainable tillage practice according to the literature study, although there are a few concerns.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study area

The study site of this project is the same site that Agenbag (1987, 2012), Agenbag and Maree (1989, 1991) and Maali and Agenbag (2003, 2006) used for their tillage research. The tillage experiment was initiated in 1975. Since then the experiment continued and is still running, therefore this experiment is already in action for 37 years.

3.1.1 Locality and climate

The research were conducted on the Langgewens research farm, 18 km north of Malmesbury in the Western Cape (33°16'34.41" S, 18°45'51.28" E). This region of the Western Cape is known as the Swartland small grain production area. The climate is typically a Mediterranean climate with warm, hot summers and mild winters that receives an average of 275-400 mm of rain per year. Eighty percent of the rainfall occur during the autumn/winter/spring months of April to September. Most of the cereal crops are planted from May after the first rain has fallen and harvested from mid-October to November. **Table 3-1** shows long-term climate data of the Langgewens research farm.

Table 3-1: Long-term monthly climate data for Langgewens research farm

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Maximum temperature (°C)	30.5	30.2	28.8	24.9	20.6	18.1	17.0	17.8	20.2	23.7	27.3	29.0	288.1
Minimum temperature (°C)	16.3	16.9	15.8	13.6	11.1	9.3	8.0	8.2	9.1	11.0	13.5	15.1	147.9
Evaporation (mm)	319.	288	245	171	105	75	71	84	120	198	267	313	2257
Rainfall (mm)	8.1	10.6	15.4	30.5	58.3	64.4	58.2	61.7	36.8	24.3	15.0	12.0	395.3
Raining days	2.3	2.3	3.0	5.6	8.8	9.1	9.5	10.0	7.9	5.7	3.3	2.9	70.4

The long-term annual aridity index can be calculated from this data by the ratio of average annual rainfall (395 mm) and average annual evapotranspiration (2268 mm). Although the aridity index uses evaporation data calculated from the Penman monteith method, the class A-pan evaporation method is used instead and will also give a good indication of the aridity index. This resulted in a long-term annual aridity index of 0.17. According to Stewart and Robinson (1997) this an arid bioclimatic zone where it is very difficult to apply and practice sustainable crop production.

Figure 3-1 shows the location of the research farm. The N7 national road can be used as a reference point. **Figure 3-2** shows where on the farm the experiment site is located and the different block is also shown. The elevation of this site varies between 214 and 230 mm with an average slope of 0.05 %.

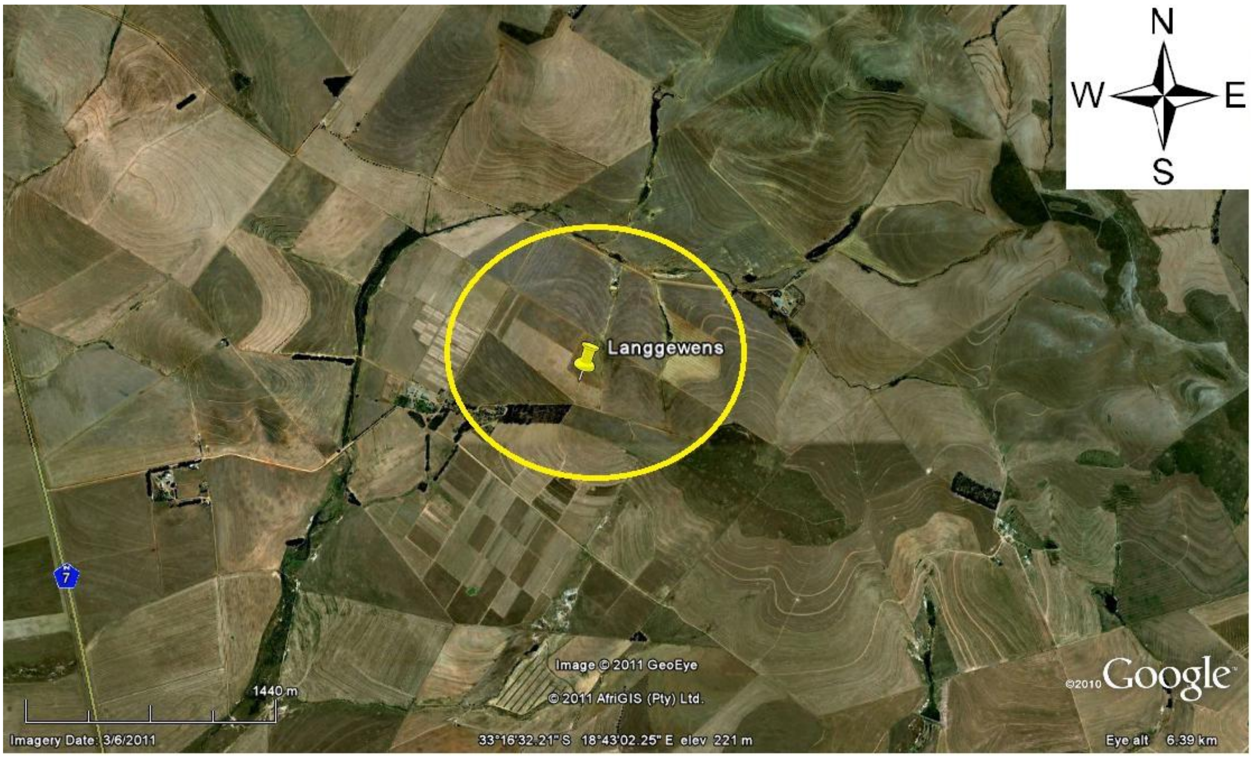


Figure 3-1: Picture of the Langgewens experimental farm

Figure 3-2: Picture of the Langgewens experiment site

3.1.2 Soil type and classification

The classification of the soil was accomplished by excavating 16 profile pits. All the profiles resembled the same soil form and family type. According to the South African classification criteria, the soil encountered is a Glenrosa soil form (Soil Classification Working Group, 1991). The soil profile has a bleached Orthic A horizon on a Lithocutanic B horizon with underlying hard shale. The profiles were mostly shallow and are seldom deeper than 900 mm. Thereafter rock and shale parent material are encountered. The A horizon depth vary from 200 to 300 mm with sandy-loam texture and is the main horizon studied. The Lithocutanic B horizon depth varies from 400 to 600 mm, is mostly very hard, and does not contain any free lime. This soil also shows no signs of wetness. These characteristics place this soil form in the Bisho family but in two occurrences, the family classification is an Overberg due to the Lithocutanic B horizon being soft. According to the Soil taxonomy classification system the soil profile is classified as a Lithic Haploxeralf (Soil Survey Staff 2010). **Figure 3-3** shows the excavator that was used digging the soil profiles. Worth mentioning is that these soils are very hard in the summer months and thus it was a difficult task for the operator to dig these profiles. The figure also gives some perspective of how shallow these soils are. **Figure 3-4** shows a picture of the Glenrosa soil form encountered at the experimental site on the Langgewens research farm.

Figure 3-3: Excavating the soil profiles

Figure 3-4: Soil profile showing the Glenrosa soil form

The soil is very stony (30-45%) and contains saprolite schist fragments (weathered shale) right through the profile. Termite and ant nests are also common in this experimental site and activity is quite high through the season. **Figure 3-5** shows a picture of a termite nest.

Figure 3-5: Termite nest encountered in some of the no-till treatment sites

3.2 Experimental design

Prof. Agenbag started the experiment in 1976 with three main tillage treatments (conventional mouldboard ploughing, tine tillage and no-tillage) in combination with two cropping systems. The initial experiment included 14 different methods of tillage compared in a wheat monoculture system. Minimum tillage was introduced later in 1990. The experiment was then split into two cropping systems, adding crop rotation. Worth mentioning is that the conventional, tine, and no-tillage treatments are still applied on the same plots as in 1976. The experimental design is randomized blocks with the four main tillage treatments and three tillage combinations, thus seven different tillage practices. The two cropping systems are wheat monoculture and wheat-lupine-wheat-canola crop rotation. There are thus fourteen different experimental treatments. The experiment also has four replicates, Blocks A, B, C and D, which make up the total of 56 experimental plots.

In this study only the four main tillage treatments with the wheat monoculture treatments will be studied. The reason is to eliminate the positive effects of crop rotation on the soil's physical and chemical properties and thus merely look at the effect of tillage on the soil properties. In our study, there are therefore sixteen experimental plots. Each plot is 5 m by 50 m with a 2 m pathway between treatments and width between blocks is approximately 10 m. **Figure 3-6** shows the layout of the different tillage treatments allocated in the four blocks. The colours indicate the different tillage practices as follows: Blue = No-tillage, Green = Minimum tillage, Orange = Tine tillage and Red = Conventional tillage. The same colour coding is used throughout this thesis.

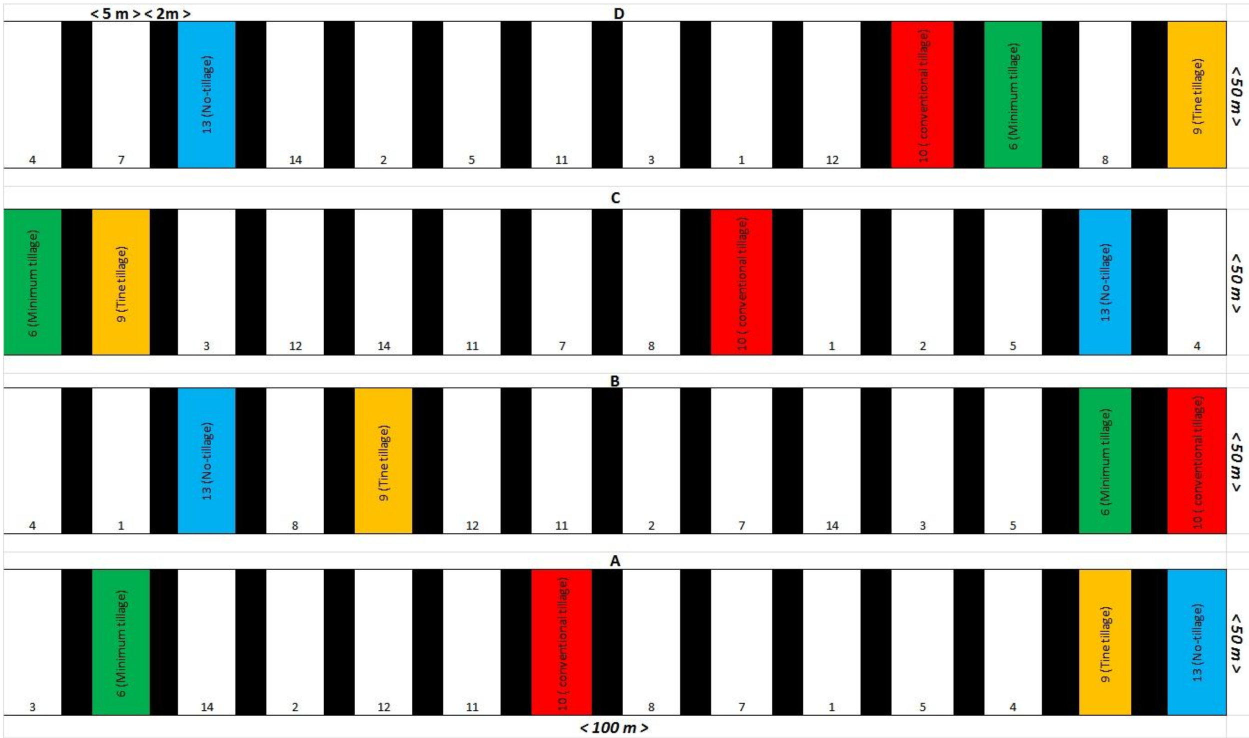


Figure 3-6: Experimental randomized block design

3.3 Tillage treatments

There are four tillage treatments: conventional tillage, tine tillage, minimum tillage and no-tillage. The treatments were as follows:

1. **Conventional tillage (CT) treatment** consist of a primary tillage with a chisel plough to a depth of 150 mm then mouldboard ploughing to a depth of 200 mm after the

first April-rain has fallen, followed by mechanical weeding with a field cultivator and levelling rod before planting to a depth of 75 mm.

2. **Tine tillage (TT) treatment** consists of a primary tillage by a scarifier (type of chisel plough) to a depth of 150 mm, followed by the same mechanical weeding as with conventional tillage, before planting.
3. **Minimum tillage (MT) treatment** consists of one tillage treatment with a chisel plough to a depth of 100 mm and weeds are controlled chemically with pre-plant non-selective herbicide
4. **No-tillage treatment (NT)** consists of only chemical weed control with pre-plant non-selective herbicide.

All plots were planted in May by an Ausplough, DBS multistream C-series, fitted with knife-openers and press wheels. The planter is shown in **Figure 3-7**.

Figure 3-7: No-till Ausplough DBS multistream C-series planter use to plant the site

3.4 Soil sampling and preparation

For each tillage treatment and replicate, a soil profile was dug with an excavator, on 2 March 2011. The soil form classification was done for each site as mentioned in section 3.1.2. Thereafter photos were taken and the GPS coordinates were recorded. The land position, slope, horizon depths and the wet and dry Munsell colours as well as the soil structure were noted for each horizon along with some visual remarks that could be seen in the profiles. Texture class, clay percentage, coarse fragments and sand grade were subjectively determined. Soil samples were excavated on 19 April 2011 when the soil was virtually dry, just before planting. This was done with a geological hammer and shovel from each horizon, to determine the physical and chemical properties. The orthic horizon was split in two sampling depths of 0-100 mm and 100-200 mm. The lithocutanic B horizon was also sampled. The sample size was 5.5 kg per depth. All the samples were air dried and passed through a 2 mm mesh diameter stainless steel sieve separating the soil and coarse fragments. No extensive crushing of the soil was done due to the shale coarse fragments being soft and could thus easy be crushed and then incorrectly pass through the 2 mm sieve. Coarse fragment percentage was calculated for all the samples. Sub-samples were obtained through a soil splitter. These sub-samples where used in the laboratory for chemical and physical analysis.

3.5 Soil chemical analysis

3.5.1 Soil pH

Soil pH was measured in distilled water and KCl on a mass basis according to Thomas (1996). pH in KCl (1 mol.dm^{-3}) solution was done in a 1:2.5 soil to solution ratio and pH in distilled water was also determined in a 1:2.5 soil to water suspension ratio for both the 0-100 mm and 100-200 mm soil sampling depths. The soil suspension of each sample was shaken with an IKA® KS 260 basic instrument for 30 minutes and thereafter centrifuged for 10 minutes to obtain a clear water suspension. Samples were then left to stand for 10 minutes to equilibrate. A calibrated *Metrohm, Swissmade, 827 pH lab* electronic pH meter was used for the determination. These results are reported as pH (KCl) and pH (H2O) respectively.

3.5.2 Soil electrical conductivity (EC)

Electrical conductivity (EC) gives an indication of the total dissolved salts concentration in the soil. Distilled water was used for the soil suspensions. The EC was determined according to a 1:5 soil to water suspension ratio on a mass basis (Rhoades, 1996) for both the 0-100 mm and 100-200 mm soil sampling depths. The soil suspension of each sample was shaken with an IKA® KS 260 basic instrument for 30 minutes and thereafter centrifuged for 10 minutes to obtain a clear water suspension. Samples were then left to stand for 10 minutes to equilibrate. Measurements were done using a calibrated *Microprocessor Capacitance Meter, RE 387 Tx, Series 3*. The EC results are reported as EC ($mS.m^{-1}$).

3.5.3 Resistance and saturated paste extract (cations and anions)

A saturated paste extract were done to determine the salts in solution according to Rhoades (1996), and provide further information on the result of the EC. Soil resistivity is a measure of how much the soil resists the flow of electricity. Resistance (ohm) of the saturated paste was determined by a *Metrohm AG. Herisau, Schweiz Konduktometer E382*. It is thus the opposite of the EC measurement and would help to support the results obtained by the electrical conductivity analysis.

This was only done for the 0-100 mm soil sampling depth conventional and no-tillage treatments because this was where the main differences in the electrical conductivity results occurred. Approximately 400 g of soil was saturated with distilled water until a smooth sludge was reached. The suspension must be semi-flowing. Thereafter the saturated soil was left to stand for one hour but from time to time it was consolidated though stamping of the beaker. A Buchner tunnel was used to separate the water from the soil under vacuum. The water samples were sent for cation and anion analysis at the Environmental Central Analytical Facility (CAF) of Stellenbosch University.

3.5.4 Total carbon content

Total carbon gives the amount of all the carbon present in the soil. Total carbon content was determined because methods currently available to use for determining organic carbon content are not very accurate. Total carbon percentage was determined for the A-horizon for the two sampling depths of 0-100 mm and 100-200 mm according to Nelson and Sommers (1996). A subsample of 10 gram soil was taken and milled to a very fine powder for 3 minutes, using a *Retsch S 1000* ball mill before it was sent for analysis at the Environmental Central Analytical Facility (CAF) of Stellenbosch University.

3.6 Soil physical analysis

3.6.1 Particle size distribution

Two methods were used to determine the particle size distribution. The standard pipet method and a relative new method called laser diffraction, which is a much faster, easier method. The new method consists of a single instrument that uses a small amount of soil to determine the particle size distribution. The main reason for using two methods is to compare and evaluate the new method.

3.6.1.1 Pipet method

Textural analysis of the soils was done for the A-horizon for the two sampling depths of 0-100 mm and 100-200 mm for all the replicates. Subsamples of 40 g of soil (<2 mm) were used. The soil particle classes was determined according to Gee and Bauder (1986). The following selected procedures were used for the analysis:

The sample was chemically pre-treated by firstly removing the organic matter using 35% by volume H_2O_2 solution. The loss of mass after organic matter removal was recorded. Secondly, clay dispersal was done by adding 10 cm^3 Calgon solution to the sample and mechanically stirring the mixture for 5 minutes at a high speed. Thereafter the dispersed soil was washed with distilled water through a 0.053 mm mesh sieve into a 1 dm^3 sedimentation cylinder separating the silt and clay from the sand fraction.

The remaining sand fraction on the 0.053 mm mesh sieve was separated in different fractions by sieving the dried sample through a series of stainless steel sieves with mesh diameters; 0.5, 0.25, 0.106 and 0.053 mm. Each sand fraction was weighed and reported as a percentage of the initial soil fraction, excluding the organic matter mass. The fine silt and clay fractions were determined last, using the sedimentation technique and a Lowey pipette. After the fine silt and clay percentages were calculated, the coarse silt percentage was obtained by subtracting the entire known fraction from 100%.

3.6.1.2 Laser diffraction

As already stated, soil particle distribution via laser diffraction was done in order to compare the results to the conventional pipet method, because human error is excluded with this instrument. This method is dependent on a particle's ability to scatter light at an angle directly related to their size, when passing through a laser beam (Webb, 2000). A particle-size instrument based on light scattering can distinguish the scattering patterns of large particles from small particles because large particles scatter strongly and principally to small angles away from the incident light beam while small particles scatter weakly, with too many larger angles (Wedd, 2003). A laser particle size analyser was used (Micrometrics Instrument Corporation, Faculty of Process Engineering, Stellenbosch University) and is able to 'see' particles smaller than 1 mm. This method differs from the pipet-method and represents the particle distribution in volumetric percentage and not as a mass percentage.

Laser textural analysis of the soils (<2 mm) was done only for the conventional and no-tillage treatments. Two separate experiments were performed. The first experiment fractions from 2 to 0.25 mm were separated through sieve method (Gee and Bauder, 1986) and the remaining fractions were determined using a laser particle size analyser. The second experiment fractions from 2 to 0.106 mm were separated through the sieve method (Gee and Bauder, 1986) and the remaining fractions were determined using a laser particle size analyser. Data was analysed with Saturn Digisizer 5200 software and converted to mass percentage. **Table 3-2** showed the particle size classes and the separation method used.

Table 3-2: Particle size classes (Soil classification working group, 1991) and method of separation

Fraction	Diameter (mm)	Separation method
Coarse sand	2 - 0.5	Sieve
Medium sand	0.5 - 0.25	Sieve
Fine sand	0.25 - 0.1	Sieve / Laser diffraction
Very fine sand	0.1 - 0.05	Laser diffraction
Coarse silt	0.05 - 0.02	Laser diffraction
Fine silt	0.02 - 0.002	Laser diffraction
Clay	< 0.002	Laser diffraction

3.6.2 Aggregate stability

Aggregate stability of the soil under the different tillage treatments was determined by the wet sieving method. Soil samples were taken on 26 March 2012 when the soil was still dry and virtually at the permanent wilting point. Aggregate stability gives a good indication on how resistant a soil's structure (soil peds) is against destructive mechanical or chemical forces.

In a trial run of the experiment, soil aggregates with a size of 1-2 mm in diameter were used, as described in the standard method. Because the soil in this study is shale derived it contains many fine shale/schist fragments that is smaller than 2 mm in diameter. When separating these small aggregates from the soil, shale fragments were often misjudged to be aggregates. The result of this pre-experiment was therefore not accurate and little significant differences were found between treatments. This was mainly because the sub samples used for determining aggregate stability contained very few aggregates and were thus not adequate to be a representative sub-sample. There was decided to use bigger aggregates of 2.35 to 4 mm in diameter. This meant that it was easier to obtain 'real' soil aggregates that were more representative of the tillage treatment.

The fraction of water-stable aggregates (WSA) per tillage treatment was determined by making use of the method based on the work of Kemper and Rosenau (1986). Samples were collected from all 16 tillage treatment sites. The wet-sieving method relies on the use of a dispersion agent and therefore soil pH was determined in both distilled water and 1 M KCl. According to the pH, one of two dispersion agents was used.

Individual aggregates were first selected from the bulk samples to exclude small shale fragments and other non-aggregate particles. Four grams of the aggregates (2.35-4 mm) where weighed and placed on a 250 µm sieve. Samples were pre-soaked with distilled water and left to stand for a few seconds. Two sets of cans were also weighed and numbered beforehand. The first set of cans (for non-water stable aggregates) were filled with distilled water and the second set of cans (for water stable aggregates) were to be filled with a dispersion agent. The dispersion agent/solution used were already mentioned according to the soil pH in water. If the soil pH is higher than 7, a 0.05 M sodium hexametaphosphate solution is needed and if the pH is below 7, a 0.05 M NaOH solution is needed to disperse the water stable aggregates.

After the samples have been pre-wetted, the sieve holder was placed in the working position, submerging the samples in the cans containing distilled water. The motor was started by setting the main switch to the ‘3 min’ position. The stroke length is fixed at 1.3 cm and the cycle at about 34 times per minute. At the end of this first sample run (3 minutes), the motor stops automatically. The sieve holder is now lifted out of the water and permitted to stand until all the excess water has drained. The cans containing the non-water stable aggregate fraction were replaced with the second set of cans containing the dispersion agent. Then the sieve holder was placed in the working position and the motor started by switching it to the ‘continue’ position. The sieving was continued until only loose soil particles were left on the sieve (about 5-10 minutes). A glass rod was used to stir the soil in each sieve to make sure that all the aggregates have disintegrated. The sieve holder was then raised and left until the excess dispersion solution has drained.

Both sets of cans were then placed in an oven and left to dry for 24 hours at 105°C. The fraction of water-stable aggregates was calculated as follows, by dividing the mass of water stable aggregates by the sum of the non-water stable and water stable aggregates. The water stable aggregates are then presented as a percentage.

3.6.3 Bulk density

3.6.3.1 Field measurement via a Troxler instrument

Field bulk density was first determined by the sand-fill method where a known mass of soil was taken and the hole in the soil was filled with sand with a standard bulk density from which the volume could be calculated (Blake and Hartge, 1986). This method proved to be inaccurate due to the soil containing high amounts of coarse fragments. These coarse fragments hampered/interfered with bulk density measurements because the hole in the soil was made via a steel cylinder and when removing it, some of the soil fell back into the hole, interfering with the volume of the soil. Another drawback of using this method in stony soils, is that when pouring the sand into the hole it was not always possible to fill the hole perfectly due to gaps created by the stones. The method was also not suitable for in situ measurements. Thus, an alternative method was used.

Field bulk density was therefore determined by a surface gamma-neutron gauge for in situ measurement according to the method described by Blake and Hartge (1986). The instrument used is a *Troxler surface gamma-neutron probe model 3401-B* from Troxler Electronics Laboratories. This method would be the most accurate because human error would be minimal and the soil variation is taken into account. The surface bulk density (0-100 mm) was measured over time using the backscatter technique. The Troxler instrument held a number of advantages; first, a single measurement takes about 1 to 2 minutes, so that many measurements (samplings) could be done in one day. In situ measurement and repeated measurements of the same sample area was also possible. Therefore temporal changes can be measured at a fixed site. Through this method a large number of measurements can be made quickly and the seasonal bulk density variation could be recorded and studied. A potential drawback of this instrument is that coarse fragments is also taken into account and may therefore influence the reading. Originally, coarse fragments also form part of the soil and should therefore be included when determining the soil bulk density, but this is augmentable.

For this study, five measurements were made on each tillage site, giving 20 bulk density replicates for each tillage treatment. Measurements were taken between planting rows, approximately every month, according to the availability of the instrument. **Figure 3-8** shows the instrument.

Figure 3-8: ***Troxler*** **bulk density instrument**

Seasonal bulk density variations were measured for the first season from 21 June 2011, 25 days after tillage operations until 12 April 2012, 321 days after planting and just for the first half of the next season from 23 May 2012, 27 days after tillage till 19 July 2012, 84 days after tillage.

3.6.3.2 Comparison of the Troxler instrument to the clod bulk density method

The Troxler instrument was calibrated using the clod method. The main reason was to evaluate the accuracy of the Troxler results and comparison of the two methods. Equations could then be derived to convert a Troxler bulk density measurement to a clod bulk density value. Carefully selected undisturbed clods were sampled on 12 April 2012 in the 0-100 soil depth (similar to the depth the Troxler uses for estimating the bulk density) on one of the five undisturbed measurement sites of each tillage treatment at all the blocks, after the bulk density was determined by die Troxler instrument. The bulk density of the clods was determined by the clod method (Blake and Hartge, 1986).

The clod method procedure: The clod was weighed to obtain the net weight in air. Thereafter the samples were oven-dried for 24 hours at 105°C and the oven-dry weight was recorded. The clod was secured with two loops of a thread at right angles to one another. Afterwards the clod was dipped in hot paraffin wax (about 70°C) for a few seconds and then lifted out, allowing the wax to dry. This step was repeated until the clod was waterproof. The clod with wax coating was then weighed to determine the net weight of the clod and wax coating. The sample was then again weighed when completely suspended in water; the water temperature was also recorded. This procedure was conducted on all the clod samples. The bulk density of each clod was then calculated from the following equation:

$$\rho b = \frac{\rho w * W_{\mathrm{ods}}}{W_{\mathrm{sa}} - W_{\mathrm{spw}} + W_{\mathrm{pa}} - (W_{\mathrm{pa}}\, \rho w / \rho p)}$$

Where:

W_{ods} = oven-dry weight of the soil sample (gram)

W_{sa} =net weight of the sample in air (gram)

W_{spw} = net weight of the sample plus wax in water (gram)

W_{pa} = net weight of the wax coating in air (gram)

ρ_p = density of the wax ($g.cm^{-3}$)

ρ_w = density of water at the temperature of determination ($g.cm^{-3}$)

The bulk density results of the Troxler instrument was plotted against the results of the bulk density of the clods and a linear regression was fitted.

3.6.3.3 Laboratory measurement for determining the bulk density of the soil fraction

Bulk density was also determined in the lab using just the fine soil fraction (< 2mm). This experiment was conducted to see if the fine soil fraction (including micro aggregates) showed the same trend that was found in the field measurements and to find maximum bulk density values to see how the coarse fragments influenced the Troxler measurement.

Thirty-two aluminium rings were taken and a Whatman 54 filter paper was glued at the one end of each ring. The diameter and height of each ring was recorded. Thereafter 50 grams of soil (< 2 mm) form the 0-100 mm soil depth of the no-tillage and conventional tillage treatments was weighed and placed into each ring and consolidated slightly. There were now 16 rings filled with no-tillage soil and 16 rings with conventional tillage soil. After the soil was levelled in each ring, the initial bulk density was determined by measuring the height of the soil in the ring with a calliper.

The soil-filled rings would now be subjected to six wetting and drying cycles. Half of the samples of each of the two tillage treatments were selected randomly and would be treated additionally with a constant consolidation treatment. The other treatment was just the wetting and drying of the soil. To wet the soil the rings were placed in a tray filled with water up to half of the ring's height. The rings were then left to stand in the water for about 30 minutes until the soil was saturated. Thereafter the rings were placed for 5 minutes on paper towels to allow the excess water to drain. The wet bulk density was then calculated after measuring the wet height of the soil in each ring. Thereafter all the rings were placed in an oven to dry for 12h at 60^{o}C. The dry bulk density was then calculated by measuring the dry soil height in each ring. The procedure was repeated five more times. **Figure 3-9** shows a photo of the aluminium rings used for the experiment.

Figure 3-9: Laboratory bulk density experiment

3.6.4 Sheer strength

A hand held Pocket vane tester was used to determine the sheer surface strength of the different tillage treatments. A complete description of this instrument can be found on the web site http://www.eijkelkamp.com under products, pocket vane tester.

Only the soil surface (0-10 mm) was used for the measurements. Fifteen measurements were taken for each tillage replicate, thus giving 60 readings for each tillage treatment. Measurements were taken between the planting dates of 23 May and 19 July 2012. Readings are given in kg/cm^2 and are converted to kPa through a simple equation. **Figure 3-10** shows the instrument used in the field. Soil samples (0-10 mm) were also taken at both measuring dates for determining gravimetric water content that can have an influence on the measurements.

Figure 3-10: Pocket vane tester used to determine the sheer strength for the different tillage practices

3.6.5 Saturated hydraulic conductivity

Saturated hydraulic conductivity was determined, according to Klute and Dirksen (1986), by taking undisturbed soil samples. Only conventional and no-tillage treatment areas were selected for this experiment. Steel pipes with external dimensions, 110 mm in diameter and 400 mm in length, were used to sample undisturbed soil columns at 19 July 2012. Each pipe was forced into the soil, (was assisted with hammer if needed) to about 250 to 300 mm in the soil profile. It was not possible to sample deeper, due to the high course fragment content and a possible plough pan in the conventional tillage treatment. Eight samples were taken. Four samples for conventional and four for no-tillage. In the laboratory, the soil columns (pipes) were subjected to a constant water head of 150 mm. Water that moved through the column was discarded for the first two hours to completely saturate the column and thereafter water that moved through the profile was collected and measured every 15 to 30 minutes. Two experiments were performed – the first one directly after the water had moved movement through the profile for two hours. This experiment took six hours and 15 minutes and consisted of 25 measurements. The second experiment was conducted after eight hours of continued water movement through the columns and left to stand for one day. The time lapse for this experiment was four hours during which eight measurements were taken. Darcy's equation was used to calculate the hydraulic conductivity in mm.h^{-1}. The equation looks as follows:

$$K = \frac{Q}{a} * \frac{L}{\Delta H}$$

Were:

K = hydraulic conductivity (mm.h^{-1})

Q = Volume of water the flowed though per time unit (mm^{-3})

A = Area the water flowed through (mm^{2})

L = Length of the column containing soil (mm)

ΔH = Height of the hydraulic head and the soil column (mm)

3.6.6 Shale (coarse fragment) water storage potential

The coarse fragments mainly consisted of shale fragments although a very small percentage of this was quartz. To analyse the water storage potential of these shale coarse fragments one profile was studied: a tine tillage treatment of Block D. The coarse fragments obtained after sieving the sampled soil were used for this experiment. The sample is therefore a composite sample, meaning that it contained all the different sizes of coarse fragments. The water storage potential of the shale coarse fragment was determined for the Orthic A and the Lithocutanic B horizons. A sample of the parent material below the Lithocutanic B horizon was also analysed. Coarse fragments larger than 2.35 mm were used. **Figure 3-11** shows the coarse fragments encountered in this Glenrosa soil profile.

