CONSERVATION AGRICULTURE AND ITS IMPACT ON SOIL QUALITY AND MAIZE YIELD: A SOUTH AFRICAN PERSPECTIVE

by

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GENERAL ABSTRACT

The countries in sub-Saharan Africa (SSA) are faced with the problem of soil degradation resulting from unsustainable soil management practices such as conventional tillage (CT) and the removal of soil biomass from crop land. Conventional tillage leads to deterioration of important soil physical properties, the decline in soil organic carbon (SOC) and increase the risk of soil erosion. The reduction of SOC further affects soil macrofauna which has important key roles in soil processes such as soil structural formation, decomposition of soil organic matter (SOM) and recycling of soil important nutrients. This combined with water scarcity, low inherent soil fertility, increasing population and the predicted negative impacts of climate change poses threat to the regions ability to self-supply enough food for current and future generations. In response to this conservation agriculture (CA) has been endorsed because of its powerful mechanism to adapt by increasing resilience to land degradation, drought and increasing water use efficiency. Soils under no-till CA have been recognised widely that they generally contain higher SOC, the key principal indicator of soil quality, than CT system. These responses, however, are site-specific and depends on soil type, cropping systems, climate, fertilizer application and other management practices. Moreover, most of the published literature on the effect of CA on soil quality parameters comes from cooler temperate regions. As a result, the effect of CA on soil quality parameters in sub-tropical semi-arid environments remains unknown or controversial. Therefore, the primary objective of the study was to assess the effect of no-till (NT), rotational tillage (RT), CT and nitrogen fertilizer application rates on selected physical, chemical and biological properties of the soil and, their influence on maize yield. The secondary objective of the study was to explore the use of visible to near infrared spectroscopy (VIS-NIRS) as a possible cheap alternative for SOC quantification.

The study was conducted at Bergville in KwaZulu-Natal Province of South Africa. The trial was established in 2003/04 growing season. This area forms the most important part of rainfed maize production in KwaZulu-Natal Province. The trial was arranged as a split plot with randomized tillage strips forming the whole plot and rate of application forming the sub-plots which are randomized within the whole plots. The experiment included three tillage treatments: 1) no-till (NT) with permanent residue cover, 2) annual conventional tillage (CT) and 3) rotational tillage (RT) every after four years. Nitrogen was applied at three rates, namely; 0 kg/ha, 100 kg/ha and 200 kg/ha. Lime ammonium nitrate (LAN) was used as a source of nitrogen.

Unsuitable soil management in agriculture is known to results in deterioration of soil health and the decline in biodiversity. The objective of the study in soil biological properties was to assess the effect of no-till CA on the abundance and order diversity of soil macrofauna in continuous maize monocropping system. Soil macrofauna was sampled at the end of the 2015/2016 growing season using 25 × 25 × 25 cm steel monoliths. The mean density of individual orders was significantly higher ($p < 0.001$) under NT (46%) and RT (38%) compared with CT (16%). However, the Shannon-Weaver index (H, E index) revealed that the diversity and evenness of orders were similar, H= 2.6 and E~ 1, for all treatments. Macrofauna patterns revealed that NT and RT contained a significantly ($p < 0.001$) higher population of orders Isoptera and Diplopoda. Order Isoptera was 51% and 17% higher in NT than CT and RT, respectively while in Diplopoda, NT was 39% and 2% higher than CT and RT, respectively. It was concluded that NT and RT mulch-based system favoured the development of macrofauna communities in the studied maize continuous monoculture cropping system but did not favour order diversity of macrofauna. This

suggests the importance of crop rotation for the development of the more diverse macrofaunal population.

Soil degradation associated with the loss of soil organic carbon (SOC) has been a major concern in sub-Saharan Africa because of the subsequent yield reduction. The objective of the study in soil physical properties was to investigate the effect of NT, RT, CT and N fertilizer applications rate on soil aggregate stability, infiltration, SOC and its size fractions at 0-10, 10-20 and 20-30 cm depth. Soil samples were taken at the end of 2015/16 growing season using soil auger. On average, total SOC did not vary ($p > 0.05$) across the tillage treatments, 27.1 t/ha (NT) *vs* 26.0 t/ha (RT) and 26.6 t/ha (CT), but varied with depth where it was stratified in the 0-10 cm depth in NT and RT. Particulate organic C, however, varied significantly ($p < 0.05$) across the treatments where it decreased with increase in tillage intensity but only in the 0-10 cm depth. Mean weight diameter (MWD) was high under NT and RT and this was correlated to higher infiltration observed in these treatments. The results of this study showed that reduced soil disturbance improves physical protection of SOC, soil structure and infiltration.

Soil management practice may change soil chemical properties and thus fertility. The magnitude of change varies depending on soil type, cropping systems, climate, fertilizer application and management practices. The objective of this study on soil chemical characteristics was to assess the effects of tillage systems, residue retention and fertilizer application rates on the amount and distribution of soil major nutrients in the 0-10, 10-20 and 20-30 cm depth. The soil samples were taken at the end of 2015/2016 growing season using soil auger and transported to the University laboratory for chemical analysis. The concentration of total Nitrogen (N) followed the same trend as that observed in soil physical properties. SOC and N were found to be concentrated on the soil

surface (0-10 cm depth). Phosphorus was significantly higher ($p < 0.001$) under NT (0.0213 t/ha) than in RT (0.0127 t/ha) and CT (0.00704 t/ha). A large amount of P was in the 0-10 cm depth in NT and it was distributed more uniformly under RT and CT. Potassium was also higher ($p < 0.05$) under NT (9.73 t/ha) than in CT (8.00 t/ha) and RT (9.52 t/ha). It was found to be uniformly distributed across the soil depths in all tillage treatments. The soils from NT and RT had lower pH values than CT at 0-10 cm depth while increased significantly in the lower depths. Cation exchange (CEC) capacity followed the same trend. The results indicated that NT treatment increased nutrient availability in the studied soil which was more linked to the distribution of SOC and variability of pH along the soil profile, thus this indicating the potential of implementing NT in the semi-arid environment.

Resilient and sustainable soil management systems are needed to overcome soil degradation, arrest soil fertility decline and to offset the predicted negative impact of climate change. This study investigated the long-term (13 years) impact of soil quality parameters (soil physical, chemical and biological properties), N fertilizer application rate and rainfall on maize grain yield. On average (across the years) maize yields were higher in NT (12.3 t/ha) and RT (12.4 t/ha) under higher rate on N fertilizer application (200 kg/ha) than CT (11.8 t/ha). However, yields decreased in NT with the reduction of N fertilizer application rate in medium N rate (100 kg/ha) and low rate (0 t/ha). The yields decreased by 1.7 t/ha, 1.4 t/ha and 0.4 t/ha from high N application rate (200 t/ha) to medium N application rate (100 t/ha) in NT, RT and CT, respectively. Under low rainfall of < 400 mm/year and high N application rate (200 kg/ha), the yield was 9.13 t/ha, 7.96 t/ha and 7.00 t/ha in NT, RT and CT, respectively across the years. However, when the average rainfall was above 600 mm/year, yields averaged at 13.3 t/ha, 13.7 t/ha and 13.5 t/ha in NT, RT and CT under high N fertilizer application rate across the years. Principal component analysis (PCA) was performed to assess some biological, physical and chemical properties of the soil that contributed to maize yield. The results showed no parameter that seemed to be related to maize yield. This was attributed to the complex interaction of bio-physio-chemical parameters with the environment. The results of this study found that yields improve over time under CA and this was more pronounced during the drought period. Yields improvements under CA require the application of the higher rate of N fertilizer in correct amount. Therefore, it is recommended that CA is implemented in semi-arid subtropical areas to improve soil conditions, water conservation and to achieve optimum yields.

Application of spectroscopy for assessment of soil nutrition in the field may be affected by the depth at which the radiation spreads to, the analysed nutrient, and management practices such as tillage systems. The visible to near infrared spectroscopy (VIS-NIRS) was explored as a technique to predict soil organic carbon (SOC) and soil organic nitrogen (SON) in soils differing in soil tillage management practices. Partial least square regression (PLSR) models were developed using the leave-one-out cross validation method. The models were then tested on independent samples (54) randomly selected from the total 324 samples. The best prediction model was observed for SOC with the coefficient of determination (R^2) = 0.993, root mean square error of prediction (RMSEP) = 0.157% and residual predictive deviation (RPD) = 2.55 compared with R^2= 0.661, RMSEP= 0.019%, RPD= 2.11 for SON. Considering the predictive statistics and accuracy created by the model in the prediction of SOC, VIS-NIRS can be recommended as a fast, accurate technique for SOC determination in the studied soil. This will significantly reduce the cost associated with SOC and SON analysis for researchers and farmers.

UKUFINYEZWA KWENDABA YONKE JIKELELE

Amazwe asezansi ne Afrikha abhekene nengwadla enkulu yokudicileka phansi nokuphelelwa umsoco komhlabathi. Lokuphelelwa umsoco komhlabathi kubangelwa izindlela zokutshala ezingalungile ezingahlali isikhathi eside njengokutshala lapho oqale ulime umhlabathi khona bese usebenzisa igeja ususe nokhula. Lokhukulima ngegeja bese ususa ukhula kubangela ukuthi umhlabathi unganothi ngoba usuke ususe amacembe namagatsha agayekile (noma ayimvuthuluka) abaluleke kakhulu ekwakheni inqalasizinda sokuthi umhlabathi ubumbane ubeyimbumba futhi ukwazi ukuthi unikeze izitshalo umsoco wokuthi zikhule kahle. Lezizimvuthuluka zezitshalo uma zingekho emhlabathini, zibangela ukuthi umhlabathi ugugulеke kokuba zona zenza umhlabathi ukuthi ubumbane ube yimbumba uhlangane uthi thaqa. Lezizimvuthuluka zezitshalo ziyabandakanyeka ekubenikhona kwezilwane ezibalulekile kakhulu ezikwazi ukuthi zidle amecembe namagatsha ezitshalo ziwagaye abe yimvuthuluka bese zibuyisele imvundo nomsoci wezitshalo emhlabathini. Lokhu kuhlangene nokusweleka kwamanzi, umhlabathi ongavundile, ukunyuka kwesibalo sabantu, nezimo ezimbi eziqaguliwe zokhuphenduphenduka kwesimo sezulu kwenza ukuthi kube nokusaba okukhulu ukuthi thina silapha enzansi ne Afrikha sokwazi ukuzondla sibuye sondle nezizukulwane zethu ezizayo. Ukubhekana nalesisimo, ukutshala ungalimanga sekuphakanyisiwe futhi kwanconywa ngokuba kona kuyakwazi ukuthi kuvimbele ukuthi umhlathi okutshalwe kuwo ukuthi ungafi, kubuye kubhekane nesomiso futhi kusebenzise amanzi ngokuwonga ezitshalweni ngesikhathi sesomiso. Ukutshala ungalimanga ucwaningo olwenziwe ezindaweni eziningi emhlabeni jikelele selutshengise ngokusobala ukuthi uba nezimvuthiluka eziningi zezitshalo zokhula uma uqhathanisa nokutshala ulimile bese ususa ukhula namahlanga. Kepha lokhu kuhluka insimu nensimu futhi kuncike ohlobeni oluthile lomhlabathi, kubuye kuncike futhi ekutheni utsha ini iyixubanani futhi yini oyishintshangayo mawutshala, kubuye futhi kuncike esimweni sezulu saleyondawo, kubuye futhi kuncike ekutheni hlobolini lwesivundiso osisebenzisayo mawutshala, kubuye kuncike ezindleleni ezinye ezinhlobonhlobo ezisetshenziswayo wawutshala noma ukhulisa izitshalo. Okunye futhi, izindaba zocwaningo eziningi ezibhaliwe mayelana nokutshala ungalimanga nemiphumela yakho ekwenzeni umhlaba onothileyo ziqhamuka le phesheya kwezilwandle, endaweni ebandayo futhi enemvula eningi. Ngalokhoke, thina lapha kwelengabadi asiyazi imiphumela yokutshala ungalimanga ukuthi iyefana yini nale yalezizindawo ezibandayo futhi elina kahulu kuyo ukuthi iyefana yini na la ekhaya, ngoba phela lana kwelakithi liyashisa futhi nemvula yakhona ayini kakhulu iyancikisela kwesinye isikhathi. Ngakhokonke lokhu okubaliwe, injongonqangi nenqikithi yalolucwaningo kwakuwukubheka imiphumela yokutshala ungalimanga ushiye ukhula namahlanga phezukomhlabathi, ukutshala ungalima ushiye ukhula namahlanga phezukomhlabathi ubuye ulime emva kweminyaka emine, ukutshala ulimile bese ususa ahlanga nokhula kanye nokusebenzisa isikhuthazakhaba esinezikalo ezahlukene ukuthi kwenza miphumelamini esakhiweni somhlabathi, nase msocweni kanye nasezilwaneni ezibonakalayo ngamehlo. Mase kucwaningiwe konke lokhu, kwabuye kwabheka ukuthi kunamuthelelamuni esivinweni sombila. Okunye okwabhekwa ukusebenzisa ubuchwepheshe obusha bothingo lwenkosazane ekukaleni imvuthuluka yezitshalo nokhula emhlabathini.

Ucwaningo lolu lwenzelwa kwelamaNgwane, kwelikaMthaniya, kwelikaPhunga nomaGeba, kwelikaShaka kaSenzangakhona, uDlungwane KaNdaba, woDlungwane woMbelebele, odlunge emanxlulubaneni, kwaze kwasa amanxuluba ebikelana, uNodumehlezi kaMenzi, lwenziwa eningizimu ne Afrikha. Ucwaningo ensimini lwaqalwa ukwenziwa ngonyaka wezinkulungwane ezimbili nantathu kuya ezinkulungwaneni ezimbili nane. Lendawo le ekwenzelwa khona ucwaningo iyindawo ebalulekekakhulu ngoba iyona etshalwe umbila kakhulu lapha kwelikaMthaniya. Lensimule, yatshalwa yahlukaniswa 1) kwabakhona indawo etshalwa ingalinywanga ushiye amahlanga nokhula, 2) etshalwa ingalinywanga ushiye amahlanga nokhula bese uyilima emva kweminyaka emine and 3) etshalwa ilinyiwe bese ususa amahlanga emva kokuvuna. Isikhuthazakhaba safakwa ngezikalo ezintathu, nazi lezizikalo; akufakwanga lutho kg/ha, ikhulu kg/ha Kanye namakhulu amabili kg/ha. Ukaliki wawufakwanjalo emva kweminyaka emibili.

Ukungalimi amasimu ngendlela efanele sekuyaziwa ukuthi kwenza umhlabathi ulahlekelwe yimvundo futhi bese lezilwanyana ezitholakala emhlabathini zibaleke noma zife. Injongo nqangi yalolucwaningo kwakuwukubheka imithelela yokutshala ungalimanga ushiye amahlanga nokhula (NT), ukutshala ungalimanga ushiye amahlanga nokhula bese uyalima emva kweminyaka emine (RT), nokutshala ulimile ususe amahlanga (CT), ezilwaneni zasemhlabathini ezibonakala ngamehlo. Amasamphula okucwaninga lezilwane athathwa emvakokuvuna umbila ngonyaka wezinkulungwane ezimbili neshumi nanhlanu kuya kuya kunyaka wezinkulungwane ezimbili neshumi nesithupa kusetshenziswa insimbi enesikalo esingamashumi amabili nanhlanu uwaphindaphinde ngamanye futhi uphindaphinde ngamanye futhi okugcina (cm^3). Sekucwaningiwe kwatholakala ukuthi lezizilwane zaziningi kakhulu ku NT (kwatholakala amashumi amane nesithupha kweziyikhulu) uma uqhathanisa naku RT (kwatholakala amashumi amathathu nesishiyagalombili kweziyikhulu) no CT (kwatholakala eziyishumi nesithupha). Uma kubhekwa ukwehlukahlukana kwazo, kwatholakala ukuthi kwakuyizinhlobo ozifanayo. Onomkoyi mamashongololo ayemaningi kakhulu ku NT no RT mawuqhathanisa namashongololo. Lolucwaningo lwakubeka obala okwezinqe ze sele ukuthi ukutshala ungalimanga ushiye amahlanga kwandisa lwzizilwane ezibalulekile zemvelo. Okunye ukutholakala kohlobo olulodwa lwalwezilwane ekutshaleni okuhlukene kukhombisa ukuthi kubalukekile ukuthi ushintshashintshe izitshalo uzokhuthaza uhlobo olunye lwezilwane ukuthi zizodla amahlanga ngoba azidli into efanayo.

Ukudicilileka phansi komhlanathi ovundile uze ufe okuhlobene nokulahleka kwemvuthuluka yamahlanga nokhula etholakala emhlabathini isibe ixhala kahulu emazweni asenzansi ne Afrikha ngoba yenza ukuthi isivuno sehle kakhulu. Injongo yalolucwaningo esakhiweni somhlabathi kwakuwukubheka kabanzi imithelela yoku NT, RT, CT kanye nezukalo ezahlukene zesikhuthazakhaba ekubumbaneni kwamagabade omhlabathi, ekungeneni kwamanzi emhlabathithi, ezimvuthwini zamahlanga nokhula emigodini yomhlabathi mawushona phansi kusuka emhlabathini phezulu uya eshumini, usuke eshumini uye emashumini amabili, usuke kwamabili uye kwamathathu. Amasampula athathwa onyakeni wezinkulungwane ezimbili neshumi nanhlanu kuya eshumini nesithupha kusetshenziswa insimbi i aga. Izimvuthulunga zamahlanga ezibalukekile akutholakalanga umahluko ocace bha, zazilingana yonke indawo. Uba ubuka ukushona phansi, kwatholakala ukuthi zaziningi uma usuka phezulu emhlabathini uya eshumini cm. Lokhu kwakucace bha okwezinqe zeselesele uma ubuka uku NT noku RT. Uma siqhubeka, ukubumbana kwamagabade kwatholakala ukuthi ayebumbene kakhulu eku NT nase RT. Ukubumbana kwamagabade nokungena kakhulu kwamanzi kwatholakala ukuthi kuyimihlathi eyazanayo. Lemiphumela yocwaningo ikubeke kwasobala okwezinqe zesele ukuthi ukatshala ungalimanga kwenzancono isimo somhlabathi ngokuwuvikela, kwandise nemvuthuluka ebalulekike, isakhiwo somhlabathi kanye nokungena kwamanzi emhlabathini.

Indlela ophatha ngayo umhlabathi nendlela owulimangayo ingashintsha amakhemikhali atholakala emhlabathini kanye nemvundo uqobo. Isikalo sendlela ashintsha ngayo incike ekutheni hloboluni lomhlabathi, iyiphi indlela otshala ngayo, isimo sezulu saleyondawo, imvundo oyifakayo

emhlabathini kanye nendlela owenzangayo emasimini. Inhloso yalolucwaningo emakhemikhalini atholakala emhlabathini kwakuwukucubungula kabanzi imiphumela yokutshala okwahlukehlukene okubalwengenhla nezikali ezahlukene zesikhuthazakhaba ekuhlukahlukaneni kwemvundo ebalulekile emhlabathini mawushona phansi. Amasampula athathwa onyakeni wezinkulungwane ezimbili neshumi nanhlanu kuya eshumini nesithupha kusetshenziswa insimbi i aga. Lamasampula ayesethathwa esiwa esikhungweni semfundo ephakeme iNyuvesi yakwaZulu-Natal eyocwaningwa kabanzi. Isikhuthazakhaba kwathokakala ukuthi sasihlobene nomungako kwemvuthuluka yomhlabathi. Ikhemikhali u P watholakala emuningi ngamalengiso ku NT uma uqhathanisa no RT no CT. U phosphorasi (P) omuningi watholakala emhlabathini ongaphezulu. U pothasiyamu (K) watholakala umningi ku NT uma uqhathano RT no CT. Umhlabathi ka NT watholakala ukuthi une esidi eningi uma uqhathathisa no CT. Ukunamathela kwemvundo kwatholakala ukuthi kuhlobene nalokhu. Lemiphumela itshengise ukuthi ukulima ungatshalanga kwandisa imvundo emhlabathimi and loku kuhlobene ncamashi nokubakhona kwemvuthulula ebalulekile emhlabathini.

Ukutshala okuzinzile nokuqhuba isikhathi eside kuyadingeka ukuze kubhekwane nengwadla yokudicililekaphansi nokufa komhlabathi ukuze sigcine umhlabathi wethu uvundile sibhekane futhi nesimo esingesihle esiqaguliwe sokuguquguquka kwesimo sezulu. Lolucwaningo luculungule imiphumela yesikhathi eside (ye sakhiwo somhlabathi, izilwane ezibonakalayo ezitholakala emhlabathini kanye nemvundo yawo) utshale ungalimanga kanye nezikalo ezahlukene zesikhuthazakhana ukuthi ziyasikhuphula yini isivumo emasimini ekuhambeni kwesikhathi. kwatholakalake ukuthi isivuno siyakhuphuka mawutshale ungalimanga ufakefuthi nesikhuthazakhaba esingamakhulu amabili Kg mawuqhathanisa noma utshale ulimile. Ngakolunye uhlangothi, kwatholakala futhi ukuthi mawunciphisa isikalo sesikhuthazakhaba usisa ekhulwini Kg

isivuno siyehla. Okunye okwatholakala ukuthi makunesomiso, isivuno asehli kakhulu uma utshale ungalimanga kunokuba utshale ulimile. Izwe lethu ngoba libuye lihlaselwe isomiso kusobala ukuthi ukutshala ungalimanga kuyakwazi ukuthi kugcine amanzi emhlabathini.

Ekugcineni kocwaningo, uthingo lwenkosazane lwabhekwa kabanzi ukuthi lungakwazi yini ukucubungunga ubungako bemvuthuluka ebalulekile emhlabathini. I partial least square regression (PLSR) yakhiwa kusetshenziswa leave-one-out cross validation method. Ama model lawa aye kalwa kuma sampula azimele angamashumi amahlanunane akhethwe ngokunganaki kwasephelele amasampula angamakhulu amathathu namashumi amabili nane. I model eqageka kahle yabonakala ezimvuthwini ezibalulekile ene coefficient of determination (R^2) engu 0.993, root mean square error yoku prediction (RMSEP) = 0.157% and residual predictive deviation (RPD) = 2.55 mawuqhathanisa R^2 = 0.661, RMSEP = 0.019%, RPD = 2.11 ye mvuthuluka ebalulekile. Uma kubhekwa lezibalo nokuqagela ushaye emhlowleni, loluthingo lwenkosazane luyancomeka ukuthi lingawenza umsebenzi wocwaningo usize nabalimi kakhulu ezindlekweni.

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CHAPTER 1

1. GENERAL INTRODUCTION AND LITERATURE REVIEW

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1.1 Abstract

Sub-Saharan Africa is faced with the challenge of improving current food security on highly degraded land. At the same time, the region has to develop strategies to ensure future food security for the increasing population under worsening climate change. Conventional tillage (CT) has for many years resulted in the deterioration of soil quality through depletion of soil organic matter. This review of the literature provides an overview of the impact of conservation agriculture (CA) on soil quality with particular emphasis on key soil physical, chemical and biological properties. This paper also discusses the impact of CA on yield, highlighting South African research gaps since the adoption is still very low in the country. The review of numerous studies indicated that soil quality and yield improvements are possible in CA although some negative results have also been reported under contrasting environments. Yield under CA was recognised to be resilient to seasonal rainfall variability compared with CT because of its ability to conserve water. CA is particularly relevant to the South African maize production given high levels of soil degradation, water scarcity and low soil fertility status. This review of the literature demonstrated that CA can have substantial positive environmental, financial, social and health benefits for South Africa and the world. However, more research on CA is required from different agro-ecological zones and socio-economic contexts since maize is the biggest produced crop in South Africa.

1.2 Introduction

The world population continues to increase, and it is projected to reach 9.1 billion by 2050 (FAO, 2009a). This increase is expected to come mostly from the developing world with Sub-Saharan

Africa highlighted on top of the list (United Nations, 2009). Therefore, the pressing need to ensure increased food supply and food security on the limited amount of land in the region is obvious. Moreover, land resource in the region is continuously losing its value as a medium for crop growth. According to FAO (2010a), Southern Africa has a high level of soil degradation and a decline in soil fertility, which threatens crop productivity. Soil degradation level in South Africa is severe and 41% of the cultivated land is highly degraded (Bai and Dent, 2007). Drought in these areas often worsens the situation, resulting in complete crop failures (FAO, 2009b), especially for poor-resourced smallholder farmers, who are often situated in marginal areas of agricultural crop production (Mabhaudhi et al., 2013).

South Africa is a water scarce country with erratic rainfall distribution and an annual precipitation of less than 500 mm/year (IWMI, 1996), which is far below than the world average of 860 mm/year (DWAF, 2002). In the long run, climate change is predicted to have a negative impact with more frequent and prolonged drought and higher temperatures (FAO, 2010b). The combination of these problems put more pressure on limited arable land and available fresh water needed for food production. This is of great concern when viewed in the context of climate change and impact this will have on agricultural production and vulnerability of subsistence farmers and poor urban communities concerning food security (Thierfelder et al., 2014). This is most likely because the incidence of crop failure will probably rise due to extreme weather events (Schulze, 2011). In response to these challenges, conservation agriculture (CA) has been proposed by many researchers (Hobbs, 2007; Hobbs et al., 2008; Giller et al., 2009) to buffer these effects because of its powerful mechanism to adapt by increasing resilience to land degradation, drought and increasing water use efficiency (FAO, 2009b). FAO (2010b) has defined CA as a concept for resource-saving agricultural productivity that strives to achieve acceptable profits together with high and sustained production levels while concurrently saving the environment. The three central themes around CA are based on systematic crop rotation, permanent soil cover by crop residues and minimum tillage and/or zero-tillage (Rusinamhodzi, 2015).

The benefits associated with CA include crop sequence intensification (Brouder and Gomez-Macpherson, 2014), better use of the cropping season window permitted by earlier field entry (Hobbs et al., 2008), increase soil organic carbon (SOC) (Rusinamhodzi, 2015), soil moisture retention while sharply reducing run-off, soil erosion and surface soil temperatures (Findlater, 2013). According to FAO (2011), the long-term effects of CA when practiced comprehensively include improved crop yields and reduction of the production costs. Crop rotation allows for the inclusion of the crops that can improve soil fertility, for example, leguminous crops (Hobbs et al., 2008) and it is also practiced to reduce the impact of pest and diseases which are more problematic in monocultural cropping systems (Kirkegaard et al., 2008). The practice specifically decreases farm sensitivity to weather variability through improving water retention and reducing water logging (Thierfelder and Wall, 2010). Therefore, increased soil water retention makes it a more reliable system for crop production in water scarce or dry countries such as South Africa and many parts of Sub-Saharan Africa.

The estimates have, however, shown that the level of adoption of CA use in South Africa is still very low (360 800 ha) compared to USA (26 500 000 ha), Argentina (25 553 000 ha), Brazil (25 502 000 ha) and Australia (17 000 000 ha) which have massive adoption of this technological advancement (Friedrich et al., 2012). In Sub-Saharan Africa, South Africa is on top of the list of countries adopting CA, followed by Zambia (200 000 ha), Mozambique (152 000 ha) and Zimbabwe (139 300 ha) (Friedrich et al., 2012). Although the adoption of CA in South Africa is the highest in Sub-Saharan Africa, it only constitutes 2.8% of the country's arable land. Various initiatives have been recently undertaken by Agricultural Research Council (Anon., 2014), farmer's organisations and government to implement CA adoption in South Africa, however, these initiatives have not yet gained momentum or penetrated in most poor-resourced small-scale farmers found in different socio-economic and agroecological regions of South Africa. Factors which frequent limits its adoption by smallholder farmers in other African countries include, competing uses for crop residues (crop-livestock mixed farming), increased labour demands for weeding and lack of access to external input such as herbicides and inorganic fertilizers (Giller et al., 2009). In commercial farming systems, FAO (2010a) reported that mindset of farmers, extension and policymakers who still believe that crop growing is synonymous with plowing and making the field clean, has contributed to its slow adoption. Clean seedbeds are part of the cause of soil degradation and yield reduction due to exposure of soil to wind and water erosion. Inadequate CA knowledge and skills, retaining residues, weed control, availability of equipment and inputs and land tenure systems are amongst the challenges reported by FAO (2010a) to reduce the rate of adoption.