From each horizon coarse fragments were divided according to size and 100 to 400 g of each size was placed in a 400 ml beaker. In the first experiment, each beaker was filled with distilled water and left for 24h to saturate completely. Thereafter the water was drained and the excess water on the rocks removed with towel paper. The wet mass of the coarse fragments was then recorded and the gravimetric water contents calculated. The second experiment was the same but the water-filled beakers were placed under suction for 24 h to remove entrapped air bubbles present in the shale coarse fragments.

The volumetric water content was also calculated, but the bulk density of shale was required in the equation. The bulk density was thus determined for 16 samples of randomly selected large shale coarse fragments taken from the profile. The clod method was used to determine the bulk density (Blake and Hartge, 1986), as already explained. Knowing the bulk density of the shale fragments, the volumetric water content of all the samples was calculated.

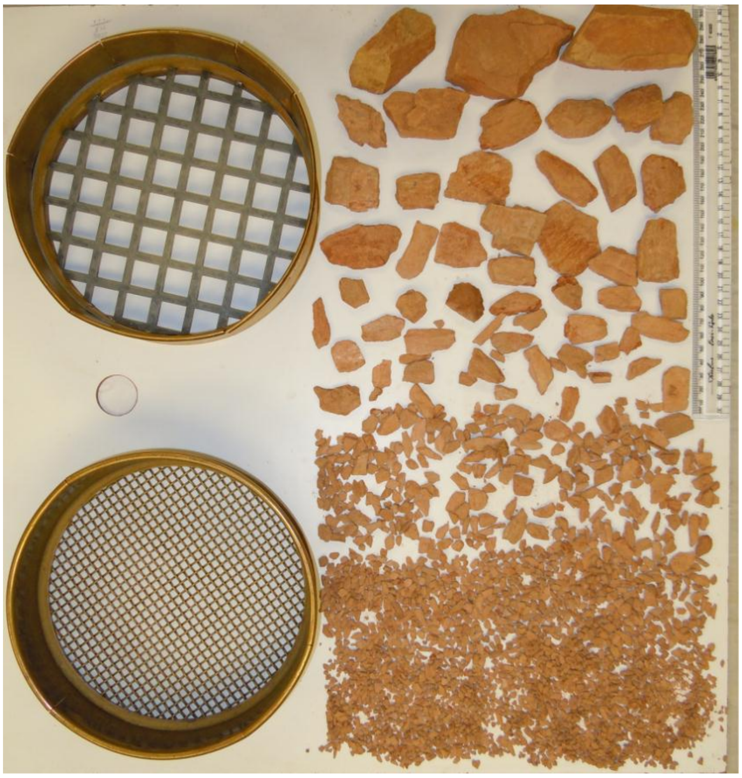


Figure 3-11: Coarse fragments of the Lithocutanic B horizon (Tine tillage treatment Block D)

3.7 Statistics

The *SAS Enterprise Guide 4.1* statistical package (Copyright © 2006 by SAS Institute Inc.) was used for statistical analysis of results obtained by the different experiments conducted. Each tillage treatment was assigned a single colour, which would be the same in all the graphs and tables. Data assumptions that were tested before any statistical analyses were done are the assumptions that data are normally distributed, homoscedasticity and independent of observations. Generally the main effects were tillage treatments, replicates, sampling depth and interaction. The data set of each soil's physical or chemical properties was first analysed by ANOVA tables to look specifically for tillage and sample depth interactions. Thereafter each sampling depth was statistically analysed separately even if there was no interaction observed. Some properties of the Lithocutanic B horizon were also analysed but separately because tillage depth was never deeper than 300 mm. Tukey's studentized range were the comparison method used to compare tillage treatments at a 0.05 significance level. Bar and line graphs contain the main effect p-values for the tillage treatment of each ANOVA table. The standard error is also shown on the graphs. Differences between tillage treatments are indicated by letters ranging from a to d. Tillage treatment is indicated with a different letter, for example by an a and b which differs significantly from each another with respect to that specific soil property analysed. Linear regressions were also performed to test for correlations where needed.

CHAPTER 4: RESULTS

4.1 Introduction

In this chapter the results of basic chemical and physical properties will be deliberated. Various regression results will also be discussed to inspect correlations.

4.2 Chemical properties

The following chemical properties were selected for analysis because these properties have a significant influence on the soil's physical properties. Tillage practices that will influence and change these properties directly will also have an indirect influence on some physical properties. A well-known example is where the soil's total carbon content affects the soil's structural properties. These interactions will be discussed at the end of Chapter 5. The chemical results will be presented in the following order: soil pH (H_2O and KCl), electrical conductivity (EC), resistance and water soluble ions and total carbon content.

4.2.1 pH in water (H_2O) and potassium chloride (KCl)

Figure 4-1 shows the results of **pH (H_2O)** for the different tillage treatments at the two sampling depths. From the graph the soil pH for the different tillage treatments are between 6.5 and 5.5 units. These values are slightly acidic, which is normal for this type of agricultural soil. It seems as if the pH is more or less the same at both sampling depths for all the tillage treatments, although no-tillage in the 0-100 mm depth has a slightly higher pH.

Analysing the dataset of pH (H_2O), no interaction was observed between tillage treatment and sampling depth ($p = 0.219$). Interpreting the main effects, sampling depth did not differ significantly ($p = 0.317$), therefore there was no difference between the two sampling depths. The replicates differed significantly from each other ($p = 0.003$) as did the tillage treatments ($p = 0.011$), showing that there were differences between treatments in the total 0-200 mm depth. No-tillage (pH 5.95) had a significant higher pH compared to minimum (pH 5.63) and tine tillage (pH 5.59) but not conventional tillage (pH 5.68) treatments. As already mentioned the sampling depth are going to be interpreted separately even if there are no interaction between tillage treatment and sampling depth. In the 0-100 mm the replicate main effect differed significantly (p = 0.003) and indicates therefore that there are soil differences. Tillage treatments also differed significantly (p = 0.002). No-tillage had a significantly higher pH in water compared to the other tillage treatments which did not differ from each other. In the 100-200 mm soil depth replicate the main effect did not differ significantly (p = 0.337). No significant differences were observed between tillage treatments (p = 0.737).

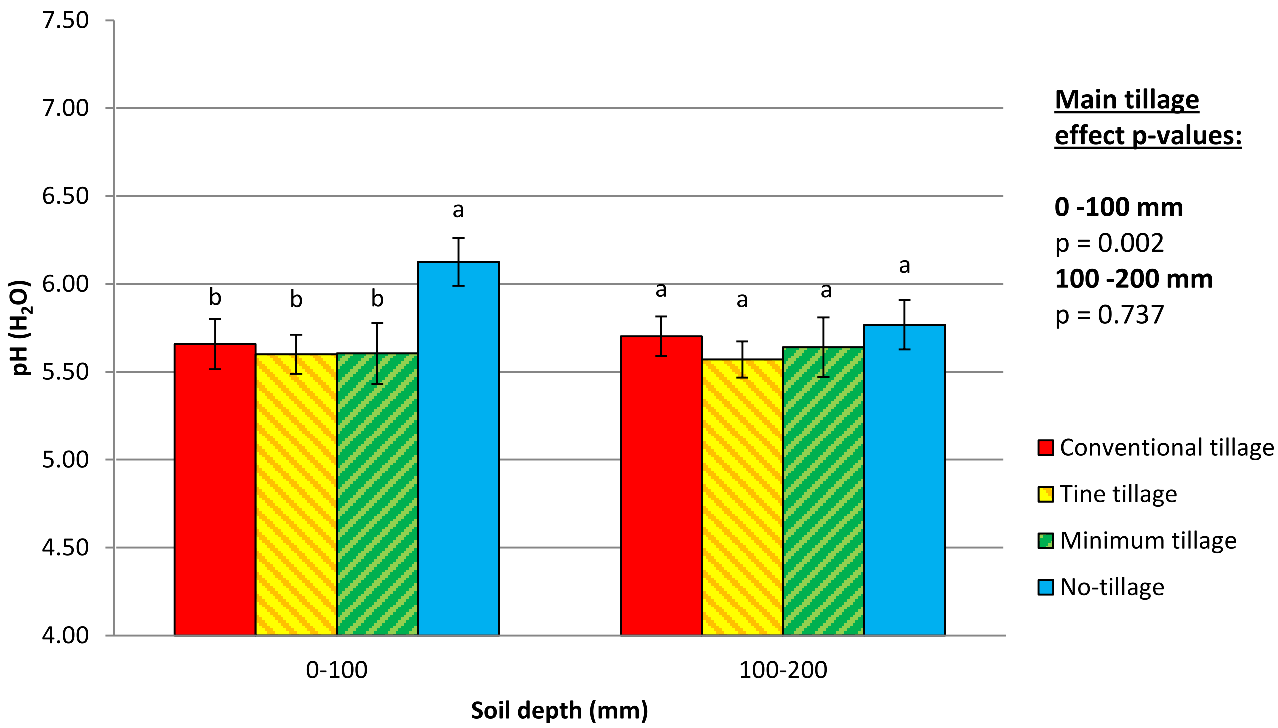


Figure 4-1: pH (H_2O) of the 0-100 and 100-200 mm soil depth for the different tillage practices

Figure 4-2 shows the results of pH (H_2O) of the different tillage treatments for the Lithocutanic B horizon. From the graph the soil pH of the different tillage treatments are between 6.9 and 5.9 units. Statically analysing the data of the Lithocutanic B, the replicate main effect did not differ significantly (p = 0.804). No difference was also found between tillage treatments (p = 0.294). Although the same trend was observed as in the 0-100 mm soil sampling depth with the no-tillage treatment showing a higher pH about 0.93 units higher than the tine tillage.

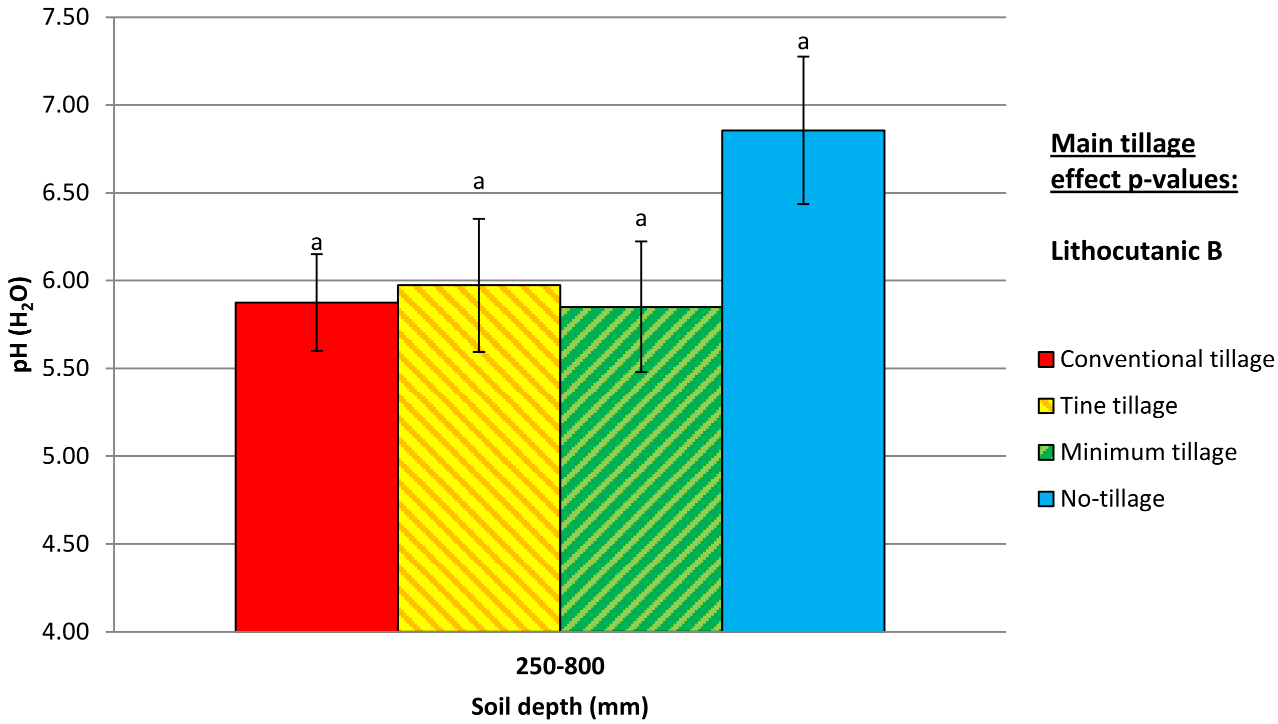


Figure 4-2: pH (H_2O) of the Lithocutanic B for different tillage practices horizon

Figure 4-3 shows the results of pH (KCl) for the different tillage treatments at the two sampling depths. Comparing the results to the pH in water, the pH values in KCl is on average one unit lower. The results of the different tillage treatments vary between 4.20 and 4.92 units and are acceptable for agricultural soil.

Analysing the dataset of pH (KCl), again no interaction was found between tillage treatment and sampling depth ($p = 0.866$). Interpreting the main effects, replicates ($p = 0.003$) and sampling depth ($p = 0.024$) differed significantly. The 0-100 mm depth had a significantly higher pH (KCl) compared to the 100-200 mm sampling depth, although the tillage treatments did not differ significantly ($p = 0.141$), and showed that there were no differences between treatments in the 0-200 mm depth. Looking at the depths separately, in the sample from 0-100 mm the replicate main effect differed significantly ($p= 0.003$), indicating that there were soil differences. No differences were observed between tillage treatments ($p= 0.053$), but no-tillage did have the highest pH. In the 100-200 mm soil depth no differences were observed for the replicates ($p = 0.270$). There were also no significant difference observed between tillage treatments ($p = 0.771$) as was observed in the pH (H_2O)

results. This is mainly due to high variance of the measurements. No-tillage and minimum tillage showed a marginally higher pH compared to conventional and tine tillage.

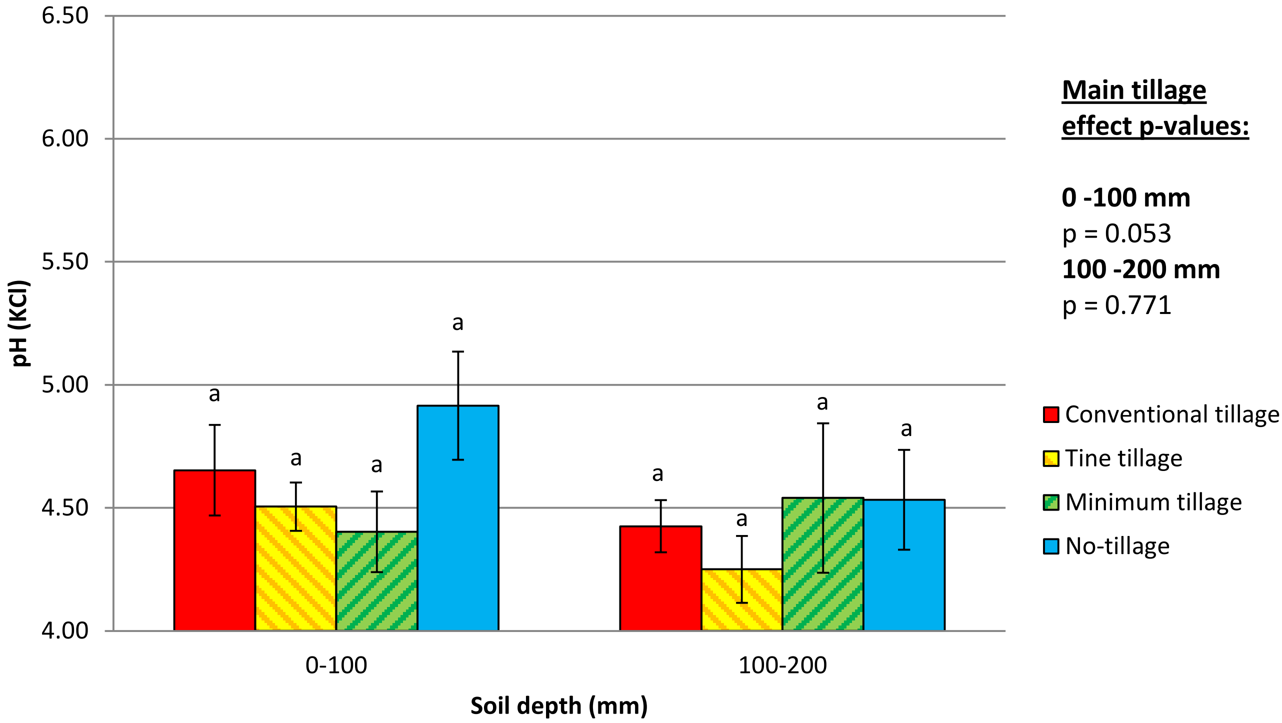


Figure 4-3: pH (KCl) of the Orthic A (0-100 and 100-200 mm) for different tillage practices

Figure 4-4 shows the results of pH (KCl) of the different tillage treatments at the Lithocutanic B horizon. From the graph the soil pH of the different tillage treatments are between 4.6 and 5.5 units. The replicates did not differ significantly (p = 0.735) and no difference was found between tillage treatments (p = 0.402). Still no-tillage showed a higher pH compared to the other tillage treatments.

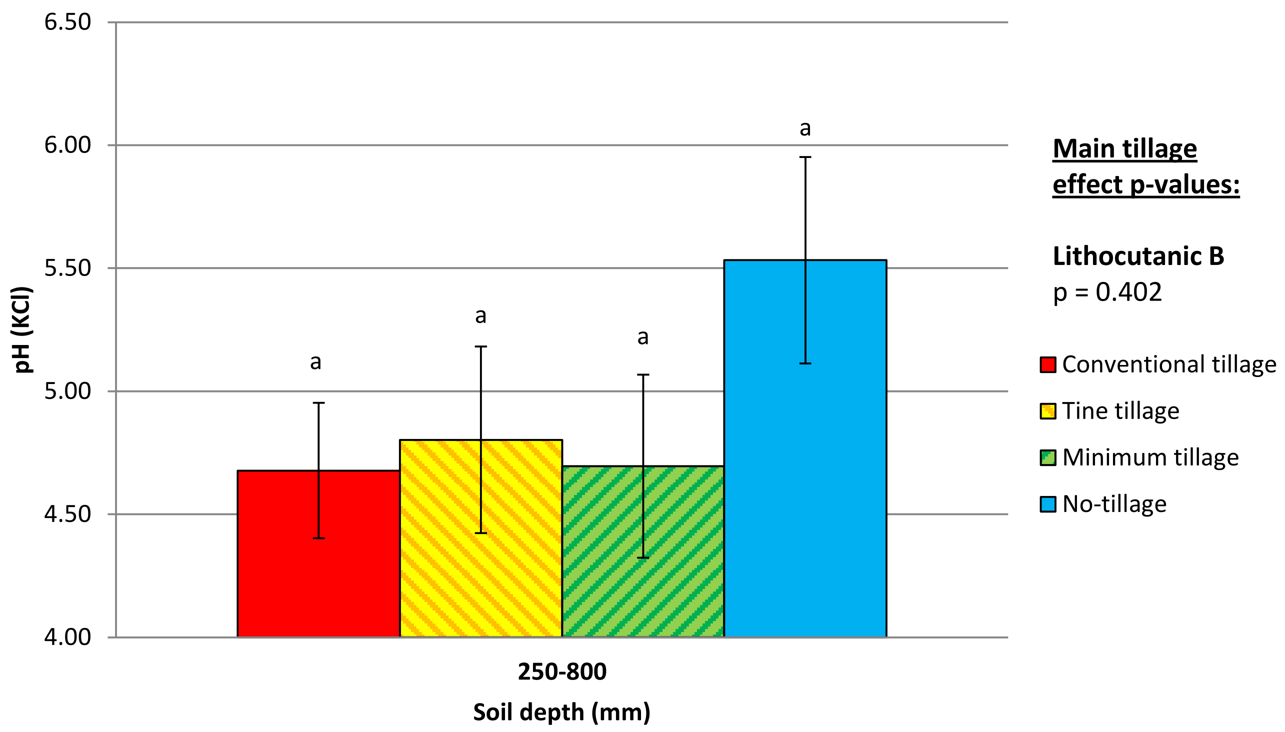


Figure 4-4: pH (KCl) of the Lithocutanic B for different tillage practices horizon

4.2.2 Electrical conductivity (EC)

Figure 4-5 shows the results of the electrical conductivity for the different tillage treatments of the two sampling depths. According to the *Fertilizer handbook of South Africa* these salinity values would have no to very little effect on plant growth because the EC values range from 6.2 to 16.5 $mS.m^{-1}$ for all the tillage treatments. EC values that are between 201-400 $mS.m^{-1}$ would only affect sensitive crops and values between 401 and 800 $mS.m^{-1}$ would lower the yields and growth of most crops.

Looking at the 0-100 mm depth one can clearly see that conventional tillage had a higher electrical conductivity (16.29 $mS.m^{-1}$) compared to the other three tillage treatments. In the 100-200 mm sampling depth, the EC values were similar across the different tillage treatments, but again the conventional tillage treatment had a slightly higher EC (8.52 $mS.m^{-1}$).

Significant interaction between tillage treatments and sampling depth was found (p = 0.035). Interaction between these two main factors indicates that the sampling depths should be analysed separately. In the 0-100 mm soil sampling depth, replicates did not differ significantly (p = 0.269), but tillage treatment did (p = 0.001). The EC was significantly higher for conventional tillage compared to the other tillage treatments. No differences were observed between the tine, minimum and no-tillage treatments. At the 100-200 mm soil sampling depth, replicates differed significantly (p= 0.004) indicating soil differences, but tillage treatments did not (p = 0.392). Conventional tillage, however, tended to have a higher EC compared to the other tillage treatments.

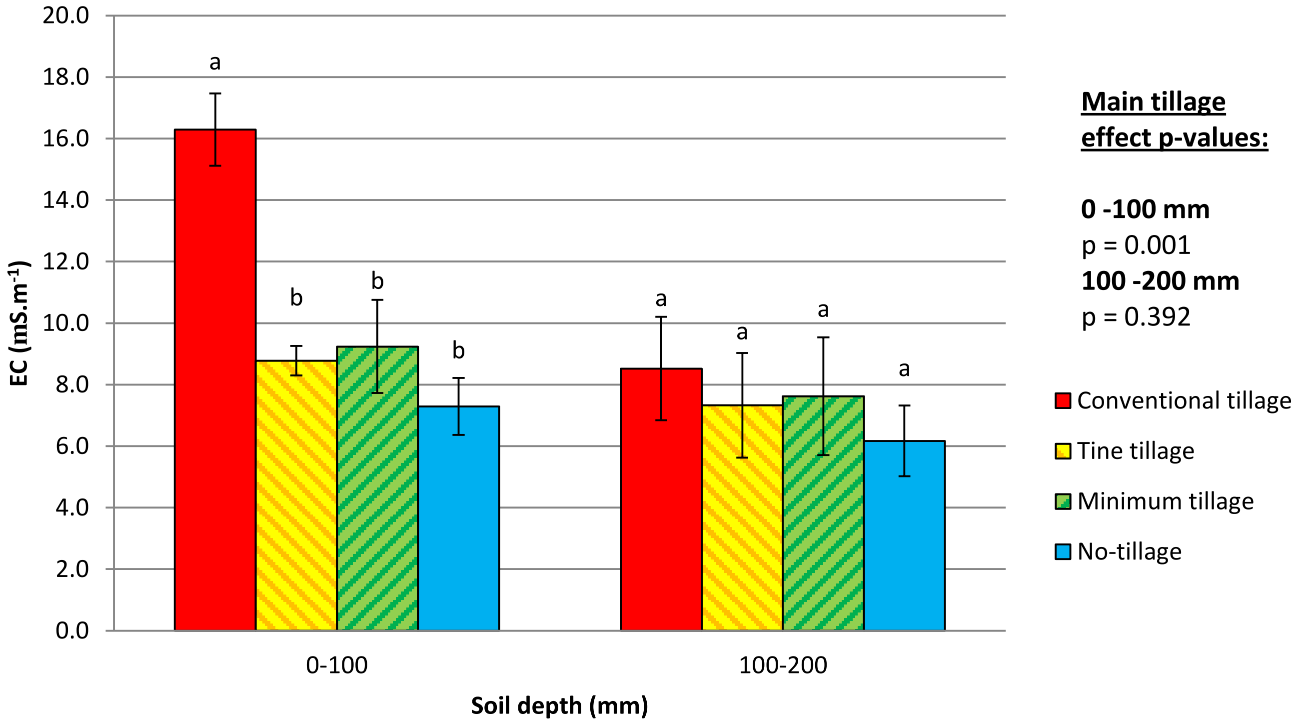


Figure 4-5: **EC of the Orthic A (0-200 mm) for the different tillage practices**

Figure 4-6 shows the results for the different tillage treatments of the EC in the Lithocutanic B horizon. Conventional tillage (9.27 $mS.m^{-1}$) had the highest EC followed by minimum (8.37 $mS.m^{-1}$) then tine (7.58 $mS.m^{-1}$), with no-tillage (6.67 $mS.m^{-1}$) having the lowest EC. The trend shows that the EC increases from no, minimum, tine to conventional tillage. Comparing to the 0-100 mm and 100-200 mm sampling depth tine, minimum and no-tillage had about the same EC. Analysing the data for the Lithocutanic B horizon, the replicates did differ significantly (p= 0.004), but there were no differences between tillage treatments (p = 0.253). This is mainly due to high variance of the measurements owing to the small fraction of soil (about 20%) in relation to the coarse fragments.

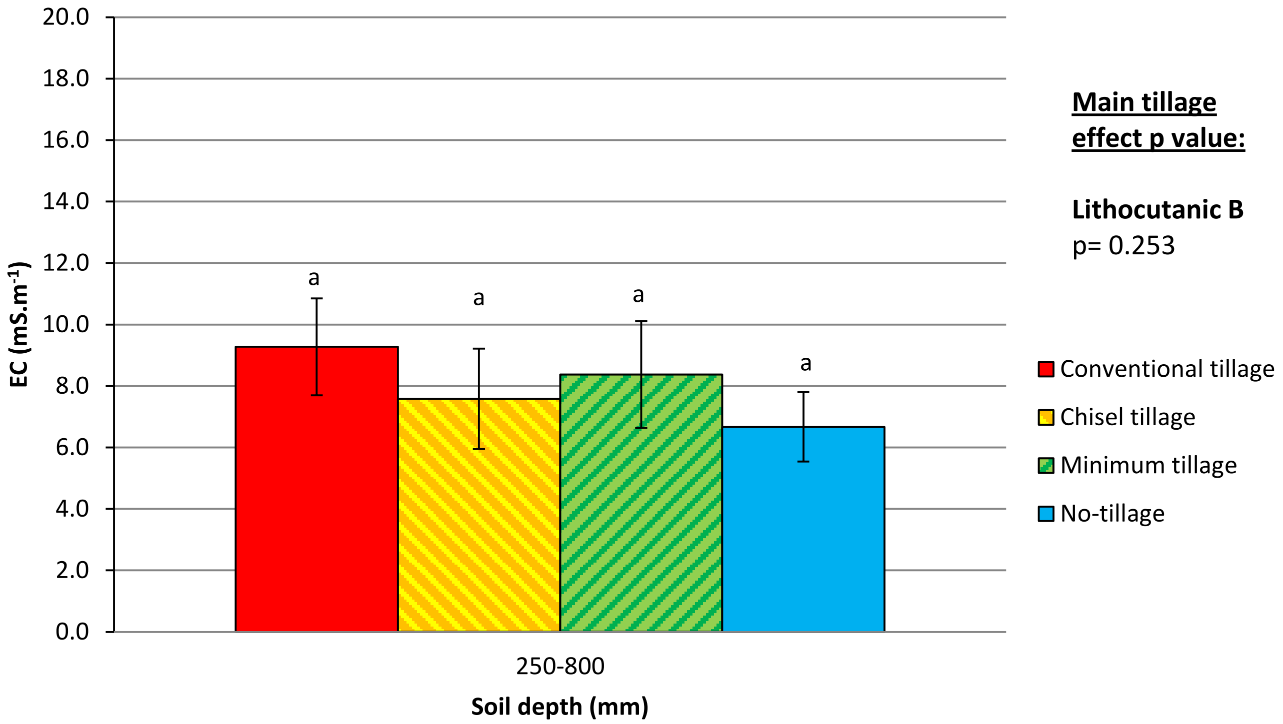


Figure 4-6: **EC for the different tillage treatments of the Lithocutanic B horizon**

4.2.3 Resistance and water soluble cations of the saturated paste extract

No statistical analysis was done for these results. These results are just to show which cations and anions contributed to the higher electrical conductivity in the conventional tillage treatment, thus also to support the EC results. Significant differences for the EC results were only found in the 0-100 mm and thus only this depth was analysed. The resistance in ohm is the opposite measurement of EC and it also done to support the results of the EC. **Table 4-1** shows the results for the two tillage treatments of the 0-100 mm soil sampling depth for the differed ions in $mmol_c/L$ and also the resistance. The sodium absorption ratio was also calculated.

Table 4-1: The concentration of the soluble cations, anions and resistance for conventional and no-tillage treatments in the 0-100 mm soil depth

	Concentration ($mmol_c$ / L)							Resistance	SAR
	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	NO_3^{-}	SO_4^{2-}	ohm	
Conventional tillage	10.28	5.02	2.85	1.37	8.67	2.56	1.96	156.5	1.03
No-tillage	2.97	1.73	1.15	1.38	1.30	3.47	0.86	1660	0.75

The higher resistance in the no-tillage treatment indicates that there are less ions present in the soil which could conduct electricity compared to the conventional tillage treatment, hence the higher EC as seen in the conventional tillage treatment. From the table it is clear that the calcium, magnesium, sodium, chlorite and sulphate ion concentration is much higher in conventional tillage than in the no-tillage treatment. Potassium and nitrate concentrations were the same.

4.2.4 Total carbon content

Figure 4-7 shows the results of the total carbon content (%) for the different tillage treatments of the two sampling depths. In general the total carbon content are quite low for all the tillage treatments at both sampling depths, namely below one percent.

In the 0-100 mm depth it is clear that conventional tillage had the lowest total carbon content percentage (0.51%) compared to the other three tillage treatments. Tine (0.83%), minimum (0.86%) and no-tillage (0.92%) had a similar total carbon percentage. In the 100-200 mm depth area the total carbon content increased from 0.33% in no-tillage to 0.51% in tine tillage, and then decreased to 0.46% in conventional tillage. Total carbon percentages in the 100-200 mm sampling depth were similar except for no-tillage.

Carbon content showed significant interaction between tillage treatments and sampling depths ($p = 0.003$). Interaction between these two main factors indicates that the sampling depths should be studied separately. Looking at the 0-100 mm sampling depth no significant difference were found between replicates ($p= 0.242$), but tillage treatments ($p = 0.023$) did differ significantly. Total carbon content was significantly lower in conventional tillage compared to the other three tillage treatments. No differences were observed for tine, minimum and no-tillage although the no-tillage tended to have a higher carbon content. In the 100-200 mm sampling depth no differences were found between replicates (p = 0.282). Significant differences were observed between tillage treatments (p = 0.045). In this deeper soil layer no-tillage had a significantly lower total carbon percentage compared to tine tillage. No differences were observed between no-tillage, conventional tillage and minimum tillage. There were also no differences between tine, conventional and minimum tillage.

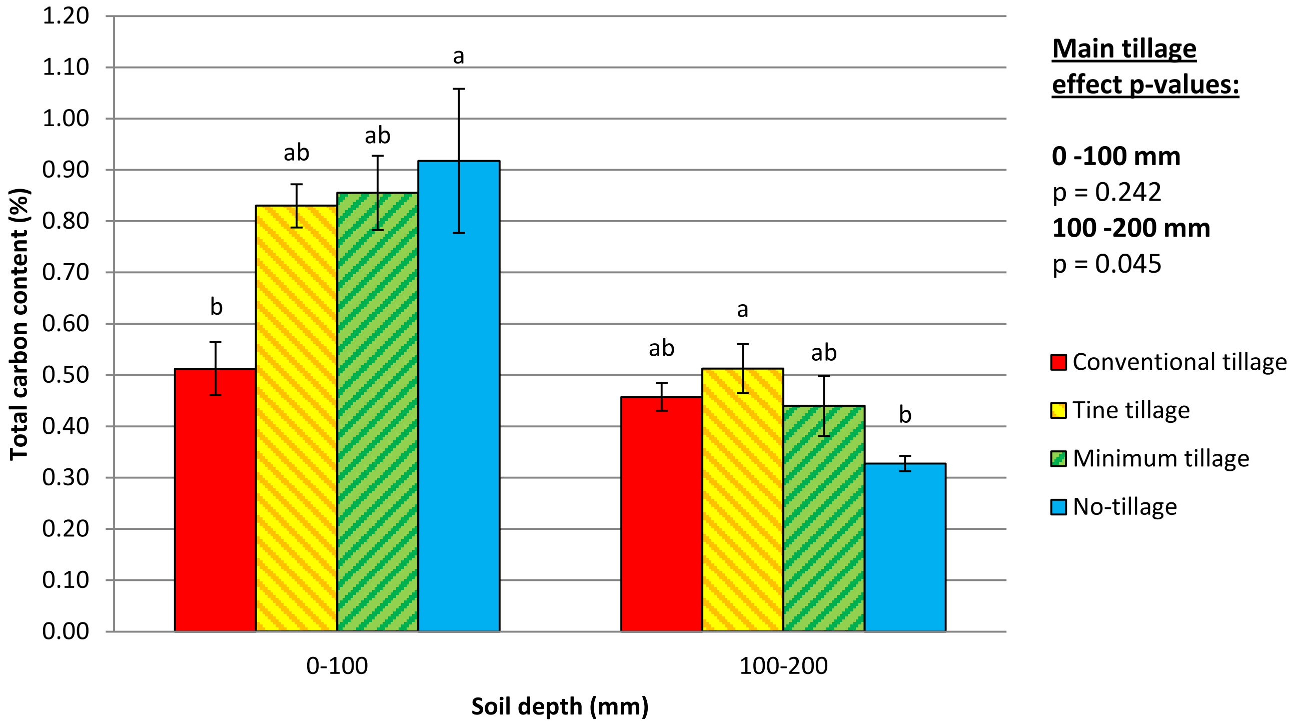


Figure 4-7: Total carbon of the Orthic A (0-200 mm) for the different tillage practices

4.3 Physical properties

The following main physical properties were analysed; particle size distribution, coarse fragment percentage, aggregate stability, bulk density, sheer strength, hydraulic conductivity and water storage potential of the course fragments. Most of these properties are generally used to describe the soil physical state and also soil quality. By knowing the long-term physical properties for each tillage treatment, critical evaluation can be performed to find the most sustainable tillage practice for this specific soil.

4.3.1 Particle size distribution

Table 4-2 shows the results of the particle size distribution for the different tillage treatments at the two sampling depths obtained via the **Pipet method** (Gee and Bauder, 1986). Comparing the 0-200 mm soil depth generally no difference was found between tillage treatments and sampling depth for all the size fractions. The only difference (p = 0.045) that were found was the significantly higher clay content in the 100-200 mm soil depth, compared to the 0-100 mm soil depth. Looking at the effect of tillage, no significant difference was found between tillage treatments, comparing most of the particle size fractions. Significant differences (p = 0.046) were found for the fine silt fraction. Conventional tillage treatment had a higher percentage of fine silt compared to no-tillage, but not significantly higher than minimum and tine tillage. The texture class of all the treatments at both sampling depths is a sandy loam and the sand grade is coarse sand. The small variation between tillage treatments and the two different depths is due to the natural variation of the soil between the different sites which is general for the Glenrosa soil form. An interesting phenomenon is that the conventional tillage treatment had similar to identical particle size distributions at both sampling depths.

Table 4-2: Particle size distribution percentages for the different tillage practices at 0-100 mm and 100-200 mm sample depths

Particle size class	Coarse sand	Medium sand	Fine sand	Very fine sand	Coarse silt	Fine silt	Clay
	2 - 0.5	*0.5 - 0.25*	*0.25 - 0.106*	*0.106 - 0.05*	*0.05 - 0.02*	*0.02 - 0.002*	*< 0.002*
				0-100 mm			
Conventional tillage	**20.78**	**9.58**	**16.98**	**18.51**	**14.21**	**11.84**	**8.10**
Tine tillage	**23.27**	**10.09**	**16.68**	**17.36**	**14.51**	**11.28**	**6.80**
Minimum tillage	**20.50**	**10.14**	**17.70**	**19.29**	**13.48**	**11.19**	**7.70**
No-tillage	**20.62**	**9.82**	**17.50**	**19.28**	**15.01**	**10.80**	**6.97**
				100-200 mm			
Conventional tillage	**20.72**	**9.67**	**17.92**	**18.08**	**13.91**	**11.74**	**7.98**
Tine tillage	**21.21**	**10.04**	**17.34**	**18.33**	**13.89**	**11.05**	**8.14**
Minimum tillage	**21.41**	**10.18**	**17.74**	**18.30**	**12.57**	**11.21**	**8.59**
No-tillage	**21.07**	**10.22**	**17.66**	**18.68**	**13.39**	**9.86**	**9.11**

Table 4-3 shows the results of the particle size distribution obtained via **laser diffraction** for the conventional and no-tillage treatments at the 0-100 mm sampling depth. In the first experiment, particles from very fine sand (0.106-0.05 mm) to clay particles were analysed. The texture class of both tillage treatments at both sampling depths is a sandy loam and the sand grade is coarse sand. In the second experiment particles from fine sand (0.25-0.106 mm) to clay particles were analysed. Again the same texture class of both tillage treatments at both sampling depths were obtained, although from both experiments the particle size percentage for the different classes differed between analysis method and the two separate experiments. The particle classes where differences are most prominent are the very fine sand and the fine sand fraction. The clay fraction was more or less correctly analysed by laser diffraction. No differences were observed between the two tillage treatments for all the particle fractions, although there were differences between analysing methods.

For the fine sand fraction there were significant differences between methods ($p = 0.043$). The pipet method showed a significantly higher percentage compared to the second laser diffraction method. No differences were observed between the second and first laser method. For the very fine sand fraction there were significant differences between the three methods ($p = 0.003$). The second laser diffraction method showed a significantly higher percentage compared to the pipet and the first laser diffraction method. The pipet method also had a significantly higher very fine sand fraction compared to the first laser diffraction method. For the fine silt fraction there were significant differences between methods ($p = 0.004$). The first laser diffraction method showed a significantly higher percentage compared to the second laser diffraction method and the pipet method, which also differed. For the clay fraction there were significant differences between methods ($p = 0.021$). The pipet method showed a significantly higher percentage compared to the second laser diffraction method. No difference was observed between the pipet- and first laser diffraction method.

Table 4-3: Particle size distribution for the different tillage practices at 0-100 mm and 100-200 mm sample depths (laser diffraction)

Particle size class	Coarse sand	Medium sand	Fine sand	Very fine sand	Coarse silt	Fine silt	Clay	Method
	2 - 0.5	*0.5 - 0.25*	*0.25 - 0.106*	*0.106 - 0.05*	*0.05 - 0.02*	*0.02 - 0.002*	*< 0.002*	
	0-100 mm							
CT	**20.78**	**9.58**	**16.98**	**18.51**	**14.21**	**11.84**	**8.10**	Pipet method
NT	**20.62**	**9.82**	**17.50**	**19.28**	**15.01**	**10.80**	**6.97**	
CT	**20.85**	**9.51**	**16.93**	***7.16***	***11.38***	***26.47***	***7.70***	Laser diffraction (1)
NT	**19.94**	**9.25**	**17.05**	***9.58***	***11.96***	***25.03***	***7.19***	
CT	**20.65**	**9.42**	***9.18***	***22.80***	***13.38***	***18.61***	***5.96***	Laser diffraction(2)
NT	**20.72**	**9.61**	***12.19***	***24.92***	***11.80***	***15.91***	***4.85***	

*** The underlined areas in the table indicate the particle size fractions analysed by laser diffraction**

4.3.2 Coarse fragment percentage

Figure 4-8 shows the results of the coarse fragment percentage on a mass basis for the different tillage treatments at the two sampling depths. In general the coarse fragment percentage is quite high. This is common for soils in the Swartland area of the Western Cape that developed from shale parent material. From the graph it is clear that at the 0-100 mm soil sampling depth, conventional tillage (40.14%) had the highest percentage of coarse fragments and no-tillage (32.93%) the lowest. The same trend was observed in the 100-200 mm soil depth, the coarse fragment percentage was highest for conventional (45.35%) and the lowest for no-tillage (36.94%) treatments.

No significant interaction between tillage treatment and sampling depth ($p = 0.240$). Interpreting the main effects, the replicates ($p = 0.597$) and sampling depth ($p = 0.051$) did not differ significantly. The coarse fragment percentage, therefore, did not differ between the two sampling depths. The tillage treatments did differ significantly ($p = 0.001$), showing that there were differences between tillage treatments compared for the 0-200 mm soil depth, with conventional tillage mostly having a higher coarse fragment percentage.

Separate analysis of the depths showed that in the 0-100 mm soil sampling depth, replicates did not differ significantly (p = 0.769), but tillage treatment did (p = 0.019). The coarse fragment percentage was significantly higher in conventional tillage compared to the no-tillage treatment. No differences were observed between the conventional, tine and minimum tillage treatments. At the 100-200 mm soil sampling depth the same trend was observed, replicates did not differ significantly (p = 0.390), but tillage treatment did (p = 0.031). Coarse fragment percentage was significantly higher for conventional tillage, compared to no-tillage. No differences were observed between the conventional, tine and minimum tillage treatments.

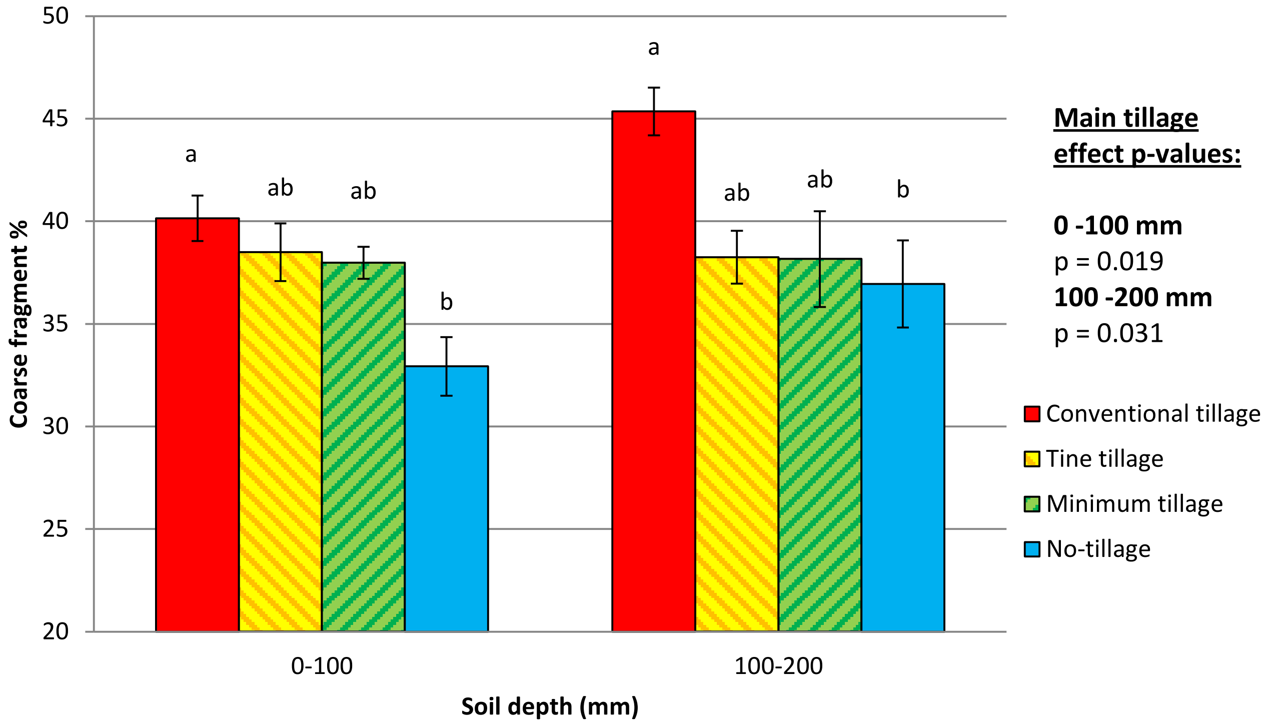


Figure 4-8: Coarse fragment percentage for different tillage practices at 0-100 mm and 100-200 mm sample depths

Figure 4-9 shows the results of the coarse fragment percentage of the different tillage treatments at the Lithocutanic B horizon. These results are just to indicate the high coarse fragment percentage of the B horizon. Tillage treatments in this long-term study were never deeper than 300 mm and would therefore have little direct effect on this horizon. Therefore it is logical that there are no differences between tillage treatments. The variation in these percentages is due to natural variation in the soil.

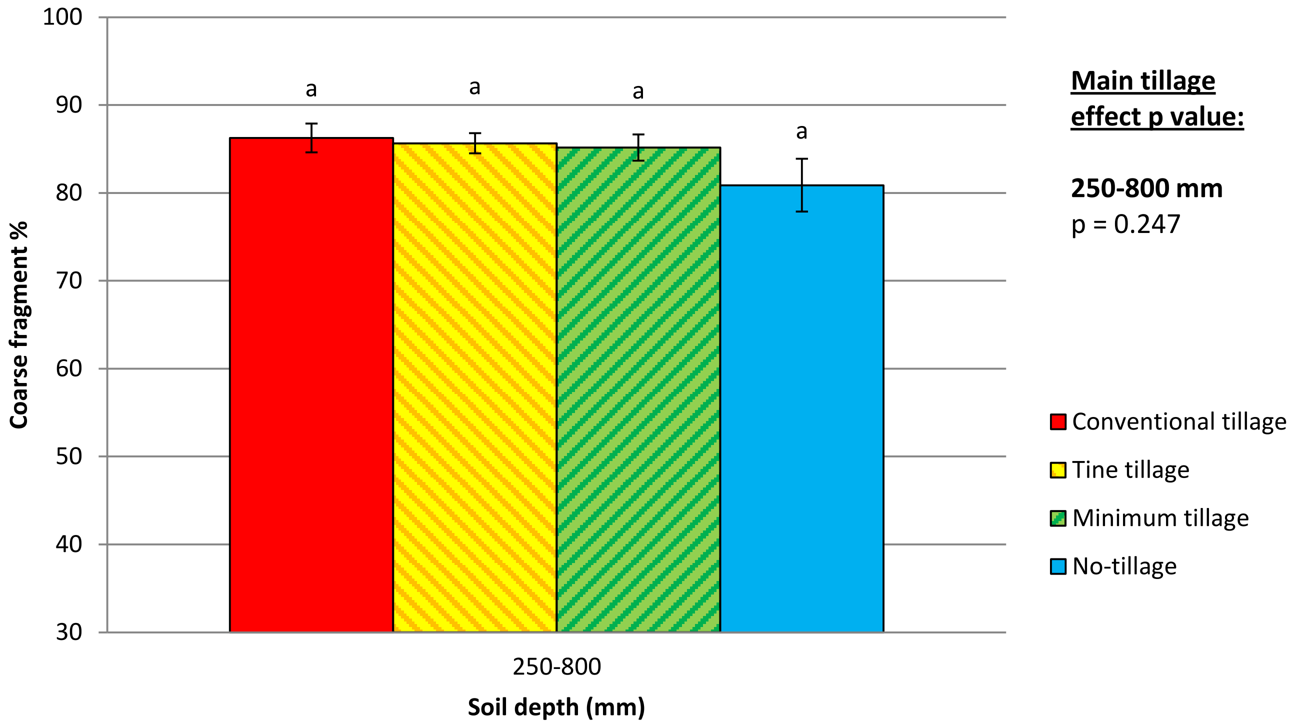


Figure 4-9: **Coarse fragment percentage of different tillage practices of the Lithocutanic B horizon for the different tillage treatments**

4.3.3 Aggregate stability

Figure 4-10 shows the results of the water stable aggregates for the different tillage treatments at the two sampling depths. It is clear from the graph that at the 0-100 mm soil sampling depth no-tillage (78.40%) had the highest percentage of water stable aggregates followed by minimum (61.43%), conventional (47.82%) and tine tillage (45.02%). The same trend was observed in the 100-200 mm soil depth, water stable aggregates was highest for no-tillage (39.34%) followed by minimum (23.00%), tine (10.60%) and conventional tillage (10.60%).

Aggregate stability indicated no significant interaction between tillage treatment and sampling depth ($p = 0.731$). Interpreting the main effects, replicates ($p = 0.015$) and sampling depth ($p = < 0.0001$) differ significantly. The 0-100 mm sampling depth had a significantly higher percentage of water stable aggregates compared to the 100-200 mm sampling depth. The tillage treatments also differ significantly ($p = < 0.0001$), showing that there were differences between tillage treatments. Looking at the sampling depth separately, the following was found. In the 0-100 mm soil sampling depth, replicates did differ significantly (p= 0.001) as did the tillage treatments (p = < 0.0001). The aggregate stability was significantly higher in no-tillage, compared to the other treatments. Minimum tillage also had a significantly higher aggregate stability compared to tine and conventional tillage. No differences were observed between the conventional and tine tillage treatments. At the 100-200 mm depth, soil replicates did not differ significantly (p = 0.242), but tillage treatment did (p = < 0.0001). At this depth exactly the same trend was observed as in the 0-100 mm soil depth.

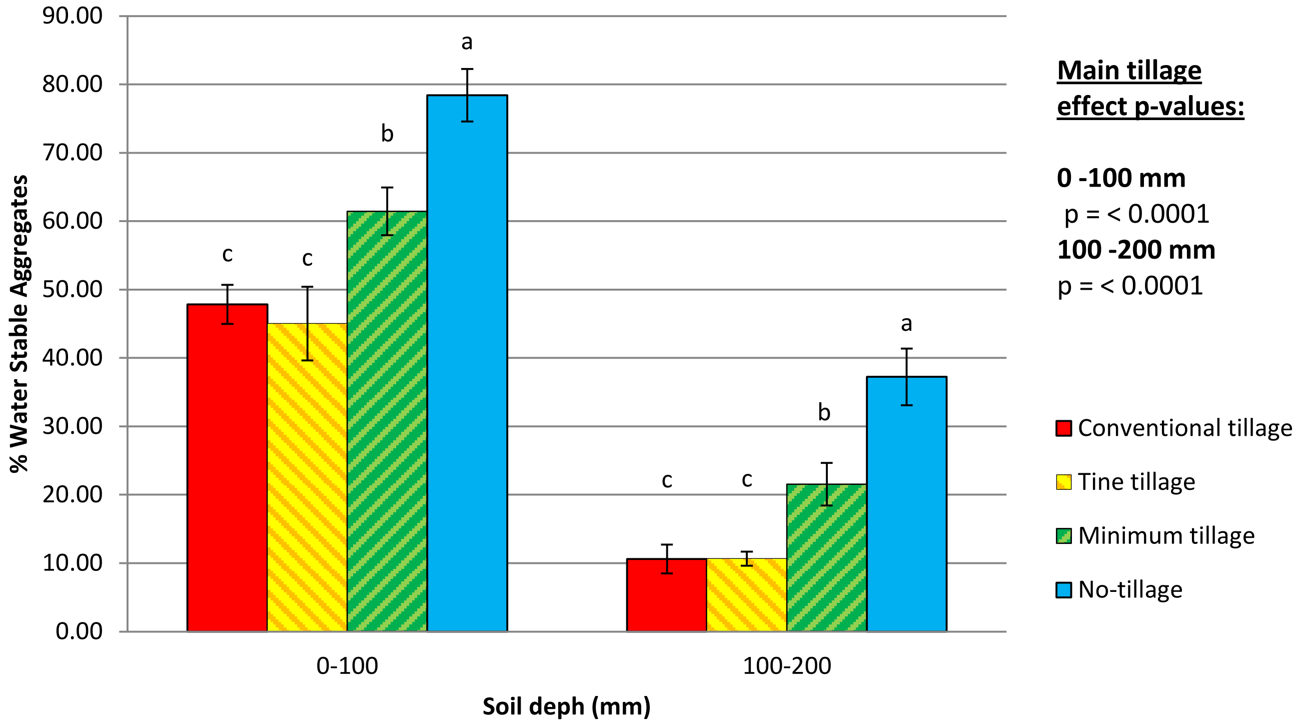


Figure 4-10: Water stable aggregate percentage for the different tillage treatments at the two sampling depths

Figure 4-11 shows visually that in the no-tillage treatment, aggregates are more water stable than the aggregates from conventional tillage areas. Aggregates from the two tillage treatments were wetted with distilled water and left for a few seconds. The conventional tillage aggregates disintegrated into smaller aggregates and prominent soil particles. The white circles indicate some of the indistinct aggregates of the conventional tillage treatment, which remained stable.

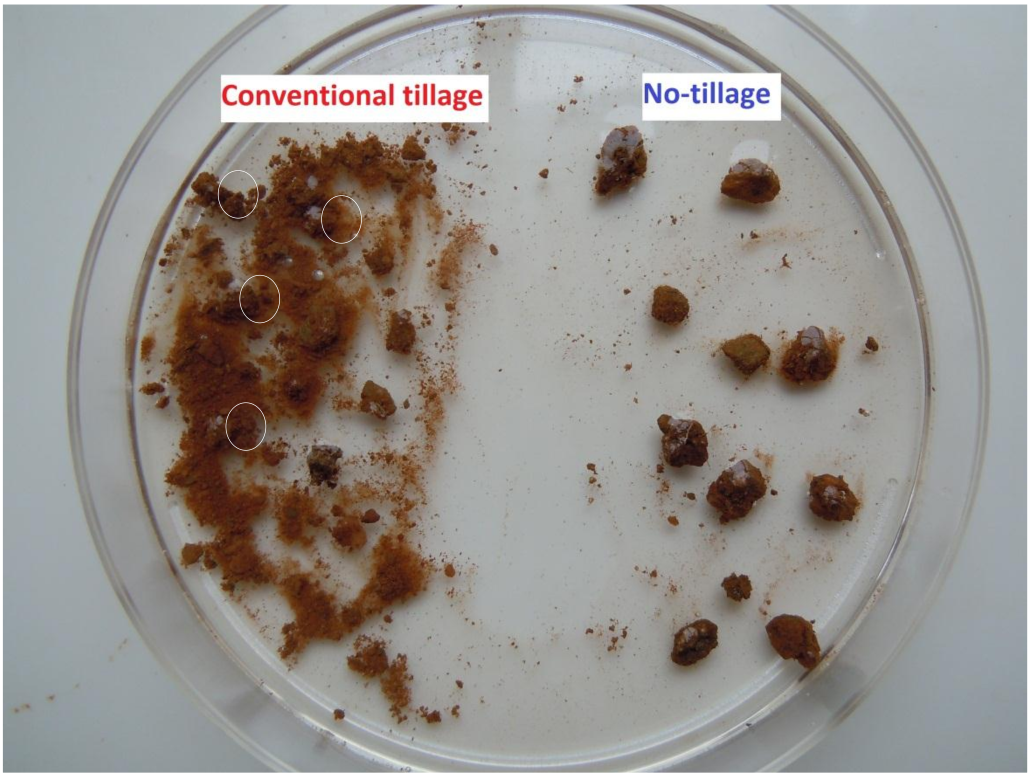


Figure 4-11: Visual representation of aggregates of the 0-100 mm soil sampling depth saturated by distilled water for the conventional and no-tillage treatments

Figure 4-12 shows the relationship between total carbon content and aggregate stability of the 0-100 mm soil depth for all the tillage treatments. A positive correlation was found ($p = 0.0003$) with a regression equation of $y = 52.682x + 19.932$. The r^2 relates that only 44% of the variation in aggregate stability is explained by the variation in total carbon content.

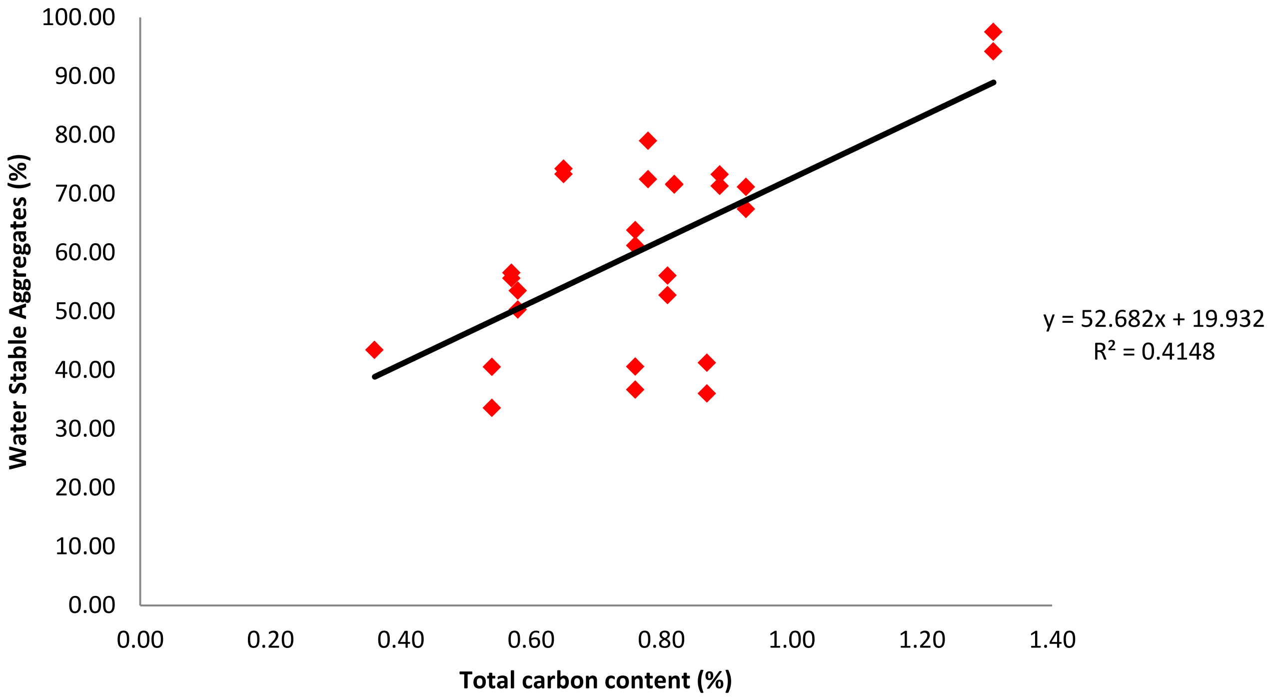


Figure 4-12: Correlation for all the tillage treatments between water stable aggregates and soil total carbon for the 0-100 mm soil depth

Figure 4-13 shows the relationship between total carbon content and aggregate stability of the 100-200 mm soil depth for all tillage treatments. No correlation were found ($p = 0.711$) and is confirmed by the very low r^2 value of 0.67%.

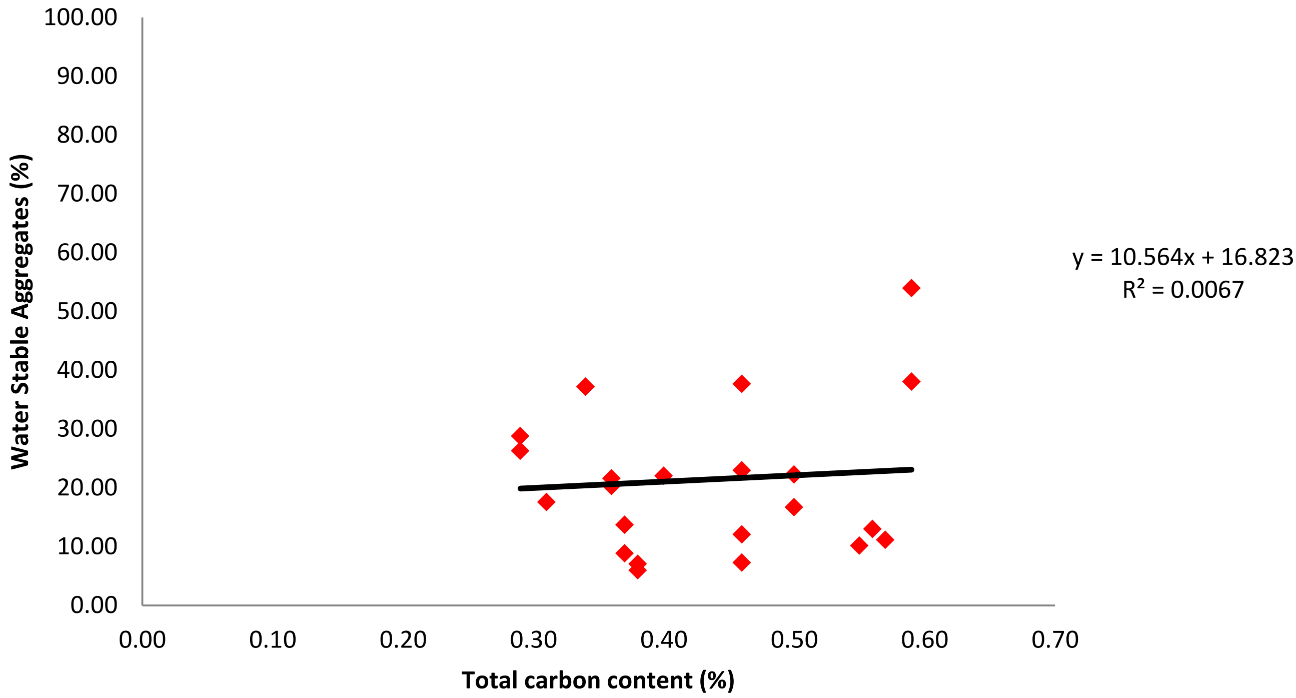


Figure 4-13: Correlation for all the tillage treatments between water stable aggregates and soil total carbon for the 100-200 mm soil depth

4.3.4 Sheer strength

Figure 4-14 shows the sheer strength measured on 6 June and 19 July 2012 for all the tillage treatments. For June the values varied not so much between tillage treatments and were in the range from 11.5 to 13.9 kPa. The variation was greater in July varying from 15.6 to 18.3 kPa among the tillage treatments.