Soil improvement properties and yield gains that accrue from CA practices are directly linked to the availability of soil organic matter (SOM) (Lafond et al., 2011), which in turn largely influences soil physical, chemical and biological properties. The accumulation of SOM is also dependent on various factors such as soil type, prevailing climate condition of the area, management practices such as tillage type and the complex interactions of these factors. The quantification of SOM, directly measured as soil SOC is very expensive because of the use of traditional chemical methods and the use of machinery. This limits the innovation possibility and articulation of research institutions to perform relevant experiments linked to SOC, the principal indicator of soil quality. This is particularly true for countries in SSA which lack infrastructural funding and other developing countries. Visible and near infrared spectroscopy (VIS-NIRS) has been proposed as a cheap, fast and accurate method because of its successful use in other industries (Minasny et al., 2011). It presents such alternative because it requires the only collection of samples as a preparation and provides accurate information of several soil properties from one spectral reading (Vohland et al., 2011). Application of VIS-NIRS collects large information about soil physical, chemical and biological properties of a sample and therefore, permits measurements of many soil properties from the single measurement (Minasny et al., 2011).

Furthermore, Friedrich et al. (2012) reported that 87% of CA adoption is concentrated in just 5 countries as mentioned above and Brouder and Gomez-Macpherson (2014) argued that the potential and environmental benefits of CA adoption for crops in agroecological regions beyond the intensive studies of Australia and Americas remain uncertain and controversial. This may be evident in South Africa, as the potential of CA to improve soil quality characteristics and associated yield gain of the different agroecological zones and socio-economic conditions across the country has not been fully explored in the scientific literature.

The data on CA practices is largely missing in the scientific literature; perhaps, due to lack of research interest since CA is a long-term project and/or lack of clear policies encouraging its implementation. This may be evident as the South African National Department of Agriculture is currently (2016) involved in drafting and establishing CA policy around the country to enforce its implementation in the nine respective provinces of the country. Promotion of CA with a view to expand it to a larger scale will depend, to a larger extent, on the availability of information relevant to agro-ecological zones and socio-economic niches about growth, development and yield of different crops. This will contribute to the documentation of scientific literature which might stimulate its expansion on the larger scale by both commercial and subsistence farmers. This information is urgently required if CA is to be promoted in the country. Ishaq et al. (2002) stated that "studies which are site specific are more important so that more accurate generalization can be made regarding conditions required for sustainable tillage".

In response to this, the Provincial Department of Agriculture in KwaZulu-Natal under Soil Analytical Services established a long-term field trial in 2003/2004 season to assess the effect of tillage type (conventional tillage, rotational tillage and no-till) and nitrogen application rates on soil fertility, maize productivity and quality, and crop diseases. This trial was laid out in Winterton Bergville KwaZulu-Natal where it forms the most important annual cropping area of KwaZulu-Natal Province. However, consideration on the effect of tillage regime and nitrogen application rate on soil physical, chemical and biological properties has not been fully explored. In response to this, an additional investigation was established to look at the effect of different tillage systems and nitrogen fertilizer application on selected soil physical, chemical properties and biological properties.

Therefore, the overall objective of the study was to assess the effect no-till, rotational tillage, conventional tillage and nitrogen fertilizer application rates on selected soil physical, chemical and biological properties of the soil and their influence on maize yield. The secondary objective was to explore the use of VIS-NIRS as a possible alternative for SOC quantification. Thus, the specific objectives of the study were:

- To assess the effect of tillage regimes and nitrogen fertilizer application rates on soil macrofaunal abundance and diversity.
- To investigate tillage regimes and nitrogen fertilizer application rates effects on selected soil physical properties.
- To investigate the effect of tillage regimes and different rates of fertilizer applications on selected soil chemical properties.
- To investigate the combined effects of soil physical, biological and chemical properties on maize yield.
- To develop spectral models for rapid assessment of soil organic carbon and nitrogen using visible and near infrared spectroscopy.

2. LITERATURE REVIEW

2.1 Introduction

This review of literature discusses conservation agriculture with particular emphasis on the current knowledge and status of its adoption in South Africa. The paper will first discuss history on the evolution of agriculture and soil cultivation practices, followed by a section encompassing effects of CA on soil quality characteristics including physical, chemical and biological properties. The next section will discuss yield gains, with a view to encourage its adoption in South Africa and to achieve the goal of sustainable agricultural production. On the basis of observed trends, the technical challenges and future research avenues on CA will be presented.

2.2 Evolution of agriculture

It was only in the Neolithic Era, about 10 000 years ago, that humans began cultivating crops and domesticating animals (Mazoyer and Roudart, 2006). Before then, to our knowledge, all human species were hunter-gathers, obtaining food from wild plants and animals. Humans became farmers the moment they were able to sow and reproduce seeds (Lamarca, 1998). According to the most commonly accepted theory of evolution, in the evolutionary branch, Homo sapiens, current humans, are the unique and latest representative of hominids which separated from primates about 6–7 million ago (Mazoyer and Roudart, 2006). This branch of evolution is the one believed to be responsible for the development of agriculture as we know it today. Homo sapiens practiced slash-and-burn agriculture which is believed to be the one that was responsible for shifting agriculture

(Vasey, 1992). This agricultural system provided a sufficient amount of nutrients to grow crops. However, this system was not sustainable, in that it destroyed forest natural resources, as a result of population increase and it leads to soil erosion and nutrients were depleted within few years of cultivation (Metzger, 2003). The later was overcome by leaving the field fallow for several years, up to 20 years, to allow the field to recover to its original state of the forest.

As the time proceeded, all the virgin reserves were used, and the population density increased the frequency and intensity of clearing increased putting more pressure on limited forest resources (Mazoyer and Roudart, 2006). Ultimately, this resulted in the impossibility of pursuing this mode of cultivation in many areas of the world (Beyer et al., 1980). According to Mazoyer and Roudart (2006), deforestation generally led to the deterioration of soil fertility, development of more or less serious erosion problem and desertification. Following this, agriculture evolved through many revolutions including hydraulic agrarian systems; agrarian systems based on fallowing and animal-drawn cultivation; agrarian systems without fallowing (the first agricultural revolution in modern times), mechanisation of animal-drawn cultivation and transport revolution and the second agricultural revolution of the modern times (motorization mechanization, synthetic fertilizers, seed selection and specialisation) (Mazoyer and Roudart, 2006). By 1930s, the second quarter of the 20th century, commercial farmers around the world were practicing intensive tillage system in their farms which evolved from industrial revolution through mechanization.

Intensive tillage, commonly referred to as conventional tillage resulted in huge loss of soil in the mid-western America (Hobbs, 2007). This is often called the American dust bowl of the 1930s which resulted from tillage as well as droughts that lasted for 4–8 years, depending on the location.

It was estimated that more than 91 million hectares of land were degraded due to inappropriate land management and according to Hobbs et al., (2008), this area of degradation has been dramatically reduced today and this was a wakeup call on how human intervention in soil management can lead to unsustainable agricultural systems. This resulted in many scientists recommending conservation tillage and recently conservation agriculture has been introduced to try and achieve sustainability in the management of agricultural resource base.

In South Africa, the development of policies to mitigate and prevent soil degradation through erosion in agricultural landscape began in 1923 with the Drought Investigation Commission Report (Mills and Fey, 2004). Following this was the Soil Erosion Advisory Council in 1930 and the Soil Conservation Act in 1946 (Mills and Fey, 2004). According to Donaldson (2002), the results of these policies were an effective control in soil erosion in many parts of the country. However, before 1978, soil scientists in South Africa were not active in soil degradation research although some isolated cases had been reported in the late 1980s and 1990s, there was an increase which was still quite low according to Laker (2004). The control of soil erosion is the first step in the management of soil natural land resource effectively; the second step requires the understanding of soil physical, chemical and biological properties that may result under different management practices (Mills and Fey, 2004). Bassett (2010) on his Master’s Thesis reported that the first no-till research in South Africa was initiated by Dr J.B. Mallet at Cedara in KwaZulu-Natal Province in the early 1970s. On his results, it was found that crop yield was higher under no-till than conventional tillage on seasons when moisture was limiting, and his studies also showed that the production cost was much reduced under no-till than conventional tillage. Bassett (2010) further reports that besides these benefits offered by no-till, farmers remained disinclined to adopt it because of the concern of the carry-over of diseases to the next season. The increase in fuel prices from 1998 encouraged further investigation of tillage management practices and led to the formation of the No-Till Club in KwaZulu-Natal Province and Conservation Farming Committee in Western Cape. These organisations with the help of non-government organisations, universities, Department of Agriculture, some commercial farmers and Agricultural Research Council (ARC) are providing information through research for sustainable agricultural management.

2.3 Soil tillage concept

2.3.1 Conventional tillage or plow tillage (PT)

Conventional tillage generally involves ploughing and intensive soil disturbance. It is defined as the tillage type that leaves less than 15% of the crop residues on the soil surface after planting the next crop (EL, 2003). This type of tillage has been recognized as the major driver of soil degradation through the depletion of soil organic matter and associated nutrients loss (Mutema et al., 2013). It relies heavily on moldboard plow followed by secondary tillage (EL, 2003) which is often drawn by heavy tractors. Plow tillage (PT) is primarily practiced by commercial farmers in South Africa with huge capital investments on mechanized machinery and inorganic inputs such as fertilizers and herbicides. In smallholder farmers, this type of agricultural practice is not prevalent due to low incomes, land limitation and limited access to implements. They usually use animal-drawn moldboard plow, small tractors and hand hoe for soil tillage.

The benefits associated with soil PT system have been summarized by Hobbs (2007) and Hobbs et al. (2008). These authors cited that soil tillage was traditionally considered to be the first step in seedbed preparation and it is used to incorporate previous crop residues, weeds, soil amendments added to soil such as organic and inorganic fertilizers. Soil disturbance as results of PT helps to aerate SOM which in turn release nutrients through mineralization and oxidation after exposure of SOM. They further reported that it controls soil- and residue-borne pest and diseases since residue burial and disturbance have been shown to alleviate this problem. Lastly, the authors highlighted that PT system can provide temporary relief for soil compaction through the use of implements that could shatter below ground formed compaction layers. The disadvantage of this tillage system is its impacts on soil quality characteristics. Conventional tillage system has been widely reported to negatively affect soil physical, chemical and biological properties (Uri, 2000; Nail et al., 2007; Moussa-Machraoui et al., 2010).

2.3.2 Conservation tillage (CT)

Conservation tillage (CT) is defined as any tillage practice that minimises soil loss and water, which often require the presence of at least 30% of the crop residues throughout the year (Benite et al., 1998). Hobbs (2007) on the other hand, stated that CT is a collective umbrella term that is commonly given to no-tillage, direct drilling and minimum tillage and ridge tillage to denote that the specific practice has a conservation goal of some nature. Baker et al. (2007) further argued that this term is not adequately defined as it also involves the conservation of fuel, time, soil water, soil structure, earthworms and nutrients. With this tillage type, traditional implements used to prepare the soil for cultivation, such as plows, disks, chisel plows, and various types of cultivators are eliminated and replaced by drills and direct seeders capable of cutting stumble and roots, leaving the seed properly placed in the soil (Lamarca, 1998).

2.3.3 Conservation agriculture

Food Agriculture Organization has defined CA as an approach of managing agroecosystem for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and environment (FAO, 2010b). According to Verhulst et al. (2010), this cultivation system has been proposed as a widely adapted set of management principles that can assure more sustainable agricultural production. This system has been adopted as a result of a realisation that agriculture should not only be based only on high yield but it must also be sustainable. The adoption of this management principle has been pushed further by ever-increasing prices of production cost, scarcity of water, climate change and degradation of ecosystem services which force farmers to look for alternatives that can reduce cost while improving natural resource base and productivity (Kassam et al., 2009).

Conservation agriculture is characterized by three main principles, namely, continuous minimum soil disturbance or reduced tillage, permanent soil cover by organic residues, and diversified crop rotation (Rusinamhodzi, 2015). According to the definition, minimum soil disturbance refers to low disturbance, no tillage and direct seeding. The disturbed area must be less than 15 cm wide or less than 25% of the cropped area (Verhulst et al., 2010). In this practice, there should be no area disturbed (by tillage) greater than the set limit. The aim for permanent soil cover is to protect the soil from water and wind erosion; reduce water run-off and evaporation; to improve water productivity and to enhance chemical, physical and biological properties associated with long-term sustainable productivity (Verhulst et al., 2010). On the other hand, the use of diversified crop rotation is to minimise the impact of pest and disease and to enhance soil nutrition through the use of crops such as legumes which can fix atmospheric nitrogen (Kassam et al., 2009).

Conservation tillage and CA definition have created some confusion among scientist and also the farming community and according to Hobbs (2007), the difference is that CT uses some of the principles of CA but has got more soil disturbance than CA. CA, on the other hand, maintains permanent soil cover and this can be a decomposed organic matter, or it can be a growing mulch. In its definition, CA contributes to environmental conservation as well as improved and sustained agricultural production as compared with CT. In addition, the area less than 30% ground cover is not considered as CA. As a result, CT system is considered as the transitional stage towards the leg of CA.

For this particular study, CA is defined as the management practice that with minimal soil disturbance and permanent soil cover. Minimal soil disturbance refer to the operation performed by the no-till planter during sowing.

2.4 Tillage effects on soil physical properties

2.4.1 Soil structure and aggregation

Soil structure refers to the arrangement of particles into units called aggregates. Aggregation results from the rearrangement, flocculation and cementation of particles. It is mediated by soil organic carbon (SOC), biota, ionic bridging, clay and carbonates (Bronick and Lal, 2005). Plow tillage is one of the major drivers of soil destruction through the physical breakdown of the soil structure as compared to reduced tillage (Duiker and Beegle, 2006). As a result, soil becomes susceptible to soil erosion due to the disintegration of soil aggregates (Bronick and Lal, 2005). Although plow tillage results in better structural distribution than reduced tillage and no-till, the components of the soil structure in PT are very weak to resist water slacking resulting in structural deterioration (Six et al., 2000; Verhulst et al., 2010). These can also result in reduced aggregation and increase turnover of aggregates and fragments of roots and mycorrhizal hyphae which are the major binding agents in soil. In conservation agriculture, soil is protected by permanent residue cover and this protects the soil from the impact of the raindrop, water and wind erosion (Six et al., 2000). In PT there is no protection of soil by the soil cover which increases chances of further destruction.

2.4.2 Bulk density and porosity

The soil is arranged into solids and voids. The voids, called pore space (porosity), are important for gas exchange, water movement, root growth and water storage. On the other hand, bulk density is the mass per unit volume of soil. The bulk density of the soil top layer (the top 30 cm) is usually lower in PT soils than in continuous no-till, reflecting the rapture effect of tillage near the surface (Dolan et al., 2006). According to So et al. (2009), PT loosens the soil structure causing the immediate increase on the soil macropores resulting in lower bulk density and higher total porosity which can benefit seedling establishment and crop growth. On the other hand, long-term trials have indicated that on the lower surface of the soil, below 30 cm (under the plow layer), soil bulk density and total soil porosity between no-till and PT is generally similar (Dolan et al., 2006). Verhulst et al. (2010) stated that a new “steady state” may be expected as a result of a reduction in tillage, with a progressive change in total porosity with time. Moreover, the implement used in PT system makes soil more compact and after repeated tilling, the hardpan is usually formed underneath the plow layer (Gao-bao et al., 2012). This, in turn, can affect the movement of air, water and inhibits root growth. Hardpan has a high bulk density with a few macro-pores for roots to grow through (Gómez et al., 1999; Gao-bao et al., 2012) and tends to reduce macro-aggregates (Jin et al., 2011). This can significantly reduce root length and trigger the formation of lateral roots (Gao-bao et al., 2012). As a result, growth, development and yield of crops may be reduced due to inefficient contact of roots with water which transport nutrients required for plant growth. In the long run, yields may become unstable especially in drier areas.

2.4.3 Water infiltration rate

Infiltration is the process by which water in the ground surface enters the soil. Soil tillage modifies soil physical properties and hence soil structural stability, bulk density and pore structure are directly linked to water infiltration (Azooz and Arshad, 1996). As a result, infiltration may be affected by the change in management practice. Generally, infiltration is higher under no-tillage system with residue retention compared to PT and zero tillage with residue removal (Verhulst et al., 2010). Infiltration measured in Zambia and Zimbabwe showed that CA treatments were able to maintain higher infiltration rate compared to PT treatments with residue retention across the sites (Thierfelder et al., 2014). The authors attributed this to an increase in macro pores which resulted in high biological activity and reduction soil surface disturbance. Hobbs et al. (2008)

reported that increased infiltration rate under no-till CA may be a result of mulching of leftover residues which is a key component that promotes more stable soil aggregates. Govaerts et al. (2009a) reported that aggregates are more stable in zero tillage than in PT and zero tillage with residue removal and due to the presence of SOM which helps to bind aggregates together. Crop residues in the soil surface prevent aggregate breakdown by direct raindrop impact as well as by rapid wetting and drying of the soils (Le Bissonnais, 1996). Lal and Shukla (2004) argued that under these conditions, rapid wetting, for instance by slacking, and wind erosion cause less aggregate breakdown and prevent surface crust formation. Based on this information, it can be concluded that residue retention on the soil surface under no-till act as a succession barrier by reducing the runoff speed and giving water more time to infiltrate (Verhulst et al., 2010). However, other authors (Thierfelder and Wall, 2009) indicated that infiltration rate may be also dependent on soil type with the potential negative impact of water logging on granitic sandy soil, which has a tendency of accumulating too much water.

2.4.4 Hydraulic conductivity (K)

Hydraulic conductivity describes the ease with which water can move through the pore spaces or fractures. Soil behaves differently in relation to tillage system (Azooz and Arshad, 1996) and soil hydraulic conductivity would be expected to be higher under zero tillage with stubble retention on the soil surface than PT system. This is mostly due to an increase in faunal activity which influences the availability of macropores over time of no-till practice (Verhulst et al., 2010). Bhattacharyya et al. (2006) highlighted that the number, continuity and stability of macro-pores influence the hydraulic conductivity of the soil. Under NT conservation agriculture, the increase in SOM in the soil surface stimulates root growth and mesofaunal activity which leads to the creation of channels (Osunbitan et al., 2005) and the continuity of these channels are then maintained due to the lack of soil disturbance. However, different studies have produced different results when comparing these two tillage treatments with others citing improved hydraulic conductivity under PT than NT and vice versa. Verhulst et al. (2010) attributed these differences to the difficulty of measuring K when the residues are present in zero tillage. Strudley et al. (2008) argued that residue presence can complicate the installation of measuring instrument and the removal of undisturbed core samples. As a result, high variation in K at a small scale may result from macro-pores and other structural attributes that are left intact by the absence of tillage. Azzoz and Arshad (1996) cited that differences in K observed between no-till and PT may be related to the transitory nature of soil structure after tillage, initial and final water content, site history, the time of sampling and the potential for soil disturbance.

2.5 Tillage effects on soil chemical properties

2.5.1 Soil organic carbon (SOC)

SOC is the C stored in soil organic matter. It enters the soil through the decomposition of plant and animal residues, root exudates, living and dead microorganisms, and soil biota. SOC has been widely reported (Haynes and Beare, 1996; Wander et al., 1998; Franzluebbers, 2002; Verhulst et al., 2010) as a primary factor that indicates soil quality because of its effect on soil key quality parameters. Soil physical, chemical and biological properties are intrinsically linked to SOC and this, in turn, influences soil quality especially on the top layer of the soil. The top layer of the soil is important because it is where most of the cropping and soil management practices take place. Therefore, soil management practices are amongst the most important factors influencing changes in SOC (Dikgwatlhe et al., 2014). Soil tillage, residue retention, crop rotation and the interactions of these factors, as in the case of CA, has been widely reported to influence SOC concentration (Verhulst et al., 2010; Higashi et al., 2014; Xue et al., 2015).

Under no-till CA, the amount of SOC generally increases compared with PT (Verhulst et al., 2010). This increase in SOC is more pronounced in the topsoil. The soil layer from 0 to10 cm has high SOC compared to the subsoil (Puget and Lal, 2005; Blanco- Canqui and Lal, 2008; Dong et al., 2009). In the subsoil, there may be either no significant difference in SOC or even in some cases decreases. In contrast to no-till system where SOC is usually stratified on the top 0–5 cm layer, a uniform distribution of SOC has been reported to up to 20 cm in PT system (Franzluebbers, 2002). However, over time, PT system generally exhibit a significant decline in SOC concentration due to the destruction of the soil structure, exposing SOM protected within soil aggregates to microbial organisms (Lal, 2007; Xue et al., 2015). Thus, the adoption of no-till system can minimize the loss of SOC leading to higher or similar concentration compared to PT.

Some long-term studies (>10 years), however, have reported no increase in SOC under no-tillage system, even when the residues have been left on the soil surface (Wander et al., 1998). In a review of literature to determine the influence of the three different components of CA on SOC, Govaerts et al. (2009a) reported that in 7 of 78 (9%) cases, the SOC was lower in no-tillage compared to PT; in 40 (51%) cases it was higher and in 31 (40%) of the cases there was no significant differences. Verhulst et al. (2010) concluded that the mechanisms that govern the balance between increased, similar or lower SOC after conversion to no-tillage are not clear but attributed the differences to climate and soil properties, differences in root development and rhizodeposits, and the stabilization of C in microaggregates-within-macroaggregates. Dikgwatlhe et al. (2014) further argued that the amount of SOC storage depends on the balance between the quantity and quality of SOM inputs- outputs which is largely determined by the combined interaction of climate, soil properties and land use management.

Moreover, residue retention on soil surface has also been shown to increase the amount of SOC concentration (Wilhelm et al., 2004). In a long-term study (11 years) conducted by Dikgwatlhe et al. (2014), it was found that zero-tillage with residue retention resulted in an increase of SOC in the 0–10 cm soil layer compared to rotary tillage with residues incorporated and PT with residue retention and removed. Similar results were observed by Blanco- Canqui and Lal (2008) in a CA study conducted over a period of 10 years. The rate of residue decomposition depends not only on the amount retained but also on the characteristics of the soil and the composition of the residues (Verhulst et al., 2010).

2.5.1.1 Soil organic carbon fractions

Soil organic carbon based on physically defined fractions is increasingly used to interpret the dynamics of SOC (Six et al., 2001). Hermle et al. (2008) distinguished three fractions in which C may be available. These are easily decomposable fraction (labile), material stabilized by physical and chemical mechanisms (intermediate) and the biochemically recalcitrant fraction (stable). Easily decomposable fraction, consisting mainly of particulate organic carbon (POC) and some dissolved C is readily available and rapidly decomposed, represents an early stage of humification and can stimulate decomposition of hemicellulose or cellulose (Valnauwe et al., 1994). On the other hand, resistant SOC such as lignin is old and in close contact with the mineral surface and is resistant to microbial decomposition. Sanger et al. (1996) reported that resistant SOC promotes the formation of a complex phenyl-propanol structure which often encrusts cellulose-hemicellulose matrix and slow decomposition on these components. POM play a crucial role in soil aggregation and it can be used as an early indicator of changes in soil management because of its rapid turnover time (Six et al., 2001; Verhulst et al., 2010). Thus, Haynes and Beare (1996) suggested that it can be used as an indicator of early changes of SOC.

Furthermore, NT conservation agriculture usually exhibits increased aggregation and SOC relative to PT (Six et al., 2000) due to the formation of stable aggregates. Stable soil aggregates reduce the susceptibility of SOC to external forces such as water, wind and microbial activity. Thus many researchers agree that SOC is the principal indicator of sustainability and soil quality given its influence on many soil properties (Brady and Weil, 2002). However, SOC is not a homogenous substance but rather composed of substances with different chemical composition and different recycling rates (Cambardella and Elliot, 1992). Thus, a simple method of size fractioning that separates the labile fraction, POC, (> 53 µm) of SOC and recalcitrant pool (< 53 µm) has been proposed by many researchers (Cambardella and Elliot, 1992; Six et al., 2001; Verhulst et al., 2010). Therefore, POC constitutes a dynamic fraction and is associated with short-term nutrient availability (Salvo et al., 2010). In a study conducted to test different sensitivity quality indicators based on changes generated by different crop long-term rotations under PT, Moron and Sawchik (2003) found that the C associated with POC greater than 212 mm was the most sensitive size fraction to changes in management practices, followed by, the fraction of POC between 53 and 212 mm and, finally, the C associated with recalcitrant pool (< 53 μm). The traditional determination of total SOC showed a poor sensitivity of changes determined by management practices. In addition, other authors also reported that POC is a highly sensitive indicator to detect changes produced by different soil uses and management practices (Elliot et al., 1994; Bayer et al., 2001).

Lastly, crop rotation has also been observed to influence the quantity and the quality of SOC (Govaerts et al., 2009b). It influences the above three different carbon fractions by altering different organic matter inputs (Verhults et al., 2010). Systems that use more diverse rotations have been reported to result in greater fine POM than monoculture (Pikul et al., 2007). Cover crops increase SOC by providing crop residues and vegetation cover during critical periods (Bowman et al., 1999).

2.5.2 Nutrient availability

2.5.2.1 Total nitrogen

An increase of SOM in the soil may also have a profound effect on nitrogen cycling because SOM is made up of 5% nitrogen (Stevenson, 1994). This, according to Stevenson (1994) implies that SOM conserves soil nitrogen. In the no-till system, Spargo (2008) estimated that an increase of 1% SOM, which is approximately 22 Mg SOM, in the top 15 cm soil layer may result in 1.1 Mg of N ha^{-1} retained in the soil. Similar trends have been reported in changes in total nitrogen as those observed in SOC with respect to depth and tillage practice (Bradford and Peterson, 2000). In no-till system, total nitrogen is usually stratified in the top layers while in PT is distributed equally across the profile. Lou et al. (2012) reported that no-till can enhance total nitrogen stock in 0–30 cm soil profile but there may be no increase when compared to PT.

2.5.2.2 Nitrogen mineralization

Plow tillage system increases the rate of residue decomposition by breaking down soil aggregates and exposing SOM protected by soil aggregates to soil microbial attack (Six et al., 2002). This, in turn, increases the rate of SOC decomposition and hence soil organic nitrogen mineralization (Kristensen et al., 2000). Spargo (2008) reported that under no-till system the portion of conserved N is potentially available for plant uptake and the mineralization rate from one growing season may range between 1 and 4% depending on a number of factors such as temperature and soil moisture content. The author concluded that increasing SOM by 1% in the 15 cm soil layer has a potential to supply between 9 and 45 kg N ha^{-1} throughout the crop growing season. This may imply that no-till with residue retention may be particularly relevant to the agricultural situation experienced in Sub-Saharan Africa characterized with low soil fertility. Moreover, tillage system determines placement and distribution of crop residues. Under plow tillage system, SOC is distributed more evenly throughout the plowed layer of the soil while in no-till system; residues are usually stratified in the topsoil surface layer. According to Verhulst et al. (2010), this contributes to the effect of tillage on nitrogen dynamics. As such, Balota et al. (2004) reported that N mineralization in PT system is 1.5 times higher than in no-till system and this also depends on residue type and interaction with N management practices.

2.5.2.3 Exchangeable bases (K^+, Mg^{2+} and Ca^{2+})

Most research on tillage systems have indicated that Ca and Mg levels are unaffected by tillage practice (Duiker and Beegle, 2006; Govaerts et al., 2007; López-Fando and Pardo, 2009). However, some opposite trends of vertical Ca and Mg stratification has also been reported. According to Duiker and Beegle (2006), the effect of tillage practice on Ca and Mg have been more frequent, particularly when CEC is primarily associated with clay particles. Edwards et al. (1992) observed higher extractable Ca concentration on Ultisol under no-till when compared to conventional tillage. These authors attributed this to higher organic matter content under no-till system. In a later study, Duiker and Beegle (2006) found a higher concentration of Ca in the 0–5 cm layer in no-till compared with the deeper layers in PT. These differences were attributed to tillage after the last lime application in PT treatments. Similar trends were observed for Mg.

In contrast to what has been reported in Ca and Mg, no-till with residue retention has been reported to conserve and possibly increase the availability of K near the soil surface where crop roots proliferate (Franzluebbers and Hons, 1996). A study by Govaerts et al. (2007) reported 1.65 and 1.43 times higher K in 0–5 cm and 5– 20 cm layers of the soil, respectively under NT compared to CT. Other authors have reported higher extractable K in no-till than in PT soils but this effect was observed to decline with increasing depth (Ismail et al., 1994). However, other studies have observed surface accumulation of K irrespective of tillage intensity (Duiker and Beegle, 2006).