Significant interaction ($p = < 0.0001$) were found between tillage treatments and measuring date and therefore indicates that each measuring date should be analysed separately. In June the measurement replicates differed significantly ($p = < 0.0001$), showing that there are soil variation early after tillage operations. Differences were found between tillage treatments ($p = < 0.0001$), with no-tillage having a significant higher sheer strength compared to the other tillage treatments. In July no difference were found between replicates ($p = 0.817$), but significant differences were found between tillage treatments ($p = < 0.0001$). Conventional tillage (18.34 kPa) had a significant higher sheer strength compared to minimum (17.04 kPa) and no-tillage (15.64 kPa) but did not differ from tine tillage (18.12

kPa). No-tillage also had a significantly lower sheer strength compared to minimum tillage. There was, therefore, a significant increase in sheer strength from June to July 2012.

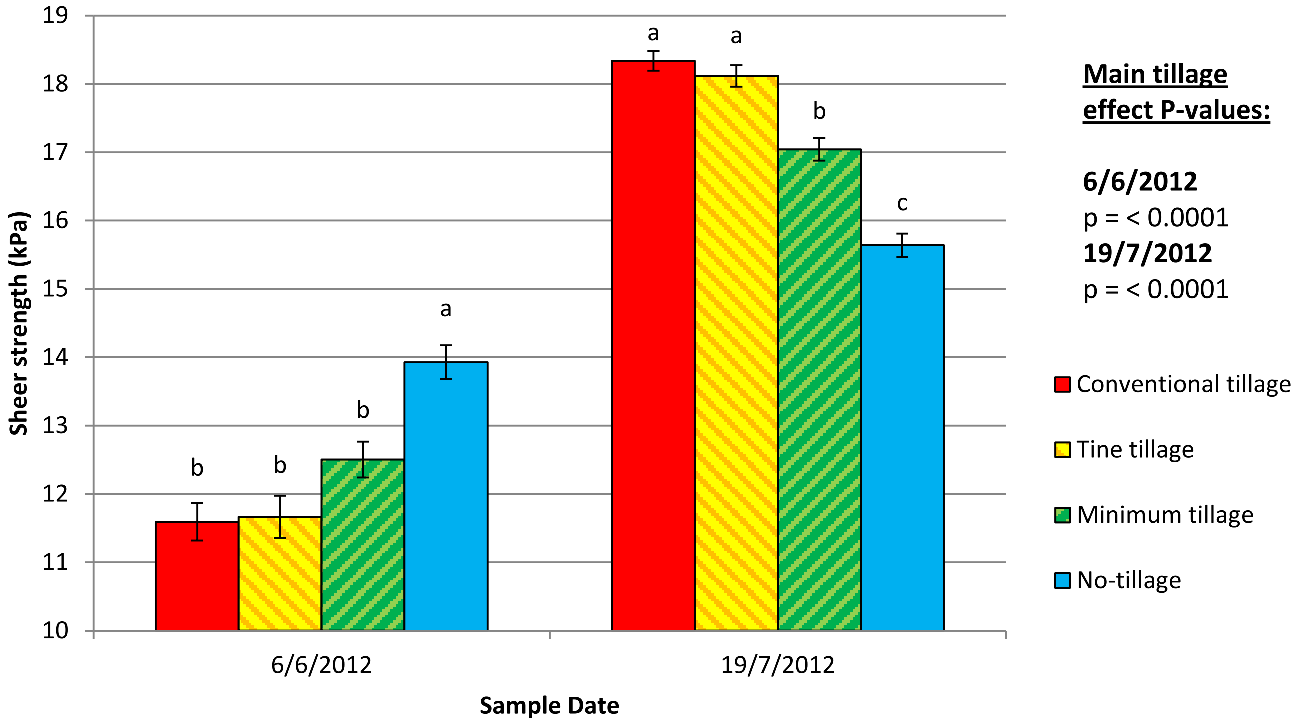


Figure 4-14: Sheer strength sampled at two dates for the different tillage treatments

Table 4-4 shows the gravimetric water content at the two dates when sheer strength was measured for all the tillage treatments. Water content of the soil may influence sheer strength and must also be included in the results.

No interaction were found between tillage treatments and measuring date ($p = 0.014$). Water content of the 0-50 mm soil surface for the two measuring dates differed significantly ($p = < 0.0001$). In July the water content was lower and this could cause an increase in the measured readings. Tillage treatments were analysed separately for each date. The difference between treatments is showed on the table.

Table 4-4: Gravimetric water content at the two measuring dates

	Conventional tillage	Tine tillage	Minimum tillage	No-tillage
	Gravimetric water content (w/w)			
6/6/2012	0.07^{c}	0.09^{a}	0.08^{ab}	0.07^{bc}
19/7/2012	0.05^{a}	0.06^{a}	0.06^{a}	0.07^{a}

[1] Values in a row followed by the same subscripts do not differ significantly at *P* = 0.05

A linear regression was conducted to evaluate the relationship of gravimetric water content (0-10 mm) on sheer strength. Sheer strength was negatively related to gravimetric water content ($p = 0.0001$) with an r^2 value of 37%. Lower water contents may thus increase the sheer strength although other factors also contribute to sheer strength variation. In our case these factors are, probably, the different tillage treatments.

4.3.5 Bulk density

4.3.5.1 Troxler bulk density results

Taking the two seasons into account, minimum and maximum average bulk densities for the different tillage practices looks as follows: conventional tillage 1340-1572 kg.m^{-3}, tine tillage 1342-1556 kg.m^{-3}, minimum tillage 1352-1512 kg.m^{-3} and no-tillage 1384-1480 kg.m^{-3}.

The description that follows refers to **Table 4-5** and **Figure 4-15**. At the first growing season (2011), measuring started 25 days after planting, as already mentioned. At this point one can see that the bulk densities of all the treatments are low, although no-tillage had the highest bulk density of the treatments. At the second measuring date, 60 days after planting, minimum and no-tillage showed little increase in bulk density, but conventional and tine tillage showed a prominent increase. From 60 to 146 days after planting average bulk density of all the tillage treatments increased significantly. If looked at the different tillage treatments until this date, the minimum and no-tillage had a less severe bulk density increase. Bulk density stabilized at 146 days after planting and remained constant till the new season when tillage and planting operations were performed. Interestingly minimum and no-tillage showed a slight dip in bulk density at 174 days after planting, after which the values stabilized. In the next season (2012) the same trend was observed. Bulk densities of all the tillage treatments were reduced by tillage, although much less in the no-tillage treatment this time around. At 27 days after planting, the no-tillage treatment had significantly the highest bulk density compared to the other tillage treatments. From 27 days until the last measuring date, 84 days after planting, bulk density increased for all tillage treatments as was also observed in the previous season. We assumed that the bulk density would also stabilize at similar levels as in season one. Again the no-tillage treatments showed less severe bulk density increases. This was to some extent also true for the minimum tillage treatment. In both growing seasons conventional tillage had low initial bulk densities after tillage and planting operations that then increased to higher bulk densities as the season progressed. Compared to the other tillage treatments, conventional tillage always had the highest bulk density about 65 to 70 days after planting. The no-tillage treatment showed the least variation in bulk density and minimum tillage to some extent.

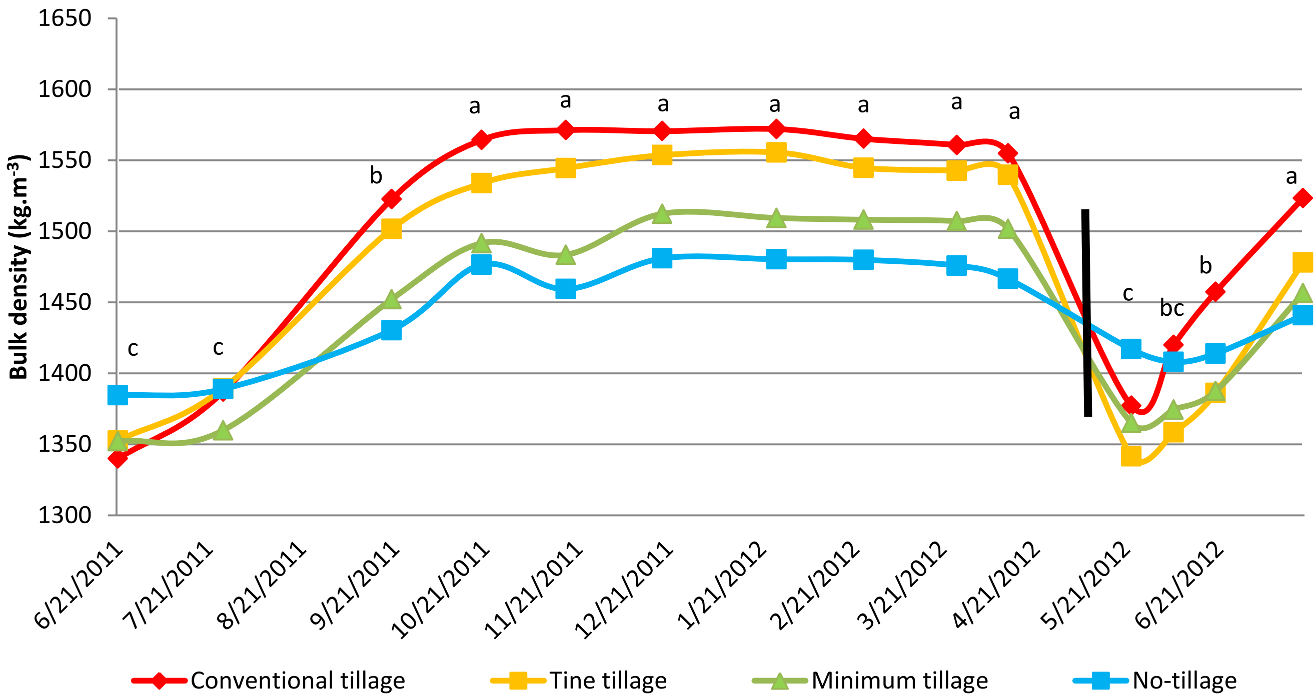
Repeated ANOVA analyses were conducted on the seasonal bulk density measurements, separately for each of the seasons. The main effects were replicates (Blocks A, B, C and D), sub blocks (measurement sites in each replicate), days after planting (number of days), tillage treatments and the interaction of days after planting and tillage treatments. Significant interaction were observed for both season one ($p = 0.0002$) and season two ($p = 0.001$). Significant interaction indicates that each measuring date should be analysed separately. Instead of describing all the effects in words, a table were constructed to explain the results. **Table 4-5** shows the average bulk densities for each of the four tillage practices at the specific measured date. The comparison between tillage treatments were done according to Tukey's studentized range and shown next to the values in superscript letters together with the standard errors. **Figure 4-15** shows the visual representation of the bulk density (0-100 mm depth) variation through the season starting in 2011 at 25 days after planting, continuing right through until the next tillage operations and planting on 26 April 2012, ending at 19 July 2012. A different ANOVA were constructed to compare the measuring dates for average combined bulk density for all the tillage treatments and to establish bulk densities significantly increased over a season. The comparison between measuring dates was also done according to Tukey's studentized range and are shown for each season by superscript letters on the graph.

Table 4-5: 0-100 mm Depth bulk density variation and standard (STD) errors over 13 months thus including two planting stages for the different tillage treatments

Measuring date	5/27/2011	6/21/2011	7/26/2011	9/20/2011	10/20/2011	11/17/2011	12/19/2011	1/26/2012	2/24/2012	3/26/2012	4/12/2012	4/26/2012	5/23/2012	6/6/2012	6/20/2012	7/19/2012
Days after planting	0	25	60	116	146	174	206	244	273	304	321	0	27	41	55	84
	Bulk density (kg.m^{-3})															
CT	Tillage operations and planting	1340^{a}	1387^{a}	1523^{a}	1564^{a}	1571^{a}	1571^{a}	1572^{a}	1565^{a}	1561^{a}	1555^{a}	Tillage operations and planting	1377^{ab}	1420^{a}	1457^{a}	1523^{a}
STD error		*16.81*	*19.34*	*17.96*	*14.48*	*12.15*	*10.72*	*10.74*	*12.81*	*17.04*	*13.05*		*11.52*	*11.04*	*14.07*	*10.98*
TT		1353^{a}	1389^{a}	1502^{ab}	1534^{ab}	1544^{a}	1554^{ab}	1556^{ab}	1545^{ab}	1543^{ab}	1540^{ab}		1342^{b}	1358^{b}	1386^{b}	1478^{ab}
STD error		*18.93*	*17.98*	*13.93*	*13.88*	*12.77*	*14.54*	*13.40*	*15.72*	*17.24*	*14.18*		*17.97*	*15.77*	*15.48*	*15.60*
MT		1352^{a}	1360^{a}	1452^{bc}	1492^{bc}	1483^{b}	1512^{bc}	1509^{bc}	1508^{bc}	1507^{bc}	1502^{bc}		1365^{ab}	1375^{ab}	1388^{b}	1456^{b}
STD error		*19.84*	*12.47*	*20.19*	*15.34*	*16.86*	*14.35*	*14.32*	*15.58*	*13.47*	*14.47*		*13.49*	*12.73*	*16.27*	*14.90*
NT		1384^{a}	1389^{a}	1430^{c}	1477^{c}	1459^{b}	1481^{c}	1480^{c}	1480^{c}	1476^{c}	1467^{c}		1417^{a}	1408^{ab}	1414^{ab}	1441^{b}
STD error		*18.81*	*16.62*	*14.53*	*12.37*	*15.34*	*10.84*	*12.53*	*9.69*	*11.28*	*13.44*		*17.55*	*16.94*	*14.33*	*12.08*

[A] Letters in a column followed by the same subscripts do not differ significantly at *P* = 0.05

CT – Conventional tillage (mouldboard); TT – Tine tillage; MT – Minimum tillage; NT – No-tillage



[A] Letters on the graph followed by the same subscripts do not differ significantly at $P = 0.05$

Figure 4-15: 0-100 mm depth bulk density for the different tillage treatments, comparing averages of the different dates (black line + tillage and planting operations, 26 April 2012)

A pairwise t-test was also performed on the bulk density results measured on the 26 April 2012 (14 days before tillage) and 23 May 2012 (27 days after tillage) for all the tillage treatments. This test would reveal whether the soil bulk density significantly decreased after tillage. The t-test involved testing whether the difference between the two dates was equal to 0 or not. Conventional, Tine and Minimum tillage all had a p-value of < 0.0001, therefore confirming that there are significant differences between before and after tillage. The no-tillage p-value was 0.039 less significant that the other three tillage treatments and not significant if a p-value of 0.001 was the significant value. No-tillage thus may not have decrease the bulk density significantly after tillage operations.

4.3.5.2 Correlation between the Troxler bulk density and cumulative rainfall

Figure 4-16 shows the correlation of the seasonal bulk density for both seasons measured with the Troxler compared to the cumulative rainfall. Each tillage treatment is again indicated by a different shape. The combined linear regression equation for all the tillage treatments are y = 0.695x + 1333 and have and r^2 value of 66.3%. The p-value for the model is < 0.0001 and thus indicates that seasonal bulk density is well correlated with cumulative rainfall. There is therefore a highly positive linear correlation. The following regression equations and r^2 are derived for each tillage treatment:

Conventional tillage: $y = 0.874x + 1335$ ($r^2 = 73.6$)

Tine tillage: $y = 0.958x + 1292$ ($r^2 = 92.0$)

Minimum tillage: $y = 0.639x + 1322$ ($r^2 = 80.2$)

No-tillage: $y = 0.309x + 1381$ ($r^2 = 61.9$)

For each equation the model had a significant p-value (< 0.05), indicating that there is a correlation between seasonal bulk density and cumulative rainfall for each tillage treatment. These separate r^2 values for each tillage treatments give a good idea of which treatments correlate better according to the two factors. From all the tillage treatments no-tillage had the lowest correlation. The r^2 for each of the equations relate the respective percentage of the variation in bulk density that is explained by the variation in cumulative rainfall.

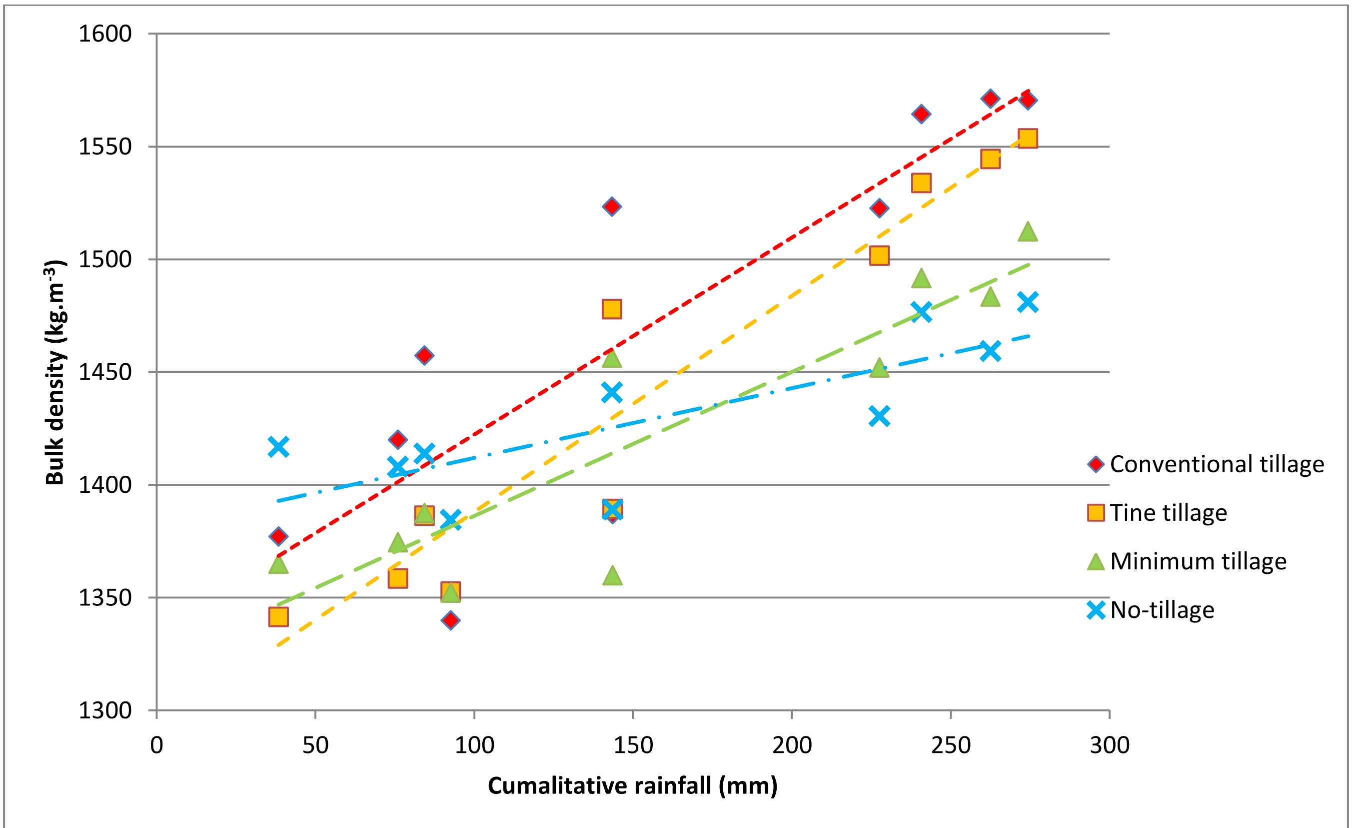


Figure 4-16: Correlation between cumulative rainfall and seasonal bulk density

4.3.5.3 Comparison between the Troxler- and clod method

Figure 4-17 shows the graph comparing the results of the two bulk density determination methods. Bulk density measured by the Troxler instrument and determined by the clod method showed significant differences between tillage treatments in both datasets. The same tillage trend was observed in different methods. In the clod method bulk density increased moving from no-tillage (1591 $kg.m^{-3}$) to conventional tillage (1655 $kg.m^{-3}$) treatments. Tine and minimum tillage treatments were in-between with bulk densities of 1620 $kg.m^{-3}$ and 1613 $kg.m^{-3}$ respectively. In the Troxler instrument's results, no-tillage had a bulk density of 1452 $kg.m^{-3}$, minimum tillage, 1481 $kg.m^{-3}$ increasing to 1555 $kg.m^{-3}$ in tine tillage and 1589 $kg.m^{-3}$ in conventional tillage.

The clod method results for the 0-100 mm soil sampling depth showed that the replicates did not differ significantly ($p = 0.814$), but tillage treatment did ($p = 0.015$). No-tillage only had a significant lower bulk density compared to conventional tillage. In the Troxler results replicates did also not differ ($p = 0.642$), but tillage treatment differed significantly ($p = < 0.0001$). Minimum and no-tillage treatments had a significant lower bulk density compared to conventional and tine tillage treatments. Tine tillage also had a significant lower bulk density compared to conventional tillage. No differences were observed between minimum and no-tillage treatments.

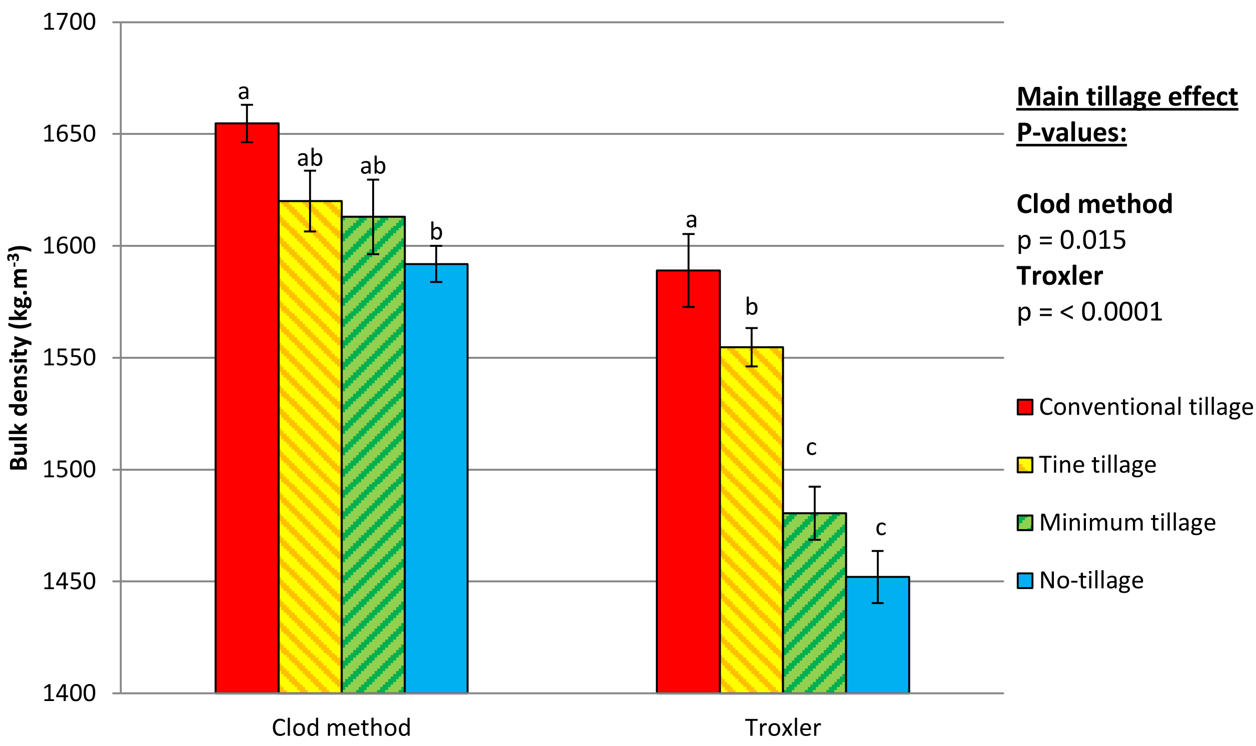


Figure 4-17: Bulk density comparison of the Troxler instrument and the clod method for the different tillage treatments

Table 4-6 shows the mean bulk densities for all the tillage treatments and also the differences between the two determination methods. It is clear that the clod method yielded higher bulk density values compared the Troxler. The difference is the same in conventional and tine tillage but is more than half of the difference of minimum and no-tillage. Again the difference in minimum and no-tillage was more or less the same. Relating the two methods statistically, the clod method yielded significant higher bulk densities ($p < 0.0001$) compared to the Troxler instrument. Comparing the difference between the methods of each tillage treatment, conventional and tine tillage were significantly lower than minimum and no-tillage. No differences were observed between conventional and tine tillage. This is also true for minimum and no-tillage treatments.

Table 4-6: Mean tillage bulk density values for the Troxler instrument and the clod method and the differences between the different tillage treatments

Method	Bulk density (kg.m^{-3})			
	Conventional tillage	Tine tillage	Minimum tillage	No-tillage
Clod method	1655	1620	1613	1592
Troxler	1589	1555	1481	1452
Difference (Δ)	66^{a}	65^{a}	133^{b}	140^{b}

[A] Letters in a row followed by the same subscripts do not differ significantly at *P* = 0.05

Figure 4-18 shows the graph where the bulk density values measured with the Troxler instrument is compared to the values determined by the clod method via linear regression. Each tillage treatment is indicated by a different shape. The combined linear regression equation for all the tillage treatments are y = 0.413x + 0.893 and have an r^2 value of 80.10%. The p-value for the model is < 0.0001 and thus indicates that the Troxler-measured bulk density values relates well to the values of the clod method. If the tillage treatments are considered separately, it is clear that the lowest bulk density points in the graph are occupied by the no-tillage treatment followed by the minimum tillage treatment and then tine tillage. The highest bulk density points are occupied by conventional tillage. Overlapping of these points occur between minimum and no-tillage and also between conventional and tine tillage. As a result of these, two overlapping main tillage groups known in literature are grouped together as conservation tillage practices explained by the lower bulk density values, as opposed to the more intensive conventional tillage practice explained by the higher bulk density values.

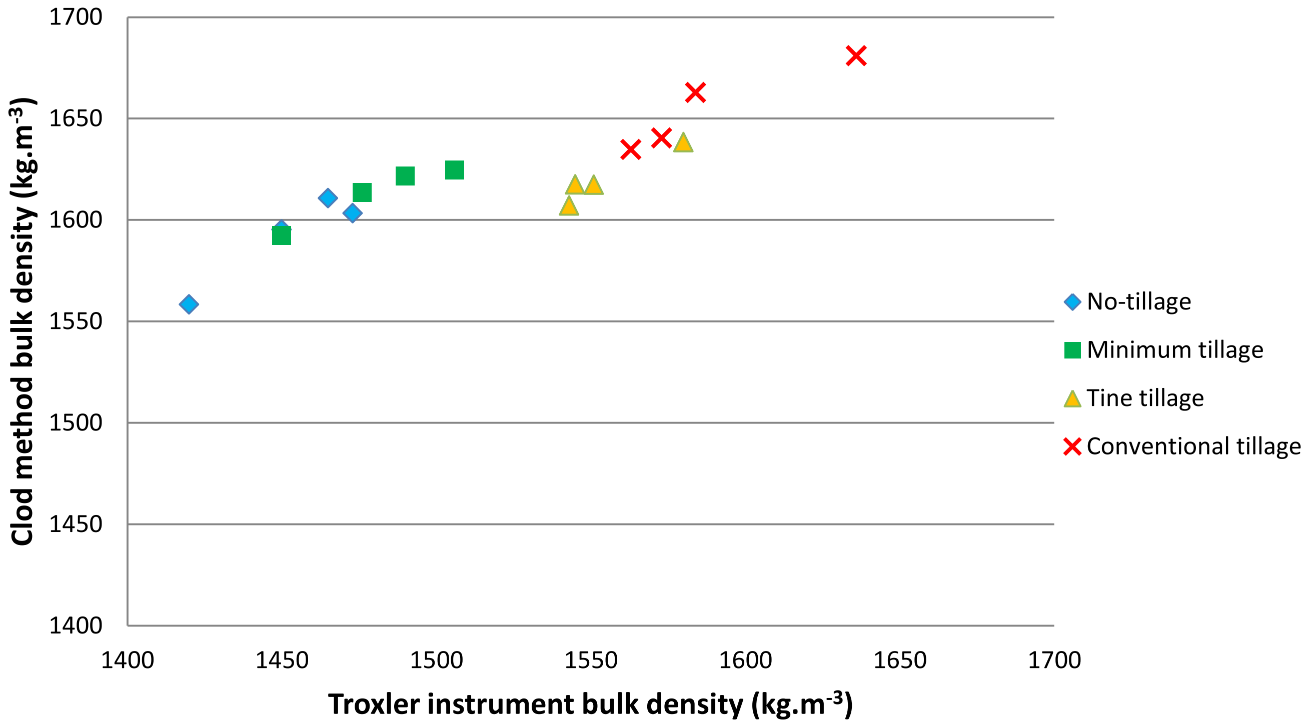


Figure 4-18: Correlation of the Troxler measurement results vs. clod method results

Regression equations derived for each tillage treatment:

No-tillage:	y = 0.947x + 0.217	(r^2 = 90.5)
Minimum tillage:	y = 0.592x + 0.736	(r^2 = 94.2)
Tine tillage:	y = 0.731x + 0.484	(r^2 = 92.2)
Conventional tillage:	y = 0.613x + 0.680	(r^2 = 87.7)

With these equations it is therefore possible to calculate a bulk density value with the Troxler instrument to a clod method bulk density value if necessary.

4.3.5.4 Laboratory soil (<2 mm) bulk density determination and consolidation tests

Figure 4-19 shows the graph of the dry bulk density values for conventional and no-tillage after five cycles of water saturating for 30 minutes and then drying for 24 hour at 105°C. There were two treatments, a natural consolidation treatment and a mechanical consolidated treatment. The '0' treatment cycle shows bulk density values for the initial dry soil (<2mm) which were placed in the aluminium rings. For all treatments the highest bulk density was reached after the first treatment cycle. The conventional tillage treatment with mechanical consolidated (MC) had the highest bulk density of 1624 $kg.m^{-3}$ followed by the conventional tillage treatment under natural consolidated (NC) conditions with a bulk density of 1565 $kg.m^{-3}$. The no-tillage MC treatment had the second highest bulk density of 1554 $kg.m^{-3}$ and the lowest bulk density was for the no-tillage NC treatment of 1468 $kg.m^{-3}$. Thereafter the bulk density of all the treatments decreases till constant values after treatment cycle four was reached. It is interesting that the mechanical consolidated and natural consolidated treatments did not differ much from each other after treatment 5 onwards.

Mechanical consolidated and natural consolidated main treatments were analysed separately. Looking at the mechanical consolidated experiment, tillage treatments differed significantly from each other, with conventional tillage having the highest bulk density ($p = < 0.0001$). Bulk density also differed significantly over the six treatment cycles ($p = < 0.0001$). This is only for the initial and treatment cycle 1 to 4, after which the bulk density stabilized. Conventional tillage stabilized at a bulk density of 1506 $kg.m^{-3}$ and no-tillage at 1457 $kg.m^{-3}$. The natural consolidated experiment resembled the same trend. Tillage treatments differed significantly from each other, with conventional tillage having the highest bulk density ($p = < 0.0001$). Bulk density also differed significantly over the 6 treatment cycles ($p = < 0.0001$). This is only for the initial cycle and for treatment cycle 1 to 3, after which the bulk density stabilized. Conventional tillage stabilized at a bulk density of 1516 $kg.m^{-3}$ and no-tillage at 1448 $kg.m^{-3}$.

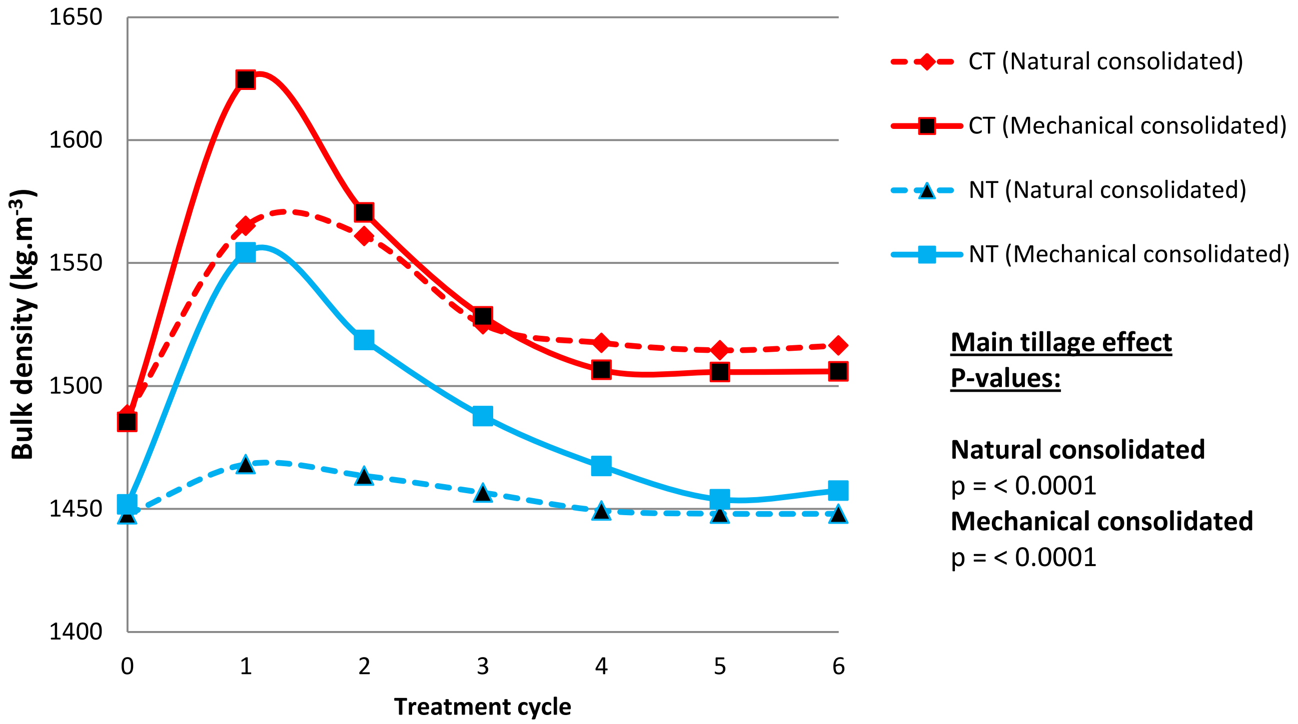


Figure 4-19: Dry bulk density variation of only the soil fraction (< 2 mm) for no-tillage and conventional tillage treatments under laboratory conditions

4.3.6 Saturated hydraulic conductivity

Figure 4-20 shows the hydraulic conductivity for the first experiment in the two tillage treatments (conventional and no-tillage). Initially in the first two hours of saturating the columns, the hydraulic conductivity was very high, reaching 100 mm.h$^{-1.}$ Thereafter the water movement through the columns stabilized and reached constant values. The average hydraulic conductivity calculated over a period of 6 hours and 15 minutes for each replicate (Blocks A, B, C, D) for both tillage treatments is shown in the graph. From the graph it is clear that there are variations between replicates. Conventional tillage values varied between 14 and 28 mm.h^{-1} and no-tillage between 27 and 58 mm.h^{-1}. The same tillage trend was observed for each replicate, for example in replicate A. No-tillage had a higher hydraulic conductivity compared to conventional tillage.

Analysing the data statistically, main effects were replicates, measuring intervals and tillage treatments. Replicates differed significantly from each other (p = < 0.0001) confirming that there are soil differences. Measurement intervals did not differ significantly (p = 0.134), indicating that the average results show a constant saturated hydraulic conductivity. Tillage treatments also differed significantly from each other. No-tillage had a higher hydraulic conductivity (40.99 $mm.h^{-1}$) compared to conventional tillage (19.98 $mm.h^{-1}$).

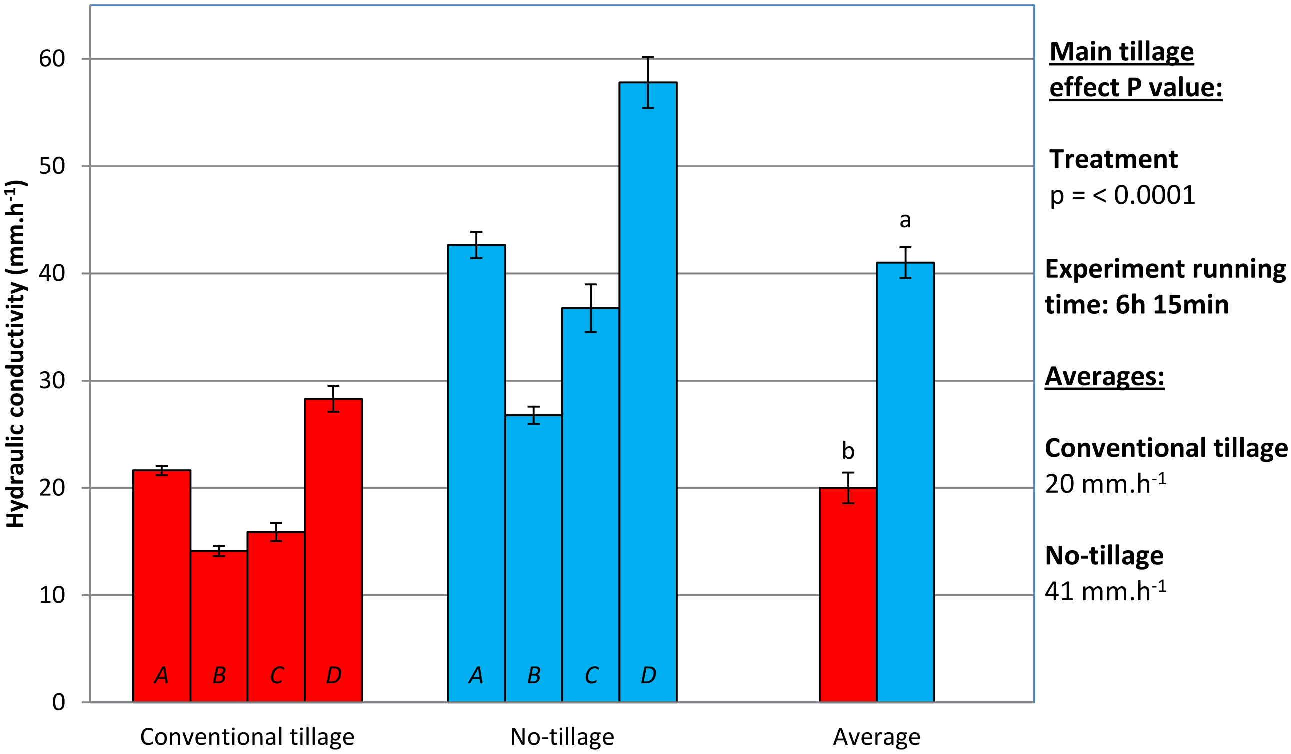


Figure 4-20: Saturated hydraulic conductivity for conventional and no-tillage (Experiment 1)

Figure 4-21 shows the hydraulic conductivity of the second experiment conducted on the same columns after the first experiment. The average hydraulic conductivity was calculated over a period of 4 hours. Compared to the first experiment on the conventional tillage treatment, hydraulic conductivity decreased meaningfully. Although it also decreased in the no-tillage treatment, it was not so prominent if the averages of the two experiments were compared. The replicates more or less resembled the same trend, except for replicate A for the conventional tillage treatment that lowered consideratedy compared to replicates B and C.

Replicates differed significantly from each other ($p = < 0.0001$), but the measurements again did not ($p = 0.874$). Tillage treatments differed significantly from each other. No-tillage had a significantly higher hydraulic conductivity (35.85 $mm.h^{-1}$) compared to conventional tillage (9.83 $mm.h^{-1}$). Comparing the two experiments there was a significant decrease in hydraulic conductivity ($p = < 0.0001$). This was only significant for the conventional tillage treatment which decreased from 19.98 to 9.83 mm.h^{-1}. The no-tillage treatment showed statistically the same saturated hydraulic conductivity in both experiments.

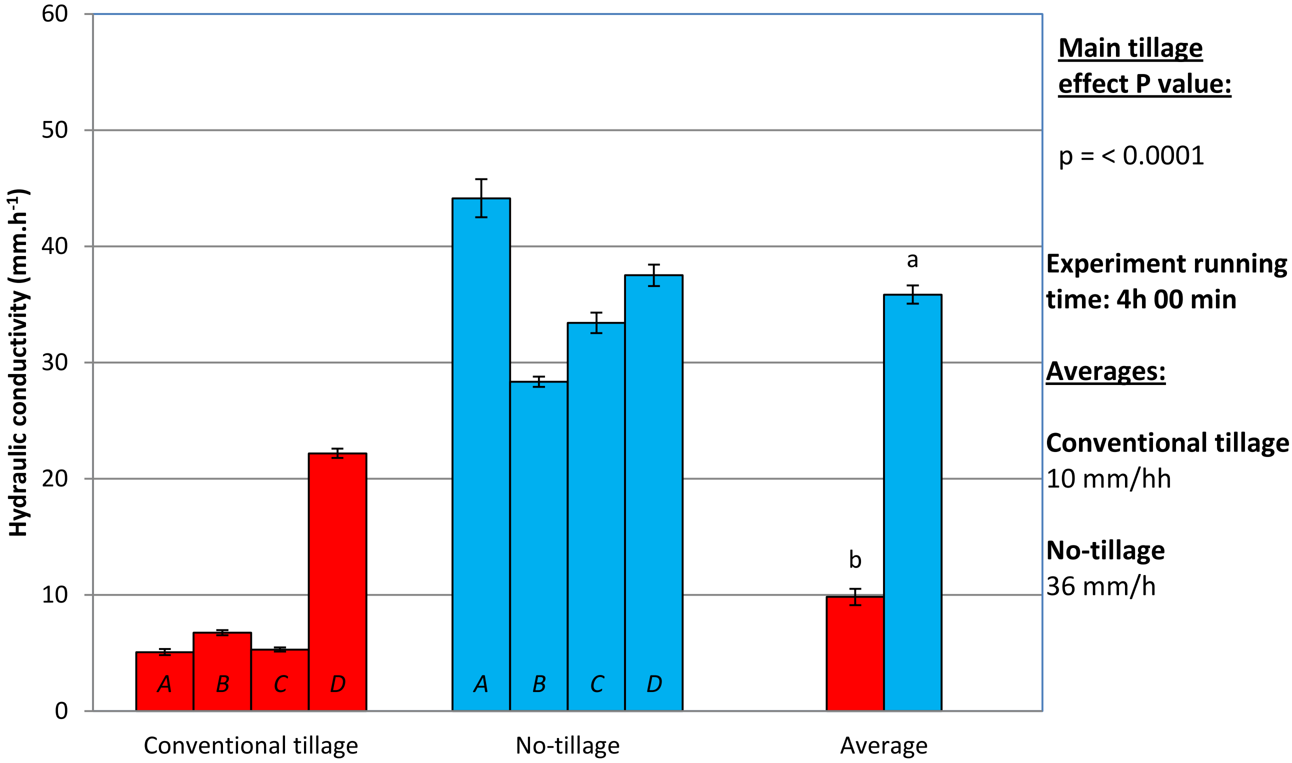


Figure 4-21: Saturated hydraulic conductivity for conventional and no-tillage (Experiment 2)

4.3.7 Coarse fragment water storage potential

To calculate the water storage potential of the coarse shale fragments, the bulk density of shale needed to be determined first to ascertain the volumetric water content.

4.3.7.1 Bulk density of shale coarse fragments

Table 4-7 shows the average bulk density determined by using 16 randomly collected shale coarse fragment samples of the parent material in selected soil profiles of the study.

Table 4-7: Average bulk density for the shale coarse fragments

Average bulk density ($kg.m^{-3}$)	Samples (N)	Standard deviation	Standard error
2311	16	31.70	7.92

4.3.7.2 Volumetric water content of shale coarse fragments

The gravimetric water content was determined before converting it to volumetric water content (data not shown). **Figure 4-22** shows the volumetric water content of the coarse fragments for the three horizons encountered in the soil. The two saturation methods, saturated in water and saturated in water under suction, are shown. The water contents of all treatments varied from 0.14 $mm.mm^{-1}$ to 0.19 $mm.mm^{-1.}$

Significant differences where encountered when comparing the saturation methods (p = 0.02). The suction saturation method had significant higher volumetric water contents comparing to the other method. The volumetric water content for different horizons did not differ significantly (p = 0.438). The coarse fragments of all three horizons, therefore, stored the same amount of water, although the parent material tends to store a higher amount of volumetric water.

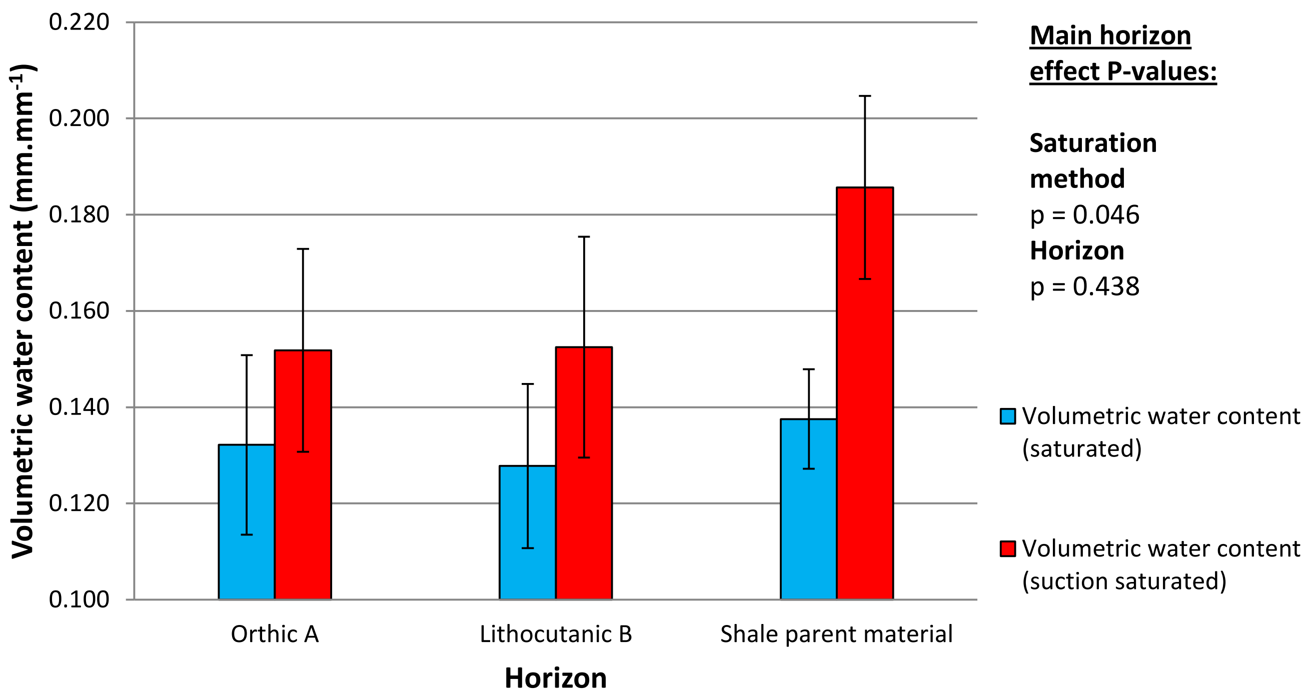


Figure 4-22: Volumetric water content of the shale coarse fragments occurring in the different horizons

CHAPTER 5: DISCUSSION

In this chapter the different results will be discussed, ending with a description of the interaction of the different soil properties as a consequence of tillage for the two extreme tillage practices, namely conventional tillage and no-tillage.

5.1 Chemical properties

5.1.1 pH (H_2O and KCl)

The results of pH (H_2O) showed that no-tillage had a significant higher pH compared to the other three tillage treatments in the 0-100 mm sampling depth. On average the pH under no-tillage was 0.51 units higher compared to the other tillage treatments. This contrasts with most of the literature. Higher nitrogen mineralization rates encountered in no-tillage usually occurred with lower pH compared to conventional tillage (Blevins *et al*., 1983; Staley and Boyer, 1997; Limousin and Tessier, 2007). The higher pH (H_2O) under no-tillage in the 0-100 mm soil depth may be as a result of lime addition (Staley and Boyer, 1997) and little soil disturbance, increasing the concentration of calcium at the surface. Because of no incorporation of lime in the no-tillage treatment, the soil surface had a higher pH compared to conventional, tine and minimum tillage where lime was incorporated into the soil, although to a lesser extent in the minimum tillage treatment. Comparing these three tillage treatments the pH was more or less uniform between the two depths, indicating that lime was also incorporated below the 100 mm soil depth, especially in the conventional tillage treatment. The high pH is most likely a result of lime amelioration since lime is applied frequently to this experiment, every 4 to 5 years, at a rate of 2000 $kg.ha^{-1}$.

Tillage practices had no significant effect on the pH (KCl) at both sampling depths. This in not in line with the pH (H_2O) results and may soil variation. Smit (2002) also did not find significant differences between tillage treatments in a study conducted on the same experimental farm. In 2008 Agenbag (2012) found, for the same tillage experiment, no significant differences between tillage treatments for the wheat monoculture and crop rotation systems. For the wheat monoculture system conventional tillage had a pH of 4.4, tine tillage 4.2, minimum tillage 4.3 and no-tillage 4.0. In contrast to our study no-tillage tends to have a higher pH (KCl) for the 0-100 mm soil depth and to a slight extent in the 100-200 mm depth. Again this may be as a result of lime addition as already explained. The pH decreased with depth, except for the minimum tillage treatment which was 0.28 units higher in the 100-200 mm sampling depth. This is in contrast with the study of Limousin and Tessier (2007), which found an increase in pH with depth.

Martinrueda *et al*., (2007) conducted research on a similar soil type (Calciortidic Haploxeralf). Their study showed that under no-tillage soil pH tended to decrease, but this decrease was also not significant. Lower pH as a result of no-tillage can be explained by increased acidification due to higher mineralization rates. Acidification is mainly due to the mineralization of organic matter, the effect of nitrification of added fertilizer and root exudation. This phenomenon is concentrated in the surface layers (Limousin and Tessier, 2007), especially for no-tillage, where the organic matter is concentrated and where the fertilizer accumulates at the surface due to no incorporation.

Both pH (H2O) and pH (KCl) showed the same trend at the three depths, indicating that no-tillage tends to result in a higher pH. Tillage doesn't directly affect the Lithocutanic B horizon. Higher pH as a result of lime addition is thus unlikely for this horizon. It might be due to better water infiltration and deep drainage in no-tillage that could, in the long term, cause calcium ions from lime additions to leech into this horizon, increasing the pH. It could also be due to natural soil variation or the secondary effect of termites, which was quite active in the no-tillage treatment plots, but this statement is not proven scientifically.

From this study, results suggest that higher pH (only significant under pH in water) observed in no-tillage is a consequence of lime addition which is done on a 5 year rotation at the Langgewens experimental farm. No significant differences were the general trend and are in line with other studies (Smit, 2002; Martinrueda *et al*., 2007; Agenbag, 2012). Our results confirm the statement of Thomas *et al*., (2007) that pH is not affected by tillage. In other literature decrease of pH under no-tillage is well documented and highlights therefore the application of lime when using no-tillage practices.

5.1.2 Electrical conductivity (EC)

Electrical conductivity (EC) shows an interesting trend. Normally one would expect a higher EC reading in no-tillage practice because fertilizer is only applied to the topsoil at planting, leading to an accumulation in the 0-100 mm soil profile. Conventional tillage also received fertilizer in the same way, but because the soil is tilled once every year, the fertilizer is incorporated evenly over the 0-200 mm soil depth and the 0-100 mm depth is expected to show a lower EC reading.

This is not true for the results obtained in this study. Conventional tillage has a significantly higher EC compared to no, tine and minimum tillage for the 0-100 mm soil profile. In the 100-200 mm soil depth, conventional tillage also showed a slightly higher EC. This phenomenon can be described by one or more of three processes. The first process relate that under conventional tillage a plough pan is created as a result of mouldboard ploughing (Pelegrin *et al*., 1990; Huggins and Reganold, 2008). A plough pan is found in this study and is also well established because this is a long-term experiment running for 37 years. A plough pan is a dense soil layer formed by mouldboard ploughing just under the tillage depth that causes a discontinuity in the soil and limits water infiltration into deeper layers (Huggins and Reganold, 2008) and thus resisting salt leaching (Morin, 1993). Evapotranspiration would thus mainly take place from the 0-200 mm depth. In the plough pan, a better capillary structure is created which causes an upward movement of water through capillary action supplying the soil surface with water for evaporation (De Clercq *et al*., 2009). Salts are thus concentrated in the surface soil depth resulting in higher salt concentrations and EC readings. A plough pan may possibly be the main problem causing the increase in EC because no differences are observed between the other tillage treatments. The second process relates to better water infiltration (Bissett and O’ Leary, 1996; Moreno *et al*., 1997; Lal, 1997), percolation (Bissett and O’ Leary, 1996; Shipitalo *et al*., 2000) and hydraulic conductivity (Benjamin, 1993; Bhattacharyya *et al*., 2009) created under conservation tillage and especially no-tillage. Improved water dynamics may result in more effective leaching of salt to the deeper soil layers compared to conventional tillage. Enhanced deep drainage of salts under no-tillage is confirmed by O’Leary (1996) and Shipitalo *et al.* (2000). A third phenomenon could be the relative higher percentage of total carbon content in tine, minimum and no-tillage. A higher total carbon content also relates to higher organic carbon in the soil, which is able to absorb more salt ions and thus lowering the EC. Although very low carbon contents encountered in all tillage practices makes this process unlikely. The higher EC encountered under conventional tillage may thus be described by one or more of these processes.

The results of EC in the Lithocutanic B horizon show the same trend as in the 0-100 mm and the 100-200 mm soil sampling depths. No-tillage showed the lowest EC and conventional tillage the highest. This also indicates better water movement through the soil profile for the no-tillage treatment, which decreases salinity due to increased leaching. Higher EC values in conventional, tine and minimum tillage treatments compared to the 100-200 mm soil sampling depth indicates that leaching of salts is not as effective as for no-tillage treatment.

In our study no-tillage is proven to be beneficial in terms of salinity. At all three sampling depths the EC was the lowest and more or less the same, 7.29, 6.17 and 5.51 $mS.m^{-1}$. Firstly, with more water infiltrating into the soil, salts accumulated to the surface are leached downwards into the shale parent material and reduces the salt concentration left in the soil (De Clercq and Van Meirvenne, 2005; Badalucco *et al*., 2010). Results of minimum and tine tillage treatments are not logically in line with conventional and no-tillage and this may be due to ineffective sampling.

5.1.3 Resistance and water soluble cations, anions

To support the EC results the electrical resistance and water soluble ions were analysed for the conventional and no-tillage treatments. These two treatments were chosen because they had the highest difference in EC and because they showed the most difference in soil disturbance. The much higher resistance of 1660 ohm for the no-tillage treatment confirms the low EC for this treatment. The low resistance of 156.5 ohm in the conventional tillage treatments relates well to better electrical conductance and thus the higher EC. Water soluble cations and anion results provide an idea of which ions contribute to the higher EC. In our case these ions are calcium, magnesium, sodium, chlorite and sulphate. The high concentrations of sodium, chlorite and sulphate ions in the conventional tillage treatment can possibly be due to restricted leaching and limited water movement as explained in the previous section. The question arises where these ions come from. Some agricultural amendments do contain small amounts of sodium, although chloride and sulphate are commonly found in fertilizers. The main reason for the higher concentration of these ions is therefore not fertilizer application. The source of these ions is the sea, which is just more than 100 km away from the study site. The ions accumulate via salts which are aerially transported from the ocean to the inland where it is deposited to the soil over long periods of time (De Clercq *et al*., 2010). These ions are thus continuously supplied by the ocean and increase the soil's salt ion concentration if not leeched through to the ground water. On average, about 20 kg of sodium per ha is deposited yearly on these soils (De Clercq *et al*., 2010).

Thomas *et al.* (2007) found that exchangeable magnesium and sodium concentrations were greater under conventional tillage compared to minimum and no-tillage. Calcium concentration was also the highest in conventional tillage but not significantly so. Pardo and Lopez-Fando (2009) found that in the 0-50 mm soil depth, exchangeable potassium was significantly higher (2.10 $mg.kg^{-1}$) in the no-tillage treatment compared to minimum (1.61 $mg.kg^{-1}$) and conventional tillage (1.45 $mg.kg^{-1}$), but magnesium concentration did not differ significantly among tillage treatments. Most of these findings relate well to our results although the concentration units used for comparison differ. High calcium and magnesium ion concentrations in the conventional tillage treatments may be due to the frequent lime and dolomitic lime additions every five years, which is a standard practice on the farm.

Sodium, chloride and sulphate ions transported from the sea are therefore continually added to the soil. In the long term these ions may result in high salinity in the soil, which can ultimately have an impact on plant growth and yield. It is thus important to apply tillage practices, which promote water infiltration and deep drainage to leach the soil and lower the EC. This can be achieved through no-tillage.

5.1.4 Total carbon content

In the 0-100 mm soil profile depth conventional tillage had a significantly lower total carbon content compared to the other tillage treatments. This shows that with the decrease of soil disturbance from conventional to no-tillage the carbon content is likely to increase. Our results is in some way consistent with results found by Agenbag and Maree (1989) at the beginning of this same experiment in 1975. They found significant differences between conventional tillage and no-tillage but not between tine and no-tillage, looking at organic carbon content. The average organic content for their results (0-100 mm soil profile) of the wheat monoculture from 1985 to 1987 was 1.1% for conventional tillage, 1.43% for tine tillage and 1.40% for no-tillage. In 2008 this content decreased and average organic carbon contents was 0.43% for conventional, 0.69% for tine, 0.68% for minimum and 0.80% for no-tillage (Agenbag, 2012).

Compared to this study's results of total carbon percentage, Agenbag's results for organic carbon percentage in 2008 (a fraction of total carbon) correlates well. From 1975 to 2008, the carbon content in the soil for all the tillage practices decreased drastically. Nevertheless no-tillage still had the highest total carbon content in the surface (0-100 mm) horizon and confirms the finding of numerous studies conducted in the Mediterranean and semi-arid climate (Agenbag and Maree, 1989; Mrabet *et al*., 2001; Hernanz *et al*., 2002; Bescansa *et al*., 2006; Sasal *et al*., 2006; Thomas *et al*., 2007; Agenbag, 2012). Tillage treatments with intermediate intensity and frequency like the tine, reduced and minimum tillage treatments generally resulted in intermediate carbon concentrations at the soil surface (Unger, 1997), which is also true for our study. Tine and minimum tillage treatments resulted in intermediate total carbon contents and are in line with the amount of soil disturbance (Agenbag, 2012). The significant lower total carbon content encountered in conventional tillage treatment is as a result of intensive soil disturbance and mixing, which promote rapid decomposition and oxidation of organic matter (Rasmussen and Collins, 1991; Du Toit *et al*., 1993; Cannell and Hawes, 1994) limiting carbon build-up in the soil. Conventional tillage, with mouldboard ploughing, therefore enhances mineralization on organic matter to form carbon dioxide, depleting the soil's carbon content.

At the 100-200 mm soil profile, tine tillage had the highest total carbon content followed by conventional, minimum and no-tillage. No-tillage, with no disturbance of the 100-200 mm soil depth, therefore limits the movement of organic matter into deeper soil layers. The total carbon content for the 100-200 mm soil depth increased in the order of no, minimum and tine tillage, except for conventional tillage. With tine and minimum tillage the chisel implement application help to incorporate a part of the crop residues, and as a result the increase in total carbon contents. In conventional tillage the mouldboard plough application (200 mm working depth), results in mixing of the whole 0-200 mm soil layer. This can be seen in the total carbon contents, which do not differ between the two sampling depths, indicating that organic carbon is uniformly distributed in the soil. Fernández-Ugalde *et al.* (2009) made similar findings, showing that organic matter content of the conventional tillage treatment was more or less the same for the two sampling depths (0-50 mm, 50-150 mm).