2.5.2.4 Phosphorus

A number of studies have reported extractable P levels to be higher under no-till than in PT (Duiker and Beegle, 2006; Thomas et al., 2007; López-Fando and Pardo, 2009). High levels of P have been commonly observed in the topsoil surface layer by several authors (Ismail et al.,1994; Franzluebbers and Hons,1996; Matowo et al., 1999) compared to deeper layers (Duiker and Beegle, 2006). In no-till system, the top 0–5 cm layer has been reported by several authors to have higher P concentration (Ismail et al., 1994; Franzluebbers and Hons, 1996; Matowo et al., 1999). Verhulst et al. (2010) highlighted that higher levels of P in the top layer is due to limited mixing of soil with fertilizer P and this, in turn, decreases P fixation. Duiker and Beegle (2006) argued that this is beneficial for crops when P is a limiting nutrient. The authors further argued that high levels of P in no-till may be a threat when P is an environmental problem because of the possibility of soluble P loses in runoff water. High levels of P in no-till may imply less need for P fertilizer application as a starter (Duiker and Beegle, 2006). This may be beneficial also under CA where residue retention may provide moisture, as a result, there may be no need for P incorporation in the deeper layers.

2.5.2.5 Cation exchange capacity

Soil organic matter and clay content are commonly associated with an increase in CEC due to the larger surface area to volume ratio as compared with sand and silt. Cation exchange capacity may be expected to be higher under no-till or in CA as compared to PT system due to observed higher concentration of SOM in the top 0– 5 cm layer. However, different authors have reported different results under different circumstances. López-Fando and Pardo (2009) reported a reduced CEC in in the top 0–5 cm depth in no-tillage as compared with PT system. The lower CEC under no-till was attributed to lower pH in no-till as compared to PT system that was observed. Lower pH is a common trend that is usually observed under no-till system and this can be a potential limitation of this system in conservation agriculture when effective lime application management strategies are not implemented. Other authors have reported an increase in CEC on permanently raised beds in the 0–5 cm layer compared to soils from which residues were removed (Govaerts et al., 2007).

2.5.2.6 Soil pH

Soil pH under zero tillage is usually lower than in PT system and this is more pronounced in the 0–5 cm than in 5–10 and 10–20 cm depth (López-Fando and Pardo, 2009; Verhulst et al., 2010). In layers below 5 cm, several authors reported a more uniform pH due to thorough soil mixing by tillage each growing season (Lal, 1997; Thomas et al., 2007; López-Fando and Pardo, 2009). Other authors, however, have reported a decline in soil pH in zero-tillage even in layers below 5 cm depth (Verhulst et al., 2010). The observation that the soil becomes more acidic under no-till than in PT system has been attributed to different processes in the mineralization of SOM, the nitrification of the surface applied nitrogen fertilizer and root exudation (López-Fando and Pardo, 2009). However, other authors suggested that pH under no-till was buffered because of the higher organic matter content (Duiker and Beegle, 2006). Duiker and Beegle (2006) on the other hand reported that lower pH in zero-tillage could be due to acidifying effect on N and P fertilizers applied more on the surface under zero-tillage than PT.

2.6 Tillage effects on selected biological properties

2.6.1 Macrofauna

Macrofauna includes those organisms with an average body width greater than 2 mm (Lavelle, 1997; Kladivko, 2001). This group of organisms is divided into two, based on their function. These are litter transformers and ecosystem engineers (Lavelle, 1997). Litter transformers consist mostly of larger arthropods and soil mesofauna while ecosystem engineers on the other hand comprised mainly of termites and earthworms. Verhulst et al. (2010) stated that ecosystem engineers have a large impact on influencing soil structure and aggregation as compared with litter transformers. In contrast, litter transformers concentrate their activities on the soil surface where they physically fragment litter and deposit mainly faecal organic pellets. In addition, ecosystem engineers ingest a mixture of organic matter and mineral soil and are reported to be responsible for the gradual introduction of dead organic material onto the soil (Verhulst et al., 2010). Plow tillage has been widely reported to affect the availability of soil macrofauna through direct physical disruption as well as habitat destruction (Kladivko, 2001). The impact has been more pronounced on larger organisms with less negative impact on species with high mobility and higher population growth potential (Decaëns and Jiménez, 2002).

2.6.1.1 Earthworms

Earthworms play a key role in the formation of soil structure. This, according to Six et al., (2004), has been recognized since Charles Darwin times in the late 1800s. The effect of earthworms on the soil structure is not only mediated by abundance but also by the functional diversity of their communities (Verhulst et al., 2010). Therefore, they vary in their ecological behaviour, thus, their effect on soil structure is different (Kladivko, 2001). Epigeic earthworms concentrate their activities on the soil surface while anaecic earthworms have their activities mainly confined inside the soil surface (Kladivko, 2001).

Moreover, earthworms play a major role in the recycling of nutrients and the formation of stable aggregates. They remove organic material from the soil and incorporate them as a stable aggregate. They ingest the organic matter and incorporate them with an inorganic material, pass the mixture through their gut and excrete it as a cast. Earlier research in temperate pastures has shown that up to 50% of surface layer soil aggregates are earthworm casts (Van de Westeringh, 1972).

Earthworms mediate soil aggregates through burrowing and cast formation (Brown et al., 2000). External pressure is exerted during burrowing on the surrounding soil and the mucus is deposited on the burrow walls (Six et al., 2004). This, in turn, assists in the formation of stable macro aggregates (>250 mm), when allowed to dry and age, due to organic mucilage and/stable organo-mineral complexes and oriented clays left lined in the burrowing walls (Six et al., 2004). In contrast, when the cast is exposed to rainfall, it can be easily dispersed and contribute to nutrient loss and soil erosion (Blanchart et al., 2004). Several studies have shown more stable structure of soil aggregation when the cast are present than the same soil with no cast (Marinissen, 1994; Lavelle, 2011; Lipiec et al., 2015). In addition, the stability of cast depends on the quality of ingested material (Six et al., 2004).

With regards to the effect of tillage to earthworm population, the general trend is that NT conservation agriculture tends to increase their population and activity compared to PT, especially in long-term experiments (Peigne et al., 2009). However, this depends on the frequency of tillage, plow depth and the amount of crop residue returned to the soil (Eriksen-Hamel et al., 2009).). Frequent tillage disrupts earthworm soil habitats and exposes them to predation and desiccation (Holland, 2004). On the other hand, deep tillage damages earthworm burrows, causing them to expend energy on rebuilding new burrows in unstructured soil rather than on reproduction (Chan, 2001). The population of both epigeic (found on the soil surface) and anecic (found on the vertical burrows) earthworms are negatively affected by tillage operation (Kladivko, 2001). However, tillage operation that aimed at removing soil compaction or incorporating crop residue serving as a food source for earthworms can enhance or maintain earthworm population (Metzke et al., 2007). For example, Bostrom (1995) found that rotary cultivation and plowing reduced earthworm populations by 73–77%, but one year later, there were five times more large adult earthworms and earthworm biomass was similar to pre-tillage levels. The incorporation of ready decomposed material such as meadow and alfalfa consumed by the dominant endogeic earthworm *Allolobophora caliginosa*, was considered to be a major factor in earthworm population recovery.

2.6.1.2 Termites and ants

Lee and Foster (1991), Verhulst et al., (2010) and Six et al. (2004) pointed out that there is less quantitative literature focusing on the effect of termites and ants on soil structure in different agroecosystems as compare to earthworms. Six et al. (2004) concluded that more research is needed focusing on the true structural building capacity of termites. These organisms are predominantly found in semi-arid to arid areas where the presence of earthworm is normally limiting (Lobry de Bruyn and Conacher, 1990) and their roles may be similar to that of earthworms in soil transformation on the drier regions (Verhulst et al., 2010).

These species have been reported to improve structural stability of soil particularly micro-aggregates (Holt and Lepage, 2000). Bignell and Holt (2002) stated that they form micro-aggregates, either by passing soil material through their intestinal system and deposit it as faecal pellets or by mixing the soil with saliva using their mandibles. Six et al. (2004) also added that the stability of such structures varies with the amount incorporated into them by the species. Nkem et al. (2000) reported that ants and termites, both subterranean and mound building species, can increase soil infiltration by improving aggregation and porosity even in situation low clay content and organic matter (Nkem et al., 2000).

Although there is less literature describing the ecological function of ants and termites on soil structure and different tillage operations, some studies have indicated that the population of these macrofauna groups decreases under PT due to the destruction of soil habitat. Sanabria et al (2016) reported a decrease in termites' population in annual cropping system compared to savannas, highlighting that the former was important in determining termites' assemblage. Other authors reported that this system does not provide the ideal conditions for the establishment of termite colonies due to tillage and application of pesticides (Costa-Milanez et al., 2014) and the absence of permanent vegetation.

Costa-Milazez et al. (2014) further reported that ant communities are strongly influenced by habitat type vegetation structure and tillage operation. This is attributed to the fact that vegetation is a major regulator of microclimatic conditions, which influences ant activity. This was supported by the study conducted by Sanabria et al. (2016) where the difference between savanna and improved pastures was observed with regards to ants' population. Ants were higher under savanna than in improved pastures.

2.6.1.3 Arthropods

Arthropods are sensitive to the change in vegetation and play an important role in the functioning of agroecosystem (Rodríguez et al., 2006). These organisms are favored by the availability of crop residues in soil as in the case of conservation agriculture (Kladivko, 2001). They partly play an important role in recycling of nutrients through degradation of organic matter (Giesy et al., 2000). Verhulst et al. (2010) reported that not all arthropods are litter transformers even most of them concentrate their activity above and/within the topsoil. The communities of arthropods are affected by mechanical disturbance of the soil through tillage operation, modification of quantity and location of plant residues and alteration of weed communities (Rodríguez et al., 2006).

2.6.2 Microfauna

Microfauna are small organisms of less than 0.2 mm body width and they live in water-filled pore space and consist mainly of nematodes and protozoa (Verhulst et al., 2010). Soil management practices, such as tillage type, influence soil microorganisms and soil microbial processes through changes in quality and quantity of organic residues entering the soil, their seasonal distribution and spatial distribution, input ratio between above and below ground, and changes in nutrient inputs (Kandeler et al., 1999). Soil microbial biomass (SMB) is the main driving force of decomposition of SOM and is frequently used as an early indicator of changes in soil properties resulting from soil management practice and environmental stress in the agroecosystem. On the other hand, soil enzymes are essential in catalysing the reactions necessary for organic matter decomposition and nutrient cycling (Verhulst et al., 2010). The measurement of both enzyme activity and SMB has been suggested as an early indicator of soil quality because of its relationship to soil biology and ease of measurement, rapid response to soil management and high sensitivity to temporal soil changes originating from management and environmental factors (Nannipieri, 1994).

2.6.2.1 Microbial biomass

Maintaining SMB and micro-flora activity and diversity is a fundamental for sustainable agricultural management (Insam, 2001). Soil microbial biomass is a reflection of soil to store and recycle nutrients, such as C, N, P & S and SOM and has a high turnover rate relative to total SOM (Carter et al., 1999). Microorganisms play an important role in physical stabilization of soil aggregates (Doran et al., 1998) and this was found to be linked to glomalin content which is an indication of the degree of hyphal network development (Douds et al., 2007). These fungal hyphae form an extended network in cultivated soil and are activated by contact with seedlings (Roger-Estrade et al., 2010). Zuberer (2008) further reported that SMB produces polysaccharides which promote cementation of soil aggregates. The hyphae produced by fungi growing in the soil allows for entanglement of soil properties (Zuberer, 2008). During PT tillage, the fungal networks are fragmented and this potentially results in the loss of cell content (Roger-Estrade et al., 2010). In contrast to the tillage system, in no-till conservation agriculture, the mycorrhizal system is more stable (Souza-Andrade et al., 2003). In addition, SMB contributes to soil health through disease suppression by being antagonistic to potential plant pathogens (Weller et al., 2002).

The dominant factor controlling the availability of SMB is the rate of C input (Campbell et al., 1997) and also the availability of N resources in the soil (Six et al., 2004). A uniform and continuous supply of C from organic crop residues serve as the energy source for microorganisms. Previous studies have shown that as the total organic C pool increased or decreases, as results of changes in C input in the soil, the microbial pool also increases or decreases (Franzluebbers et al., 1999). Plow tillage promotes the release and decomposition of previously protected SOM in the soil, initially increasing soil microbial biomass (Roger-Estrade et al., 2010). However, the long-term effects are less obvious because they depend on the amount of C re-injected in the soil each year to compensate for mineralization (Roger-Estrade et al., 2010). In the early stages of CA adoption, the availability of nitrogen usually decreases in the soil due to increase in microbial activity due to surface residue decomposition and lack of incorporation in the soil and this is more pronounced in the organic material with higher C/N ratios. In the long-run, however, studies have shown that they may be a significant increase in C or SMB in the topsoil in various CA system (Vian et al., 2009).

The effect of tillage practice on SMB-C and N seems to be mainly confined in the surface layers with stronger stratification when tillage is reduced (Salinas-Garcia et al., 2002). Aslam et al., (1999) found that SMB content was twice in permanent pasture and no-till treatments in 0–5 cm depth as in 5–20 cm depth soil after 2 years of cropping following permanent pasture in a silt loamy soil (Gleyic Luvisol (FAO)). Similar results were reported by Alvear et al. (2005) and Pankhurst et al. (2002) in different soil types. This can be attributed to higher level of C substrate available for microorganism growth, better soil physical condition and water retention under reduced tillage.

2.6.2.2 Enzyme activity

Soil enzymes play a crucial role in catalysing reactions associated with organic matter decomposition and nutrient cycling (Jin et al., 2009). They have been suggested as potential indicators of soil quality because of their important function in soil biology, ease of measurements and rapid response to changes in soil management practices and environmental conditions (Dick et al., 1996). They respond to management practices such as tillage, fertilizer application, crop rotation, residue management and pesticides and in this way, they may alter the availability of plant nutrients (Verhulst et al., 2010). They are a valuable tool for assessing soil's ability to function or bounce back after disturbance (Jin et al., 2009).

Generally, the activities of enzymes decrease with soil depth (Green et al., 2007) and they vary with seasons and depend on physical, chemical and biological characteristics of the soil (Niemi et al., 2005). No-till management practice increase stratification of soil enzyme activities near the soil surface, perhaps due to the similar vertical distribution of SOM in NT than in PT and the activity of microbes (Green et al., 2007). The activities of enzymes are mainly confined in the 0–5 cm depth in NT practice for different soil in different environmental conditions than in PT and below 5 cm depth, no difference has been found in enzyme activities between NT and PT (Alvear et al., 2005; Roldan et al., 2007). Furthermore, seasonal variability also affects the enzyme activity. As a result, a single enzyme assay may not be a representative of overall microbial community activity and do not take into account seasonal changes and inherent differences in enzyme activity (Roldan et al., 2005).

2.7 Conservation agriculture and maize yield

Maize is one of the most staple crop consumed in South Africa and the rest of Sub-Saharan Africa. Drought occurrence (Sithole and Modi, 2015), poor inherent soil properties, soil degradation, in the adequate application and incorrect timing of fertilizer (Chuma et al., 2000) are the frequent factors commonly cited that lead to poor maize yield in Sub-Saharan Africa. In such cases, CA has been promoted in most countries of Sub-Saharan Africa to buffer the effects of soil degradation and erratic rainfall distribution during the growing season and to improve soil fertility status. On-farm trials that capture some of the agroecological regions found in the region have been conducted in countries such as Zimbabwe, Malawi, Zambia, Kenya, Ethiopia and some other African countries within the region. However, South Africa has not benefited in this development with scant information found in peer-reviewed literature. Nevertheless, some reports from farmer's organisations such as No-Till Club in KwaZulu-Natal Province pioneered by no-till legend Antony Muirhead; Farmer's Weekly and a research institute, Agricultural Research Council have reported soil improvements and soil water conservation (Phillips, 2015; Findlay, 2015) which ultimately led to yield gains in maize in some subsistence (Phillips, 2012) and most commercial farmers in most of the dry regions of South Africa (Table 1). Figure 1 below shows a rough estimation of CA adoption in South Africa where Western Cape Province is leading with more than 70% followed by the Province of KwaZulu-Natal with 50-60%. A farmer in North West Province, Hannes Otto, reported a yield increase in maize from an average of 4.8 t/ha to 5.5 t/ha after two years of no-till conservation agriculture and the farmer was surprised by this results as he expected the yield decline on the first three years of adoption (Hittersay, 2010). Ralf Kusel who has been practicing CA for 14 years in high rainfall area (>900 mm/ year) of KwaZulu-Natal achieved an average of more than 10 t/ha maize grain yield (Phillips, 2013). The author further reported that they experience a 5–15% yield reduction in the maize-after-maize rotation (11 t/ha average yield) compared with maize-after-soya bean (12.5 t/ha average yield). Hittersay (2012) reported the results on the trial conducted by Agricultural Research Council at its Zeekoegat experimental farm in Roodeplaat established in 2007 that the average grain yield over four years was 4.13 t/ha under no-till CA compared with 3.89 t/ha under PT. But when different years were compared, it was observed that reduced tillage CA performed better (7.04 t/ha in one season compared with 6.29 t/ha under PT) while in other years PT was better (5.06 t/ha in two seasons compared with 4.8 t/ha under reduced tillage CA). In all cases, maize was planted in a rotation with legumes and some other few crops depending on the farmer's conditions. Table 1 summarises some on the success stories reported by farmers in different provinces of South Africa while Fig. 1 presents a rough estimate of CA adoption in the country.

Furthermore, when looking also in Sub-Saharan Africa where there has been a lot of CA research, recent reviews have shown positive improvements on maize yield although some negative impacts were also reported. In their review to evaluate yield response of maize to conservation agriculture on four countries representing major agroecological regions found in Southern Africa, Thierfelder et al. (2015) found that 80% of the cases yield was higher in CA as compared with conventional tillage. In 20% of the cases, there was a negative response to CA and the authors attributed this to lack of experience by farmers in the initial years, slow increase in soil fertility at the representative sites and water logging in some years due to high rainfall. Yield benefits increased with the increase in years of practice of CA and this was more pronounced in trials with more clay and silt content in the topsoil and was more resilient to seasonal rainfall variability than conventionally tilled treatments. Brouder and Gomez-Mcpherson (2014) reviewed evidence on the impact of CA and crop yields in Sub-Saharan Africa and South Asia, based on recent literature, and reported that zero-tillage (key CA component) may not be initially beneficially for crop yield (in the short term) and the authors attributed this to direct impact of weed pressure in the initial stage of CA adoption which becomes less severe in the long term. The authors concluded that the negative short-term impact on maize yield decreases over time and may eventually lead to a yield advantage especially in those systems linked with mulching. In contrast, in this review, it was found that most of the studies lacked critical data needed for systematic reviews and statistical analysis necessary to meet the criteria for credible meta-analysis. The authors concluded with important recommendations for future studies and this includes minimum data set requirements, an adequate description of management practices, and systematic approaches in the meta-analysis for CA and appropriate statistical analysis. In no-till soil with residues removed Fuentes et al. (2009) observed the poorest soil quality (low SOC and N, compaction, low aggregate stability and, lack of moisture and acidity) which produced the lowest yield especially with a maize monoculture. Similar results were observed by Govaerts et al. (2005).

In contrast to low rainfall rainfed low input areas, Sayre et al. (2005) observed that on irrigated agricultural systems, the application of irrigation appears to hide or postpone the expression of degradation of many soil properties until they reach the level that they can no longer sustain yields, even with irrigation. In addition, a reverse relationship between soil quality and crop yields has also been documented by some authors. For example, Lal (1995) estimated that yield reduction in Africa due to past soil erosion may range between 2 and 40% and this according to Verhulst et al. (2010) may depend on soil type, weather conditions during the growing season, soil management, farming system and ameliorative input used.

Many stakeholders of maize production in the region are becoming aware of the plight of our environmental conditions. Sometimes, fear and panic are the reactions we get from fanatics, media, and authorities. Although the situation has deteriorated to the current state, conservation agriculture, including no-till or minimum tillage is one of the positive practices with the potential of restoring some of the negatives done to the environment. This is true considering that South Africa losses close to 400 million ton of topsoil annually from water erosion which end up as sediments in dams (Venter, 2016). However, the advantage of CA does not come without certain trade-offs. An example is over-reliance of CA on the use of herbicides to control weeds. Cultivation is the way in which conventional agriculture controls weeds, both before and after planting. In no-till farming, at least as it is practiced today, herbicides take the place of the plow. More often, significantly more herbicides are used in no-till farming compared to what is typically applied to tilled fields. However, several weed species have developed resistance to glyphosate and other herbicide mechanisms of action (Beckie, 2007). Hence, the threat to gains of CA is growing because of the dire need to manage these resistant weeds through other means necessary, including tillage. Furthermore, in a CA system, crop residues may harbour insect pests, leading to the use of insecticides as well, which might threaten soil macrofauna and microfauna (Giller et al., 2009).

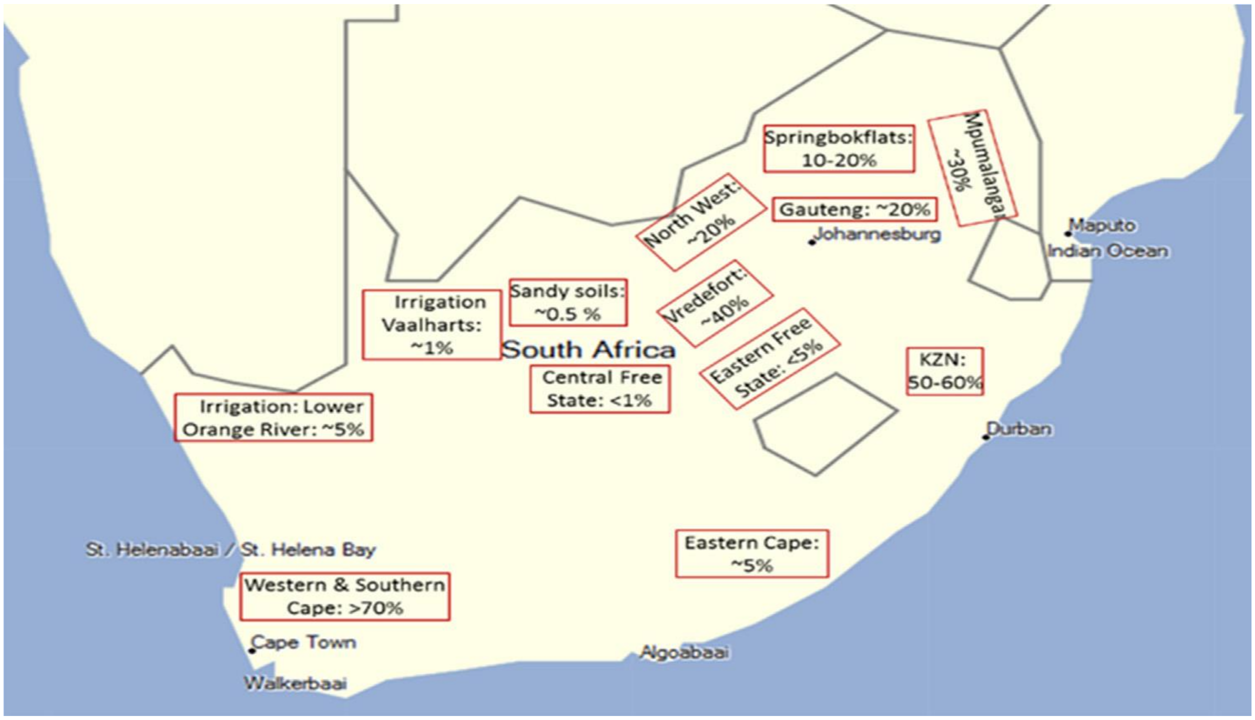

Fig. 1: Estimate of CA adoption in South Africa. Source: Richard Findlay, committee member and coordinator, No-Till Club of KwaZulu-Natal, South Africa, unpublished data.

Table 1: Summary of farmers reports on yield after CA adoption.

Author	Source	Farm type	Farm size (ha)	Farmer’s name	Year of adoption	Province/ town	Mean annual rainfall (mm)	Soil conditions	Yields (t/ha)
Findlay 2015	Personal comm.	Large scale	400	Antony Muirhead	23	KwaZulu-Natal, Bergville	643	Improved	+
Phillips (2013)	Farmer’s Weekly	Large scale	1250	George Steyn	5	North West	550	Improved	+
Phillips (2012)	Farmer’s Weekly	Small holder	1.8 (+29 other farmers)	Nicholas Madondo	10	KwaZulu-Natal	745	Improved	+ (4-5)
Hittersay (2012)	Farmer’s Weekly	Agricultural research council (ARC)	ND	Zeekoegat experimental farm	4	Pretoria, Roodeplant	704	Improved	+ (4.8-5.5)
Hittersay (2013)	No-Till Club	Commercial	2600	Jan Grey	5	Mpumalanga, Ermelo	-	Improved	+ (4-6.5)
Hittersay (2014)	No-Till Club	Large scale	2814	Manjoh Ranch	7	Mpumalanga, Delmas	687	Improved	+ (7.5)
Phillips (2013)	Farmer’s Weekly	Large scale	690	Ralf Kusel	14	KwaZulu-Natal, Paulpietersburg	950	Improved	+ (12.5)

ND, no data provided.

+indicates yield gains compared to plow tillage.

2.8 The use of visible and near infrared spectroscopy (VIS-NIRS) in predicting SOC and N

Soil organic carbon is a key component of the soil where it plays a central role in important functions of the soil. It is regarded as a key indicator of soil quality because of its involvement in physical, chemical and biological processes of soil functioning. Its quantification enables to assess soil quality through its structural stability, water retention, as well as biological and chemical fertility (Reeves, 1997). Therefore, its decline in soil is one of the main threat to soil degradation. Moreover, monitoring of SOC and N in soil has become expensive with the use of a traditional chemical method (Walkley, 1947; Jackson, 1973) and recently the use of machinery (Leco Corporation, 2012). Traditional chemical methods require chemical reagent and tedious sample preparation. Therefore, a rapid and accurate approach for measurements of SOC allowing huge analysis of samples within a short period of time, low effort and budget, and for precision agriculture is ideal.

The visible and near infrared spectroscopy (VIS-NIRS) present such an opportunity. Spectroscopy is the science that studies the interaction between matter (solid, liquid and gas) and its electromagnetic radiation (Crouch and Skoog, 2007). The visible region of the electromagnetic spectrum is from 400-700 mm and the near infrared region in from 780-2500 nm (NASA, 2014) in this study. The VIS-NIRS (400-2500 nm) has been used successfully in many industries such as such as pharmaceuticals, petrochemicals, crop production and food processing (Minasny et al., 2011). VIS-NIRS provide a large number of information on the organic and inorganic component on soil (Milos and Bensa, 2007). The absorption on the visible range (400-700 nm) provides a measure or SOM and soil colour (Ben-Dor et al., 1999) and iron minerals (Sherman and Waite, 1985). On the other hand, the NIR (780 nm-2500 nm) portion of the electromagnetic spectrum is associated with the stretching and bending of CH, OH and NH groups (Viscarra Rossel and Behrens, 2010).

In recent years, there has been an increased interest in studies of SOC. This is caused by its predicted effects on climate change (Guerrero et al., 2016) and the increased effort for sustainable agricultural management such as CA. The amount of SOC varies spatially due to natural soil variability, climate and management practices. Thus, measurements of SOC require a large number of samples to hold high statistical robustness, otherwise, they would be limited by huge uncertainties causing misleading inferences (Muukkonen et al., 2009). Therefore, the application of visible to near infrared spectroscopy (VIS-NIRS) for assessing SOC is arguably the most appropriate technique, than the mid infrared (MIR) for example, possessing the afore-mentioned requirements of low cost, fast, less time for preparation and accuracy.

This limits the innovation possibility and articulation of research institutions to perform relevant experiments linked to SOC, the principal indicator of soil quality. This is particularly true for countries is SSA which lack infrastructural funding and other developing countries.