From this study results showed that the no-tillage treatment increases total carbon content and that conventional tillage, which incorporates the residues below ground, reduces the total carbon content significantly. It was expected that no-tillage treatment after more than 30 years would have increased the carbon content of the soil to much higher percentages, a phenomenon that is well documented in the literature. This was not observed in our study and others (Smit, 2002; Agenbag, 2012), compared to conventional tillage. The no-tillage treatment in our study only resulted in a total carbon percentage of 0.41% more. The average total carbon content of the no-tillage treatment of 0.92% measured in 2011 compared to the average organic carbon content of 1.34% in 1987 for the same mono-culture plots indicate that there is a substantial decrease in carbon in the soil. This decrease could be due to three contributing factors. First it can be as a result of the continued wheat cropping, which is not effective in increasing soil carbon content compared to crop rotation (West *et al*., 2002). Secondly it may be due to poor management of the crop residues, leaving too little after making hay, extensive grazing by animals or low crop residue production. Thirdly it may be as a result of the Mediterranean climate of the Western Cape, which is harsh with mainly high mean temperatures, low rainfall and high evaporative demand, which promotes mineralization of organic matter and limits the build-up of organic matter (Badalucco *et al*., 2010).

Stimulating organic matter accumulation using no-tillage practices in this area may thus be much more complex or nearly impossible, considering the climate. Critically organic matter accumulation is one of the main advantages of no-tillage because of the positive effects on the soil physical properties like aggregate stability.

5.2 Physical properties

5.2.1 Particle size distribution

The **Pipet method** is the standard method for determining the soil texture and is used universally, making it easy to compare texture results among articles. Normally soil texture is seen as a soil property which is stable and do not change over time. In some cases when soil is subjected to long-term tillage, especially intensive mouldboard ploughing, particle size distribution may be altered as shown in the study of Lal (1997). He found that on an Alfisol in Nigeria, after eight years of tillage, sand content was significantly lower and clay particle sized content significantly higher in the 0-100 mm soil profile of no-tillage compared to the conventional tillage treatments. The conventional tillage treatment thus caused the larger sand particles to be broken down to smaller-sized particles.

Results show no differences in particle size distribution between all four tillage treatments of both sampling depths. Comparing separate size classes, no differences were found except for the small difference is fine silt content. This confirms that soil texture is a stable soil property and is not easy to alter even after more than 30 years of tillage. The results of Paz-González *et al.* (2000) confirm our findings. He stated that tillage has no significant effect on particle size distribution. On the other hand our particular experimental site was initially managed under conventional mouldboard ploughing (for many years before 1975). As a result, texture could have been altered and could have reached equilibrium before the other tillage practices was introduced, causing a homogeneous particle size in all treatments. One way of confirming this statement would be to analyse the particle size distribution of a nearby undisturbed natural soil and compare it to these results. This was not tested in our study because most agricultural soils in the Swartland are initially managed under conventional tillage, switching to no-tillage would thus also have no effect on the texture. If virgin soil would be directly managed under no-tillage differences may occur.

The texture class of all the treatments at both sampling depths is a sandy loam, the sand grade being coarse. Sandy loams with a high fine sand fraction are especially highly susceptible to compaction and hard setting (Bodmin and Constantin, 1965; Bennie, 1972) because soil texture affects bulk density (Terry *et al*., 1981). Batey and Davies (1971) made similar findings. Soils with relatively high contents of silt and fine sand have a tendency towards structural instability and compaction, particularly if the organic carbon content is low (Singh *et al*., 1994). Seasonal bulk density and consolidation experiments were thus conducted to see the effect of tillage on re-compaction susceptibility.

Laser diffraction is a relative new method for determining the soil texture but is not used as widely as the pipet method. A universal method is also not yet described and established. As technology progresses, new ways of analysing particle size distributions of soil are constantly being developed. The advantages of using a laser particle size analyser are that every sample is treated in exactly the same manner and under the same conditions, thus limiting experimental error. The standard sieve and pipet method have some critical disadvantages; it is time-consuming, very dependent on laboratory technique and operator skill (Syvitski *et al*., 1991) and large amounts of material (soil) is needed (Beuselinck *et al*., 1998). These common drawbacks make it nearly impossible to do rapid and accurate analysis of large numbers of samples (Beuselinck *et al*., 1998). New methods that use a single instrument will thus be much more practical. Although this specific instrument is only able to detect all particles smaller than 1 mm, in our case it was not true. In the first practice runs (tests) we did, it became clear that only soil particles smaller than 0.25 mm could be detected accurately. This was the first limitation as the whole soil fraction cannot be analysed by this particular instrument. A possible solution to this problem could be to increase the circulation speed of the sample and increase the speed of the ultra-sonic stirring devise but this would be a risk because particles could be broken down to smaller ones.

During the first experiment all particles smaller than 0.106 mm was analysed (very fine sand to clay fraction). The results were very different from the pipet method. The very fine sand fraction differed significantly between the two methods and was about 11% less for conventional and 10% less for no-tillage. The fine silt fraction also differed significantly between the two methods and was about 15% more for conventional and 14% more for no-tillage. Coarse silt fraction was more or less the same compared to the pipet method. The clay fraction was the same for both methods. In the second experiment all particles smaller than 0.250 mm (fine sand to clay fraction) were analysed. Again the results differed significantly from the pipet method with the fine sand fraction being about 8% lower for conventional and 5% lower for no-tillage. The fine silt fraction was about 7% more for conventional and 5% more for no-tillage. The clay content was analysed more or less correctly compared to the pipet method.

Comparing the two methods, the very fine sand differed significantly among the three experiments. This may be as a result of insufficient representative sampling which is the second limitation of the particular instrument. It may also be possible that these particles were not detected by the instrument. The sample mass needed for analysis is very little – only a gram of soil is used. To get a representative 1 gram sample of a soil is impossible. The clay fraction and to some extent the coarse silt fraction being analysed correctly with little error gives an indication that this particular instrument is more effective in analysing small silt and clay sized particles. Referring to the literature, it is generally accepted that laser diffraction grain sizes measure higher silt and lower clay contents than the reference sieve pipette method (Buurman *et al*., 1997; Beuselinck *et al*., 1998; Eshel *et al*., 2004). In some cases sand contents detected by laser diffraction are also lower compared to the sieve-pipette method (Beuselinck *et al*., 1998; Eshel *et al*., 2004) which confirms some of our results. No differences were also found comparing no-tillage and convention tillage particle size distribution via laser diffraction analysis. This result confirms the conclusions based on the pipet method.

From the experiment with laser diffraction, it is derived that the specific instrument used is not suited for particle size distribution analysis of soil (< 2 mm), although it may be used to determine fractions of small particles like clay and to some extent also the silt fraction. High variation in some of the fractions analysed also reduced the practicality of the laser diffraction instrument.

5.2.2 Coarse fragment content

Coarse fragments of the soil (> 2 mm) form part of the soil particle size distribution to some extent. In this study the coarse fragments are mainly shale fragments from the Lithocutanic

B horizon as a result of weathering of the deeper lying parent material, although coarse quartz fragments are also present (< 5% of the soil mass). These fragments are brought to the surface from the Lithocutanic B horizon as a result of tillage actions. At both sampling depths, it is observed as a general trend that an increase in tillage intensiveness or amount of soil disturbance (no-tillage to conventional tillage) causes the coarse fragments in the profile to increase.

At both depths conventional tillage had the highest amount of coarse fragments although only significantly more than no-tillage. Tine and minimum tillage contents lie between those of conventional and no-tillage. The scarifier with a working depth up to 150 mm, used in tine tillage, causes coarse fragments in the 100-200 mm depth to move towards the surface. In minimum tillage a chisel plough is used and the working depth is said to be 75 mm but the coarse fragment content is nearly the same as tine tillage and suggest that the working depth might be deeper. After speaking to the farm manager of Langgewens he confirmed that the chisel plough used in the minimum tillage treatment does tend to go deeper than 100 mm. The noticeable higher coarse fragment percentage in conventional tillage is the result of deep ploughing over many years (Vieira *et al*., 2000). These results show that the use of agricultural implements results in the process of segregation or kinetic sieving and confirms the phenomenon described by Oostwoud Wijdenes and Poesen (1999). In the no-tillage treatment the soil is only disturbed up to a depth of 100 mm once a year when planting, and thus the process of segregation does not appear to take place to the same extent. For this reason there is a significantly lower coarse fragment content compared to conventional tillage. The fact that no or only a little segregation occurs in no-tillage is therefore due to less soil disturbance as well as the shallow planting depth.

As seen from the literature study, the impact of higher amounts of coarse fragments at the soil surface may be negative or positive. No-tillage with the lowest amount of coarse fragments in the 0-100 mm soil depth has a higher soil to coarse fragment ratio. This surface layer would thus have a higher water holding capacity improving seed germination and growing in dry winters. Seed/soil contact would also be higher.

5.2.3 Aggregate stability

Aggregate stability is one of the most important soil properties because it relates directly to soil structural stability and also indirectly to soil sustainability. Minimum and no-tillage showed stable aggregation at both sampling depths. Significant differences were encountered at the 0-100 mm as well at the 100-200 mm soil depth. In both cases the same trend was observed, namely that no-tillage treatments had the highest percentage of water stable aggregates followed by minimum tillage and the two more intensive tillage treatments, tine and conventional tillage. The results of Abid and Lal (2008) is more or less the same compared to the current study. In the 0-100 mm soil depth no-tillage had an aggregate stability of 78.53% and conventional tillage 58.73% compared to our results of 78.40% and 47.82% respectively. Although in the 100-200 mm soil depth the water stable aggregate percentage for their results were much lower (more than 20% on average) compared to their results. Gwenzi *et al.* (2008) also made similar general findings, namely that water stable aggregates also differed significantly between tillage treatments at the 0-150 mm soil depth. At the 150-300 mm no differences were observed between minimum and no-tillage but it was still significantly higher than with conventional tillage. The significant lower water stable aggregates encountered in the conventional tillage treatment suggest the amount of carbon in the soil and the degree of soil disturbance might play an important role in formation of water stable aggregates. Filho *et al.,* (2002) reported that two main factors responsible for high stable aggregates indeed was organic carbon concentration and soil tillage intensity. Poor aggregate stability under conventional and tine tillage is related to the weakening of aggregates due to periodic disturbance of the soil by tillage implements (Yang and Wander, 1998; Kasper *et al*., 2009) and exposing soil organic carbon to oxidation decreasing the carbon content (Gwenzi *et al.*, 2008). Thus higher organic carbon contents, encountered in no-tillage due to the improved residues and roots, generally influences the formation and stabilization of soil aggregates (Filho *et al*., 2002). This statement is true for the study, because higher total carbon content at the 0-100 mm soil depth led to higher water stable aggregates. The opposite is true also for the conventional tillage which has the lowest total carbon content and water stable percentage. Although this trend is not the same for the 100-200 mm soil depth, the no-tillage treatment here has the lowest total carbon content but still the highest water stable aggregate percentage. A decrease in tillage intensity thus improved soil aggregation (Alvaro-Fuentes *et al*., 2008).

Abid and Lal (2008) stated that the effect of tillage on distribution of water stable aggregates is manifested through the change in organic carbon concentration. Organic matter thus acts as a binding agent for aggregate formation (Bronick and Lal, 2005). Regression analysis showed a significant ($p = 0.0003$) linear relationship between total carbon content and water stable aggregate percentage (coefficient of determination (r^2) = 44%) at the 0-100 mm soil depth for our results. This coefficient of determination is similar to coefficient of determination found in Abid and Lal (2008), study (r^2 = 42%) for their regression analysis of organic carbon ($g.kg^{-1}$) and water stable aggregates. This indicates that only 44% of the variation in aggregate stability is explained by total carbon content. At 100-200 depth, there was no significant relationship between total carbon content and water stable aggregate percentage ($p= 0.711$), probably due to higher total carbon content of the conventional tillage treatment with still a very low water stable aggregate percentage. Total carbon is thus not a major factor controlling the aggregate stability of the 100-200 mm soil depth. Abid and Lal (2008) made similar findings in their study for the 100-200 mm soil depth. Other studies reported similar relationships between organic or total carbon content and aggregate stability (Chan *et al.*, 1994; Gwenzi *et al.*, 2008).

The relationship between soil organic carbon and aggregate stability suggests that the observed differences in aggregate stability among tillage systems at 0-100 mm depths are due to changes in total carbon content although other factors are also involved. Filho *et al.* (2002) observed that not only organic carbon content were associated with macro-aggregates but also high quantities of nitrogen (N). Unger (1984) and Alvaro-Fuentes *et al.* (2008) stated that tillage method also influences aggregation especially aggregate size. Tillage can also destroy previously formed aggregates. Tillage type and the amount of soil disturbance are thus also linked to aggregate stability. The higher SAR (sodium absorption ratio) evident in conventional tillage compared to no-tillage may also influence aggregate stability.

The findings from this study support those from other studies which showed higher aggregate stability under no-tillage and minimum tillage than in more intensive tillage practices such as tine and conventional tillage (Unger, 1997; Martinez *et al*., 2008; Abid and Lal, 2008; Gwenzi *et al*., 2008). Water stable aggregate is directly linked to soil quality and thus also soil sustainability (Unger, 1997). By inference, minimum and no-tillage are important for preserving and improving the structural stability to maintain production sustainability of Glenrosa soils in the Western Cape. High water stable aggregate parentages are important for maintaining water infiltration, reducing the potential for erosion by water and increasing the potential for greater water storage (Unger, 1997). With low stability aggregates in the event of rain or irrigation, water break down and rearrange aggregated soil particles, thus forming a surface seal that retards infiltration and results in run-off and erosion (Hillel, 1980; Unger, 1997).

5.2.4 Sheer strength

Sheer strength is the potential of soil to withstand the impact of external forces (Hillel, 1980) and is related to bulk density and thus to soil structure. Sheer strength increases as bulk density increases. Therefore it also gives an indication of soil compaction and the degree of aggregation (Baumgartl and Horn, 1991). This property was measured to determine if soil compaction occurs after planting and to what degree it varies between the tillage treatments. However, it also supports the bulk density results.

At 6 June 2012, 41 days after planting, significant differences were found between tillage treatments. Significant higher sheer strength measured in the no-tillage treatment indicates that tillage reduces sheer strength. Similar values for conventional, tine and minimum tillage treatments show that the soil surface (0-10 mm) is disturbed to the same degree, although minimum tillage (a less intensive tillage treatment) showed a higher average sheer strength. Tillage treatments with limited soil disturbance, such as no-tillage and to some extent minimum tillage, will thus lead to higher sheer strength values after tillage. This is mainly because in the no-tillage treatment, most of the soil structure stays intact and because no-tillage has a better aggregate stability. Yavuzcan, Vatandas and Gurhan (2002) stated that soil strength is reduced by tillage, especially by conventional, mouldboard ploughing that cause the greatest soil loosening and thus the lowest soil strength.

At the second measurement date in July, 84 days after tillage an increase in sheer strength was noticeable in all tillage treatments. Conventional and tine tillage showed significant higher sheer strength compared to minimum tillage, no-tillage significantly had the lowest sheer strength. The Glenrosa soil form with a sandy loam texture encountered in the study thus re-compacts after tillage. This may be due to this particular texture with a high fine sand fraction which is highly susceptible to compaction and hard setting (Bodmin and Constantin, 1965; Bennie, 1972). Re-compaction as the season progressed may also be as a result of natural processes and wheel traffic (Yavuzcan *et al*., 2002, 2005). In the study wheel traffic was very limited and measurements were taken where no tracks were evident. The increased sheer strength is therefore caused by many natural processes. The no-tillage treatment showed the lowest increase in sheer strength and this is probably due to better soil structure, which resisted re-compaction. Better soil structure is less prone to re-compaction (Baumgartl and Horn, 1991). From the results it is clear that directly after tillage, better soil structure causes higher sheer strength and that later in the growing season, re-compaction is the reason for higher sheer strength. These results mainly point toward the 0-10 mm soil depth which were measured and thus higher sheer strengths encountered in the conventional and tine tillage treatments may be due to a surface seal or surface crust forming due to low water stable aggregates and high sodium concentrations (Morin, 1993).

Soil water content influenced sheer strength measurements. Higher water contents may decrease sheer strength. The regression analysis showed that water content was negatively related to gravimetric water content ($p = 0.0001$) with an r^2 value of 37%. This relation is weak and is confirmed by the results of the first sampling date due to no differences observed in water content between tillage treatments. There were still significant variations in sheer strength. The total average gravimetric water content of the soil surface was significantly lower at the second measuring date (0.017 units lower). This may therefore have increased the sheer strength values of all the tillage treatments but due to the decrease in water content being so little the influences can be neglected. Water content influence on sheer strength in our case could thus be ignored, although it is related to sheer strength.

Sheer strength results showed that the soil structure of the no-tillage treatment stayed intact and was significantly higher at the first measuring date compared to the more intensive tillage treatments. Later in the season, at the second measuring date, the more intensive tillage treatments (conventional and tine tillage treatments) increased to significantly higher values compared to no-tillage. Soil under no-tillage management thus has more stable sheer strength. To some extent conventional and tine tillage may both cause the development of a surface crust.

5.2.5 Bulk density

5.2.5.1 Troxler bulk density

Soil bulk density is a vital soil property that influences many other soil properties directly. After planting, especially in the early stages of seedling development, topsoil conditions are very important in dry land agriculture because it impacts seed germination, seedling growth, root growth and thus in the end also yield, directly.

Focusing on the differences between tillage treatments measured for the full 2011-season and the first half of 2012, a general trend is observed. No-tillage had higher bulk densities in the beginning of the season directly after tillage but as the season progresses very little increase in bulk density occurred before it stabilized. This is mainly because no-tillage causes very little soil disturbance. The soil structure thus stays integral. Better soil structure is less prone to re-compaction (Cameron *et al*., 1987; Baumgartl and Horn, 1991) and bulk density does not vary over the season. For conventional, tine and minimum tillage treatments the opposite were found. Due to more intensive tillage operations bulk density is significantly decreased at tillage operations. Intensive tillage treatments destroy aggregates and soil structure (Agenbag and Stander, 1988; Yang and Wander, 1998; Huggins and Reganold, 2008; Kasper *et al*., 2009) and as a result create many macro pores that decrease bulk density (Martinez *et al*., 2008). Although, as the season progressed, the bulk density significantly increased in the order minimum, tine and conventional tillage, until it stabilized. The increase in bulk density is largely because of no to very little stable aggregates and soil structure apparent in intensive tillage treatments. Minimum tillage did not show the same severe increase in bulk density. This may be due to the fact that some of the soil structure was still left undisturbed as in the case of no-tillage.

After soil compaction has taken place in both seasons, the bulk density magnitude is in line with the intensity of soil disturbance of each tillage treatment. No-tillage with the least amount of soil disturbance showed the lowest bulk density, compared to conventional tillage with the most intensive soil disturbance that had the highest bulk density. These results are line with the finding of Lal *et al.* (1994) that after 28 years of tillage mean bulk densities of three different crop rotations measured prior to application and planting were 1180 for no-tillage, 1240 for tine tillage, and 1280 $kg.m^{-3}$ for conventional tillage. Abid and Lal (2008) also found that no-tillage had a lower bulk density (1460 $kg.m^{-3}$) compared to conventional tillage (1560 $kg.m^{-3}$) in the 0-100 mm soil depth, although when these measurements were taken, is not clear. He *et al.* (2011) made similar findings on bulk density measured at the end of the growing season.

The pairwise t test revealed that the bulk density significantly decreased after tillage. Fourteen days before tillage and 27 days after tillage the bulk densities differed significantly. The no-tillage treatment also decreased the bulk density after tillage but this was less significant ($p = 0.039$) and tillage will not have lowered the bulk density significantly at 0.001 significance level. This might not have been significant if planting was performed on the same planting rows, which will be explained in the next paragraph.

In all tillage treatments an increased bulk density was visible through the season. For the 2011-season the increase in bulk density units were 232 $kg.m^{-3}$ for conventional tillage, 214 $kg.m^{-3}$ for tine tillage, 160 $kg.m^{-3}$ for minimum tillage and 96 $kg.m^{-3}$ for no-tillage. This is mainly because Glenrosa soil forms with a sandy loam texture as encountered in this study are highly susceptible to re-compaction. This is due to the texture of this particular soil, namely a high fine sand (19%) and silt (25%) fraction, which is highly susceptible to natural compaction and hard setting (Bodmin and Constantin, 1965; Batey and Davies, 1971; Bennie, 1972) as stated in previous sections. Pelegrin *et al.* (1990) also found that bulk density also increased with time (days after planting) in the arable layer and ascribed it to natural compaction and wheel traffic. Rousseva *et al.* (1988) and Osunbitan *et al.* (2005) made similar findings and stated that the soil compacted after tillage under the influence of rainfall and particle resettlement with the combination of cycles of wetting and drying. Rousseva *et al.* (1988) stated that in their study major bulk density changes occurred in the 0-100 mm soil depth and that the changes were strongly correlated with the amount of water applied to the soil, which can be rain or irrigation. In this study total cumulative rainfall was also strongly correlated to the increase in bulk density through the season. Regression of all the tillage treatments in our study resulted in an r^2 value of 66.3% which is good, but if separate regressions were made, better r^2 values and correlations were obtained. Conventional tillage had r^2 of 73.6%, tine tillage an r^2 of 92.0%, minimum tillage an r^2 of 80.2% and no-tillage an r^2 of 61.9%. No-tillage thus showed a lower correlation which may be due to the little seasonal change in bulk density. The unusual variation in the no-tillage treatment through the season was initially not expected. If bulk density is measured between planting rows and planting take place in the same row each year (by GPS assisted tractors and planters), bulk density should not vary as much because the soil between the planting rows is not disturbed or is only disturbed to a slight degree. In our study planting operations were not constantly applied on the same tillage rows of the no-tillage treatment and thus the soil areas between rows were also disturbed. In the second season new measurement sites had to be started as a result. The increase in bulk density for the no-tillage treatment may thus be due to the fact that planting of the seeds was not always done in the same planting rows of the previous year. Planting the same rows in no-tillage would thus cause a steady, more stable bulk density right through the season and this correlation could therefore have been much lower or even non-significant. Good correlation of conventional, tine and minimum tillage indicate that as the season progressed, bulk density increased as a result of consolidation of the soil caused by rain drop impact and wetting and drying of the soil (Rousseva *et al*., 1988). Compaction of the soil surface layer is thus the result of natural processes (Ferreras *et al*., 2000; Yavuzcan *et al*., 2002, 2005), but also due to the high fraction of fine sand and silt.

Bulk density increase over the season in this study, is a result of natural compaction and is facilitated by rainfall. This can be described as the effect of hardsetting. Hardsetting of soil is a process of compaction, with increase in bulk density, that occurs without the application of an external load (Morin, 1993). This is mainly caused by internal effects such as the wetting and drying of unstable soil and other natural processes as already stated.

Hardsetting involves the collapse of some or all of the aggregated structure of a soil with an initial low bulk density. This phenomenon can be divided into two physically distinct processes: slumping and uniaxial shrinkage, which is explained thoroughly by Morin (1993). Hardsetting crusts are also most readily formed in kaolinitic soil types which are the dominant clay in our study's soil. The increase in bulk density of the 0-100 mm soil depth may therefore be due to hardsetting of the soil.

Concluding on the seasonal bulk density variation for the four tillage treatments, it is clear that no-tillage with very little soil disturbance have the most stable bulk density through the season. This suggests that stable soil structure is present in the no-tillage treatment (Cameron *et al*., 1987; Singh *et al*., 1994; Hernanz *et al*., 2002; Birkás *et al*., 2004; Bronick and Lal, 2005) that counters the increase in bulk density (hardsetting). Present soil structure is difficult to observe by the eye in the no-tillage treatment, but is confirmed by the significant higher aggregate stability, there may thus be some sort of micro structure. If planting was done on the same planting rows every year, an increase in bulk density for the no-tillage treatment might not have been observed and showed constant values. Conventional and tine tillage treatments significantly lowered the bulk density at tillage and planting operations as a result of intensive soil disturbance, destroying any soil structure development. Then as the season progressed the bulk density significantly increased to high levels which is well correlated to the cumulative rainfall and plays a vital role in hardsetting of the soil (Morin, 1993). Minimum tillage with limited soil disturbance is intermediate with regards to bulk density, mostly because some of the soil's structure stays intact. This suggests that minimum tillage is also less prone to natural compaction.

5.2.5.2 Comparison between the Troxler and clod method

Importantly in both bulk density measurement methods the same trends were observed. Bulk density increased in the order no, minimum, tine and conventional tillage. Also in both methods no-tillage had a significantly lower bulk density compared to conventional tillage. Comparing the values of the two methods, the clod method yielded significant higher bulk densities compared to the Troxler instrument. This is because the clod method usually gives higher bulk density values than other methods (Tisdall, 1951), mainly due to the clod method which do not take interclod spaces into account (Blake and Hartge, 1986). The

Troxler instrument included interclod spaces. These interclod spaces may play a bigger role because significantly higher differences where observed in minimum and no-tillage treatments compared to conventional and tine tillage. It shows therefore that minimum and no-tillage have more interclod spaces and relates to better soil structure. Interclod spaces may be the result of old root channels, termite or ant burrowing holes, cracks and openings in the soil and empty spaces between rocks.

The combined linear regression for all the tillage treatments between the bulk density values measured with the Troxler instrument and determines by the clod method confirms that the Troxler instrument is accurate (r^2 of 80.10%). Coarse fragment contents in this case do not significantly affect the readings of the Troxler instrument. These results conclude thus that the Troxler is a viable instrument to determine in situ bulk density for this study.

5.2.5.3 Laboratory soil (<2mm) bulk density determination and consolidation tests

Comparing the bulk density of only the soil fraction for conventional and no-tillage is important because this is the fraction where the plant roots grow. These tests were especially conducted to compare the fine soil bulk density (including micro aggregates) to the total in situ bulk density measured by die Toxler instrument. The mechanical consolidation treatment were conducted mainly to see if bulk density will increase to higher values if an external shaking force was applied.

The spike in bulk density after the first cycle for both consolidation treatments and tillage treatments may be due to the disturbed soil binding together. Thereafter, though wetting and drying of the natural consolidated samples, the particles could rearrange to form soil structure (Morin, 1993) as air could move into the samples. The stable bulk densities (after a few treatment cycles) for the natural and mechanical consolidated treatments did not differ for each of the tillage treatments. This means that the mechanical treatment was not severe enough to cause significant compaction.

In both treatments the soil fraction (< 2 mm) from the no-tillage treatment had the lowest bulk density (significantly) through all the treatment cycles. Looking at the initial bulk densities, there are also differences between conventional and no-tillage. This may be as a result of the no-tillage treatments having more and/or bigger aggregates (Kemper and Rosenau, 1986; Yang and Wander, 1998). Lower bulk densities observed in the no-tillage treatment after the treatment cycles is mainly because of the soil having a higher water stabile aggregate percentage (Filho *et al*., 2002; Abid and Lal, 2008; Gwenzi *et al*., 2008). Wetting and drying of the samples thus did not destroy most of the aggregates. In the conventional tillage treatment, the aggregates dispersed and disintegrated when the samples were wetter (Morin, 1993). This is due to the very low aggregate stability of this tillage treatment. Aggregate disintegration led to higher measured bulk densities (Abid and Lal, 2008). The little variation in bulk density observed in the natural consolidation treatment for the no-tillage treatment indicates that no-tillage causes a stable fine soil fraction (stable micro aggregates) that is resistant to wetting and drying of the soil even if the soil is disturbed beforehand. These results support the results of the seasonal bulk density variation.

Maximum average and bulk density recorded in the in situ Troxler bulk density measurement for conventional tillage was 1572 $kg.m^{-3}$ compared to the 1516 $kg.m^{-3}$ for the natural consolidated laboratory treatment. The no-tillage area showed the highest in situ bulk density measurement 1480 $kg.m^{-3}$ compared to the 1448 $kg.m^{-3}$ measured in the natural consolidated treatment. The in situ measurement via the Troxler instrument thus yielded higher bulk densities and this is mainly because of the average coarse fragment content of about 35% in the 0-100 mm soil depth. These results confirm that the same trend is observed between tillage treatments when the bulk density of only the soil fraction (< 2 mm) is used for comparison. Significant differences observed between no-tillage and conventional tillage in the seasonal in situ measurements, the clod method and the laboratory consolidation tests suggest that the coarse fragments affect the bulk densities for the different tillage treatments to the same degree (increasing the bulk density) but do not cause an influence in differences between tillage treatments.

5.2.6 Saturated hydraulic conductivity

Hydraulic conductivity is an important soil physical property that describes the rate of water movement though the soil profile; in our experiment the vertical movement from the soil surface through the first 300 mm of the soil profile. Tillage practices which improve hydraulic conductivity are beneficial because it would facilitate higher infiltration rates. Erosion and run-off would be limited, thus increasing the capacity for water movement through the soil and enhance the soil's water holding capacity.

Significant variation between replicates indicates that there are soil differences. These differences may be attributed to various chemical, physical and biological processes (Hillel, 1980), mainly as a result of natural soil variation but also because of variation in fauna activity. The standard errors in these two experiments show that there were some variations in the amount of water that moved through the columns measured in increments over time. This is a general phenomenon experienced when determining hydraulic conductivity and can be attributed to consolidation of the soil and changes of water flow paths in the columns. In both the first and second experiments clear significant differences were observed between no-tillage and conventional tillage treatments. In the first experiment, no-tillage had a 205% higher average saturated hydraulic conductivity and for the second experiment 365% higher. Higher hydraulic conductivity in no-tillage can be attributed to the significantly lower bulk density of 1441 $kg.m^{-3}$ compared to the 1523 $kg.m^{-3}$ measured 84 days after planting (2012) and also due to a better soil structure in no-tillage explained by the significant higher water stable aggregates (Singh *et al*., 1994). Bulk density is linked directly to porosity, which influences hydraulic conductivity (Hillel, 1980). This relates to the statement of Benjamin (1993) and Bhattacharyya *et al*., (2006) that higher hydraulic conductivity in no-tillage is attributed to greater pore continuity (better intrinsic permeability) and water flow through very large pores. Additional reasons may be the fact that no-tillage have more old root channels and also because this tillage practice create a more favourable environment for faunal activity and thus also increase the number of biopores and -tunnels (Shipitalo *et al*., 2000). No-tillage thus has more preferential flow paths compared to conventional tillage. Osunbitan *et al.* (2005) concluded that soil saturated hydraulic conductivity decreased with the degree of the intensiveness of tillage operations as a result of the disturbance or the continuity of stable macropores. Conventional tillage, on the other hand, may cause the formation of a plough pan (Huggins and Reganold, 2008) at the tillage depth of around 200 mm. This plough pan is a dense soil layer that causes a discontinuity in the soil pore system, reducing the hydraulic conductivity

(Huggins and Reganold, 2008). Agenbag and Maree (1991) detected a sharp increase in penetrometer measurements on the same long-term experiment for conventional tillage at 161-193 mm which may be an indication of the tillage depth but also a plough pan. Pelegrin *et al.* (1990) also found a plough pan on the same soil type. Hydraulic conductivity could thus also be influenced by a discontinuity in the pore structure and also preferential flow paths due to a possible plough pan in the conventional tillage treatment.