2.9 Conclusion and future prospect for South Africa

Continued and increased crop production to ensure food security for future generations requires sustainability in the management of natural resource base. Conventional tillage system has, over many years, resulted in degradation of natural land resource base. Although, it for many years has resulted in increased yields due to improvement in seedbed preparation, weed control and better placement of seed and mixing of fertilizers and agrochemicals with soil. It has resulted in the substantial loss of soil and SOM which is a key factor in soil quality because of its intrinsic relationship with soil physical, chemical and biological properties. Conventional tillage has resulted in physical disruption of the soil structure, displacement of the macrofauna population and exposing SOM to microbial attach and thus, facilitating its oxidation process and the loss of nutrients. This has resulted in a reduced aggregate stability of many farmlands due to disruption of soil structure and as a results soil has become highly exposed to various soil types of erosion and many areas in the world have been degraded due to this practice. This has been more pronounced in African countries, particularly the Sub-Saharan African region. This is of great concern in ensuring food security for increasing population and protection of natural resource base for the current and future generations in light of the predicted impacts of climate change. In response to these challenges, CA has been proposed as one such avenue in which farmers can better utilise the natural resources to their disposal by following it three fundamentals i.e., permanent soil cover, minimum soil disturbance and systematic crop rotation.

In South Africa, although there has been some success in the adoption of CA, the adoption rate has remained rather too low accounting for about 2.8% of the country arable land. The statistics on adoption rate for subsistence and commercial farmers has remained unclear because there has been hardly any extensive information or research to account for adoption rate. Various farmers' organizations have been formed to advocate for CA with No-Till Club being the leader in KwaZulu-Natal Province. The Club has reported less than 500 of the small-scale farmers that have adopted CA. However, most of these farmers are being subsidised by Government and commercial farmers for their inputs for instance herbicides, fertilizer and seeds. Various farmers' organisations, formal and informal, have reported CA to reduce production cost and to improve soil quality and yield. However, the reported information is based on farmers' experiences and it is too narrative and is not available in scientific literature. Most farmers may have this information available on indigenous knowledge system or "grey literature" of which both are not peer-reviewed. This, therefore, necessitates more research on CA practices and its impact on soil quality and yield for different agroecosystems and socio-economic niches relevant to South African context to ensure sustainability in the management of our natural resource base.

2.10 Thesis structure

A number of experiments were conducted to answer specific objectives of this study. The thesis is structured in manuscript or paper format answering a specific objective of the study. Each chapter is formatted according to the guideline of a specific journal in which the paper was submitted to or accepted. It must be noted also that although the literature review has been published it also contains some additional information to align it with the whole thesis.

Chapter 2: This paper answers the specific objective on the soil biological properties. In this study, we focused only on soil macrofauna.

Chapter 3: This manuscript answers the specific objective about some important soil physical properties. However, it also deals with C because it is difficult to discuss soil physical properties without including C as a principal soil health indicator.

Chapter 4: This manuscript answers specific objective about soil chemical properties. Again, here there is some overlap with the previous chapter in relation to C.

Chapter 5: This manuscript combines what has been observed in soil biological, physical and chemical properties in relation to yield over time. It answers specific objectives on maize yield.

Chapter 6: This manuscript answers the specific objectives about the use of VIS-NIRS in SOC and N prediction.

Chapter 7: The general discussion. It provides the holistic discussion that combines all individual manuscripts and highlights the major findings of the study.

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CHAPTER 2

The long-term impact of no-till conservation agriculture on abundance and order diversity of soil macrofauna in continuous maize monocropping system

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2.1 Abstract

Unsuitable soil management in agricultural land is known to results in the deterioration of soil health and the decline of biodiversity, which in turn threatens food security. The experiment tested whether (1) no-tillage with mulch (NT), which has been shown to restore maize production, could boost biological activity of macrofauna population in a maize continuous monocropping system compared with (2) rotational tillage with mulch, (RT) every after 5 years, and (3) conventional tillage (CT) tillage system. This was evaluated, in Ferralsols Haplic, 13 years after implementation of NT treatment in Bergville KwaZulu-Natal Province, South Africa. Soil macrofauna was sampled at the end of the 2014/2015 growing season using 25 × 25 × 25 cm steel monoliths. The mean density of individual orders was significantly higher ($p < 0.001$) under NT (46%) and RT (38%) compared with CT (16%). However, the Shannon-Weaver index (H, E index) revealed that the diversity and evenness of orders were similar, H= 2.6 and E~ 1, for all treatments. Examination of macrofauna patterns revealed that NT and RT contained a significantly ($p < 0.001$) higher population of orders Isoptera and Diplopoda. Order Isoptera was 51% and 17% higher in NT and RT than CT, while order Diplopoda was 39% and 2% higher in NT than RT and CT, respectively. Order Coleoptera was among the dominant orders, however, there were no significant differences in all treatments although it showed trends toward high population in NT treatment. It was concluded that NT and RT mulch-based system, in Ferralsols Haplic, favoured the development of macrofauna communities in the studied maize continuous monoculture cropping system but did not favour order diversity of macrofauna. This suggests the importance of crop rotation for the development of the more diverse macrofaunal population.

Keywords: conservation agriculture, soil invertebrates, macrofauna diversity, Shannon-Weaver index

2.2 Introduction

Agriculture in the sub-Saharan Africa faces the challenge of increasing food production without significantly increasing the area of land under agricultural production, while protecting natural resources, due to increasing population (Stevenson et al., 2013) and high levels of human-induced soil degradation (Bai and Dent, 2007). In South Africa, one-third of the surface land and about 40% of the agricultural land is degraded due to combined effects of CT, overgrazing (Bai and Dent, 2007; Vlek et al., 2010) and continuous maize mono-cropping, particularly in small subsistence farmers. According to these authors, soil degradation in South Africa is severe and widespread. The increase in demand for food on the limited available dry land in light of highly degraded soil and declining soil fertility and future threats of climate change and variability have increased the need for more sustainable crop production management systems (Thierfelder et al., 2014). Soil management system such as conventional tillage and removal of soil biomass from cropland have, for many years, resulted in the decline of soil organic matter content, deterioration of important soil physical properties and has increased the risk of soil erosion (Ouedraogo et al., 2006). The reduction in soil organic matter further affects soil macrofauna which has an important role in key soil processes such as soil structural formation, decomposition of soil organic matter and recycling of nutrients.

The effect of macrofauna on soil physical properties, particularly, the soil structural formation has been well documented (Mando and Midiema, 1997; Brown et al., 2000; Six et al., 2004) with earthworms and termites considered "ecosystem engineers" because of their key role in reworking the soil. Earthworms modify soil structure through biological and physicochemical changes and through their burrowing and casting activities, both of which have a significant effect on soil physical properties such as water infiltration and aeration (Blanchart et al., 2004). On the other hand, termites through their activities of selecting, transporting, manipulating and cementing soil particles, bring an immediate change in soil structure and its properties (Mando and Midiema, 1997). Other groups of soil macrofauna which have, however, minor effect on soil structure are litter transformers, such as epigeic earthworms and Mollusca (Lavelle, 1997). These organisms concentrate their activities on the soil surface where they physically fragment litter and deposit mainly organic faecal pellets (Verhulst et al., 2010). Therefore, maintaining conditions that are conducive for macrofauna settlement in the cropped land is important for long-term soil health and sustainability of agricultural production.

Soil management systems such as tillage type and nitrogen fertilizer application rate, climate condition of the area and soil type all influence macrofauna population and diversity (Chan, 2001; Blankinship et al., 2011). This combined with negative effects of continuous monocropping, such as the build-up of pest and diseases and ever-increasing levels of chemical inputs, may have serious implication on yields and thus food security. Inappropriate soil management system leads to reduced functionality, a reduction in ecosystem services and in some cases, permanent damage to the ecosystem (Cardinale et al., 2012). With maize being the staple crop in many countries in the sub-Saharan Africa, both for humans and animal feed, inappropriate soil management may have serious implication on food security. This may results in unsustainable agriculture if measures to ensure the protection and rehabilitation of degraded land are not taken.

To ensure the sustainability of agricultural land and crop yield, the South African Department of Agriculture, No-Till Cub, and the Agricultural Research Council have embarked on implementing soil restoration measures with conservation agriculture (CA) being the main focus (Sithole et al., 2016). While the introduction of CA has been shown to improve soil quality and yield in South Africa (Sithole et al., 2016) and other parts of the world (Stevenson et al., 2014; Thierfelder et al., 2015), to our knowledge, fewer or no studies in South Africa has focused on long-term impact on macrofauna organisms particular in semi-arid agroecosystem of a particular soil conditions, yet similar organisms are also important in the sustainability of the soil health. Similar observations have also been made in other developing countries (Brevault et al., 2007; Mutema et al., 2013). Therefore, the ultimate mechanisms that influence the abundance and diversity of macrofauna communities in the contrasting soil environment have not been well elucidated and in general, the data on the impact of soil management systems on macrofauna are scarce.

Therefore, the objective of this experiment was to evaluate macrofauna order diversity and abundance of the continuous maize mulch-based monocropping system that has been managed for over 10 years under no-till conservation agriculture. This was compared with conventional tillage and rotational tillage treatments. It was hypothesised, therefore, that less soil disturbance with residue mulch will result in better settlement of macrofauna communities than a more disturbed system and that continuous monocropping will result in reduced faunal diversity between tillage systems.

2.3 Materials and methods

2.3.1 Experimental site

The experiment was established in 2003/2004 growing season, in a field that has been managed since 1990 under no-till, in Gourton Farm (28°55'26.83"S, 29°33'38.64"E) (Fig. 1) by Department of Agriculture and Environmental Affairs in KwaZulu-Natal Province, South Africa. The experiment was initiated to investigate the combined effects of tillage intensity (conventional tillage and no-till) and nitrogen fertilizer application rate (limestone ammonium nitrate (LAN) and urea) on soil fertility and maize yield. Previously, the site has been part of the dryland commercial production field to maize and soybean in the rotation that has been managed under no-till since 1990/1992 and it was converted into different tillage treatment in the 2002/2003 crop growing season. Prior to that, the land was under conventional tillage to maize. The soil was classified as Hutton non-swelling with clay loamy soil texture (Soil Classification Working Group, 1991) or Ferralsols Haplic (FAO, 2006). The mean annual rainfall of the area is 643 mm per annum which is received mostly in the summer months, between October and March and the mean air temperature of the site is 19.3 °C in June and 27.9 °C in January (SA Explorer, 2009). The temperature and the amount of rainfall received in the 2015/2016 growing season when sampling took place are shown in Fig. 2. The trial is planted with dryland maize in summer and left fallow during the winter season. Soil analysis of the trial in the 0-20 cm depth showed that the pH (KCl) ranged from 5.39 in tilled plots to 5.80 in the untilled plots trials, bulk density, ranged from 1.33

g/cm^3 in tilled plots trials to 1.43 g/cm^3 in untilled plots and SOC ranged from 3.9 % on un-tilled plots to 1.7 % in tilled plots.

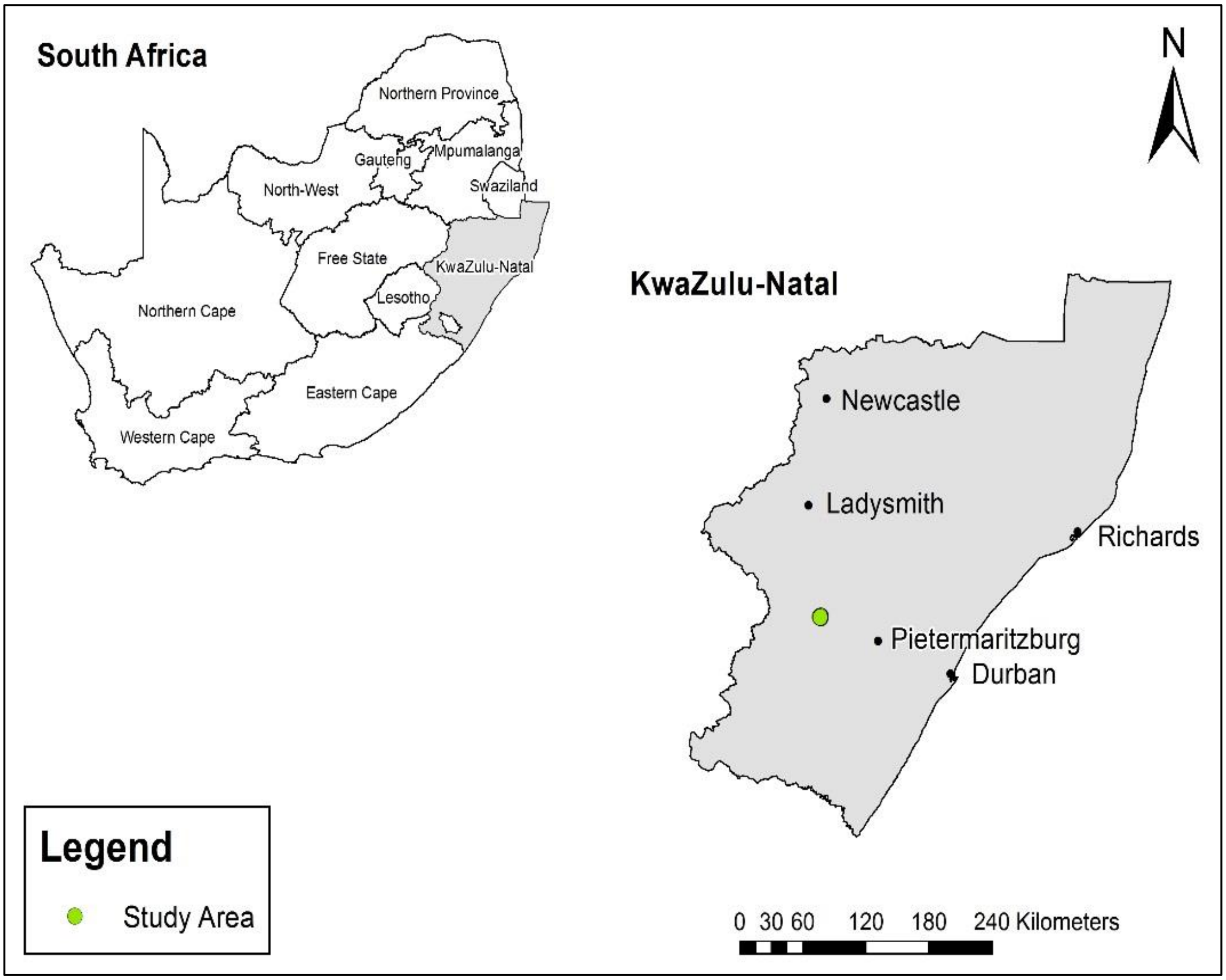

Fig. 1: The location of the study area (28°55'26.83"S, 29°33'38.64"E)

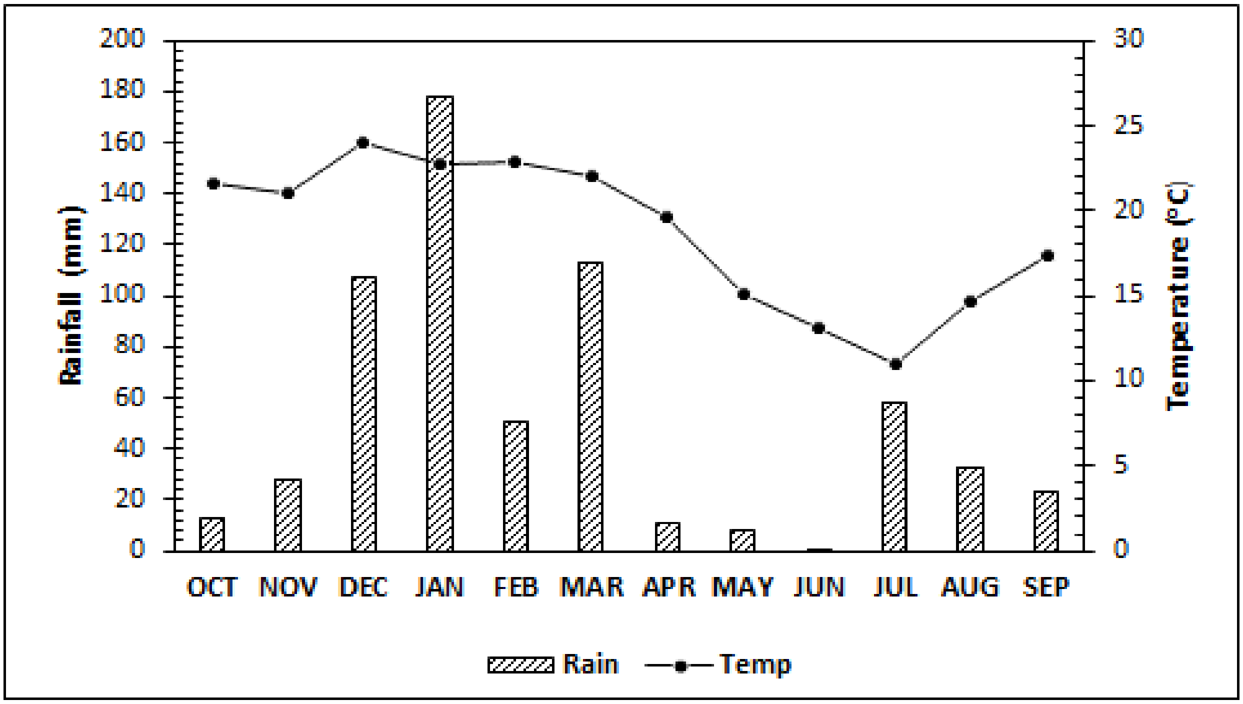

Fig. 2: The rainfall distribution and temperature data of the experimental area (Bergville, KwaZulu-Natal Province in South Africa) during the sampling season (2015/2016).

2.3.2 Experimental design

The trial was arranged as a split plot with randomized tillage strips forming the whole plot and N source and rate of application forming the sub-plots which are randomized within the whole plots. The sub-plots had 9.5 m × 12 rows of maize at a density of 70 000 plants/ha. The experiment included three tillage treatments: 1) no-till (NT), 2) annual conventional tillage (CT) and 3) rotational tillage (RT). In NT and RT treatments maize residues were left in the soil surface to cover the soil every year, thus forming permanent soil cover, while in CT treatments residues were removed in the soil surface after harvest. No-tillage involved direct seeding into the undisturbed soil using NT planter, CT, on the other hand, involved ploughing with mould board plough up to a depth of 30 cm and disking to a depth of 10 cm while RT involved CT after every four years of NT. The treatments were replicated three times. Nitrogen was applied at five rates (0, 50, 100, 150 and 200 kg/ha) as either urea or LAN. For this particular experiment, only LAN trials were investigated due to logistical constraints. However, before the 2008/2009 season, the application rate was 0, 40, 80, 120 and 160 kg/ha. However, due to the linear response observed in 2007/2008 maize production to fertilizer application rate, the rates were adjusted to 0, 50, 100, 150 and 200 kg/ha. Nitrogen was applied as top dressing four weeks after planting. For this particular experiment, nitrogen rates were ignored when analysing data due to insignificant differences observed in different tillage treatments. Potassium and Phosphorous were applied at planting in the band at a rate of 50 and 20 kg/ha, respectively. Lime was applied at a rate of 2 Mg/ha every second season to the entire plot. It was incorporated during ploughing in CT plots and surface applied in NT plots. Weeds were controlled chemically using a combination of mesotrione, atrazine, S-metolachlor and 2,4-D. The only pesticide applied at planting was pyrethroid (Decis

Forte) to control cutworms. Leaf fungal disease (grey leaf spot, northern corn leaf blight and rust) were controlled using carbendazim plus flusilazole and azoxystobin. Tractor-drawn ring equipped with an 18 m wide boom sprayer was used in the application of chemicals.

2.3.3 Sampling

Macrofauna sampling was done only once at the end of 2015/2016 rainy season using the method previously described by Anderson and Ingram (1993). Briefly, steel monoliths of 25 cm x 25 cm x 25 cm were driven through the soil using a steel hammer on all plots of each treatment replicated three times on the randomly selected positions. Thereafter, macrofauna were collected by sifting through the monoliths and preserved in glass bottles containing 70 % alcohol for subsequent laboratory identification. Macrofauna included all the organisms visible by eye (4-80 mm) which spend most of their important life cycle in soil or immediate surface including surface litter (Gobat et al. 1998). Finally, all the organisms collected were classified according to their typical ecological behaviour. These data allowed the computation of diversity (Shannon-Weaver index, H'), abundance (number of collected individuals per surface unit) and evenness (Pielou index, E). At the beginning of the experiment, controlled traffic was implemented where the same lanes were used and all samples were taken from the inter-row of non-traffic lanes.

2.3.4 Data analysis

Macrofauna abundance (density) was computed using Eq. 1 as demonstrated by Shannon-Wiener (1963).

$$N = \frac{P}{A} \tag{1}$$

Where:

N = macrofauna abundance (density)

P = fauna population in soil cube

A = monolith surface area

The Shannon-Weaver index (Shannon-Wiener, 1963) was calculated using Eq. 2.

$$H = -\sum(Pi\ In\ Pi) \tag{2}$$

It takes into account the number of orders encountered. With i = 1 to s, where $Pi =$ probability of meeting a taxon i on a plot, s= total number of taxa encountered on the plot (Brevault et al., 2007). H = 0 when there is only 1 taxa and is at maximum a when all taxa are of equal abundance. (Brevault et al., 2007).

Macrofauna evenness is the ratio between calculated diversity and the theoretical maximum diversity and is computed by the method described by Pielou (1977) using Eq. 3.

$$E = \frac{H}{InS} \tag{3}$$

The evenness index represents the distribution of taxa and this is used to compare communities that present a different number of taxa, with the aim of evaluating the balance of the populations. *E* tends to 0 when one taxon largely dominates the community and is equal to 1 when all taxa are of equal abundance (Brevault et al., 2007).

2.3.5 Statistical analysis

All data were subjected to analysis of variance (ANOVA) using GenStat® (Version 15.1, VSN International, UK). Means of significant different variables were separated using least significant differences (LSD) at a probability level of 5%. Kruskal-Wallis test was used to analyse the diversity of orders and species.

2.4 Results

There were highly significant differences ($p < 0.01$) observed in mean density of individual orders in the soil cubes with respect to different soil management systems, with NT treatment harbouring more individuals than RT and CT, respectively (Fig. 3). Isoptera, Coleoptera and Diplopoda were amongst the top 3 dominant orders of macrofauna observed in all treatments, with NT treatment harbouring more individuals than other treatments (Fig. 4).

Table 1: Major macrofauna taxa recorded in different tillage treatments after 13 years of implementation.

Phylum	Class	Order	Family	Number of individuals collected		
				NT	RT	CT
Arthropoda	Insecta	Coleoptera (Beetles)	Carabidae	1	2	2
			Tenebrionidae	11	10	10
			Scarabaeidae	7	8	11
			Meloidae	0	1	1
			Coccinellidae	0	0	1
		Isoptera (Termites)	Termitidae	52	36	0
		Diplopoda (Millipedes)	-	29	28	5
		Chilopoda (Centipedes)	-	1	4	4
		Isopoda (Woodlice)	-	2	1	0
		Dermaptera (Earwigs)	Forficulidae	9	5	2
			Labiduridae	0	1	1
	Arachnida	Araneae (Spiders)	-	3	4	4
Annelida	Oligochaeta (Earthworms)	-	-	3	1	0
		Hemiptera (True bugs)	Pentatomidae	2	0	0
			Reduviidae	0	3	0
		Orthoptera (Grasshoppers)	Gryllidae	1	1	0
		Lepidoptera (Butterflies)		0	1	0
Mollusca	Gastropoda (Snails)	-	-	0	0	1
Total				**121**	**106**	**42**

Note: NT= no-till treatment with mulch, RT= rotational tillage with mulch and CT= conventional tillage.

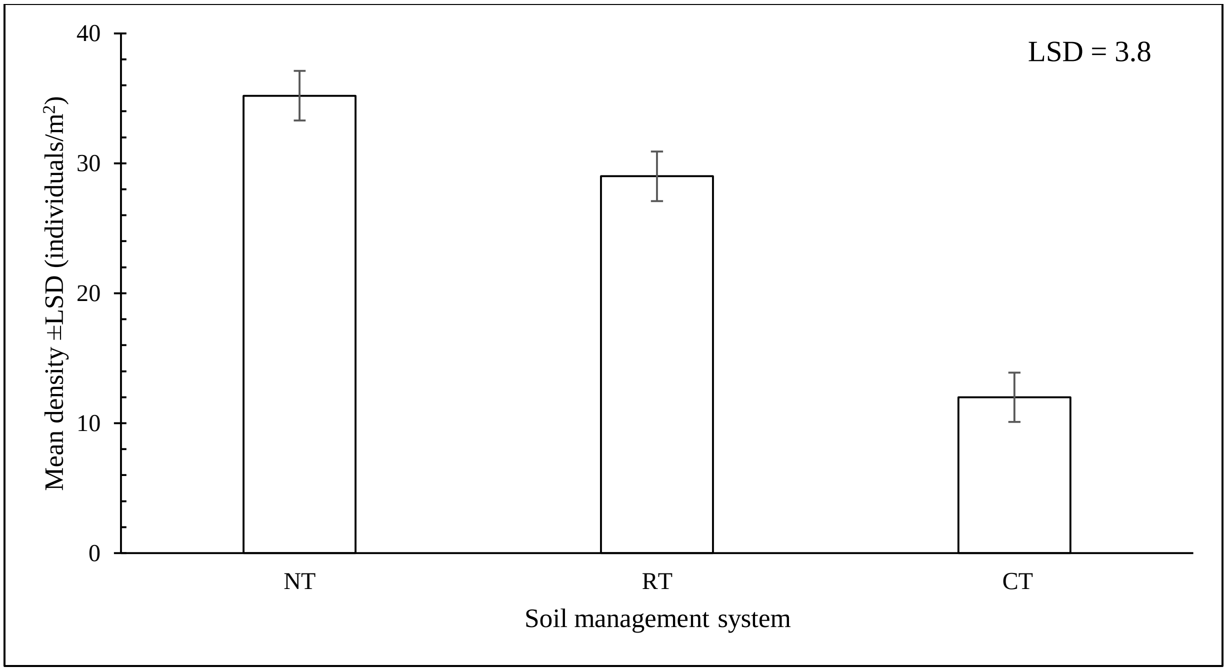

Fig. 3: The abundance of soil macrofauna in different tillage treatments after 13 years of implementation. Note: NT = no-till treatment with mulch, RT = rotational tillage with mulch and CT = conventional tillage.

Significant effects ($p < 0.001$) were also observed in mean density of individuals in the soil cubes, within the same orders, in different tillage treatments (Fig. 4) with the order Isoptera, Diplopoda and Dermaptera showing higher population in NT and RT than in CT (Fig. 4). There were no significant differences observed in orders such as Araneae, Gastropoda, Hemiptera, Isopoda, Chilopoda, Lepidoptera, Oligochaeta and Orthoptera in all tillage treatments. While the mean density of individuals (abundance) in the soil cubes was significantly higher in the NT and RT, the diversity (Figs. 5 and 7) and evenness (Fig. 5) of these organisms were observed to be similar in all treatments. Although at the order level there were no significant differences observed in the diversity of macrofauna, NT and RT were observed to have a significantly higher number of species than CT treatment, respectively (Fig. 6).

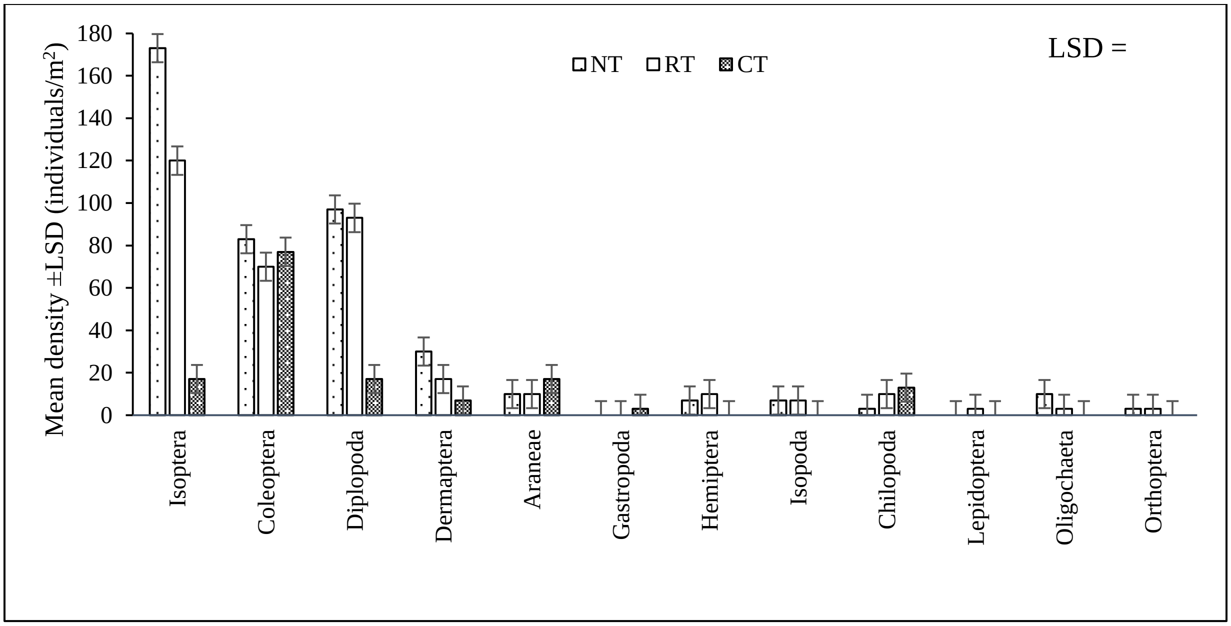

Fig. 4: The abundance of macrofauna and order diversity in different tillage treatments after 13 years of implementation. Note: NT = no-till treatment with mulch, RT = rotational tillage with mulch and CT = conventional tillage.

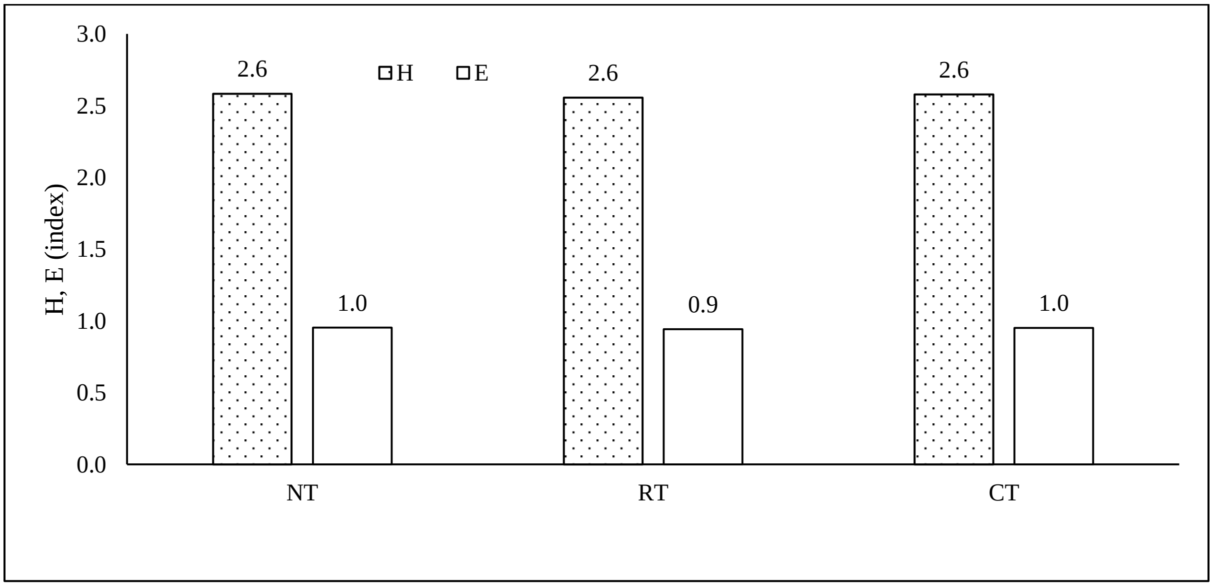

Fig. 5: Diversity (H) and Evenness (E) index of soil macrofauna in different tillage treatments after 13 years of implementation. Note: NT = no-till treatment with mulch, RT = rotational tillage with mulch and CT = conventional tillage.

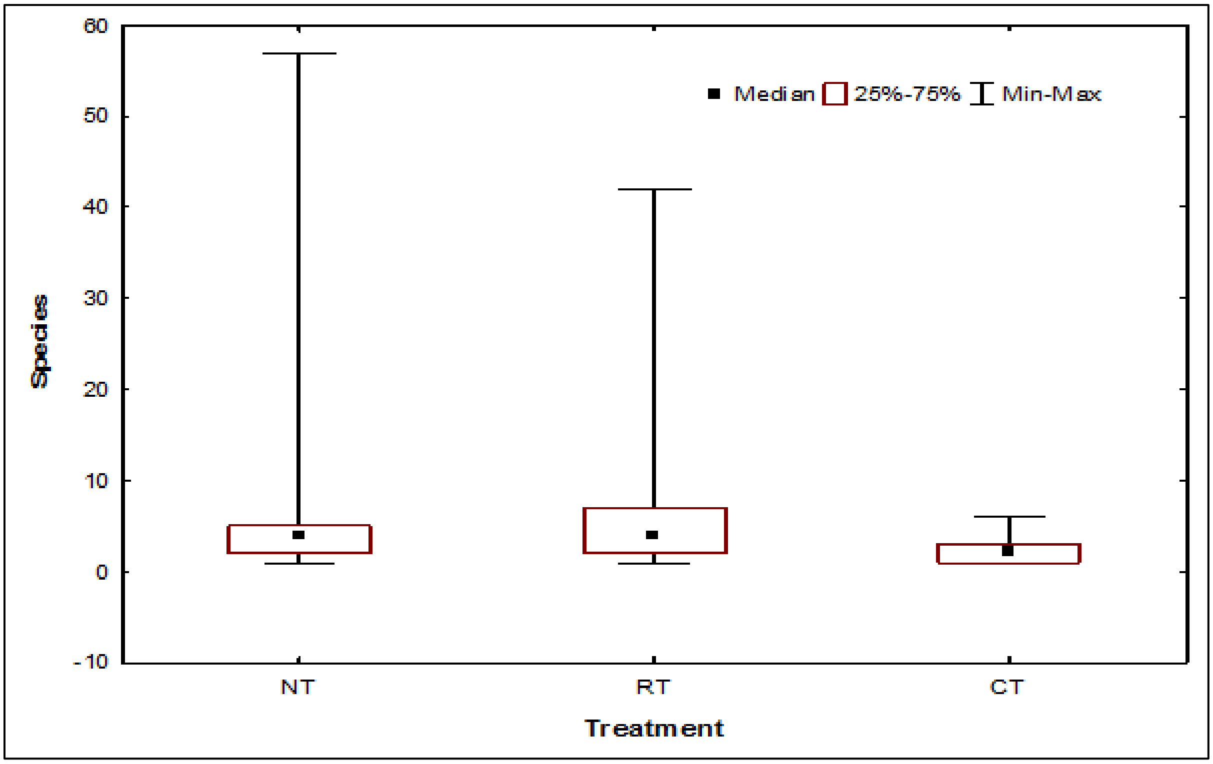

Fig. 6: The diversity of species observed in different tillage treatments after 13 years of implementation. Note: NT = no-till treatment with mulch, RT = rotational tillage with mulch and CT = conventional tillage.

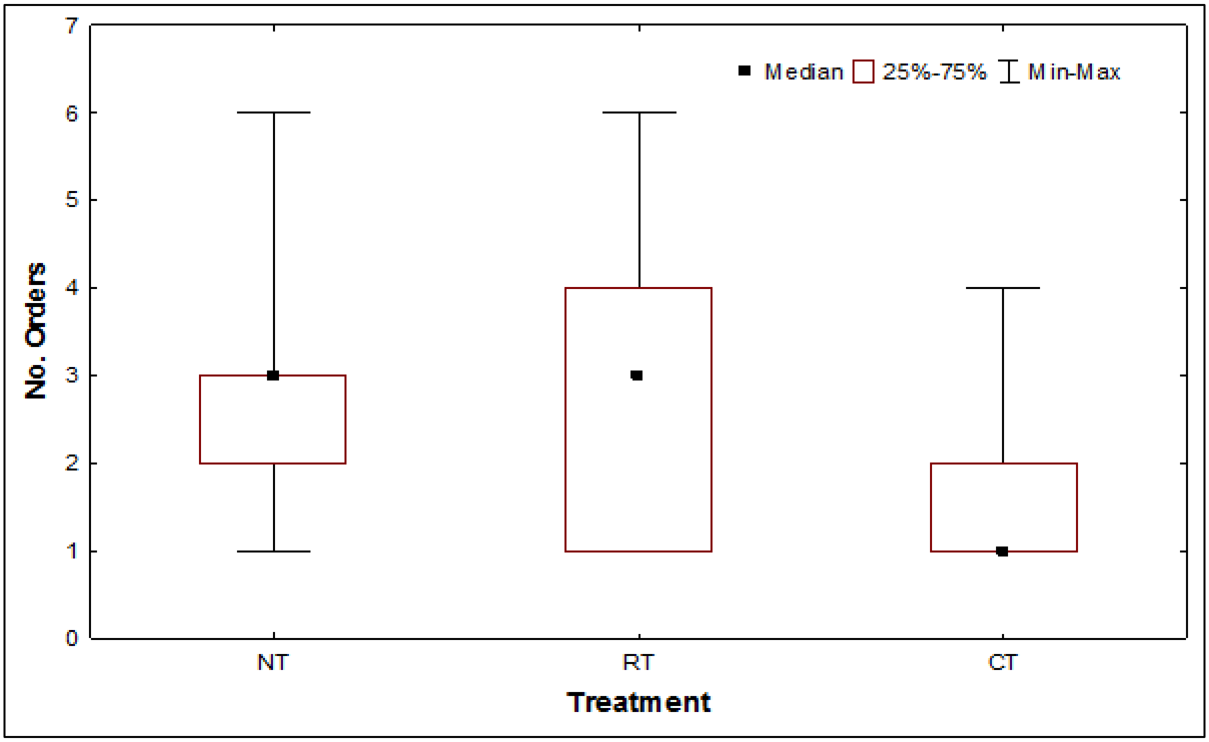

Fig. 7: The diversity of orders observed in different tillage treatments after 13 years of implementation. Note: NT = no-till treatment with mulch, RT = rotational tillage with mulch and CT = conventional tillage.

2.5 Discussion

The results showed that the abundance of macrofauna was significantly higher under mulch-based cropping system, after 13 years of implementation of NT, with NT (No-till) and RT (Rotational tillage) treatments yielding more organisms than CT (Conventional tillage), respectively (Figure 3). Similar findings were observed by Marasas et al. (2001); Sileshi and Mafongoya (2005); Blanchart et al. (2007); Mutema et al. (2013) in providing evidence that reduced tillage (NT & RT) soil management strategy with mulch provide better conditions for macrofauna settlement which resulted in a large population of these soil organisms. Reduced soil tillage with mulch improved the environmental condition for macrofauna settlement through reduction of habitat destruction by tillage implements and by reducing soil erosion through the impact of raindrop and wind. Soil cover with mulch further protect the soil organisms by protecting the habitat against extreme variation in temperature and humidity and increasing soil organic matter as a source of food, therefore providing a stable environment for macrofauna settlement (Kladivko, 2001; Blanchart et al., 2006). In contrast to NT, native soil organisms may migrate from cropland due to mechanical habitat destruction and removal of soil organic matter under CT, thus increasing predation risk (Thorbek and Bilde, 2004; Brevault et al., 2007) and the outbreak of crop pest and diseases if proper measures to control these are not taken into consideration.

However, the diversity and evenness of macrofauna did not vary under different soil tillage treatments as shown in Fig. 5. The similarity of organisms (diversity) and evenness observed in different tillage treatments may be explained by the continuous similar type of organic resource feed. It appears that continuous maize farming where maize straw is the only biomass that provides fresh organic input has provided the type of feeding environment that enhances the similar type of organisms in all treatments. A similar observation has also been made in continuous monocropping sorghum farming conditions (Zida et al., 2011). On the other hand, when crop rotation (the third leg of CA principle) is implemented, it appears that the diversity of macrofauna population increases (Verhulst et al., 2010). Hence, macrofauna population and diversity is not only influenced by the quantity of organic input retained in soil but it is also a function of the quality of diverse organic feed resource input. Species diversity in agroecosystem is vital due to their differences in ecologically behaviour which in turn influence soil structural properties such as, porosity, water infiltration, aggregate stability (Mando and Midiema, 1997; Brown et al., 2000;

Six et al., 2004; Bottinelli et al., 2015) and soil physiochemical characteristics such as soil organic C, CEC and the availability of nutrients in soil (Lal, 1988).

The results also showed that the termites (Isoptera) were the most abundant macrofauna group under continuous maize monocropping system with NT having the highest density than RT and CT, respectively (Fig. 4). This has been observed also by other authors (Giller et al., 1997; Brady and Weil, 1999; Zida et al., 2011) that termites' population increases under monoculture cropping system particularly in semi-arid to arid environments where other ecosystem engineers (earthworms) are limiting. Termites are primary shredders of most dry organic materials and they are the main agent that break down surface mulches under CA (Mutema et al., 2013) and their abundance has been shown to be strongly correlated with the availability of recalcitrant organic material over easily decomposable organic resources (Ouedraogo et al., 2004). Therefore, increasing soil organic residues under dryland cropping system may serve as a strategy to increase the availability of these organisms which are important also in soil structural formation and recycling of nutrients. Their abundance has been correlated with increased soil water infiltration (Mando and Miedema, 1997). This proves that the application of two CA principles, no-till and permanent soil cover, has the potential to increase termite prevalence. Similar observations have also been made by Mutsamba et al. (2016).

This experiment yielded similar results with that of other authors (Kladivko, et al. 1997; Kladivko, 2001; Chan, 2001) who showed that earthworm population tends to be very low under dryland cropping system especially under CT, where there is more soil disturbance, as compare with RT and NT treatments, respectively. It has been also suggested that earthworms are also influenced by the type of organic resource input and they are more competitive than termites in decomposing easily decomposable organic material (Zida et al., 2011). This suggests that earthworms are more effective in a decomposing material with lower C/N ratio, which in turn explain the abundance of termites in this experiment due to higher C/N ratio of maize stubble.

Furthermore, the experiment also showed a significant effect on millipedes (Diplopoda) abundance with NT and RT treatments yielded a significantly higher population than CT (Fig. 4). On the other hand, although beetle (Coleoptera) population was high and comparable to that of termites and millipedes, there were no significant differences observed in all tillage treatments although NT treatment showed trends towards high density than CT and RT. This may probably be due to high mobility and higher population growth potential of this order which make it less sensitive to change in tillage management. Other studies, however, have revealed that beetles are sensitive to anthropogenic changes (Kromp, 1999) and hence the similarity in all treatments may be due to the mobility of these organisms resulting from the close proximity of different treatments. Millipedes and beetles sampled were both mixture of carnivores (beetles) and herbivores arthropods, which are important in the decomposition of organic matter and recycling of nutrients in the soil. The abundance of millipedes in NT and RT treatments suggest their preference to dwell under maize debris and thus performing their important roles in facilitating ecosystem processes such as soil structure and chemistry. Similar observations were made under no-till with mulch in a cotton plant where millipedes' population was high under the soil with mulch (Brevault et al., 2007). However, the negative impact of these organisms may rise if the food source (debris) is depleted and become a pest to the growing crop (Brevault et al., 2007), for example, Mutsamba et al. (2016), Ayuke (2010) and Sands (1977) found that in the absence of crop residue at harvest crop attach may arise irrespective of whether initial residue application rates were high or low. This, in turn, highlights the importance of quantifying the amount of crop residues enough for macrofauna population in a specific environment. With regards to the observed high population of beetles in all treatments, it has been reported that most species are natural enemies of agricultural pests (Kromp, 1999) which in turn may help in the control of pests. However, negative results may also arise. For example, in rice grown with mulch in Madagascar, black beetles (*Heteronychus* spp.) were observed to cause damage in rice seedlings. The current data has, however, shown that the majority of the species observed belongs to *Tenebrionidae* and *Scarabaeidae* family (Table 1) of which both can feed on plant debris.

Although the abundance of other orders was available in such a smaller population, they are important in maintaining the predator-prey relationship, thus contributing to the biological control of pests. Earwigs (Dermaptera) under family *Forficulidae*, centipedes (Chilopoda) and spiders (Aranaeae) observed (Table 1) are amongst the predators observed feeding on other arthropods. According to Stinner and House (1990), this fauna group contributes to the regulation of biological activity by acting on top of the food chain by feeding on other organisms.

The results of this experiment have indicated that no-till conservation agriculture with permanent mulch cover has a positive effect on influencing macrofauna population as compared with traditional mould board plow system under continuous maize monocropping. This was attributed to reduced soil disturbance and higher SOC content on untilled plots as compared with CT plots which provided a better condition for macrofauna settlement. These organisms are important in soil structural formation and the recycling of important nutrients into the soil, thus maintaining good quality which is vital for the sustainability of agricultural production. Rotating tillage after every 4 years has proved to be a viable alternative in the maintenance of soil quality parameters since the macrofauna population was comparable to NT plots. This is particularly important where soils with a problem of compaction and soil-borne diseases are a problem and there is need of ripping the soil from the subsoil. In this experiment, no differences were observed, however, in the diversity and evenness in different tillage treatment and this was attributed to continuous monocropping which supplies similar type of organic feed which may in turn influence macrofauna species distribution. Orders Isoptera, Diplopoda and Coleoptera were amongst the three dominant orders observed in this experiment. The organisms belonging to these orders have a crucial function in soil structural formation, soil health and functioning of the ecosystem. Other orders which were not dominant were reported to play a vital role in controlling the predator-prey relationship thus contributing to the control of pest cropland.

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CHAPTER 3

The long-term impact of no-till conservation agriculture and N-fertilizer on soil aggregate stability, infiltration and distribution of C in different size fractions

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3.1 Abstract

Soil degradation associated with the loss of soil organic carbon (SOC) has been a major concern in sub-Saharan Africa because of the subsequent yield reduction. It is not fully understood how long-term addition of C through biomass and N-fertilizers impact on C distribution in soil aggregates and its effects on soil aggregate stability and infiltration in sub-tropical maize monocropping system. The study, therefore, assessed long-term changes in total SOC (TSOC), aggregate-associated C, particulate organic C (POC), aggregate stability (MWD) and infiltration in the 0-10, 10-20 and 20-30 cm depths under different tillage systems after 13 years of implementation of the trial. The three tillage systems were no-till (NT), rotational tillage (RT) both with permanent residue cover and conventional tillage (CT) with residue removed. N-fertilizer was applied at a rate of 0, 100 and 200 kg/ha. On average, TSOC did not vary ($p > 0.05$) across the tillage treatments, 27.1 t/ha NT *vs* 26.0 t/ha RT and 26.6 t/ha CT, but varied with depth where it was stratified in the 0-10 cm depth in NT and RT. Particulate organic C, however, varied significantly ($p < 0.05$) across the treatments where it decreased with increase in tillage intensity but only in the 0-10 cm depth. Carbon associated with large aggregates (> 2000 µm) differed marginally ($p = 0.085$) with tillage treatment with NT having 38.0 t/ha, RT 36.6 t/ha and CT 29.7 t/ha. However, differences ($p < 0.05$) were observed in small macroaggregates (250-2000 µm) with NT having 37.8 t/ha, RT 33.5 t/ha and CT 30.4 t/ha in the surface depth. The results found a strong effect of residue retention in NT and RT in the soil surface with aggregate stability which was correlated with the high rate of infiltration rate in these treatments. The results of this study indicated that reduced soil disturbance improves physical protection of SOC, soil structure and infiltration.

Keywords: aggregate-associated C, soil organic matter, mean weight diameter, ferralsol haplic

3.2 Introduction

Meeting the needs of the increasing population requires the protection of our arable land base and improvement of productivity (Lafond et al., 2011). This is particularly true for countries in the sub-Saharan Africa (SSA), which face significant challenges of increasing food production without significantly increasing the area under agricultural production (Stevenson et al., 2013). However, meeting these demands seems impossible because of high levels of human-induced soil degradation (FAO, 2010a) and low to medium agricultural potential due to low inherent soil fertility (Eswaran et al., 1997) and mining of nutrients in agricultural fields (Drechsel et al., 2001; Henao and Baanante, 2006). Global estimates indicate that 45% of the arable land is affected by degradation (Lal, 2007). A large portion of land degradation is ascribed to sub-Saharan Africa where the levels are exceptionally high, ~ 65% (Bai and Dent, 2007). In South Africa, Bai and Dent (2007) reported that the level of soil degradation is severe and approximately 40% of the cultivated land is degraded due to human-induced activities such as conventional tillage, continuous cropping with insufficient inorganic and organic fertilizers inputs which leads to production of insufficient amount of organic matter (Oldeman et al., 1991). This, in turn, possesses more threat to food security in this region considering the growing population, water shortages and the predicted negative impacts of climate change. In response to these challenges, conservation agriculture (CA) has been proposed by many researchers as a widely adopted set of management principles that can encounter the negative impact associated with these challenges and ensure more sustainable agricultural production (Hobbs, 2007; Hobbs et al., 2008; Giller et al., 2009, Verhulst et al., 2010).

Conservation agriculture has been defined as a concept for resource-saving agricultural productivity that strives to achieve acceptable profits while concurrently minimising negative impacts on the environment (FAO, 2010b). In SSA, it is promoted to reverse the negative impacts on cultivated land such as degradation and to increase stock in the soil (Erenstein et al., 2008). According to Wall (2007), the term "conservation agriculture" has been used to distinguish this more sustainable agriculture from the narrow-defined term "conservation tillage" which is a widely used terminology to describe soil management system that leaves at least 30% of the crop residues in the soil surface after seeding of the subsequent crop (Jarecki and Lal, 2003). Conservation agriculture is based on three basic principles, namely, a) the reduction in tillage and/or no-till, b) retention of adequate levels of crop residues and soil cover and c) the use of diversified crop rotations (FAO, 2008; Verhulst et al., 2010). Potential benefits of CA includes an increase in SOM, C sequestration and soil aggregation (Rusinamhodzi, 2015); increase in crop sequence intensification (Brouder and Gomez-Macpherson, 2014). It also improves infiltration rate and soil water retention (Findlater, 2013); better use of the cropping season window permitted by earlier field entry (Hobbs et al., 2008) and increased and more stable yields (Hobbs, 2007). In contrast to developed countries such as America and Australia, CA adoption in SSA has been very low, accounting for 0.78% of the world total, (Friedrich et al., 2012) and reportedly in South Africa it only constitutes 2.8% of the country's arable land (Sithole et al., 2016) and larger percentage of this adoption (> 98%) is ascribed to commercial farmers. Therefore, more work that needs to be done in order to increase its adoption rate and improve soil quality in different agro-ecological regions of the country relevant to farmers situations.

Soil aggregate size distribution and stability are the vital factors of soil physical quality that reflect the impact of soil management and land use on aggregation and degradation (Castro Filho et al., 2002). In this, soil organic matter serves as a major binding agent of mineral particles into aggregates while on the other hand soil aggregates protect SOM from rapid decomposition by microorganisms and act as a storage for C and other key important soil nutrients (Elliot et al., 1986). Soil organic matter further stimulates the activities of the soil biota (Ayuke et al., 2011) and maintain physiochemical conditions of the soil such as cation exchange capacity (CEC) and pH (Vanlauwe et al., 2005). The aggregate-associated C and N are protected from mineralization because of their being less vulnerable to microbial, enzymic and physical degradation (Six et al., 2004). In addition, stable aggregates reduce soil erosion and degradation, surface runoff and crusting.

Further, changes in total SOC and N with management, climate or land use is difficult to detect since these changes occur slowly and are relatively small compared to the abundant SOC stock and natural soil variability which vary both spatially and temporally (Franzluebbers et al., 1995; Six et al., 2002). In addition, various pools of SOC/N do not react and transform at a similar rate (Cheng and Kimble, 2001), thus, isolating SOC pools sensitive to management, climate or land use change could be useful in detecting these changes. Particulate organic matter (POM) is a labile fraction composed of partially decomposed material with a turnover rate of weeks to months or even years and with particle size ranging between 53 and 2000 µm (Wander, 2004) compared with a more recalcitrant pool, the mineral associated organic matter (Zhong et al., 2015). POM is young minimally transformed and less associated with mineral constituents of the soil and therefore constitute a dynamic fraction that is associated with short-term nutrient availability (Galantini et al., 2004). In addition to this, it has a fast recycling rate and is associated with soil microbes, soil particle aggregation and aggregate stability (Six et al., 2000).

Bergville forms the most important part of the cropping area in KwaZulu-Natal Province in South Africa (Lamprecht et al., 2008) and commercial farmers in this area have adopted CA ranging from continuous monocropping to a full package of CA. Therefore, it is important to increase the knowledge base of the local soils in South Africa because the magnitude and direction of the tillage-induced changes are soil and site-specific. This, in turn, will ensure that the country increases its maize productivity which is a staple food crop for a larger population. In addition, despite the considerable interest on CA in developed countries, rigorous data on CA practices and its benefits in sub-Saharan Africa is largely inconsistent (Paul et al., 2013) and missing in the scientific literature particularly in South Africa (Sithole et al., 2016). Therefore, the present study investigated soil aggregate stability, infiltration, SOC and its size fractions at different depth of 0-30 cm in soil planted with maize monocrop in an area that has received different rates of N-fertiliser since 2003/2004 growing season.

3.3 Materials and methods

3.3.1 Experimental site and climatic condition

The experiment was conducted in Bergville, Winterton (28°55'26.83"S, 29°33'38.64"E, 1038 asl), KwaZulu-Natal Province, South Africa in an already existing trial that was established in 2002/2003 growing season. The field trial was established and has been managed by the Department of Agriculture and Environmental Affairs in KwaZulu-Natal Province to assess the combined effects of tillage intensity and fertilizer application rates on soil fertility and maize yield. The mean annual rainfall is 643 mm.year^{-1} received mostly during the summer season between October and March and the mean air temperature of the site is 19.3 °C in June and 27.9 °C in January. Previously, the trial site has been managed under no-till since 1990 under dry land maize commercial production in rotation with soybean until the establishment of the trial in 2002/2003 growing season. Currently, since the beginning of the experiment, the trial site is planted to dry maize continuous monocrop in summer and left fallow during the winter months. The soil was classified as Ferralsols Haplic (FAO, 2006) or Hutton non-swelling with clay loam soil texture (Soil Classification Working Group, 1991). The average pH (KCl) of the top 30 cm of the trial was 6.62.

3.3.2 Experimental design and trial management

The field experiment was set up as a split plot design with randomized tillage strips forming the whole plot and N source and the rate of application forming the sub-plots which are randomized within the whole plots. The sub-plots had 9.5 m × 12 rows of maize at a density of 70 000 plants/ha. The experiment included three tillage treatments, namely, no-till (NT), annual conventional tillage (CT) and rotational tillage (RT). In NT and RT treatments, about 10-12 t/ha/yr maize residues were left in the soil surface, thus forming permanent soil cover, while in CT treatments residues were removed in the soil surface after harvest. No-tillage involved direct seeding into the undisturbed soil using NT planter. CT, on the other hand, involved ploughing with mouldboard plough up to a depth of 30 cm and disking to a depth of 10 cm while RT involved CT after every four years of NT. The treatments were replicated three times. Nitrogen was applied at five rates (0, 50, 100, 150 and 200 kg/ha) as lime ammonium nitrate (LAN). For this particular experiment, only three fertilizer application rates were investigated, at 0, 100 and 200 kg/ha. Nitrogen was applied as top dressing four weeks after planting. Potassium (K) and phosphorous (P) were applied at planting in the band at a rate of 50 and 20 kg/ha, respectively. Lime was applied at a rate of 2 Mg/ha every second season to the entire plot. It was incorporated during ploughing in CT plots and surface applied in NT plots. Weeds were controlled chemically using a combination of mesotrione, atrazine, S-metolachlor and 2,4-D. The only pesticide applied at planting was pyrethroid (Decis Forte) to control cutworms. Leaf fungal disease (grey leaf spot, northern corn leaf blight and rust) were controlled using carbendazim plus flusilazole and azoxystobin. Tractor-drawn ring equipped with an 18 m wide boom sprayer was used in the application of chemicals.