In the second experiment conducted after eight hours of continued flow of water through the columns, a decrease was noticed for both the conventional and no-tillage treatments. The decrease was significant for the conventional tillage treatment that decreased by 50.8%. The no-tillage treatment only decreased by 12.5%. The decrease in hydraulic conductivity for the conventional tillage may be attributed to the low water stable aggregates. These aggregates could thus have broken down causing the soil structure to fail and become more dense, but also detachment and migration of clay and other particles during the prolonged flow which may result in clogging of the pores (Hillel, 1980) decreasing the hydraulic conductivity drastically. The significant higher eclectic conductivity of conventional tillage could also contribute to aggregate dispersion (Hillel, 1980). The constant hydraulic conductivity observed in no-tillage is a result of the stable soil structure staying intact due to the better water stable aggregates (Singh *et al*., 1994). Similar findings were made in other studies with no-tillage having a higher hydraulic conductivity compared to more intensive tillage treatments (Benjamin, 1993; Bissett and O' Leary, 1996; Osunbitan *et al*., 2005).

Saturated hydraulic conductivity is thus significantly higher under no-tillage and maintains a constant rate over longer periods of time compared to conventional tillage. The main reasons being higher water stable aggragates and lower bulk density which creates more macropores and preferential flow paths formed by fauna activity.

5.2.7 Shale coarse fragment water storage potential

The average bulk density of shale coarse fragments collected from the Orthic A horizon, the Lithocutanic B horizon and the Parent material is 2311 kgm^{-3}. This value correlates well with the results of (Farmer, 1968). He found the bulk density of shale fragments varied from 2000 to 2400 $kg.m^{-3}$. Hanson and Blevins (1978) found that smaller, more weathered shale rock fragments 5-25 mm in diameter had a lower average bulk density of 2070 $kg.m^{-3}$. This suggests that smaller, more weathered shale coarse fragments would have the potential to store more water. The average bulk density was used for the calculation of the volumetric water content of our study because it is difficult to determine the accurate, reliable bulk density of small coarse fragments.

The results of the shale coarse fragments encountered in this study confirm that these fragments store a significant amount of water. Saturating the coarse fragments under suction showed that significantly more water can be stored and indicates therefore that the fragments are porous and would contain entrapped air if saturated under normal conditions. On average these shale coarse fragments can contribute to about 0.13 $mm.mm^{-1}$ (saturated) and 0.16 $mm.mm^{-1}$ (suction saturated) of the total water content of the soil of this study, although it is not sure how much of these amounts are available to plants. Zhongjie *et al*. (2008) found that the mean volumetric water content of the rock fragments were as high as 20%. In the literature it is shown that neglecting the water storage potential of coarse fragments in the soil, the total and plant available water content can be overestimated. The study by Cousin *et al.* (2003) on rock fragments in a calcareous soil found that if the coarse fragments in the soil was not taken into account the available water content was overestimated by 34% and percolation underestimated. Although if the coarse fragments were taken into account but considered as inert, meaning that they do not exhibit any specific water retention characteristics, the available water content is underestimated and as a consequence percolation is overestimated by values of up to 15% (Cousin *et al*., 2003). In some cases rock fragments can contribute to as much as 25% of the total available water (Fies *et al*., 2002).

These experiments showed that the shale coarse fragments encountered in our study can store a significant amount of water, which can contribute to plant available water content. In future, if water content of these soils is to be calculated the water storage potential of the coarse fragments should be included. Especially to explore if conventional tillage with more coarse fragments in the top soil have a higher total water storage capacity.

5.3 The interaction of the different soil properties measured as a result of tillage

This long-term study revealed that soil tillage significantly affected most of the soil properties studied, although all properties were not affected to the same degree. Properties not affected or only to a slight extent, were soil pH and the particle size distribution (soil texture). In this section the result of tillage on the soil properties studied and the interaction between these properties over the season will be described, discussed and summarized. Soil property interaction in this study is best described by the two extreme tillage treatments. These two extremes are the conventional tillage treatment which is the most intensive tillage treatment that completely disturbed the 0-200 mm soil depth by a few tillage operations including mouldboard ploughing and then the no-tillage treatment that only disturbs the soil once every season by planting the seeds in the 0-100 mm soil depth. Right through the study tine and minimum tillage treatments showed intermediate results and one may thus also expect intermediate soil interactions. The overall soil interaction process of the measured soil properties that occurs through the season are described according to the two tillage treatments in the following paragraphs.

The soil interaction process for the **conventional tillage** treatment can be explained by three time phases. Phase one is the tillage and planting operations, phase two is from after planting until before harvest (growth season) and phase three is from harvest until before the next tillage operations (fallow period). Phase one thus includes the soil preparations and planting conducted between May and July just after the first winter rain has fallen. After primary tillage with a chisel plough loosening the soil, mouldboard ploughing takes place to a depth of 200 mm. This means that the whole Orthic A horizon is thoroughly disturbed. Mechanical weeding just before planting insures that the seedbed is clean and aerated. Through these tillage operations any signs of soil compaction or surface seal are uplifted and changed to a uniform low bulk density, although unwanted coarse fragments are brought to the surface. This lowers the soil volume and water holding capacity of profile. Tilling of the soil through mouldboard ploughing results in a uniform mixing and distribution of the soil and also in amendments in this depth. The pH is thus even over the 200 mm tillage depth. Excessive yearly, long-term mouldboard ploughing results in sorting of the soil particles and because the soil texture class is already prone to compaction (Bodmin and Constantin, 1965; Batey and Davies, 1971; Bennie, 1972) it also cause the formation of a plough pan. Compaction occurs therefore through the season because soil texture affects bulk density (Terry *et al*., 1981). Continuous mouldboard ploughing cause incorporation of stubbles, increase in mineralization and decomposition, decreasing organic matter content, thus restricting organic carbon built-up (Rasmussen and Collins, 1991; Du Toit *et al*., 1993; Cannell and Hawes, 1994). Low total carbon content then results in low water stable aggregates due to the correlation between these two properties (Hernanz *et al.,* 2002; Abid and Lal, 2008). Low aggregate stability is also created due to intensive tillage practices that disturb and break down aggregates and soil structure that may be present (Yang and Wander, 1998; Kasper *et al*., 2009). Low water stable aggregates in conventional tillage thus will result in little stable soil structure. The end result after planting is a homogenous 0-200 mm soil layer with a low bulk density and few small aggregates that is highly aerated with many macropores. **Figure 5-1** shows the diagram that illustrates phase one.

1. Bulk density (1340-1377 kg.m^{-3})
2. Sheer strength (11.5 kPa)
3. Coarse fragments
    a. 0-100 mm (40.1%)
    b. 100-200 mm (45.4%)
    c. 250-800 mm (86.7%)
4. pH (KCl)
    a. 0-100 mm (4.7)
    b. 100-200 mm (4.4)
    c. 250-800 mm (4.1)

Uniform distribution of soil in the 0-200 mm soil depth, soil structure and preferential flow paths are destroyed. Below the tillage depth is a definite plough pan with no defined thickness.

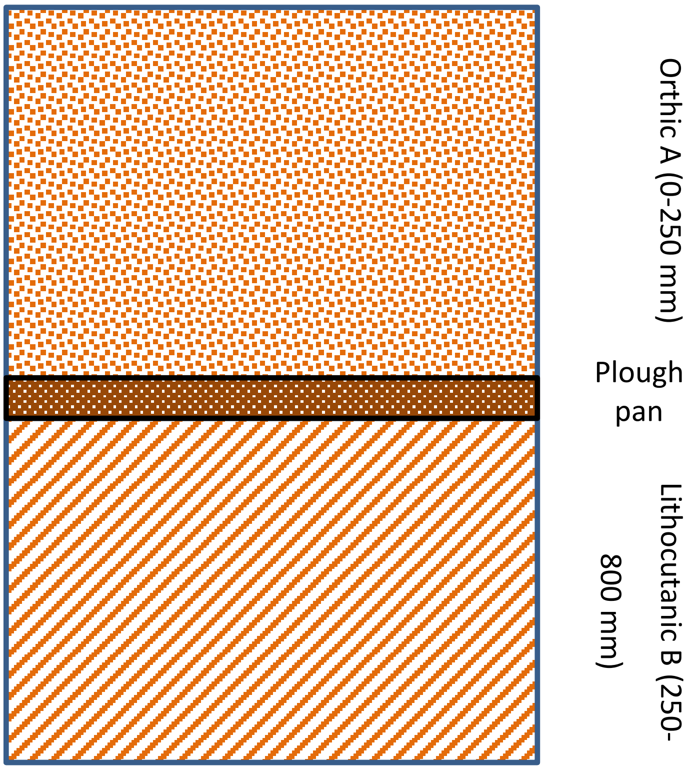


Figure 5-1: Phase 1 of conventional tillage, tillage and planting operations at the beginning of the season

Phase two is the period after planting till after harvesting, therefore growing of crop through the rain season. A noticeable soil physical change after tillage is the increase in bulk density. The initial low bulk density starts to increase to higher bulk densities as the season progresses. This is mainly due to re-compaction of the soil surface (Pelegrin *et al*., 1990; Ferreras *et al*., 2000; Yavuzcan *et al*., 2002, 2005; Osunbitan *et al*., 2005). Compaction was thus manifested in the increase in bulk density (Yavuzcan *et al*., 2005) and sheer strength that occurs over the season is due to a few reasons. Firstly the macropores formed by conventional tillage is not stable (Sasal *et al*., 2006) and diminish easily. Secondly, as already mentioned, the texture class of this specific soil is prone to compaction. Thirdly, due to the low water stable aggregates present in conventional tillage, aggregates break down and disperse when the soil saturates. The soil structure of conventional tillage therefore has a high susceptibility to fail and compact. Contributing to these reasons is the fact that long-term mouldboard ploughing result in the formation of a plough pan (Pelegrin *et al*., 1990; Huggins and Reganold, 2008) just below the tillage depth (200 mm). This plough pan is a severely compacted layer that causes a discontinuity in the soil and disruption of preferential flow paths. Compaction, in the end, limits hydraulic conductivity.

In the Swartland area salts are transported from the sea and deposited on the land (De Clercq *et al*., 2010). As a result these salts do not get completely leeched, increasing the EC (electric conductivity) of the soil surface (0-100 mm) with Na^+ being one of the dominating cations. Due to low hydraulic conductivity the 0-200 mm soil depth saturates faster and Na^+ ions get into solution and disperse the already low amount of aggregates (Hillel, 1980) that is still left after tillage. This leads to further disintegration of the soil structure. Particles of dispersed aggregates may also move in pores and between cracks of the surface causing a surface seal to develop, which further decreases the already low hydraulic conductivity (Hillel, 1980). Low hydraulic conductivity and the appearance of a surface seal may cause run-off to occur with high rain intensities for long periods. Other implications of the plough pan are that due to discontinuity created just below 200 mm, it also limits the soil profile depth for roots to grow. The plough pan has a very high bulk density with many micropores. This creates a good 'base' capillary structure that creates the upward movement of water and salts in this layer. The more compacted upper soil profile also improves capillary structures. Water is thus easily moved upward to the soil surface and thus causes the salts to concentrate at the 0-100 mm soil depth and thus resulting in a higher EC. The higher EC encountered in conventional tillage is thus a result of limited leaching due to a low hydraulic conductivity and the concentrating of salts in the soil surface through capillary action driven by evaporation. These salts are mainly Na^+ containing salts which will cause the dispersing of aggregates (low water stable aggregates) and then also contribute to the compaction of the soil (Agassi *et al*., 1985). Conventional tillage thus causes a negative cycle regarding electric conductivity, aggregate stability, soil structure, bulk density and hydraulic conductivity. These negative effects can result in serious run-off and erosion problems (Huggins and Reganold, 2008). **Figure 5-2** shows the diagram that illustrates phase two visually.

1. Bulk density (1387-1523 kg.m^{-3})
2. Water stable aggregates
    a. 0-100 mm (49%)
    b. 100-200 mm (11%)
3. Sheer strength (18.4 kPa)
4. Hydraulic conductivity (20-10 mm.h^{-1})

Re-compaction of the surface horizon occurs through the season. The plough pan causes discontinuity below the tillage depth. As a result hydraulic conductivity is low, with regard to no-tillage and the 0-200 mm profile depth saturate faster. Deep drainage rate is very low and run-off is likely to occur. Evaporation takes place only from the 0-200 mm profile due to the plough pan. This dense layer improves capillary action that causes salts to accumulate at the surface.

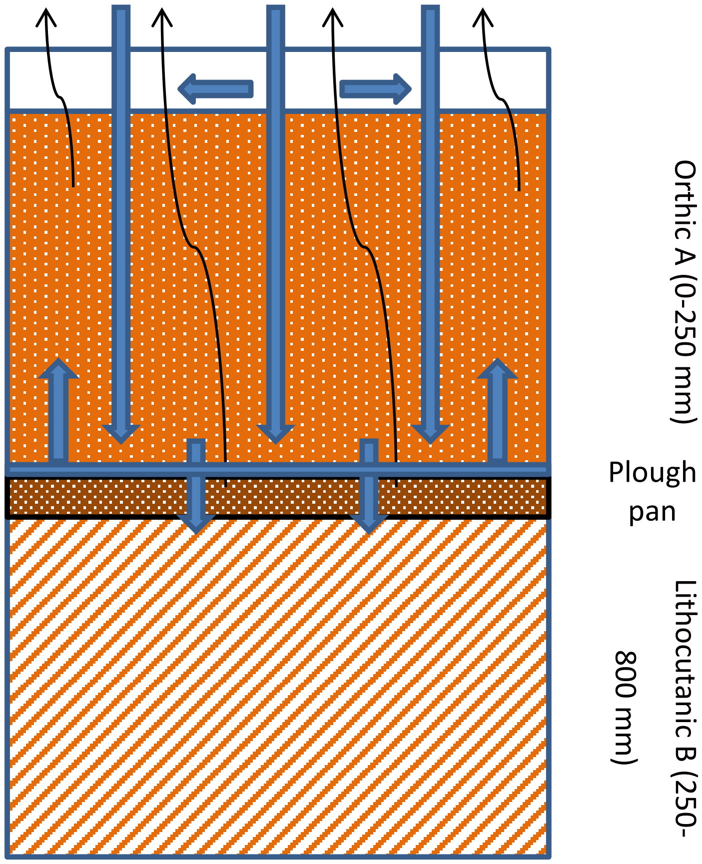


Figure 5-2: Phase 2 of conventional tillage, the growth season

Phase three stretches from the harvest and includes the fallow period. At the end of the growing stage, at the beginning of harvesting, no further compaction occurs and bulk density values stabilize. The soil surface is especially hard and resembles one massive unit. It is impossible to dig a hole with a shovel. An excavator was used to make profile holes in

2011. This is mainly due to hardsetting of these soils. The high bulk density and the possibility of a surface seal being present may limit water infiltration. As a result of this, run-off may be a problem, causing soil erosion if sporadic rain falls in the summer. **Figure 5-3** shows the diagram that illustrates phase three visually.

1. Bulk density (1523-1572 kg.m^{-3})
2. Electric conductivity
   a. 0-100 mm (16.3 mS.m^{-1})
   b. 100-200 mm (8.5 mS.m^{-1})
   c. 250-800 mm (9.3 mS.m^{-1})
3. Na^+ concentration of the 0-100 mm (2.85 mmol$_c$/L)

In the summer months during the fallow period run-off may occur during sporadic rain events due to the low hydraulic conductivity and hardsetting of the soil. Concentration of salts at the surface forms as a result of evaporation and poor leaching during the growing season.

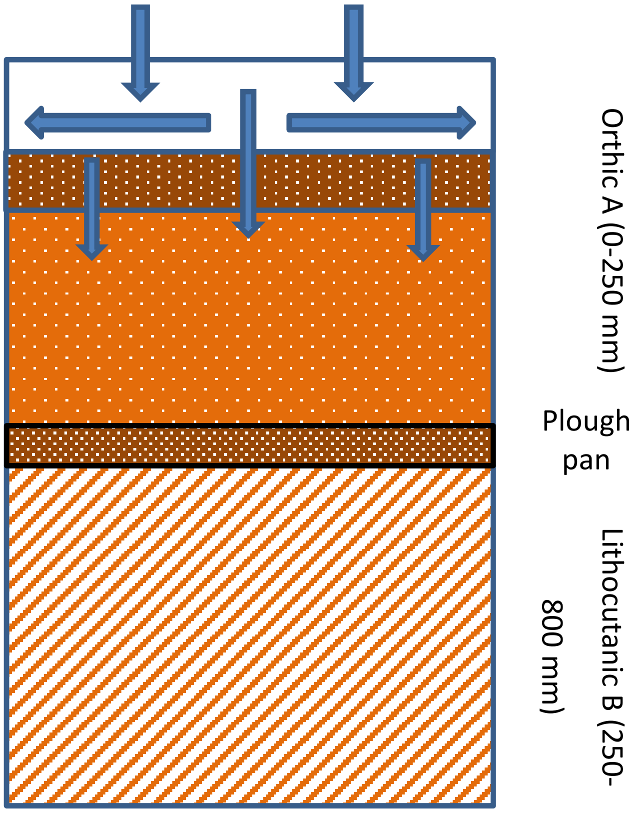


Figure 5-3: Phase 3 of conventional tillage, the fallow period at the end of the growth season

The soil interaction process for the **no-tillage** treatment can be explained by the same three time phases. At phase one soil disturbance is very little because the soil is only disturbed by planting in the rows, most crop residues is thus retained. In the long term, microbial and biological activity (Benjamin, 1993; Birkás *et al.*, 2004) is not disrupted as much and is visible in higher ant- and termite activity in the no-tillage plots. Most of the biochannels and old root channels therefore stay intact (Benjamin, 1993; Shipitalo *et al.*, 2000) and is functional. Soil amendments are not incorporated into the soil and pH variation in the 0-100 mm and 100-200 mm soil depth may vary considerably. The initial bulk density after planting as a result of limited tillage is higher compared to other more intensive tillage treatments. The sheer strength of no-tillage was also higher. This is an indication of the better soil structure present under no-tillage (Singh *et al*., 1994; Hernanz *et al*., 2002; Birkás *et al*., 2004; Bronick and Lal, 2005). In no-tillage, no plough pan is present and the soil profile pores system is continuous. **Figure 5-4** shows the diagram that visually illustrate phase one.

1. Bulk density (1384-1417 kg.m^{-3})
2. Sheer strength (13.9 kPa)
3. Coarse fragments
    a. 0-100 mm (32.9%)
    b. 100-200 mm (36.9%)
    c. 250-800 mm (80.9%)
4. pH (KCl)
    a. 0-100 mm (4.9)
    b. 100-200 mm (4.5)
    c. 250-800 mm (5.5)

Soil disturbance is very low and most of the soil structure and preferential flow paths stay intact.

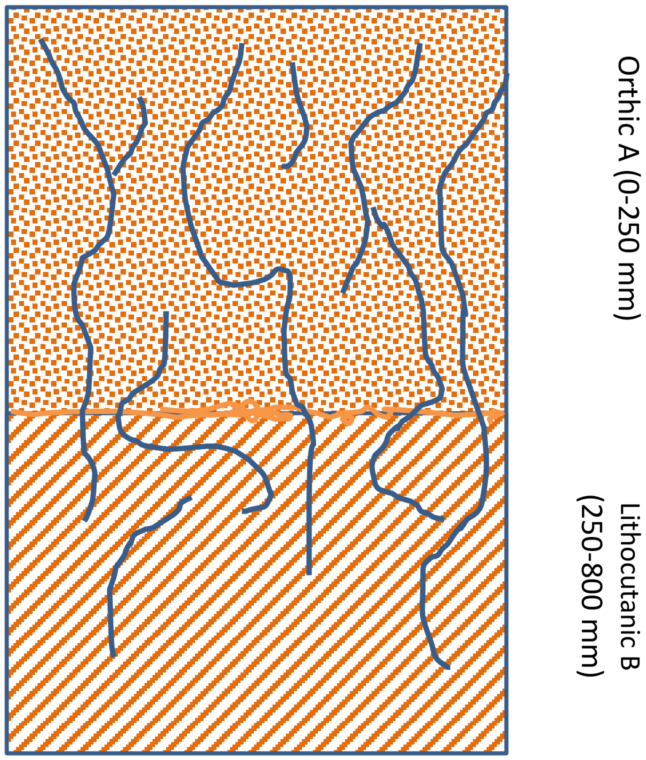


Figure 5-4: Phase 1 of no-tillage, tillage and planting operations at the beginning of the season

Phase two includes the growing of crops though the rain season beginning after planting. Some compaction (increase in bulk density and sheer strength) occurs in the 0-100 mm soil profile over the season because planting did not take place in the same rows. New rows thus disturbed the soil between the old rows of the previous year. It is suggested that if planting takes place on the same planting row every year, very little increase in bulk density should occur. The increase in bulk density was still significantly lower compared to conventional tillage. No-tillage bulk density is thus only higher for one month. Bulk density for conventional tillage increased severely after one month. Less compaction through the season is a result of a more stable soil structure present in no-tillage. The better soil structure is explained by the significant higher water stable aggregates found in the no-tillage treatment, which is correlated to the higher total carbon content (Chan *et al*., 1994; Abid and Lal, 2008; Gwenzi *et al*., 2008). Less disturbance of the soil thus improves the soil structure, especially in the long term. In the rain season, aggregates stay intact and compaction is not so severe. More stable aggregates can retain more water over a period of time. Better soil structure thus relates to a higher water holding capacity for no-tillage (Birkás *et al*., 2004; Abid and Lal, 2009).

Mid-season a significant higher hydraulic conductivity is a result of lower bulk density, the absence of a plough layer, better aggregate stability, higher number of preferential flow paths and better pore continuity (Benjamin, 1993; Singh *et al*., 1994; Osunbitan *et al*., 2005). The Orthic A horizon, therefore, seldom reaches saturation point, due to good internal drainage. Movement of water right through the profile facilitates effective leaching of the salts from the profile (O'Leary, 1996; Shipitalo *et al*., 2000). This is confirmed by the significant lower EC compared to conventional tillage. Effective water movement to the Lithocutanic B horizon help to leech salts as said but also increase the potential of this horizon to store water, because the course fragments in these rocky shale horizons can store a significant amount of water (Cousin *et al*., 2003). **Figure 5-5** shows the diagram that visually illustrates phase two.

1. Bulk density (1380-1441 kg.m^{-3})
2. Water stable aggregates
    a. 0-100 (78%)
    b. 100-200 (39%)
3. Sheer strength (15.6 kPa)
4. Hydraulic conductivity (41-36 mm.h^{-1})

Compaction of the soil very little due to stable soil structure. Hydraulic conductivity is high compared to conventional tillage as a result of preferential flow paths, no plough pan and lower bulk density. Water movement takes place through the whole profile. These soils therefore have good internal drainage.

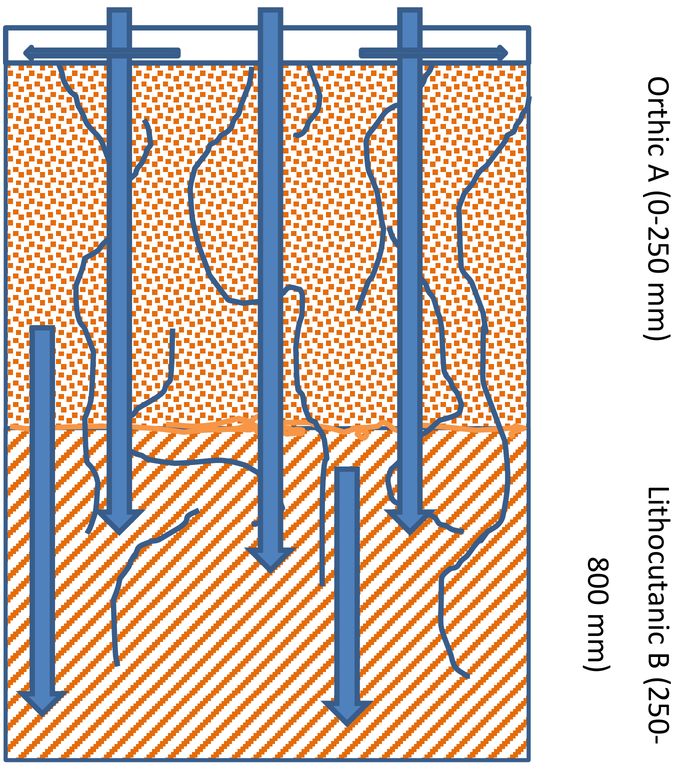


Figure 5-5: Phase 2 of no-tillage, the growth season

Phase three consists of the harvesting and fallow period. In no-tillage, bulk density stabilizes to significant lower values compared to conventional tillage after the rain season. Sporadic summer rainfall may thus infiltrate with little run-off that is also reduced by the retained stubbles (Hoffman, 1990). Although the bulk density is significantly lower in the summer, the soil surface is still very hard and not possible to dig with a shovel. Higher active fauna activity as was seen by more termite and ant nests in the no-tillage treatments may lower bulk density in the summer to some extent as was seen in last bulk density measurements on 4 December 2011. **Figure 5-6** shows the diagram that visually illustrates phase three.

1. Bulk density (1459-1480 kg.m^{-3})
2. Electric conductivity
    a. 0-100 mm (7.3 mS.m^{-1})
    b. 100-200 mm (6.1 mS.m^{-1})
    c. 200-600 mm (6.7 mS.m^{-1})
3. Na^+ concentration of the 0-100 mm (1.15 mmol$_c$/L)

In the summer months, during the fallow period, run-off may occur during sporadic rain events but will not be as high compared to conventional tillage. Salts are distributed evenly through the profile due to effective leaching through the growing season.

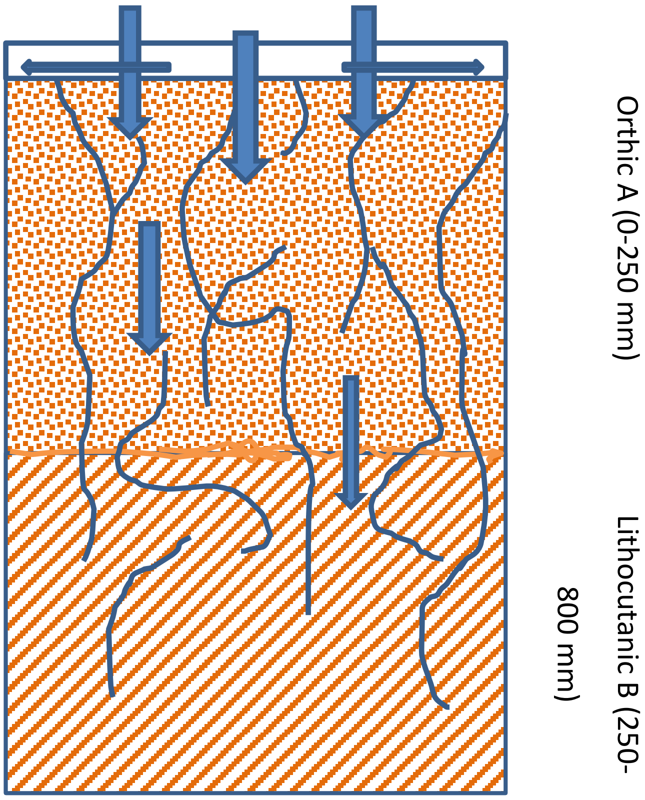


Figure 5-6: Phase 3 of no-tillage, the fallow period at the end of the growth season

From these descriptions and diagrams it is clear that no-tillage exhibits a better soil physical state right through the growing season compared to conventional tillage. Lower seasonal bulk density, better aggregate stability and higher hydraulic conductivities evident in no-tillage are the biggest contribution towards improving soil conditions. According to their soil properties, tine and minimum tillage would be placed between conventional and no-tillage.

This long-term study thus reveals that, compared to the basic soil properties studied, no-tillage is a more sustainable tillage practice and confirms the statement of Agenbag (2012). He stated that no-tillage is a tillage practice that can be successfully used in the Swartland wheat producing area of the Western Cape to produce spring type wheat crops under rain-fed conditions, especially if used in combination with crop rotation and high nitrogen fertilizer rates.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Soil as a natural resource must be utilized efficiently in the short- as well as long-term to make agriculture more sustainable. The main aim of this study was to quantify and qualify the physical and some chemical properties of the soil after 37 years of continuous application of four different tillage applications on a research site of the Langgewens Farm. The secondary aim was to establish which of the tillage treatments were the most sustainable regarding the soil properties.

This long-term experiment, initiated in 1975, delivered valuable data for the Mediterranean climate of the Western Cape about the effect of tillage on basic soil properties. Prominent differences were observed between tillage treatments for most of the soil properties quantified. These properties were electrical conductivity, total carbon content, water stable aggregate percentage, sheer strength, seasonal bulk density and saturated hydraulic conductivity.

No-tillage proved to be beneficial in terms of salinity and had the lowest electrical conductivity, indicating that salts leeched out of the profile whereas conventional tillage leads to an increase in EC.

Total carbon content was in general very low and in the 0-100 mm soil depth it decreased in the order of no, minimum and tine tillage and conventional tillage which had a significantly lower content compared to the other tillage treatments. This proves that tillage practices that caused little soil disturbance, would cause an increase in carbon content at the surface, although the extent to which it can increase is limited by the Mediterranean climate. In the 100-200 mm depth conventional, tine and minimum tillage showed higher carbon contents compared to no-tillage and indicated that soil disturbance caused organic matter to move into the deeper soil profile and in the end increase the total carbon content.

Aggregate stability showed good results with meaningful differences. Conventional and tine tillage significantly had the lowest aggregate stability at both depths and can be explained by the relative low amount of total carbon in the soil combined with the tillage intensity.

Significant correlation between total carbon content and aggregate stability confirmed that an increase in total carbon in the soil would lead to an increase in aggregate stability. No correlation were observed for the 100-200 mm soil depth, which suggests that soil disturbance also play a role in the stability of aggregates. Increased aggregate stability under the no-tillage treatment would therefore indicate that the soil may have some stable structure present which is also true to some extent for minimum tillage.

Sheer strength showed that soil structure stays intact with no-tillage and that it is significantly higher after tillage operations compared to the more intensive tillage treatments. Later in the season the intensive tillage treatment's sheer strengths increased to significant higher values compared to no-tillage. Soil under no-tillage management thus has more stable sheer strength at the soil surface whereas soil managed under conventional tillage may show signs of a surface crust developing.

Seasonal bulk density variation was the lowest in no-tillage, which supports the manifestations of stable soil structure as found in the sheer strength results. More intensive tillage treatments such as conventional and tine tillage only showed lower bulk densities for the first month. Thereafter it increased to significant higher values as the season progressed. This was mainly as a result of hardsetting of the soil which is driven by natural processes, rainfall and which is also due to the sandy loam texture that is particularly prone to compaction. No-tillage showed the least variation in bulk density right through the season. This also reveals that a more stable soil structure is present.