3.3.3 Soil analysis

3.3.3.1 Aggregate size fraction

Three undisturbed soil samples were collected from randomly selected positions of each treatment at three depths: 0-10, 10-20 and 20-30 cm depth. The soil was then air dried and passed through 8 mm then to 5 mm sieve. Aggregates were then separated by wet sieving the soil through a series of three sieves (2000, 250 and 53 µm) to obtain four aggregate size classes (Elliott, 1986), large macroaggregates (> 2000 µm), small macroaggregates (250-2000 µm), microaggregates (53-250 µm) and silt and clay (< 53 µm). A subsample of 80 g was submersed in distilled water on top of 2000 µm sieve for five minutes before sieving. The sieving was done manually by moving the sieve 3 cm, 50 times in 2 minutes (Six et al., 2002). Water plus the soil that went through 2000 µm sieve was poured to the next sieve and sieving was repeated. The aggregates received at each sieve were carefully back washed and oven dried at 60 °C for 48 hours weighed back and stored for C and N analysis. Mean weight diameter was determined as a sum of weighed mean diameters of all fraction classes using Eq. 1 described by Elliott (1986).

$$MWD = \sum_{n=1}^{n} \bar{x}iwi \qquad 1$$

Where:

MWD = mean weight diameter (mm)

$\bar{x}i$ = mean diameter of each size faction

Wi = proportion of total sample weight

N = number of size fractions

3.3.3.2 Infiltration

Infiltration was measured using a method described by Johnson (1963). Briefly, double-ring infiltrometer was hammed to a depth of 30 mm. Water was applied to fill up, first the outer compartment, and then the inner compartment. Timing was made immediately. Using the ruler in mm, the drop in height of water level in the inner compartment was measured. The time was recorded for every 5 mm decline in water level.

3.3.3.3 Bulk density

Soil bilk density was determined by the method described by Cresswell and Hamilton (2002). Briefly, four replicate of undisturbed soil samples of each treatment which were collected randomly from 0-20 cm (A-horizon) and 20-40cm (B-horizon) and oven dried at 105 °C for 12 hours. A spade was used to collect soil samples to avoid the shearing effect of soil auger. The bulk density was expressed as the mass per unit volume.

3.3.3.4 Soil organic C

Soil organic C was analysed by the Automated Dumas dry combustion method using a LECO CNS-2000 (Leco Corporation, Michigan, USA) (Matejovic, 1996). Briefly, this method involves weighing samples into a ceramic crucible to which 0.5g of vanadium pentoxide is added as a combustion catalyst. The crucible is introduced into a horizontal furnace, where the sample is burned in a stream of oxygen at 1350^{o} C. The gases produced are passed through two infra-red cells where C is determined as CO_2 and nitrogen are determined N_2 in a thermal conductivity cell.

3.3.4 Statistical analysis

The data collected was subjected to analysis of variance using GenStat 17th Edition (VSN International, Hemel Hempstead, UK) and means were separated using Tukey's least significant difference (LSD) at 5% level of significance. Correlation analysis and linear regression were used to assess the strength of the relationship between fertilizer level and SOC and aggregation.

3.4 Results

3.4.1 Aggregate fractions

Significant differences ($p < 0.001$) in aggregate size fraction were found across the tillage treatments (Fig. 1). No-till treatment contained larger macroaggregates (11.6 g/100g) than RT (5.9 g/100g) and CT (6.4 g/100g), although the differences in the latter two treatments were not statistically significant. In small macroaggregates, the CT treatment had a significantly ($p < 0.001$) lower aggregate fractions (41.2 g/100g) than NT (47.3 g/100g) and RT (47.3 g/100g). In contrast to what was observed in large and small macroaggregates, CT had a significantly higher microaggregates (45.5 g/100g) than RT and NT with 41.5 g/100g and 36.5 g/100g, respectively. Silt and clay were also found to be higher in CT treatment (4.36 g/100g) than in NT (3.41 g/100g) and RT (3.34 g/100g) treatments.

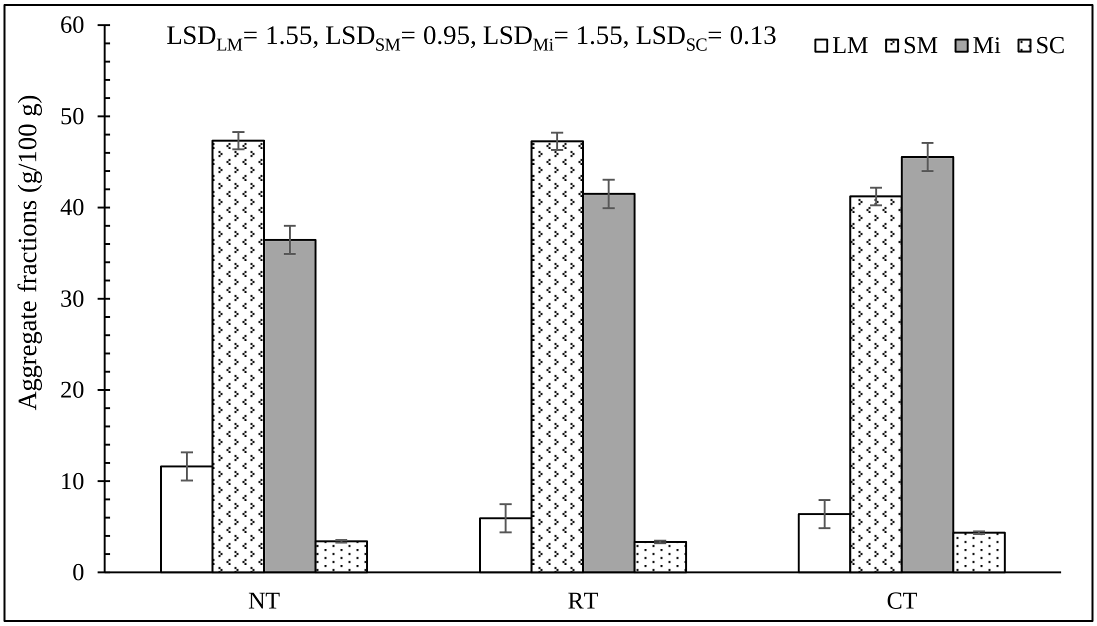
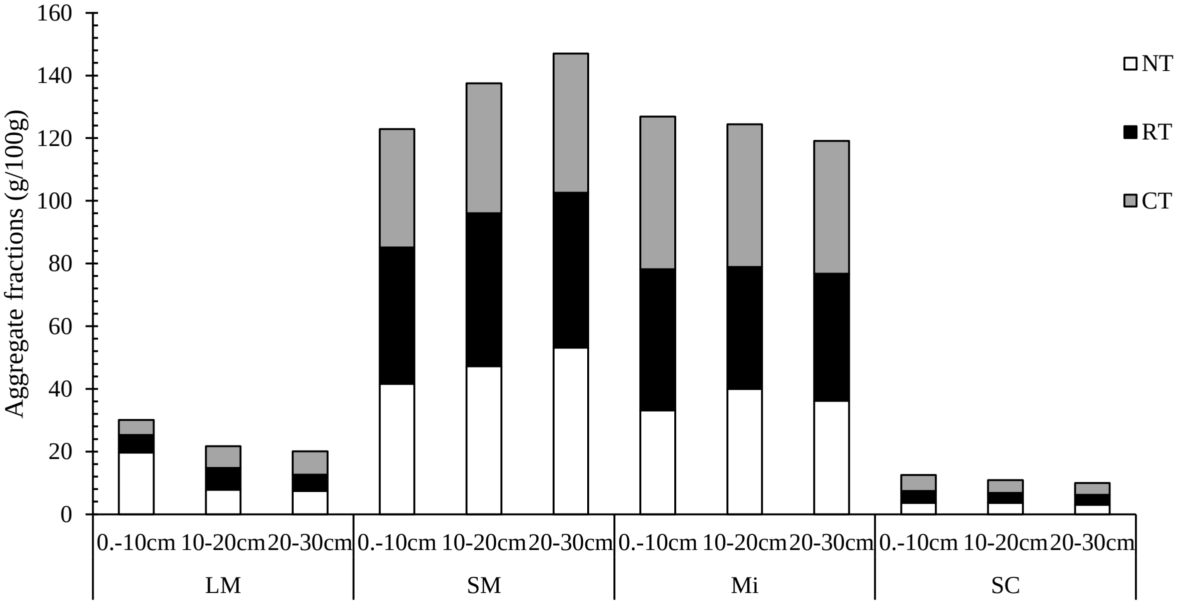


Fig. 1: Aggregate fractions of different tillage treatments after 13 years of implementation of the trial. *Note: LM = large macroaggregates (> 2000 µm), SM= small macroaggregates (250-2000 µm), Mi = microaggregates (53-250 µm) and SC = silt and clay (< 53 µm).*

Larger macroaggregates were only significantly higher ($p < 0.001$) in 0-10 cm depth under NT treatment (19.20 g/100g) (Fig. 2) compared to RT (5.66 g/100g) and CT (4.84 g/100g). In all other depths, 10-20 and 20-30 cm, there were no significant differences ($p > 0.05$) in large macroaggregates, although NT treatment showed a trend towards larger aggregates. Small macroaggregates were consistently and significantly ($p < 0.05$) lower, under CT than in NT and RT (Fig. 2). However, the differences were not observed in these treatments, in 0-10, 10-20 and 20-30 cm depth. Microaggregates were significantly ($p < 0.05$) higher in CT than in NT treatments in all treatment depths. This was more pronounced in 0-10 cm depth with CT treatment having 12% and 2% more microaggregates than NT and RT treatment, respectively. Silt and clay content was also observed to be higher ($p < 0.05$) in CT than in NT and RT and this was more apparent in 0-10 cm followed by 10-20 cm and 20-30 cm depth, respectively. Silt and clay content was observed to decrease with depth, with no significant differences observed between NT and RT treatments.



Tillage	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
Tillage*depth	$p < 0.001$	$p < 0.05$	$p < 0.05$	$p < 0.05$
LSD_T	0.90	0.96	1.55	0.13
LSD_{T*d}	1.55	1.66	2.68	0.23

Fig. 2: Aggregate fractions at 0-10, 10-20 and 20-30 cm depths measured 13 years after implementation of the trial. *Note: NT = no-till with mulch, RT = rotational tillage with mulch, CT = conventional tillage, LM = larger macroaggregates (> 2000 µm), SM= smaller macroaggregates (250-2000 µm), Mi = microaggregates (53-250 µm) and SC = silt and clay (< 53 µm).*

There was a weak insignificant correlation as determined by the regression coefficient (R^2) between fertilizer application rates and aggregate formation in all tillage treatments (Fig. 3). Application rate at 200 kg/ha was observed to weaken the regression between NT and CT tillage treatments.

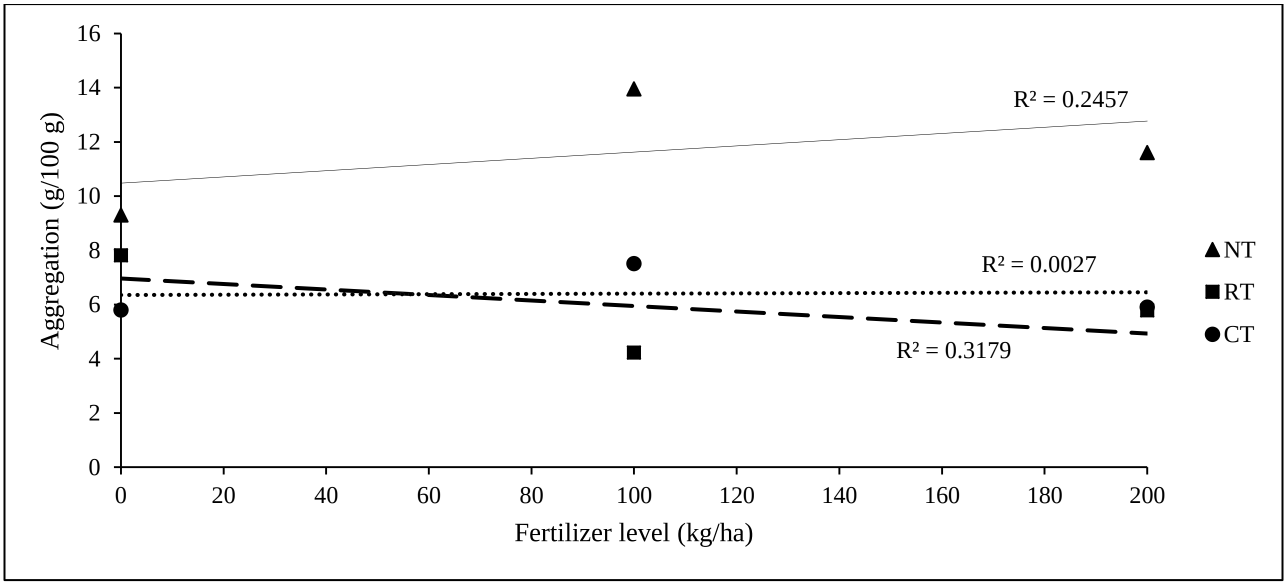


Fig. 3: Relationship between fertilizer application rate and aggregate formation in three tillage treatments of NT (no-till), RT (rotational tillage) and CT (conventional tillage).

Significant differences ($p < 0.001$) across the tillage treatments were observed in mean weight diameter (MWD) with NT treatment having a mean amount of 1.19 mm *vs* 0.91 mm in RT and 0.88 mm in CT treatment (Fig. 4). A significant interaction ($p < 0.001$) in MWD of tillage × depth was also observed in NT treatment with a mean amount of 1.53 mm vs 1.00 mm and 1.04 mm in 0-10, 10-20 and 20-30 cm, respectively. However, there were no differences in 10-20 and 20-30 cm depth. In RT and CT treatments, no significant differences were observed in MWD of the tillage × depth interactions. Significant differences ($p = 0.02$) were also observed in MWD in the interaction of tillage × fertilizer level but these differences did not have significant correlation trend across all treatments (Fig. 5). For example, in NT treatment MWD was higher in 100 LAN followed by 200 and 0 LAN treatments while in RT treatment, it was higher in 0 LAN followed by 200 and 100 LAN treatments which were not different ($p > 0.05$). On the other hand, there were no differences ($p > 0.05$) observed in CT treatment.

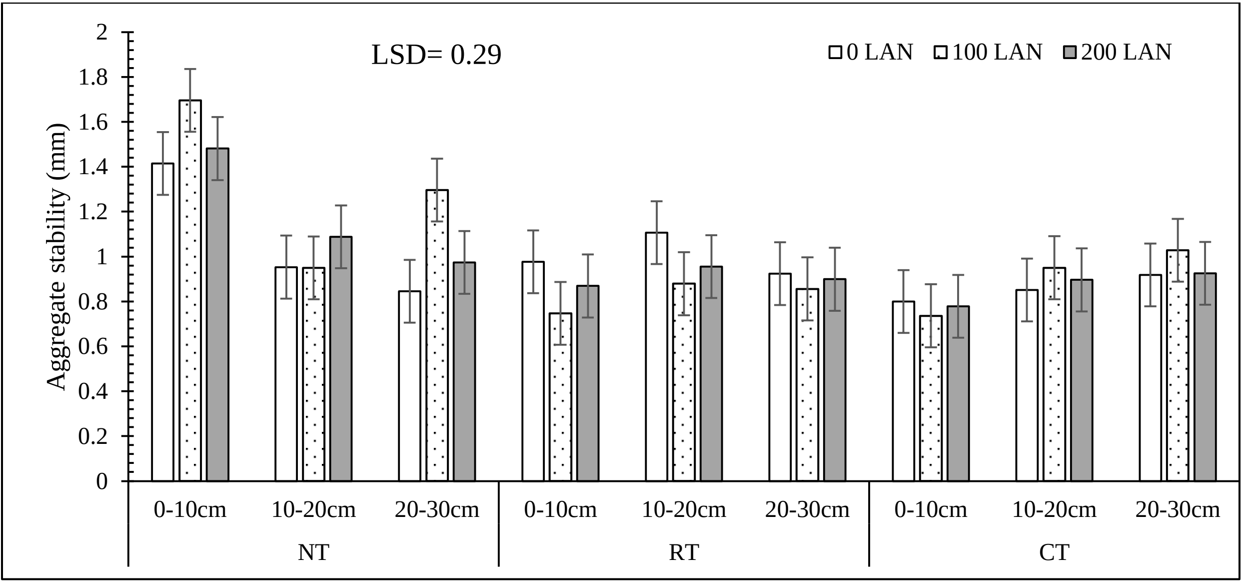


Fig. 4: Aggregate mean weight diameter (MWD) in different treatments, depths and levels of nitrogenous fertilizer measured 13 years after implementation of the trial.

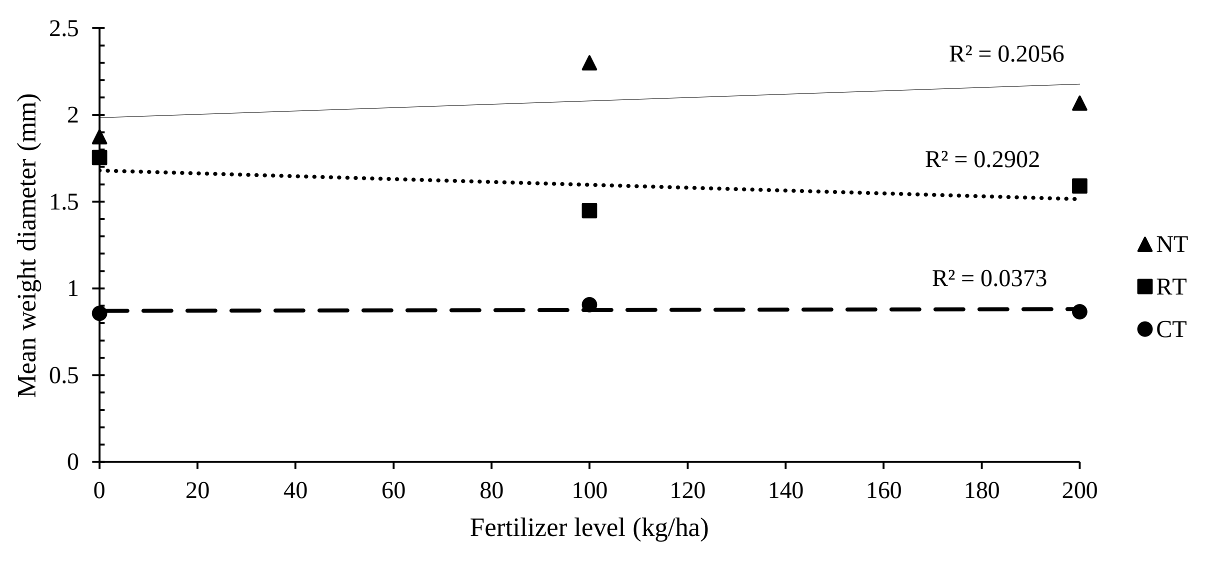


Fig. 5: Relationship between MWD and fertilizer application rate in NT, RT and CT treatments.

3.4.2 Infiltration and bulk density

Cumulative infiltration was significantly higher ($p < 0.001$) across the treatments with CT having a significantly lower infiltration rate than RT and NT treatments (Fig. 6). No-till treatment took less than 5 minutes to reach 160 mm while on the other hand, CT treatment took more than 50 minutes and RT it took about 20 minutes. Lastly, there were no differences ($p > 0.05$) found in bulk density across the tillage treatments (Fig. 7).

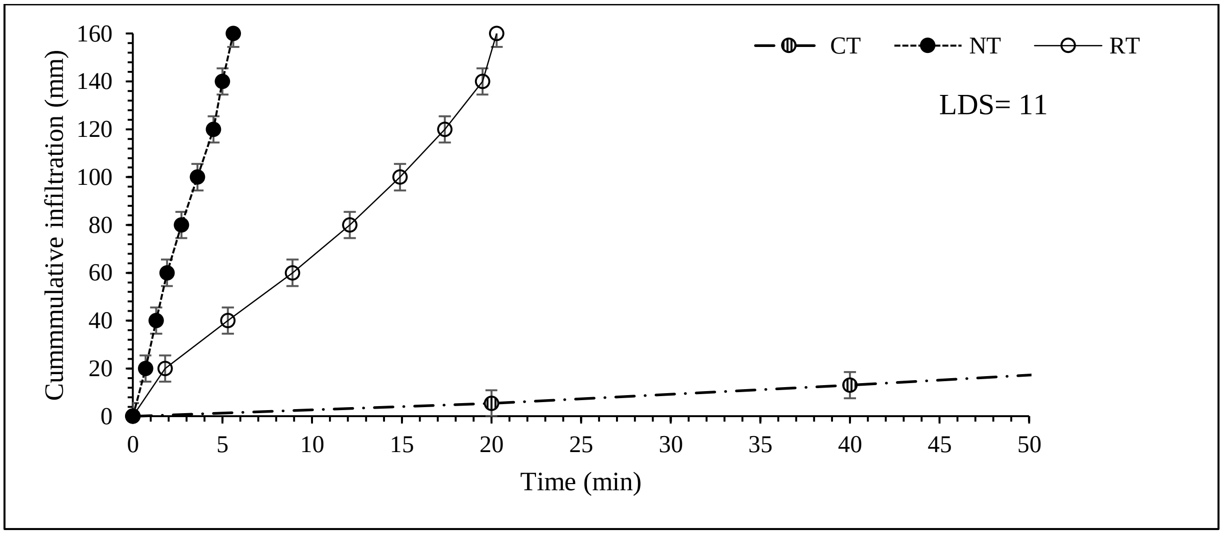


Fig. 6: Cumulative infiltration measured in 13 years after implementation of the field trial.

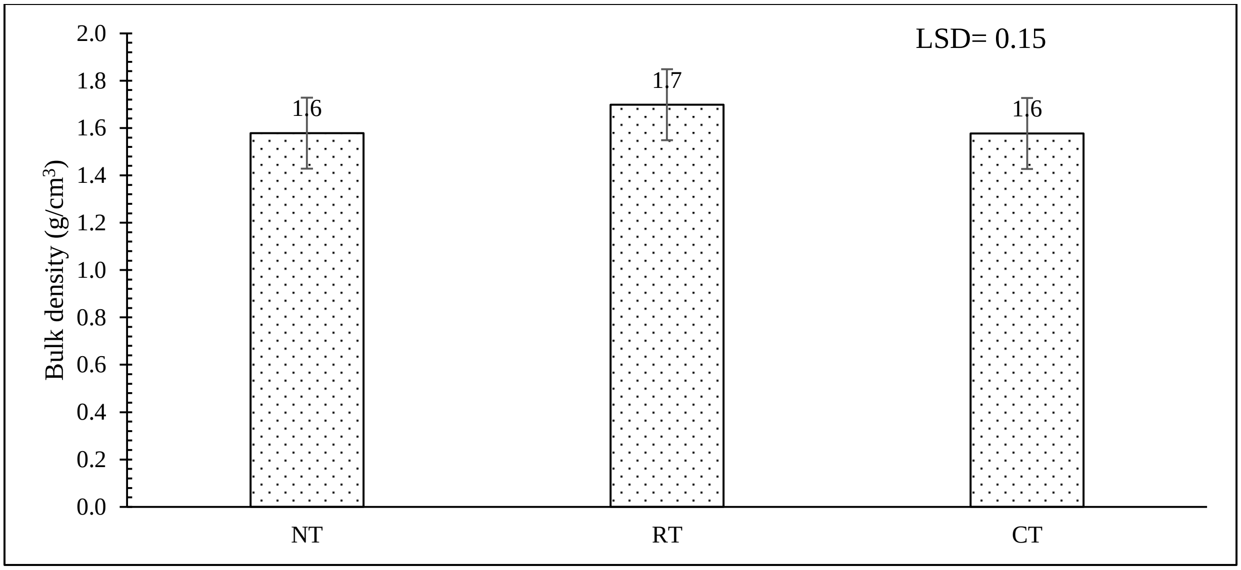


Fig. 7: The bulk density of different tillage treatments measured 13 years after implantation of the field trial.

3.4.3 Soil organic carbon

On average, the total SOC did not vary across the tillage treatments, 27.1 t/ha (NT) vs 26.0 t/ha (RT) and 26.6 t/ha (CT) (Fig. 7). However, significant differences ($p < 0.05$) with respect to depth distribution were observed with 0-10 cm depth having the highest concentration than 10-20 cm and 20-30 cm depths. Particulate organic carbon varied significantly across the tillage treatments with NT (25.3 t/ha) having the higher amount than RT (23.3 t/ha) and CT (20.7 t/ha) in the top 0-10 cm depth, respectively, where the differences were not observed in the latter treatments (Table 2). Particulate organic C decreased significantly with depth particularly in NT and RT where it was found to be stratified on the top layers, 0-10 and 10-20 cm, of the soil. In CT treatments, the stratification effect of POC was much reduced in the 0-10 and 10-20 cm depth.

Carbon associated with large macroaggregates varied marginally (*p* = 0.085) with tillage treatments and the differences were only observed in the 0-10 cm depth. No-till treatment had the highest C concentration (38.0 t/ha) associated with large macroaggregates compared with RT (36.6 t/ha) and CT (29.7 t/ha). Significant differences in large macroaggregates C were only observed across the depths in NT and RT treatments with CT treatment showing a more uniform distribution of C across the tillage depths. Carbon associated with small macroaggregates varied significantly with tillage treatment where it decreased significantly with increase in tillage intensity; NT (37.8 t/ha), RT (33.5 t/ha) and CT (30.4 t/ha); in the 0-10 cm depth. In the lower depths, 10-20 cm and 20-30 cm it was found to be distributed uniformly across the treatments where no significant differences were found. However, significant effects were clear in tillage × depth interactions with C amount decreased with depth. No significant interactions were found in C associated with microaggregates in the 0-10 cm and 10-20 cm across the tillage treatments although the amount showed a decrease with increase in tillage intensity in the 0-10 cm depth, CT (25.2 t/ha), RT (23.0 t/ha) and CT (22.7 t/ha), respectively. Carbon amount decreased significantly with depth in NT and RT treatments and in CT, no significant difference was observed. Similar trends were observed in C associated with silt and clay as in microaggregates. There were no significant trends found between fertilizer application rate and total SOC in NT and CT treatments (Fig. 9). The strong positive correlation was only found in RT treatment. On the other hand, significantly higher differences ($p < 0.001$) were observed in aggregate-associated C in each tillage treatment with large and small macroaggregate having the higher concentrations than the micro-aggregates (Fig 10). Larger macroaggregates were having higher amounts of SOC than the small macroaggregates and micro-aggregates.

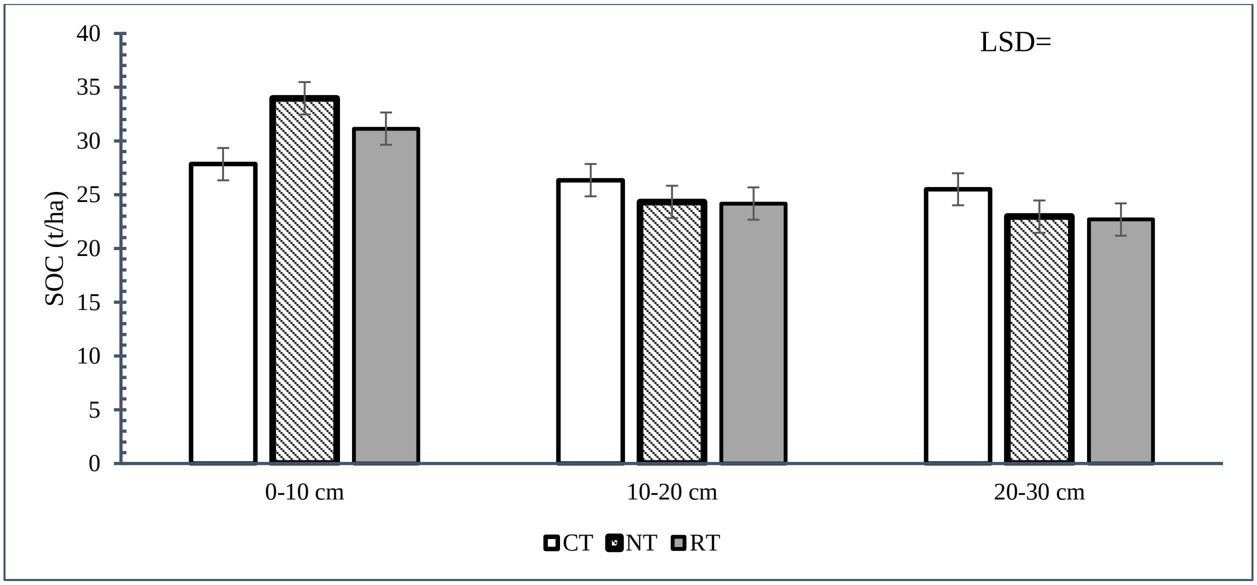


Fig. 8: Total soil organic carbon of different tillage treatments in different soil depth measured 13 years after implementation of the trial.

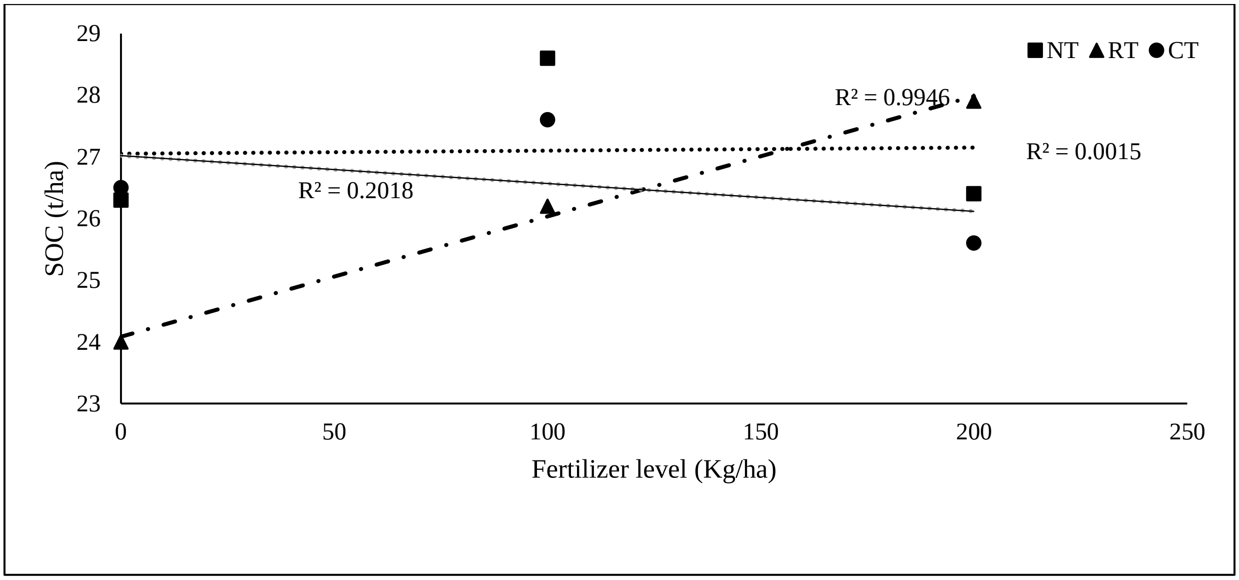


Fig. 9: Correlation between total soil organic carbon (SOC) and fertilizer application rate at different tillage treatments after 13 years of implementation of the trial.

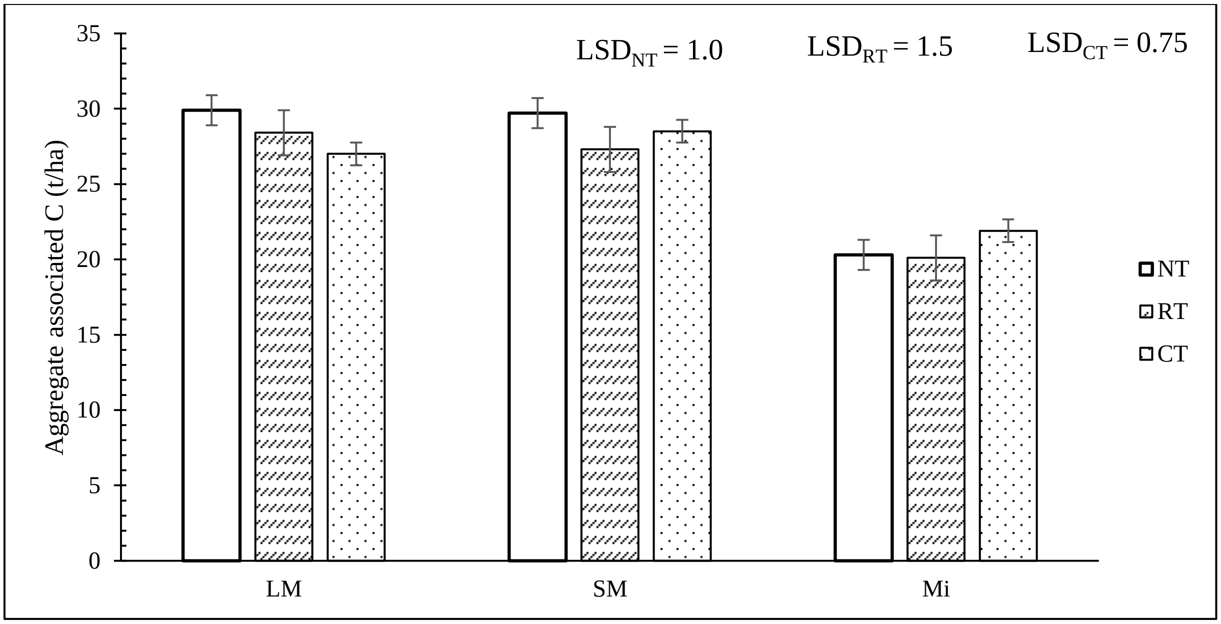


Fig. 10: Comparison of aggregate-associated C in NT, RT and CT treatments observed after 13 years of implementation of the trial. *Note: LM= large macroaggregates (> 2000 µm), SM= small macroaggregates (250-2000 µm) and Mi= microaggregates (53-250 µm).*

Table 2. Particulate SOC and aggregate size fraction C at 0-10, 10-20 and 20-30 cm depth after 13 years of implementation of the trial.

		0-10 cm					10-20 cm					20-30 cm				
Treatment	Fertilizer level	Aggregate fraction C (t/ha)					Aggregate fraction C (t/ha)					Aggregate fraction C (t/ha)				
		POC	LM	SM	Mi	SC	POC	LM	SM	Mi	SC	POC	LM	SM	Mi	SC
NT	0	24.2^{bcde}	35.0^{abc}	37.2^{cde}	24.5^{bcd}	35.5^{c}	17.3^{abc}	26.5^{abc}	25.4^{abcd}	17.5^{abc}	25.9^{abc}	16.2^{ab}	25.9^{abc}	22.0^{a}	16.8^{ab}	23.3^{ab}
	100	26.9^{e}	42.7^{bc}	38.9^{e}	25.9^{d}	33.9^{c}	18.7^{abcde}	28.9^{abc}	27.3^{abcde}	18.7^{abcd}	25.5^{abc}	18.2^{abcd}	24.8^{ab}	27.7^{abcde}	20.2^{abcd}	28.4^{abc}
	200	24.7^{cde}	36.3^{abc}	37.4^{de}	25.1^{cd}	35.1^{c}	17.4^{abc}	24.9^{ab}	$27.2a^{bcde}$	17.4^{abc}	26.6^{abc}	16.2^{ab}	24.0^{a}	24.1^{ab}	16.8^{ab}	21.4^{a}
	Mean	**25.3^{d}**	**38.0^{b}**	**37.8^{d}**	**25.2^{c}**	**34.9^{c}**	**17.8^{ab}**	**26.8^{a}**	**26.6^{ab}**	**17.9^{a}**	**26.0^{a}**	**16.9^{ab}**	**24.9^{a}**	**24.6^{ab}**	**17.9^{a}**	**24.4^{a}**
RT	0	20.5^{abcde}	30.0^{abc}	29.5^{abcde}	22.5^{abcd}	27.1^{abc}	17.3^{abc}	24.8^{ab}	25.3^{abcd}	19.0^{abcd}	25.5^{abc}	15.1^{a}	22.8^{a}	21.2^{a}	16.4^{a}	23.2^{ab}
	100	23.5^{bcde}	36.5^{abc}	35.0^{bcde}	22.5^{abcd}	32.7^{bc}	16.2^{ab}	22.4^{a}	23.9^{ab}	18.4^{abcd}	27.1^{abc}	17.0^{abc}	26.5^{abc}	23.5^{ab}	18.2^{abcd}	27.4^{abc}
	200	25.8^{de}	43.3^{c}	35.9^{bcde}	24.1^{abcd}	34.4^{c}	18.2^{abcd}	25.7^{abc}	26.8^{abcde}	20.3^{abcd}	30.8^{abc}	16.9^{abc}	23.7^{a}	24.6^{abc}	19.2^{abcd}	25.6^{abc}
	Mean	**23.3^{cd}**	**36.6^{b}**	**33.5^{cd}**	**23.0^{bc}**	**31.4^{bc}**	**17.2^{ab}**	**24.3^{a}**	**25.3^{ab}**	**19.3^{ab}**	**27.8^{ab}**	**16.3a**	**24.3^{a}**	**23.1^{a}**	**17.9^{a}**	**25.4^{a}**
CT	0	20.3^{abcde}	31.2^{abc}	28.8^{abcde}	21.3^{abcd}	28.7^{abc}	17.7^{abcd}	25.4^{abc}	26.4^{abcde}	18.9^{abcd}	28.6^{abc}	19.1^{abcde}	24.7^{ab}	27.3^{abcde}	24.5^{bcd}	31.6^{abc}
	100	22.0^{abcde}	29.0^{abc}	33.4^{abcde}	25.4^{cd}	28.9^{abc}	20.5^{abcde}	28.4^{abc}	29.7^{abcde}	23.7^{abcd}	31.2^{abc}	18.3^{abcd}	25.3^{abc}	27.4^{abcde}	20.6^{abcd}	28.0^{abc}
	200	19.9^{abcde}	28.7^{abc}	29.1^{abcde}	21.6^{abcd}	27.8^{abc}	19.0^{abcde}	25.7^{abc}	29.6^{abcde}	20.7^{abcd}	27.7^{abc}	17.5^{abcd}	24.0^{a}	25.1^{abcd}	20.7^{abcd}	26.8^{abc}
	Mean	**20.7^{bc}**	**29.7^{ab}**	**30.4^{bc}**	**22.7^{bc}**	**$28.5a^{b}$**	**19.0^{ab}**	**26.5^{a}**	**28.6^{abc}**	**21.1^{ab}**	**29.2^{ab}**	**13.3^{ab}**	**24.7^{a}**	**26.6^{ab}**	**21.9^{bc}**	**28.8^{ab}**
t × d × f	LSD_{POC}= 4.3, LSD_{LM}= 9.3, LSD_{SM}= 6.5, LSD_{Mi}= 4.1, LSD_{SC}= 5.4															

Note: NT= no-till with mulch, RT= rotational tillage with mulch, CT= conventional tillage, LM= large macroaggregates (> 2000 µm), SM= small macroaggregates (250-2000 µm), Mi= microaggregates (53-250 µm) and SC= silt and clay (< 53 µm). t= tillage, d= depth and f= fertilizer leve.

3.5 Discussion

3.5.1 Tillage system and fertilizer application rate on soil aggregation and infiltration

Tillage intensity affected aggregate size distribution in all treatments (Fig 1). Larger macroaggregate decreased significantly with the increase in tillage intensity and this was more pronounced on the 0-10 cm depth where RT and CT were found to be significantly lower than NT treatment. Mechanically disruption of tillage may have a bigger impact on larger aggregates compared with smaller aggregates. Smaller macroaggregates were also affected by tillage intensity where it was found to be significantly reduced under CT than RT and NT where differences were not observed in these treatments across soil depth. However, the impact and magnitude of tillage in small macroaggregates was much reduced compared to large macroaggregates. The increase of large macroaagregates in NT system, especially in the 0-10 cm depth, could be attributed to less mechanical disturbance and permanent return and placement of organic soil cover and larger biological activity under this system. Soil organic matter is a major binding agent which binds soil particles together into soil aggregates. Further, NT in this trial was, on the other study conducted on the same trial, found to contain a higher population of termites, beetles and millipedes (Sithole et al., 2017) and these might have an influence on soil aggregation under dry conditions where other ecosystem engineers (earthworms) are limiting. Although studies on termites in soil aggregation are limiting, but it is evident that they influence microstructure through the formation of fecal and oral pellets in microaggregates size class under semi-arid to dry conditions (Fall et al., 2001). These results were in agreement with those of Paul et al. (2013) in the study conducted in Ferralsols which indicated that the amount of large and small macroaggregates were consistently higher under reduced tillage compared with conventional tillage in the trial that has been for over five years under high rainfall region. Higher large and smaller macroaggregates and more abundant soil macrofauna, particularly termites and millipedes, in these treatments may also have increased infiltration rate in the NT and RT treatments as compared with CT treatment. Mando et al. (1996) reported that termites may have a great impact on soil properties and genesis. The dense network of termite galleries improve porosity and aeration, infiltration and water storage and as a result, improves soil primary productivity.

Water stable aggregates represented by mean weight diameter (MWD) was also influenced by tillage intensity (Fig 4) where NT was found to be 10% higher than both CT and RT. The effect of tillage treatment on MWD was only observed in the soil surface, 0-10 cm, where NT treatment had a significantly higher water stable aggregates than RT and CT treatments, respectively. This was also attributed to the increase in bulk SOC concentration in the soil surface under these treatments. Similar results were also reported by Zhang-liu et al. (2013). In addition, non-significant water stable aggregate observed in CT treatment across the tillage depth could be attributed to a more even distribution of soil organic residues in the soil profile caused by tillage. For example, in a study conducted in 26 agricultural soils using wet sieving method, it was found that high significant correlation for the relationship between SOM and aggregate stability and no other soil constituent investigated had a significant relationship with aggregate stability indicating that SOM was mainly responsible for the stabilization of the aggregates in these soils (Chaney and Swift, 1984).

With respect to the effect of fertilizer application rate on soil aggregation and aggregate stability, there were no significant correlation trends found in all treatments which can be explained with certainty. From 0 N to 100 kg/ha N application rate, aggregate stability and aggregation increased and at a high rate, 200 kg/ha N application, these decreased perhaps due to the observed similar trend found in SOC correlation with N-fertilizer application rate. Soil organic carbon is the major binding agent of the soil particles and its changes across the treatments may also influence soil aggregation and stability. This is in contrast with some studies which have suggested that the increase in N-fertilizer application rate will increase biomass production and consequently SOC and aggregate stability. This could be attributed to the complex interaction of soil type, climate and the environment which in turn highlight the importance of site-specific studies to improve our understanding of mechanisms involved in sustainable soil management practices.

3.5.2 Tillage system and N-fertilizer application rate on SOC

In the present study, no significant changes were detected in the SOC even after 13 years of implementation of NT with permanent soil residue cover and application of higher rates of nitrogen fertilizer. Significant differences were only observed in the depth distribution of SOC as affected by tillage type with NT and RT having high SOC in the soil surface than in sub-soil. This is consistent with the recent literature which have shown that overall C stock is often not enhanced under CA when considering the upper 0-30 cm depth or deeper despite the higher C content in the upper centimeters of the soil (Bationo et al., 2007; Govaerts et al., 2009; Luo et al., 2010; Anyanzwa et al., 2010). Particulate organic C, on the other hand, varied significantly with tillage treatments but only in the top 0-10 cm depth where it decreased with increase in tillage intensity.

On reduced tillage treatments, it was found to be stratified on the top 0-10 cm depth and in CT treatment it was distributed uniformly across the treatment depths. Similar results of high SOC in the soil surface under NT have been reported (Blanco-Moure et al., 2013). The stratification of the SOC pool in the soil surface is due to the residue placement on the surface and reduces disturbance and decomposition in the soil surface (Lopez-Garrido et al., 2011).

Carbon associated with large and small macroaggregates decreased marginally with an increase in tillage intensity in the top 0-10 cm depth and it significantly decreased across the sampling depth. When looking at each treatment, C associated with large macroaggregates was higher than that associated small macroaggregates and microaggregates in all treatments which indicates that implementation of reduced tillage and application of residues soil cover results in the formation of larger stable aggregates which can sequester more C. Similar results were observed by Sainju et al. (2009). Aggregates protect the mineralization of soil C by reducing microbial access that binds them (Six et al., 2000). Macroaggregates has a higher concentration of C than smaller macroaggregates and microaggregates because macroaggregate is composed of binding agents plus microaggregates (Elliott, 1986). However, different results have been reported in other studies where there were no differences in aggregate-associated C between tilled and reduced tillage systems (Ayuke et al., 2011; Paul et al., 2013). The differences in these studies indicate the importance of site-specific studied to better understand C stabilization across different agroecosystems.

3.6 Conclusion

The results of this study clearly showed that tillage practice affects the distribution of aggregates and aggregate stability over time. Conventional tillage practice negatively affected aggregate stability compared with NT management practice indicating the increasing susceptibility to soil degradation. Tillage practice did not affect total SOC across the treatments, but it affected POC only in the soil top surface of the 0-10 cm indicating that this C pool is a sensitive indicator of tillage-induced changes. Macroaggregates increases C protection in the studied soil. The weak interaction between residue retention and/SOC and fertilizer application rate has highlighted the need for a better scientific understanding of carbon stabilization across different semi-arid of 1:1 clay minerals in sub-tropical soils.

3.7 Acknowledgements

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CHAPTER 4

Long-term changes of soil chemical characteristics in no-till conservation agriculture in a semi-arid environment

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4.1 Abstract

Soil management practices may change soil chemical properties and thus fertility. The magnitude of change varies depending on soil type, cropping systems, climate and management practices. The objective of this study was to evaluate the effect of no-till (NT), rotational tillage (RT) and conventional tillage (CT) treatment on soil chemical properties of a semi-arid Ferralsols Haplic in Bergville (28°55'26.83"S, 29°33'38.64"E) South Africa. Soil chemical properties were measured 13 years after the implementation of the trial. Differences ($p < 0.05$) were found in total soil organic carbon (SOC) with NT having the highest concentration (81.3 t/ha) compared to RT (78.0 t/ha) and CT (79.6 t/ha). The concentration of Nitrogen (N) followed the same trend where it was found to be higher under NT than RT and CT, respectively. SOC and N were found to be highly concentrated in the 0-10 cm depth. Phosphorus was significantly higher ($p < 0.001$) under NT (0.0213 t/ha) than RT (0.0127 t/ha) and CT (0.00704 t/ha). A large amount of phosphorus was in the 0-10 cm depth in NT and it was distributed more uniformly under RT and CT. Potassium was also higher ($p < 0.05$) under NT (9.73t/ha) than RT (9.52t/ha) and CT (8.00 t/ha). It was found to be uniformly distributed across the soil depths in all tillage treatments. No significant differences were found in the concentration of calcium across the tillage treatments, however, it was observed to increase with an increase in depth under NT and RT and to decrease with increase in depth in CT. The soil of NT and RT treatments had lower pH values (5.80 and 5.86) than CT (6.68) at 0-10 cm depth while in the lower depths, 10-20 and 20-30 cm depth was observed to increase significantly, by 1.2 and 0.9 units in NT and RT respectively. Similar trends were observed in CEC. These results indicated that NT treatment increase nutrient availability in the studied soil which was more linked to the distribution of SOC and variability of pH along the soil profile, thus indicating the potential of implementing NT in the semi-arid environment.

Keywords: Ferralsols Haplic, soil chemistry, no-till, conservation agriculture

4.2 Introduction

Long-term sustainability of crop production depends on soil quality and fertility. Poor soil management practices such as the use of conventional mouldboard plow can lead to soil degradation and a decline in environmental quality and consequently crop yields (Karlen et al., 1997). Soils under no-till conservation agriculture have been recognised widely that they generally contain higher soil organic carbon (SOC) than conventional mouldboard plow system (Conant et al., 2007). Differences in nutrient distribution and transformation have been observed which are linked more to SOC (Galantini et al., 2000). Interacting factors such as less soil disturbance and mixing, increased residue return, decreased risk of soil erosion, reduced soil temperature and higher moisture content are reported to results in this increase of SOC under no-till system (Blevins and Frye, 1993; Franzluebbers et al., 1995; Hussain et al., 1999).

Tillage type has been also shown to affect other important soil chemical characteristics and differences between no-till and conventional mouldboard plow system has been observed with respect to pH, cation exchange capacity (CEC) and other important plant nutrients (Lopez-Fando and Pardo, 2009). However, the response of soil fertility to tillage is site-specific and depends on soil type, cropping systems, climate, fertilizer application and other management practices

(Thomas et al., 2007; Rahman et al., 2008; Verhulst et al., 2010). For instance, long-term experiments have shown that the effects of no-till on SOC and other nutrients are positive although most of these studies were concentrated on temperate, cooler environment (West and Marland, 2002; Six et al., 2002; Thomas et al., 2007). In sub-tropical environments, there may be higher chances for soil organic matter (SOM) decomposition because of higher temperatures. And a semi-arid climate condition may have a low biomass production and C input than humid and a sub-humid region (Dalal and Chan, 2001). As a result, the effect of tillage on SOC and other soil important nutrients in sub-tropical, semi-arid areas may be different from temperate, cooler and wetter climates. Consequently, Ishaq et al. (2002) concluded that studies that are site specific are more important so that more accurate generalisation can be made regarding the conditions required for sustainable tillage.

Bergville in South Africa has a sub-tropical and semi-arid climate and it forms the most important part of the dryland maize production system in KwaZulu-Natal Province. One of the potential constraints to long-term adoption of continuous no-till is the possibility of densification. This is particularly true in this region and other arid and semi-arid areas in the country and rest of sub-Saharan Africa, particularly in the commercial cropping enterprises, and this may complicate well-established fertilization methods. In addition, low levels of SOM, the predominance of 1:1 low activity clay and lack of freezing and thawing and soil compaction can be a severely limiting factor in these areas. This may alter water and chemical movement resulting in environmental problems (Hamza and Anderson, 2005). In such cases where continuous no-till has been practiced over an extended period, periodic or rotational tillage and different tillage methods have been recommended to encounter the problem (Lopez-Fando and Pardo, 2009).

Therefore, the objective of this study was to assess the effects of tillage system, residue retention and fertiliser application rate on the amount and distribution of SOC and nutrients in the 0-10, 10-20 and 20-30 cm depth of a Ferralsols Haplic in a sub-tropical and semi-arid environment.

4.3 Materials and methods

4.3.1 Experimental site

The experimental site was located approximately 35 km south of Bergville in Winterton, Gourton Farm (28°55'26.83"S, 29°33'38.64"E, 1038 m above sea level), KwaZulu-Natal Province. The trial was established in 2002/2003 growing season in an area that was under no-till since 1990. The mean annual rainfall of the area is 643 mm/year receive mostly during the summer season between October and March and the mean air temperature of the site is 19.3 °C in June and 27.9 °C in January. Previously, the trial site has been under dry maize commercial production in rotation with soybean until the establishment of the trial in 2002/2003 growing season. Since the beginning of the experiment, the trial site was planted to dry maize continuous monocropping, in summer and left fallow during the winter months. The soil was classified as Ferralsols Haplic (FAO, 2006) equivalent to Hutton non-swelling with clay loam soil texture (Soil Classification Working Group, 1991). The average bulk density of the top 0-30 cm depth was 1.6 g/cm^3 for NT and CT and 1.7 g/cm^3 for RT.

4.3.2 Experimental details

The experiment included three tillage treatments, namely, no-till (NT), annual conventional tillage (CT) and rotational tillage (RT). In NT and RT treatments about 10-12 t/ha/year of maize residues were left on the soil surface, thus forming permanent soil cover, while in CT treatments residues were removed on the soil surface after harvest. The field experiment was set up as a split plot design with randomized tillage strips forming the whole plot and N-fertilizer application rates forming the sub-plots which were randomized within the whole plots. The sub-plots had 9.5 m × 12 rows of maize at a density of 70 000 plants/ha. The treatments were replicated three times. No-tillage involved direct seeding into the undisturbed soil using NT planter. CT, on the other hand, involved ploughing with mouldboard plow to a depth of 30 cm and disking to a depth of 10 cm while RT involved CT after every four years of NT. Nitrogen was applied at three rates, 0, 100 and 200, as lime ammonium nitrate (LAN). Nitrogen was applied as top dressing four weeks after planting. Potassium (K) and phosphorous (P) were applied at planting in the band at a rate of 50 and 20 kg/ha, respectively. Lime (Calcitic) was applied at a rate of 2 Mg/ha every second season to the entire treatments. It was incorporated during ploughing in CT plots and surface applied in NT plots. Weeds were controlled chemically using a combination of mesotrione, atrazine, S-metolachlor and 2,4-D. The only pesticide applied at planting was pyrethroid (Decis Forte) to control cutworms. Leaf fungal disease (grey leaf spot, northern corn leaf blight and rust) were controlled using carbendazim plus flusilazole and azoxystobin. Tractor-drawn ring equipped with an 18 m wide boom sprayer was used in the application of chemicals.

4.3.3 Soil sampling and analysis

Soil samples were taken at the end of 2015/2016 growing season from three undisturbed soil samples on a randomly selected position of each treatment at three depths: 0-10, 10-20 and 20-30 cm using the soil auger. Soil samples were air-dried, sieved through 8 mm sieve then 5 mm sieve and mixed before the analysis.

The pH was measured using 1M KCl at a ratio of 1:2.5 (Diez et al., 2004). The supernatant liquid was stirred with a glass rod and allowed to stand for 30 minutes. An electrode pH meter (PHM 210) was used to measure the pH of the supernatant liquid.

Soil organic C and N were analysed by an automated Dumas dry combustion method using a LECO CNS-2000 (Leco Corporation, Michigan, USA) (Leco Corporation, 2012). Briefly, air-dried soil samples were passed through a 0.5 mm sieve size, then a 0.5 g sample was then measured and put into the LECO for analysis of C and N. The procedure was based on dry combustion of air-dried samples in crucibles, subjected to a 1350 °C furnace temperature for about 7 minutes.

Exchangeable bases and P were extracted using 70% nitric acid by EPA 3052 method (EPA, 1996). Briefly, 0.5 g soil samples were placed in reaction vessels and 8 mL of nitric acid was added. The soil was then heated at 180°C for 30 minutes then filtered into 0.45 micropores syringes before analysis. The soil was then analyzed using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, 5300 DV, Perkin Elmer, USA), 5300 DV, for Ca, Mg, K and Na using a wavelength of 550 nm (Wolf and Beegle, 2009). CEC was determined as the sum of bases.

4.3.4 Statistical analysis

The data collected was subjected to analysis of variance using GenStat 17th Edition (VSN International, Hemel Hempstead, UK) and means were separated using Tukey's least significant difference (LSD) at 5% level of significance. Correlation of physio-chemical properties were subjected to principal component analysis (PCA) based on correlation matrix and biplots for all tillage regimes and fertilizer application rate.

4.4 Results and discussion

4.4.1 pH response to tillage management

Soil pH was significantly different ($p < 0.001$) among the different tillage treatments. The pH of CT (6.30) and RT (6.35) was observed to be significantly higher than of NT (6.06) treatment (Fig. 1). However, there were no differences between NT and RT. There were also no differences ($p > 0.05$) found with respect to fertilizer application rate. This may be due to the lime that was applied every second season in the field trial which may have decreased the acidifying effects of nitrogen fertilizer at the higher rates of application. Many studies (Franzluebbers and Hons, 1996; Matowo et al., 1999; Limousin and Tessier, 2007) have reported the decrease in pH with the increase in the application of nitrogen fertilizers where lime was not applied at all. As a result, the pH was reduced at higher rates of application in these studies. Furthermore, NT treatment and RT exhibited a strong pH vertical gradient than CT. The pH of NT and RT increased significantly by 1.2 and 0.9 units respectively with the increase in soil depth (from the soil surface to a depth of 30 cm) while that of CT treatment was more uniform. Our results are in line with those previously reported by Lopez-Fando and Pardo (2009) where a more uniform pH distribution in CT with an increase in depths was observed. Uniform pH distribution is probably due to thorough cultivation of the soil every season. Numerous studies (Franzluebbers and Hons, 1996; Limousin and Tessier, 2007; Thomas et al., 2007) have reported that the soil becomes more acidic under NT than CT because of the greater soil organic matter accumulation in the topsoil in NT which led to acidity from decomposition of organic material (Franzluebbers and Hons, 1996).