Hydraulic conductivity studied for conventional and no-tillage showed significant differences. No-tillage had a noticeable higher conductivity, which remained constant for the two experiments compared to conventional tillage. The main reasons for this increased constant hydraulic conductivity being higher water stable aggregates and lower bulk density, but also increased fauna activity which creates macropores and preferential flow paths (Benjamin, 1993; Shipitalo *et al*., 2000). The significant decrease in hydraulic conductivity for the conventional tillage treatment may be ascribed to the disintegration of aggregates, causing the soil structure to fail and become more dense, but also the blockage of pores (Hillel, 1980). Rainfall would thus move more effectively through a soil profile managed under no-tillage.

From the soil properties studied the no-tillage treatment proved to show a stable soil structure developed over the long term, although not visible to the eye. Minimum tillage proved to be next in line for the next best option after no-tillage. Structure formation of a Glenrosa soil form is therefore stimulated under less intensive tillage treatments, especially in the long term. This structure is apparent in no-tillage-managed soils with normally low stability, thus significantly improving soil properties quantified in this study. These properties may influence processes such as water infiltration, water storage, run-off and drainage positively, due to soil property interaction.

Social pressure on agriculture to become more sustainable is a reality and tillage practices that limits soil disturbance and enhance soil stability are thus indicating the best practices for cultivation in future. No-tillage, in terms of soil physical quality, quantified by the soil properties studied, proved to be superior compared to conventional and tine tillage but to a lesser extent if compared to minimum tillage. No-tillage is therefore the most sustainable in a soil conservation context; but is it sustainable for the farmer/producer? Looking at yields, the success of dry land agriculture in the Mediterranean area of the Western Cape is highly dependent on rainfall, water infiltration and water storage in the soil. In a previous study conducted on the same site, no-tillage also improved the water holding capacity by showing higher water contents right through the season (Agenbag and Maree, 1991) and thus the treatment also delivers economical yields (Agenbag, 2012). In the long term, no-tillage therefore improves important soil properties overall and as a result this tillage practice can be used successfully in combination with crop rotation in the Swartland wheat producing region (Agenbag, 2012). Globally, conservation tillage and no-tillage practices are also accepted as an effective alternative to intensive tillage practices because it improves the soil quality, sustains natural resources, reduces soil erosion and still deliver economical yields (Huggins and Reganold, 2008; Gwenzi *et al*., 2008; Cavalieri *et al*., 2009; Moussa-Machraoui *et al*., 2010; Morell *et al*., 2011). Especially for winter cereals, conservation tillage has a higher probability than conventional tillage (Hernanz *et al*., 1995).

6.2 Recommendations

This study indicated that no-tillage is the best practice for the future due to the sustainability towards lowest environmental impact and to the economics of the endeavour, specifically for the no-tillage crop rotation management system. The difference in success between no-tillage and conventional tillage will become more pronounced if rainfall patterns in the Western Cape changed and become drier due to lower rainfall. No-tillage is likely to outperform other tillage practices in dryer seasons (Agenbag and Maree, 1991; Morell *et al*., 2011). It must also be kept in mind that as one reduces tillage intensity, nitrogen application for the soil should be increased (Morell *et al*., 2011; Agenbag, 2012).

If one decides to change from conventional tillage to no-tillage, it is important to remember that soil properties would take around five to eight years to develop to new equilibriums (Voorhees and Lindstrom, 1984), especially structure formation. This was recorded by Agenbag (1987), but at this stage differences in bulk density between the same tillage treatments were not observed compared to our findings. The improvement of soil properties is thus slow and in the case of micro soil structure development, it may take decades. It is thus likely that in the first few years after adopting no-tillage that fundamental loss in yield may occur. It would thus be a wise decision to gradually move from conventional tillage to minimum tillage first and then after a few years adopt no-tillage. Also to not switch the whole farm at once; start with a few hectares and expand on a small scale yearly. Soil tillage management would thus be critical to convert a farm successfully to no-tillage. Applying a deep ripping tillage application to conventional mouldboard tillage managed soils which is deeper than the mouldboard tillage depth would also be advisable, mainly to break any possible plough pans that will cause problems as already discussed.

6.3 Future research

Seasonal run-off studies will be valuable towards, firstly, the correlation to the seasonal bulk density variation and secondly, quantifying of the relationship between water infiltration and run-off. One may then estimate and model the effective water infiltration into the soil profile. Long-term tillage studies under different soil types are also a necessity and must be initiated on research farms to broaden tillage knowledge. These studies would contribute further to the improvement and success of crop production in South Africa.

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APPENDIX A: Important soil description, chemical and physical data

1. Selected profile descriptions

Profile number:	D1 (Conventional tillage)	Aspect:	East
Latitude and longitude:	33°16’34.79”S /18°42’55.92”E	Terrain unit:	Crest
Soil from:	Glenrosa	Aaltitude:	224 m
Soil family:	Bisho	Surface coarse fragments:	(25-60%)
Parent Material:	Shale	Wetness:	None
Slope:	2%	Crop:	Wheat (monoculture)
Slope form:	Convex		

Horizon	Depth (mm)	Description	Diagnostic horizon/material
A	0-300	Dry; dry colour: Yellowish Brown 10YR5/6; moist colour: brown 10YR4/3; structure: weak sub angular blocky; consistence: loose, slightly firm; sandy clay loam; common gravel 2-6mm; common roots; clear wavy transition.	Orthic
B	300-700	Dry; dry colour: yellowish brown 10YR5/6; moist colour: brown 10YR4/3; structure: medium sub angular blocky; consistence: very hard, firm; clay loam; many coarse gravel 6-25 mm; very few roots; gradual transition into rocks.	Lithocutanic
R	>700	Hard rock; common cracks	Shale

Profile number:	D2 (Tine tillage)	Aspect:	East
Latitude and longitude:	33°16’36.97”S /18°42’55.20”E	Terrain unit:	Crest
Soil from:	Glenrosa	Aaltitude:	229 m
Soil family:	Bisho	Surface coarse fragments:	(25-60%)
Parent Material:	Shale	Wetness:	None
Slope:	2%	Crop:	Wheat (monoculture)
Slope form:	Convex		

Horizon	Depth (mm)	Description	Diagnostic horizon/material
A	0-300	Dry; dry colour: very pale brown 10YR7/4; moist colour: yellowish brown 10YR4/6; structure: weak subangular blocky; consistence: loose, slightly firm; sandy clay loam; common gravel 2-6mm; common roots; clear wavy transition.	Orthic
B	300-800	Dry; dry colour: yellowish brown 10YR5/4; moist colour: dark yellowish brown 10YR4/4; structure: medium subangular blocky; consistence: very hard, firm; clay loam; many coarse gravel 6-25 mm; few roots; gradual transition into rocks.	Lithocutanic
R	>800	Hard rock, common cracks	Shale

Profile number:	D3 (Minimum tillage)	Aspect:	East
Latitude and longitude:	33°16’36.80”S /18°42’55.35”E	Terrain unit:	Crest
Soil from:	Glenrosa	Altitude:	229 m
Soil family:	Bisho	Surface coarse fragments:	(25-60%)
Parent Material:	Shale	Wetness:	None
Slope:	2%	Crop:	Wheat (monoculture)
Slope form:	Convex		

Horizon	Depth (mm)	Description	Diagnostic horizon/material
A	0-300	Dry; dry colour: very pale brown 10YR7/4; moist colour: yellowish brown 10YR4/6; structure: weak sub angular blocky; consistence: loose, slightly firm; sandy clay loam; common gravel 2-6mm; common roots; indistinct wavy transition.	Orthic
B	300-600	Dry; dry colour: yellowish brown 10YR5/4; moist colour: dark yellowish brown 10YR4/4; structure: medium subangular blocky; consistence: very hard, firm; clay loam; many coarse gravel 6-25 mm; common roots; gradual transition into rocks.	Lithocutanic
R	>600	Hard rock, common cracks	Shale

Profile number:	D4 (No-tillage)	Aspect:	East
Latitude and longitude:	33°16’34.79”S /18°42’55.92”E	Terrain unit:	Crest
Soil from:	Glenrosa	Altitude:	229 m
Soil family:	Bisho	Surface coarse fragments:	(25-60%)
Parent Material:	Shale	Wetness:	None
Slope:	2%	Crop:	Wheat (monoculture)
Slope form:	Convex		

Horizon	**Depth (mm)**	**Description**	**Diagnostic horizon/material**
A	0-300	Dry; dry colour: very pale brown 10YR7/4; moist colour: yellowish brown 10YR4/6; structure: weak sub angular blocky; consistence: loose, slightly firm; sandy clay loam; common gravel 2-6mm; common roots; gradual transition.	Orthic
B	300-600	Dry; dry colour: yellowish brown 10YR5/4; moist colour: dark yellowish brown 10YR4/4; structure: medium sub angular blocky; consistence: very hard, firm; clay loam; many coarse gravel 6-25 mm; common roots; gradual transition into rocks.	Lithocutanic
R	>600	Hard rock, common cracks, very few roots	Shale

2. Chemical properties

Table A. 1: Selected average chemical properties for the different tillage treatments

Tillage Treatment	Sampling Depth	Block	pH (H_2O)	pH (KCL)	EC ($mS.m^{-1}$)	Total carbon (%)
Conventional tillage	0-100	A	5.75	4.81	15.61	0.36
		B	5.44	4.22	18.60	0.58
		C	5.42	4.51	17.64	0.54
		D	6.02	5.07	13.31	0.57
Tine tillage		A	5.61	4.63	10.16	0.76
		B	5.52	4.42	8.65	0.93
		C	5.37	4.27	8.36	0.87
		D	5.90	4.70	7.94	0.76
Minimum tillage		A	5.45	4.41	10.16	0.78
		B	5.57	4.39	6.82	0.76
		C	5.30	4.33	13.13	0.81
		D	6.10	5.03	6.85	1.07
No-tillage		A	5.79	4.67	5.57	0.89
		B	6.23	4.54	5.91	0.65
		C	6.05	4.92	9.40	0.82
		D	6.43	5.53	8.29	1.31
Conventional tillage	100-200	A	5.90	4.65	11.95	0.38
		B	5.41	4.14	5.79	0.49
		C	5.85	4.48	10.86	0.50
		D	5.65	4.43	5.49	0.46
Tine tillage		A	5.44	4.15	12.06	0.56
		B	5.67	4.33	7.41	0.55
		C	5.36	3.94	4.28	0.37
		D	5.81	4.58	5.57	0.57
Minimum tillage		A	5.45	4.13	13.21	0.46
		B	5.36	4.04	6.27	0.40
		C	5.63	4.13	4.50	0.31
		D	6.12	5.31	6.51	0.59
No-tillage		A	6.07	4.76	9.52	0.36
		B	5.75	4.90	4.30	0.29
		C	5.40	3.98	5.58	0.32
		D	5.85	4.49	5.27	0.34

Table A. 2: Cations and anions of the saturated paste and resistance for conventional and no-tillage treatments in the 0-100 mm soil depth

Tillage treatment	Block	Concentration (mg/L)							Resistance (ohm)
		Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	NO_3^{-}	SO_4^{2-}	
Conventional tillage	C	261	75	63	29	314	792	nd	147
	D	151	47	68	78	301	396	94	166
No-tillage	C	42	14	29	44	42	103	41	1440
	D	77	28	24	64	50	215	42	1880

3. Physical properties

Table A. 3: Soil particle size distribution for the different tillage treatments

Tillage Treatment	Sampling Depth	Block	Coarse sand	Medium sand	Fine sand	Very fine sand	Coarse silt	Fine silt	Clay	Coarse Fragments (% of the total soil mass)
			Percentages							
			2 – 0.5	*0.5 – 0.25*	*0.25 – 0.106*	*0.106 – 0.05*	*0.05 – 0.02*	*0.02 – 0.002*	*< 0.002*	> 2 mm
Conventional tillage	0-100	A	17.03	8.61	16.54	21.05	17.71	11.03	8.03	37.04
		B	20.34	9.41	16.72	17.69	13.45	13.06	9.34	42.18
		C	24.58	10.67	17.11	16.48	11.79	11.62	7.74	41.10
		D	21.16	9.61	17.56	18.81	13.90	11.67	7.29	40.23
Tine tillage		A	0.00	0.00	0.00	0.00	100.00	0.00	0.00	40.11
		B	24.02	11.25	17.15	17.44	11.91	11.28	6.96	38.57
		C	20.56	9.55	17.59	15.17	19.25	10.73	7.15	34.51
		D	25.25	9.47	15.31	19.48	12.36	11.84	6.30	40.77
Minimum tillage		A	20.85	10.30	17.80	19.41	13.41	10.07	8.15	37.39
		B	17.89	9.79	16.90	18.15	13.02	14.15	10.1	39.14
		C	19.87	10.47	19.09	19.97	13.68	10.45	6.48	36.02
		D	23.41	9.99	16.99	19.64	13.80	10.10	6.08	39.32
No-tillage		A	17.42	8.90	18.82	20.00	15.83	10.80	8.22	36.94
		B	24.31	12.37	19.18	15.84	12.44	9.75	6.11	30.98
		C	22.07	9.07	15.00	18.89	16.93	11.59	6.46	33.03
		D	18.67	8.95	17.01	22.39	14.85	11.05	7.08	30.76
Conventional tillage	100-200	A	17.39	8.64	18.31	19.94	17.38	10.44	7.90	44.42
		B	19.74	9.59	17.50	17.21	14.16	12.69	9.11	46.63
		C	25.96	10.74	16.76	15.72	11.70	11.42	7.70	47.80
		D	19.78	9.71	19.09	19.42	12.40	12.40	7.19	42.57
Tine tillage		A	17.20	9.31	18.75	20.95	13.29	10.70	9.80	34.84
		B	23.48	11.19	17.12	16.76	12.91	11.27	7.28	40.55
		C	21.13	9.88	17.75	19.17	13.66	10.43	7.98	37.68
		D	23.04	9.78	15.75	16.44	15.70	11.81	7.49	39.90
Minimum tillage		A	19.09	10.23	18.30	17.90	14.65	10.77	9.06	34.18
		B	23.96	9.68	16.90	16.60	10.00	12.45	10.4	44.19
		C	20.96	10.47	18.07	19.77	12.04	10.61	8.10	39.49
		D	21.65	10.34	17.70	18.94	13.57	11.03	6.77	34.77
No-tillage		A	18.15	8.95	18.71	20.08	14.39	10.21	9.51	42.58
		B	24.45	12.93	19.10	16.09	10.86	10.19	6.38	35.63
		C	21.81	9.81	15.76	17.64	14.48	7.61	12.9	37.17
		D	19.89	9.18	17.08	20.94	13.84	11.44	7.64	32.40

Table A. 4: Water stable aggregate percentage for the different tillage treatments at the two sampling depths

Tillage Treatment	Block	Repetition	Depth (mm)	
			0-100	100-200
Conventional tillage	A	1	43.45	7.06
		2	49.04	5.92
	B	1	53.51	6.29
		2	50.29	7.35
	C	1	40.52	22.22
		2	33.55	16.67
	D	1	55.64	12.07
		2	56.59	7.27
Tine tillage	A	1	34.05	6.91
		2	33.07	12.99
	B	1	67.39	7.04
		2	71.15	10.14
	C	1	41.24	14.42
		2	36.02	11.11
	D	1	40.59	8.84
		2	36.67	13.70
Minimum tillage	A	1	79.03	22.95
		2	72.48	37.68
	B	1	61.21	14.08
		2	63.83	22.01
	C	1	56.10	17.53
		2	52.74	27.97
	D	1	52.87	21.60
		2	53.20	8.48
No-tillage	A	1	73.29	20.29
		2	71.32	38.02
	B	1	94.24	53.93
		2	97.52	50.00
	C	1	71.67	43.41
		2	71.56	37.16
	D	1	74.27	26.28
		2	73.33	28.79

Table A. 5: **Average sheer strength measurements in kPa for the two dates for the 0-10 mm soil surface**

Tillage treatment	Block	6/6/2012	18/7/2012	Gravimetric water content	
				6/6/2012	18/7/2012
Conventional tillage	A	9.99	18.3	0.073	0.050
	B	13.12	18.88	0.064	0.051
	C	11.37	18.3	0.055	0.045
	D	11.88	17.86	0.067	0.061
Tine tillage	A	12.25	18.74	0.091	0.056
	B	11.88	18.23	0.088	0.055
	C	11.52	17.64	0.067	0.076
	D	11.01	17.86	0.099	0.045
Minimum tillage	A	12.03	16.26	0.092	0.056
	B	14.36	16.84	0.083	0.044
	C	12.39	17.79	0.078	0.051
	D	11.23	17.28	0.072	0.071
No-tillage	A	15.16	14.58	0.080	0.063
	B	14.51	15.82	0.071	0.072
	C	13.49	16.11	0.062	0.082
	D	12.54	16.04	0.074	0.054

Table A. 6: **Conventional tillage seasonal bulk density (kg.m^{-3}) variation for the 0-100 mm soil depth, measured with a Troxler bulk density instrument**

Block	Date and days after planting	6/21/ 2011	7/26/ 2011	9/20/ 2011	10/20 /2011	11/17 /2011	12/19 /2011	1/26/ 2012	2/24/ 2012	3/26/ 2012	4/12/ 2012	5/23/ 2012	6/6/ 2012	6/20/ 2012	7/19/ 2012
		25	60	116	146	174	206	244	273	304	321	27	41	55	84
A	1	1281	1230	1437	1553	1535	1493	1494	1537	1508	1565	1404	1410	1399	1475
	2	1241	1312	1472	1495	1500	1530	1531	1458	1458	1495	1424	1423	1472	1538
	3	1453	1455	1596	1627	1634	1619	1621	1610	1602	1609	1276	1433	1380	1409
	4	1326	1500	1583	1597	1594	1580	1582	1604	1526	1552	1373	1466	1487	1547
	5	1345	1450	1542	1561	1542	1556	1558	1551	1493	1498	1431	1470	1477	1528
B	1	1345	1468	1468	1501	1501	1521	1522	1518	1601	1542	1395	1386	1413	1517
	2	1247	1276	1370	1527	1532	1504	1505	1522	1531	1511	1408	1461	1452	1540
	3	1495	1474	1656	1673	1683	1625	1626	1668	1705	1670	1412	1501	1504	1588
	4	1297	1345	1490	1502	1548	1551	1552	1537	1612	1538	1391	1401	1438	1565
	5	1286	1370	1534	1629	1618	1612	1613	1624	1676	1623	1387	1398	1389	1460
C	1	1327	1406	1564	1555	1570	1589	1591	1602	1563	1553	1415	1413	1409	1488
	2	1483	1499	1619	1658	1651	1646	1648	1635	1729	1638	1384	1414	1498	1524
	3	1270	1310	1614	1587	1594	1580	1582	1573	1543	1606	1411	1503	1545	1562
	4	1362	1550	1600	1626	1598	1604	1606	1643	1571	1614	1468	1444	1535	1588
	5	1276	1307	1529	1586	1581	1584	1586	1592	1571	1569	1321	1342	1364	1509
D	1	1415	1402	1435	1418	1493	1534	1535	1514	1464	1545	1305	1410	1427	1553
	2	1305	1333	1488	1508	1559	1517	1518	1528	1496	1493	1287	1313	1370	1453
	3	1405	1390	1586	1625	1639	1614	1615	1591	1567	1549	1348	1401	1562	1516
	4	1348	1353	1479	1521	1521	1638	1640	1514	1490	1482	1319	1354	1472	1505
	5	1290	1311	1389	1538	1531	1513	1514	1480	1508	1446	1383	1456	1552	1601

Table A. 7: Tine tillage seasonal bulk density (kg.m-3) variation for the 0-100 mm soil depth, measured with a Troxler bulk density instrument

Block	Date and days after planting	6/21/2011	7/26/2011	9/20/2011	10/20/2011	11/17/2011	12/19/2011	1/26/2012	2/24/2012	3/26/2012	4/12/2012	5/23/2012	6/6/2012	6/20/2012	7/19/2012
		25	60	116	146	174	206	244	273	304	321	27	41	55	84
A	1	1418	1416	1535	1562	1522	1576	1577	1496	1516	1584	1332	1370	1324	1436
	2	1444	1508	1580	1599	1601	1567	1567	1609	1588	1565	1350	1344	1351	1445
	3	1397	1430	1598	1612	1533	1626	1627	1645	1601	1655	1212	1292	1353	1414
	4	1353	1460	1492	1481	1526	1530	1530	1550	1515	1514	1247	1277	1268	1378
	5	1285	1467	1542	1595	1612	1613	1614	1636	1516	1579	1446	1450	1484	1533
B	1	1402	1416	1439	1566	1585	1599	1599	1591	1633	1575	1291	1280	1340	1425
	2	1128	1280	1439	1493	1516	1518	1518	1540	1578	1503	1302	1335	1313	1445
	3	1394	1398	1441	1461	1495	1497	1497	1485	1588	1533	1252	1285	1305	1436
	4	1409	1390	1567	1505	1582	1551	1551	1584	1607	1511	1301	1342	1323	1423
	5	1321	1297	1541	1508	1564	1560	1560	1576	1608	1550	1389	1356	1371	1518
C	1	1463	1501	1581	1617	1591	1699	1690	1571	1565	1573	1267	1298	1383	1520
	2	1431	1433	1557	1536	1576	1578	1578	1537	1631	1577	1316	1352	1381	1450
	3	1265	1327	1455	1553	1520	1564	1564	1582	1629	1577	1365	1375	1388	1520
	4	1318	1494	1500	1602	1661	1641	1638	1645	1606	1673	1274	1290	1387	1550
	5	1451	1389	1521	1494	1517	1486	1486	1502	1457	1512	1544	1550	1488	1690
D	1	1375	1410	1465	1454	1462	1445	1480	1467	1416	1458	1328	1328	1398	1420
	2	1381	1345	1437	1498	1505	1526	1526	1482	1442	1456	1385	1360	1399	1435
	3	1288	1311	1434	1454	1509	1490	1495	1422	1433	1488	1433	1449	1499	1502
	4	1248	1290	1378	1448	1417	1440	1450	1400	1402	1428	1378	1398	1479	1504
	5	1281	1226	1530	1639	1595	1566	1564	1575	1523	1482	1418	1438	1491	1515

Table A. 8: Minimum tillage seasonal bulk density (kg.m^{-3}) variation for the 0-100 mm soil depth, measured with a Troxler bulk density instrument

Block	Date and days after planting	6/21/ 2011	7/26/ 2011	9/20/ 2011	10/20 /2011	11/17 /2011	12/19 /2011	1/26/ 2012	2/24/ 2012	3/26/ 2012	4/12/ 2012	5/23/ 2012	6/6/ 2012	6/20/ 2012	7/19/ 2012
		25	60	116	146	174	206	244	273	304	321	27	41	55	84
A	1	1261	1331	1403	1405	1421	1451	1448	1441	1411	1449	1363	1424	1384	1435
	2	1284	1320	1369	1553	1463	1482	1479	1527	1507	1512	1393	1424	1407	1519
	3	1272	1319	1367	1410	1434	1480	1477	1461	1433	1468	1280	1290	1231	1345
	4	1256	1389	1341	1406	1353	1432	1429	1386	1366	1382	1374	1387	1387	1358
	5	1239	1416	1473	1480	1488	1493	1490	1522	1485	1469	1401	1364	1431	1383
B	1	1248	1264	1321	1410	1489	1514	1511	1476	1497	1469	1360	1281	1334	1459
	2	1355	1452	1413	1446	1383	1367	1364	1489	1516	1443	1269	1275	1257	1292
	3	1297	1310	1401	1464	1401	1475	1472	1481	1565	1488	1263	1304	1308	1483
	4	1393	1469	1528	1567	1562	1527	1524	1534	1583	1495	1262	1303	1298	1481
	5	1314	1307	1315	1418	1399	1461	1458	1449	1531	1413	1363	1324	1388	1515
C	1	1445	1320	1467	1456	1516	1492	1489	1375	1465	1471	1321	1405	1318	1500
	2	1312	1408	1517	1512	1493	1536	1533	1527	1535	1553	1391	1421	1433	1461
	3	1387	1321	1473	1510	1509	1534	1531	1491	1480	1505	1411	1437	1429	1527
	4	1492	1345	1425	1488	1493	1507	1504	1534	1469	1494	1389	1390	1427	1529
	5	1588	1392	1585	1528	1557	1588	1585	1590	1550	1563	1367	1433	1462	1450
D	1	1374	1380	1559	1525	1584	1592	1589	1561	1546	1610	1374	1393	1422	1463
	2	1382	1345	1401	1558	1464	1564	1561	1509	1507	1491	1424	1422	1462	1518
	3	1374	1301	1512	1457	1437	1515	1512	1531	1505	1521	1363	1375	1437	1456
	4	1369	1381	1548	1606	1586	1591	1588	1650	1602	1613	1481	1401	1437	1432
	5	1403	1429	1624	1634	1637	1646	1643	1629	1590	1626	1450	1438	1498	1520

Table A. 9: **No-tillage seasonal bulk density ($kg.m^{-3}$) variation for the 0-100 mm soil depth, measured with a Troxler bulk density instrument**

Block	Date and days after planting	6/21/ 2011	7/26/ 2011	9/20/ 2011	10/20 /2011	11/17 /2011	12/19 /2011	1/26/ 2012	2/24/ 2012	3/26/ 2012	4/12/ 2012	5/23/ 2012	6/6/ 2012	6/20/ 2012	7/19/ 2012
		25	60	116	146	174	206	244	273	304	321	27	41	55	84
A	1	1323	1417	1479	1568	1551	1543	1602	1551	1511	1530	1508	1455	1500	1490
	2	1412	1314	1328	1492	1477	1414	1468	1432	1469	1388	1409	1392	1400	1375
	3	1452	1452	1423	1465	1450	1453	1509	1470	1418	1450	1401	1429	1421	1458
	4	1416	1402	1334	1422	1393	1483	1540	1461	1458	1385	1410	1422	1425	1432
	5	1441	1328	1361	1426	1421	1468	1525	1476	1461	1441	1421	1400	1401	1439
B	1	1431	1348	1383	1407	1349	1498	1478	1479	1539	1463	1525	1501	1486	1523
	2	1432	1301	1400	1482	1455	1502	1482	1507	1540	1482	1365	1396	1400	1445
	3	1335	1402	1389	1467	1494	1508	1488	1490	1504	1378	1520	1502	1519	1518
	4	1459	1366	1408	1452	1450	1517	1497	1500	1542	1487	1483	1433	1374	1480
	5	1459	1337	1457	1460	1436	1458	1439	1466	1517	1421	1423	1450	1458	1446
C	1	1363	1316	1384	1440	1363	1430	1411	1431	1431	1476	1249	1227	1380	1411
	2	1237	1413	1422	1432	1429	1444	1425	1505	1464	1473	1208	1198	1200	1304
	3	1361	1600	1396	1377	1358	1394	1375	1360	1338	1458	1479	1482	1462	1494
	4	1381	1489	1410	1515	1426	1514	1494	1528	1446	1504	1426	1411	1408	1451
	5	1545	1489	1453	1555	1586	1457	1438	1469	1477	1614	1421	1390	1392	1456
D	1	1333	1347	1460	1487	1469	1480	1460	1476	1437	1408	1412	1398	1413	1479
	2	1308	1341	1526	1503	1504	1488	1468	1493	1476	1425	1440	1395	1402	1445
	3	1205	1353	1499	1525	1471	1434	1415	1487	1490	1460	1376	1415	1414	1398
	4	1318	1412	1563	1594	1595	1597	1576	1558	1540	1550	1448	1462	1421	1354
	5	1480	1351	1533	1462	1509	1537	1517	1457	1458	1536	1414	1404	1402	1420

Table A. 10: Saturated hydraulic conductivity ($mm.h^{-1}$) for the different soil columns of Experiment 1

Repetition	Time (min)	Conventional tillage				No-tillage			
		A	B	C	D	A	B	C	D
1	15	25.15	16.59	18.75	24.51	40.61	34.52	63.64	74.12
2	30	23.47	15.12	21.44	28.96	32.27	32.46	36.66	64.30
3	45	23.27	18.23	21.57	30.33	33.87	32.17	55.00	83.69
4	60	22.97	17.25	22.52	21.54	30.68	32.57	51.66	71.03
5	75	21.25	15.99	17.93	20.49	35.64	32.44	50.34	85.72
6	90	15.17	15.13	17.21	19.71	39.81	32.62	37.36	69.86
7	105	20.34	14.50	15.93	20.22	34.03	33.11	37.47	40.38
8	120	24.30	15.79	16.07	29.93	42.47	28.18	30.83	40.87
9	135	24.46	14.25	19.84	34.55	44.41	27.22	35.84	54.59
10	150	23.59	13.66	14.12	34.55	50.97	23.26	52.62	42.13
11	165	23.02	12.88	11.88	30.75	51.39	24.51	50.80	58.65
12	180	23.03	12.41	9.88	24.37	45.65	24.08	33.83	58.91
13	195	22.79	12.29	9.16	18.37	40.47	23.51	33.41	49.46
14	210	23.18	12.13	10.03	28.55	50.63	22.97	29.55	58.09
15	225	19.54	11.90	9.86	22.72	50.34	22.59	23.59	51.49
16	240	20.03	11.62	10.10	24.19	49.90	23.77	24.35	58.66
17	255	20.60	13.91	16.87	25.63	43.67	25.24	22.49	59.47
18	270	20.43	21.12	12.43	25.21	41.94	23.74	21.28	64.03
19	285	20.34	10.17	12.34	35.95	41.77	23.47	26.96	51.41
20	300	19.69	11.17	22.31	36.99	38.48	24.12	31.78	51.76
21	315	19.92	14.23	20.90	38.14	51.76	24.41	35.68	57.21
22	330	21.42	12.96	17.57	36.62	43.42	23.69	33.40	51.60
23	345	20.05	12.34	17.20	34.34	43.64	24.28	33.03	49.28
24	360	21.09	13.81	15.52	30.02	44.23	24.86	33.90	49.42
25	375	21.82	13.69	15.92	30.74	44.03	25.63	33.38	48.86

Table A. 11: Saturated hydraulic conductivity ($mm.h^{-1}$) for the different soil columns of Experiment 2

Repetition	Time (min)	Conventional tillage				No-tillage			
		A	B	C	D	A	B	C	D
1	30	6.62	5.64	5.36	21.00	56.85	26.95	35.60	31.67
2	60	6.31	5.53	5.30	22.49	47.96	27.10	33.22	34.54
3	90	6.18	7.16	5.75	24.82	52.99	27.40	35.38	33.05
4	120	5.09	6.29	4.70	20.17	46.50	27.80	32.14	37.43
5	150	4.12	5.98	4.11	18.41	40.43	25.85	28.78	35.96
6	180	4.61	8.16	7.11	23.05	37.95	33.00	42.12	40.32
7	210	3.56	6.48	5.58	20.95	35.83	29.71	31.51	42.97
8	240	3.42	5.75	4.53	20.01	34.60	28.98	28.57	44.16