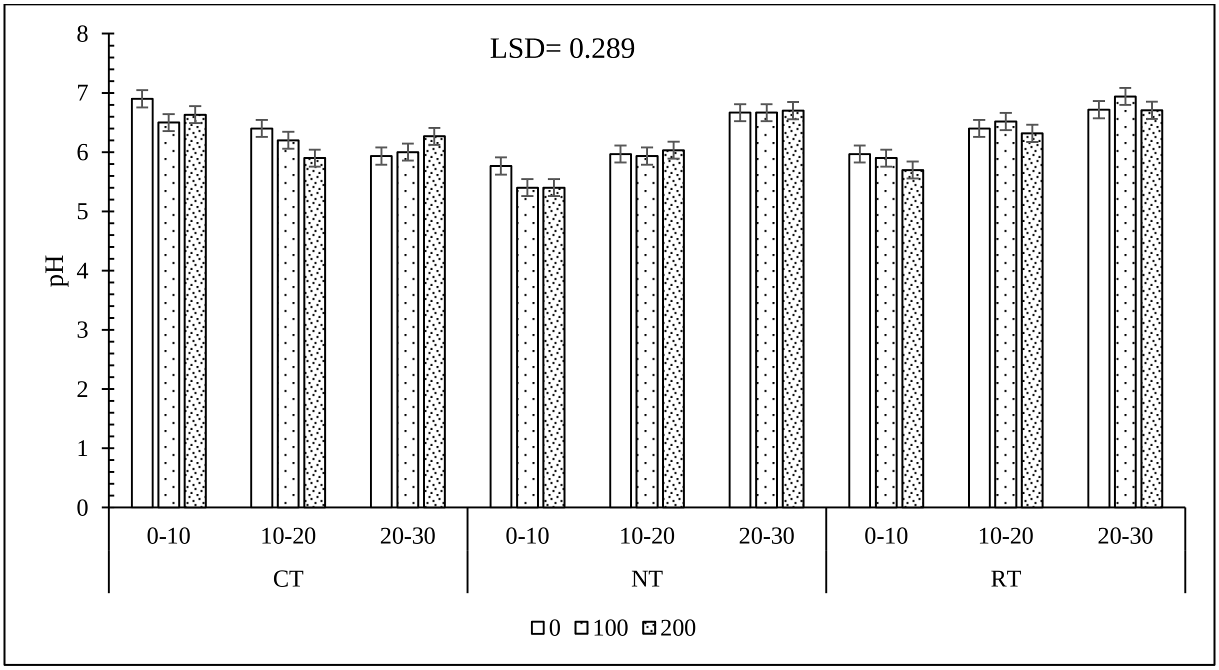

Fig. 1: Soil profile distribution of pH as affected by tillage and N-fertilizer application rate at 0-10, 10-20 and 20-30 cm depth. Note CT= conventional tillage, NT= no-till and RT= rotational tillage.

4.4.2 Soil organic C and N

Marginal differences of C concentration were found in different tillage treatments in the 0-30 cm depth with NT having the highest C concentration (Table 1). In reduced tillage treatments (RT & NT) a large amount of SOC was concentrated in the top 0-10 cm depth while in CT treatment SOC was uniformly distributed across the profile within 0-30 cm depth. Similar trends were observed in soil organic nitrogen (SON) (Table 1). Other authors have also reported similar results of a strong concentration gradient of SOC and N under NT from the surface to subsurface layers (Dalal et al., 1991; Heenan et al., 1995; Limousin and Tessier, 2007). Our expectations were to find significant differences between NT and CT treatment in total SOC concentration after 13 years of implementation of NT system where about 10 t/ha/yr of residue were left each year in the soil surface, however, the results only showed marginal differences. Verhulst et al. (2010) cited that the mechanisms that govern the balance between increased, similar or lower SOC after conversion to NT are not clear especially in tropical and sub-tropical areas. Our results, therefore, might indicate that the biochemical kinetics of the processes involved in the breakdown of soil organic matter after conversion to NT occurs very slowly in the studied soil, Ferralsols Haplic.

The C/N ratios of the top 0-20 cm of all tillage treatments were similar (Table 1). However, significant ($p < 0.05$) differences were observed in NT and RT treatments with increase in depth. In both cases, C/N ratio was observed to increase with depth while in CT it remained uniform. The increase in C/N ratio low layers, especially under NT where significant differences were observed between 0-20 and 20-30 cm (Table 1), may indicate that SOC is less humified perhaps due to low nitrogen needed by microorganisms. Thomas et al. (2007) in semi-arid subtropic Luvisol observed an increase in N in the top 0-10 cm compared to lower depth, 20-30 cm, which suggested greater immobilization of N in the soil surface than in the subsoil which resulted in increase in C/N ratios.

Table 1: Soil organic carbon, soil organic nitrogen and C/N ratio of different tillage treatments.

		Tillage system		
	Soil depth (cm)	NT	RT	CT
Soil organic C (t/ha)	0-10	34.0d	31.1cd	27.8bc
	10-20	24.3ab	24.2ab	26.3abc
	20-30	23.0a	22.7a	25.5ab
	Total	**81.3b**	**78.0a**	**79.6ab**
Pt= 0.46, LSD= 1.72 P_{t*d} < 0.001, LSD= 3.00				
Soil organic N (t/ha)	0-10	2.30d	1.69c	1.58c
	10-20	1.47bc	1.21abc	1.35bc
	20-30	0.86a	1.00ab	1.31abc
	Total	**4.63b**	**3.90a**	**4.24a**
P_t = 0.024, LSD= 0.17 P_{t*d} < 0.001, LSD= 0.30				
C:N ratio	0-10	14.8a	18.4ab	17.6ab
	10-20	16.5a	20.0ab	19.5ab
	20-30	26.7c	22.7bc	19.5ab
	Total	**17.5a**	**20.0a**	**18.8a**
P_t= 0.33, LSD= 3.04 P_{t*d}= 0.003, LSD= 5.27				

Note: t= tillage, t*d= tillage*depth. Numbers in the same cilumn not sharing the same letter differ significantly at LSD (P= 0.05).

4.4.3 Nutrient stocks

Phosphorus concentration was significantly ($p < 0.001$) higher under NT (0.0213 t/ha) compared to RT (0.0127 t/ha) and CT (0.00704 t/ha) (Table 2a). Depth distribution of P concentration was uniform under CT and RT while in NT treatment was observed to be stratified in the soil top 0-10 cm layer although it increased again in the 20-30 cm depth in 100 and 200 N-fertilizer application rate. Nitrogen fertilizer application rate did not seem to affect P in the studied soil. Our results are similar to those of Thomas et al. (2007) and Lopez-Fando and Pardo (2009) who reported that the concentration of P was higher in the top 0-10 cm of the soil depth. These authors reported this effect to result from less mixing of fertilizer P with soil resulting from no tillage or less tillage, possible increase of organic P and shielding of P adsorption sites (Schomberg et al., 1994).

Significant differences ($p < 0.05$) were found between the tillage treatments in K concentration in the soil with NT having the highest concentration (10.4 t/ha) followed by CT (9.73 t/ha) and RT (9.52) (Table 2b). Potassium concentration was found to be uniformly distributed across the tillage depths in all tillage treatments and no trend was observed on the effect of N-fertilizer application rate on K distribution. These results support those by Limousin and Tessier (2007) as well as Lopez-Fando (2009) who observed higher concentration of K under NT but contradict other studies which found higher concentration gradient of K in the top 10 cm of the soil depth (Lal et al., 1990; Asghar et al., 1996; Thomas et al., 2007). This could have been due to the lower pH observed under NT which may increase the weathering of minerals, thus making K exchangeable (Limousin and Tessier, 2007). While in the treatment of CT and RT, higher pH could have increased the availability of K in the soil surface.

No significant differences ($p > 0.05$) were found in Ca concentration across the tillage treatments (Table 2c). Significant differences ($p < 0.001$) were only observed in the tillage × depth interaction. In NT and RT treatments, Ca increased with increase in depth but only in the 0-10 and 10-20 cm depth and it decreased in the 20-30 cm depth while in CT treatment the concentration decreased with increase in depth. Calcium concentration in CT treatment in the 20-30 cm depth was 68%, 34% and 36% smaller in 0, 100 and 200 N-fertilizer application rates. Our results are in line with those by Lopez-Fando and Pardo (2009) on the study that was conducted in the semi-arid area in Calcic Luvisol which found an increase in Ca concentration with depth in reduced tillage treatments and an increase in its concentration in conventional tillage treatments. This may be due to increase in pH with an increase in depth which may increase the availability of Ca. Limousin and Tessier (2007) also observed similar results where they found a strong correlation ($r^2 = 0.95$) between exchangeable Ca and pH under NT as compared to CT system.

No differences ($p > 0.05$) were found between the tillage treatments in Mg concentration. Differences ($p < 0.05$) were only found in tillage × depth interaction but only in CT treatment. The concentration of magnesium decreased ($p < 0.05$) with an increase in depth. Magnesium and Ca are two divalent cations similar in nature (Table 2d). However, Mg did not seem to follow the behavior of Ca. Limousin and Tessier (2007) argued that plants could have influenced the distribution of this element and their uptake could have been more important for Mg than Ca. Furthermore, this could be attributed also to the fact that Mg is involved in isomorphic substitution of clay minerals while Ca is not. As a result, this could have influenced the retention of Mg in the upper layers in reduced tillage treatments. Sodium (Na) on the other hand was found to be distributed uniformly across the tillage treatments and across the treatment depths (Table 2e). Mineralogical nature and climate condition could probably have influenced the distribution of this mineral (. Limousin and Tessier, 2007)

Table 2a: Extractable P as affected by tillage system and N-fertilizer application rate.

Treatment	Depth (cm)	Fertilizer level (t/ha)		
		0N	100N	200N
CT	0-10	0.007a	0.011ab	0.008a
	10-20	0.002a	0.013ab	0.004a
	20-30	0.003a	0.002a	0.011ab
RT	0-10	0.010a	0.013ab	0.025ab
	10-20	0.010a	0.008a	0.009a
	20-30	0.014ab	0.017ab	0.010a
NT	0-10	0.069c	0.025ab	0.038b
	10-20	0.003a	0.010a	0.010a
	20-30	0.000a	0.015ab	0.022ab

$P_t < 0.001, LSD_t = 0.004$

$P_{t*d} < 0.001, LSD_{t*d} = 0.008$

$P_{t*d*f} < 0.001, LSD_{t*d*f} = 0.013$

Note: t= tillage, t*d= tillage*depth and t*d*f= tillage*depth*fertilizer level of nitrogen. Numbers in the same cilumn not sharing the same letter differed significantly at LSD (P= 0.05).

Table 2b: Extractable K as affected by tillage system and N-fertilizer application rate.

Treatment	Depth (cm)	Fertilizer level (t/ha)		
		0N	100N	200N
CT	0-10	9.17ab	9.44ab	10.5ab
	10-20	8.18ab	11.0b	11.2b
	20-30	9.09ab	10.7ab	8.3ab
RT	0-10	8.88ab	10.5ab	10.4ab
	10-20	9.60ab	10.2ab	9.39ab
	20-30	7.41a	10.1ab	9.26ab
NT	0-10	10.4ab	10.4ab	10.6ab
	10-20	9.66ab	10.5ab	10.9b
	20-30	9.84ab	10.9b	10.8b

$P_t = 0.007, LSD_t = 0.58$

$P_{t*d} = 0.44, LSD_{t*d} = 1.00$

$P_{t*d*f} = 0.08, LSD_{t*d*f} = 1.74$

Note: t= tillage, t*d= tillage*depth and t*d*f= tillage*depth*fertilizer level of nitrogen. Numbers in the same cilumn not sharing the same letter differed significantly at LSD (P= 0.05).

Table 2c: Extractable Ca as affected by tillage system and N-fertilizer application rate.

Treatment	Depth (cm)	Fertilizer level (t/ha)		
		0N	100N	200N
CT	0-10	7.06d	5.13bcd	4.78abcd
	10-20	3.66abc	3.95abc	3.73abc
	20-30	2.27a	3.41abc	3.06abc
RT	0-10	3.73abc	3.89abc	4.19abc
	10-20	4.14abc	3.60abc	5.54cd
	20-30	3.49abc	2.56ab	3.23abc
CT	0-10	3.71abc	3.54abc	3.41abc
	10-20	3.95abc	4.19abc	4.05abc
	20-30	4.50abcd	3.58abc	3.63abc

Pt = 0.38, LSDt = 0.48
Pt*d <0.01, LSDt*d = 0.83
Pt*d*f = 0.092, LSDt*d*f = 1.44

Note: t= tillage, t*d= tillage*depth and t*d*f= tillage*depth*fertilizer level of nitrogen. Numbers in the same column not sharing the same letter differed significantly at LSD (P= 0.05)

Table 2d: Extractable Mg as affected by tillage system and N-fertilizer application rate.

Treatment	Depth (cm)	Fertilizer level (t/ha)		
		0N	100N	200N
CT	0-10	3.54bc	3.47bc	3.90c
	10-20	2.50ab	3.20abc	3.10abc
	20-30	2.54ab	3.14abc	2.32a
RT	0-10	2.74ab	3.44abc	3.57bc
	10-20	3.01abc	3.02abc	3.06abc
	20-30	2.34a	2.69ab	2.69ab
NT	0-10	3.01abc	2.91abc	3.33abc
	10-20	2.90abc	3.15abc	3.18abc
	20-30	3.07abc	3.07abc	3.12abc

$P_t = 0.32$, $LSD_t = 0.19$
$P_{t*d} = 0.002$, $LSD_{t*d} = 0.33$
$P_{t*d*f} = 0.22$, $LSD_{t*d*f} = 0.58$

Note: t= tillage, t*d= tillage*depth and t*d*f= tillage*depth*fertilizer level of nitrogen. Numbers in the same column not sharing the same letter differed significantly at LSD (P= 0.05).

Table 2e: Extractable Na as affected by tillage system and N-fertilizer application rate.

Treatment	Depth	Fertilizer level (t/ha)		
		0N	100N	200N
CT	0-10	0.33a	0.34a	0.81b
	10-20	0.28a	0.38a	0.40a
	20-30	0.29a	0.45a	0.28a
RT	0-10	0.30a	0.36a	0.33a
	10-20	0.33a	0.35a	0.31a
	20-30	0.28a	0.32a	0.29a
NT	0-10	0.32a	0.31a	0.32a
	10-20	0.32a	0.32a	0.35a
	20-30	0.33a	0.33a	0.37a

$P_t = 0.005, LSD_t = 0.05$

$P_{t*d} > 0.02, LSD_{t*d} = 0.08$

$P_{t*d*f} > 0.05, LSD_{t*d*f} = 0.317$

Note: t= tillage, t*d= tillage*depth and t*d*f= tillage*depth*fertilizer level of nitrogen. Numbers in the same column not sharing the same letter differed significantly at LSD (P= 0.05).

4.4.4 Cation exchange capacity

Highly significant differences ($p < 0.001$) were observed in CEC as affected by tillage practice (Fig. 2). On average, conventional tillage had a significantly lower (86.9 mmolc.kg^{-1}) CEC than RT (98.3 mmolc.kg^{-1}) and NT (102.6 mmolc.kg^{-1}). Significant differences were also found in the interaction of tillage × depth. Cation exchange capacity increased with increase in depth in NT and RT and it remained relatively uniform in the CT treatment. This was similar to what was observed in pH results. The vertical gradient of CEC followed that of pH (Fig. 1). Similar trends were observed by other authors where pH was positively correlated to CEC regardless of the tillage system (Limousin and Tessier, 2007; Lopez-Fando and Pardo, 2009). According to Morais et al. (1976), as the pH decreased, CEC associated with organic matter decreases due to a reduction in pH-dependent cation exchange sites. Thus, the observed trend of lower pH in NT treatment than CT may have resulted in lower CEC in the top 0-10 cm soil depth with higher SOC under NT (Table 1). The impact of pH on CEC is on pH-dependent charges mainly of oxides of Al and Fe. The negative charges responsible for retaining bases/cations become less negative as pH drops due to the introduction of a proton (H^+). The variable charges are not associated with O.M but Fe and Al oxides OH^- functional groups which are subject to protonation a process common in the soil reported in the study (Limousin and Tessier, 2007).

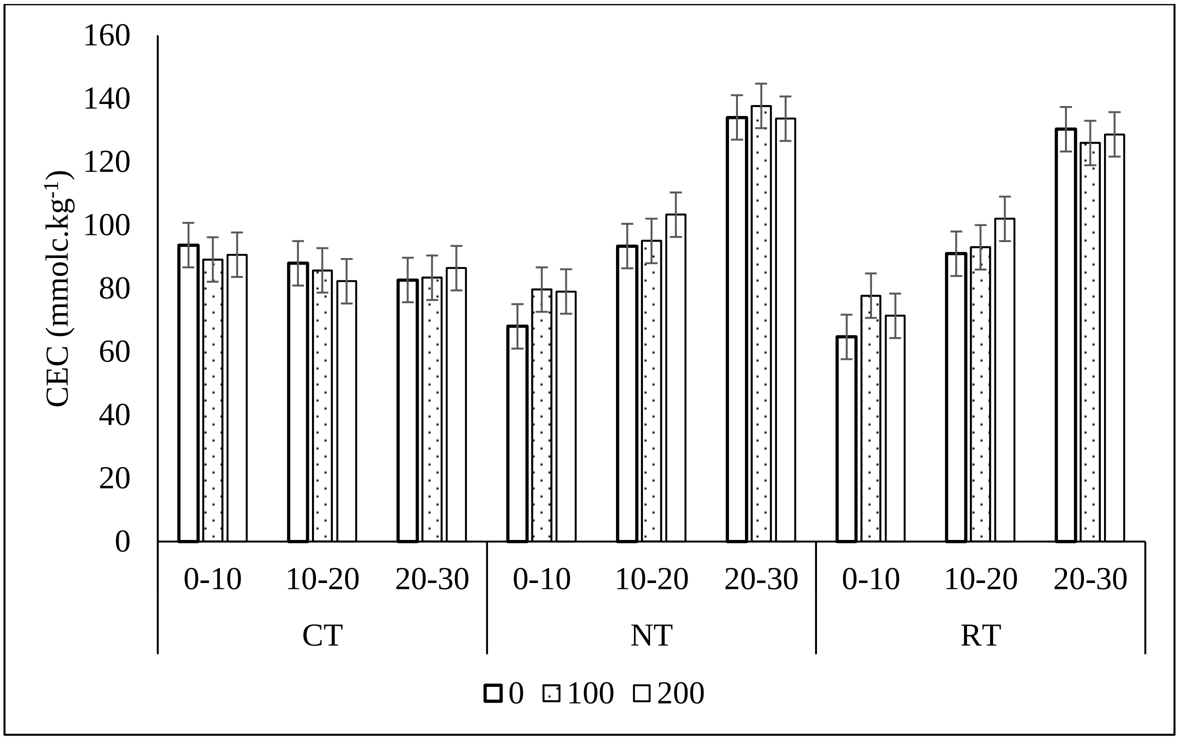

Fig. 2: Soil profile distribution of CEC 13 years after implementation of the trial as affected by tillage and N-fertilizer application rate at 0-10, 10-20 and 20-30 cm depth. Note: CT= conventional tillage, NT= no-till and RT= rotational tillage.

4.4.5 Correlation of soil major chemical properties

The results of the study showed a strong positive correlation between SOC, N and P (Fig. 3). These elements were found to be highly concentrated in the top 0-10 cm depth and they decreased with increase in depth (Table 1 & Table 2). This was attributed to more SOM that is found in the soil surface which increases the availability of these soil nutrients and decreases their availability with its decrease. Thomas et al. (2007) also found similar results where the concentration of these nutrients was highly correlated with the availability of SOC. Cation exchange capacity and pH were also found to be positively correlated. The pH is a master variable that controls the availability of soil nutrients. When pH increases the amount of nutrients in the exchange sites also increases and when it decreases, the amount of nutrients also decreases due to increase in aluminum toxicity and other trace elements. On the other hand, Ca and Na occupied the same position and direction meaning that they were exactly correlated. This is where there were no differences between the tillage treatments. Magnesium and K were also closely correlated with each other.

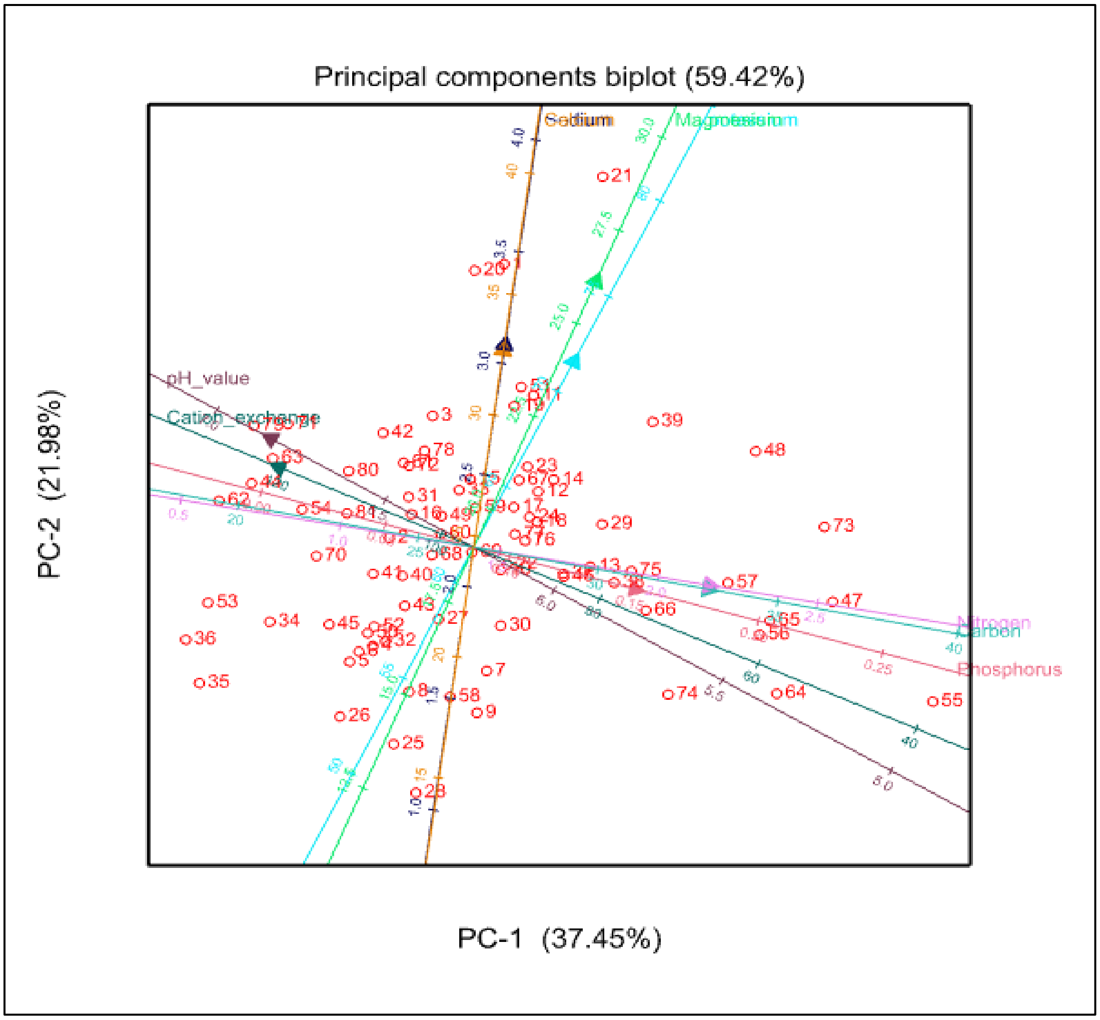

Fig. 3: Principal component (PC) analysis biplot showing the relationship between the measured soil chemical properties.

4.5 Conclusion

In conclusion, Ferralsols Haplic in this study was significantly affected by different tillage practices and residue retention. However, N-fertilizer application rate did not seem to have any effect. Soil pH, distribution of SOC and N, nutrients and CEC were affected as a result of various tillage treatments. Soil organic carbon accumulated in the soil surface in no-till and rotational tillage treatments compared to conventional tillage. The pH of NT and RT was lower in the soil surface and increased with increase in depth compared to CT where a more uniform distribution of organic matter was found. Similar trends were observed for CEC. Phosphorus and K concentration was found to be high under NT treatment compared to CT. Phosphorus was stratified in the soil surface while K was uniformly distributed across the tillage treatments. Calcium was high under NT and RT and increased with increase in depth while in CT it decreased with increase in depth. These results suggest that in the semi-arid area, nutrients are increased and this increase is not just concentrated in the topsoil but the entire plowing profile. They also indicate that the acidification under NT can be better managed by periodic addition of lime which accumulates in the sub-soil over time thus increasing the pH. They have shown that the decomposition of SOC sequestration is very slow in the studied soil.

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CHAPTER 5

Long-term effects of no-till conservation agriculture on maize grain yield under semi-arid rain-fed condition

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5.1 Abstract

Resilient and sustainable soil management systems are needed to overcome soil degradation, reduce soil fertility decline and to offset the predicted negative impact of climate change. Conservation agriculture (CA) has been recommended as the possible alternative for improving soil quality parameters and yields. However, maize yields under rain-fed conditions are usually variable and concerns have been raised about lack of evidence for CA benefits in sub-Saharan Africa. This study assessed the long-term effect of no-till (NT) with mulch, rotational tillage (RT) with mulch, conventional tillage (CT) without mulch removed, rainfall and soil quality parameters on maize yield. On average maize, yields were increased in NT (12.3 t/ha) and RT (12.4 t/ha) under higher rate of N application (200 kg/ha) than CT (11.8 t/ha) than low and medium N application rates. However, yields decreased in NT with the reduction of N rate to medium N rate (100 kg/ha) and low rate (0 t/ha) and it was 10.6 t/ha and 6.6 t/ha as compared to RT and CT. Under low rainfall < 400 mm/year, the average yield in higher N rate was 9.13 t/ha, 7.96 t/ha and 7.00 t/ha in NT, RT and CT, respectively across the years. However, when the average rainfall was above 600 mm/year, yields averaged at 13.3 t/ha, 13.7 t/ha and 13.5 t/ha in NT, RT and CT under high N rate (200 kg/ha) across the years. Principal component analysis (PCA) to assess some biological, physical and chemical components of the soil that contributed to maize yield showed no parameter that seemed to be related to maize yield. This was attributed to the complex interaction of bio-physio-chemical parameters with the environment. The results of this study found that yields improve over time under CA and this is more pronounced during the drought period. Yields improvements under CA require the application of the higher rate of N fertilizer in correct amount. Therefore, it is recommended that CA is implemented in semi-arid areas to improve soil conditions, water conservation and to achieve optimum yields.

Keywords: Maize yield, clay loam, feralsols Haplic, conservation agriculture

5.2 Introduction

Soil degradation is a major problem in sub-Saharan Africa (SSA). This combined with water scarcity, the predicted impacts of climate change and ever-increasing population poses a threat to the region’s ability to self-supply enough food for current and future generations. In such cases, conservation agriculture (CA) has been endorsed by many researchers because of its powerful mechanism to adapt by increasing resilience to land degradation, drought and increasing water use efficiency (Hobbs, 2007; Hobbs et al., 2008; Giller et al., 2009). Its effectiveness in resilience characteristics is expected to be measured in terms of crop yield. CA is defined as a concept for resource-saving agricultural productivity that strives to achieve acceptable profits while concurrently minimising negative impacts on the environment (FAO, 2010). It involves reduced tillage or no-till, permanent soil cover and crop rotations to protect soil against soil erosion, enhance soil fertility and to supply food for the increasing population (Rusinamhodzi et al., 2011). Other benefits associated with CA include the reduction in input cost and profit maximisation (Dumanski et al., 2006; Knowler and Bradshaw, 2007).

In South Africa, CA is mostly adopted by mechanized commercial farmers (Sithole et al., 2016) with the wide use of glyphosate for weed control (Derpsch, 2005; Friedrich et al., 2012). However, implementing CA in SSA, particularly in semi-arid regions by smallholder farmers, present different challenges from where CA originated, (i.e Australia and Americas). Farming systems in SSA are predominantly mixed crop-livestock systems with low crop productivity, maize grain yield average at 1.5 t/ha, and the majority of crop residues are grazed in field by livestock (Mapfumo and Giller, 2001; Zingore et al., 2007). Thus, the success of CA in semi-arid region depends on farmer's ability to retain enough crop residue cover and to ensure adequate weed control (Giller et al., 2009) and systematic crop rotation to increase soil fertility and reduce root borne pathogens.

However, the interactions between CA components and their effects on crop yields are complex (depends on climate, soil type and management system) and often site-specific and long-term trials are needed to give a better understanding (Rusinamhodzi et al., 2011). They provide a unique information about sustainable crop production systems and interaction between different management practices and the broader environment (Powlson et al., 2006). Thus, the knowledge of crop specific responses to the type of tillage, crop permanent residue cover as affected by soil type, climate and nitrogen fertilization is vital in the selection of suitable tillage and crop residue management for improved crop production (Aina et al., 1991). Maize being the important staple crop for a larger population in SSA, we investigated the long-term impact of soil quality parameters and rainfall on maize grain yield in a sub-humid semi-arid region in South Africa under different tillage treatments. This area forms the larger part of the dryland maize production in South Africa.

5.3 Materials and methods

This study combined the materials and methods of soil biological, chemical and biological properties (please refer to chapter 2, 3 and 4). The chapter summarizes the effects of soil quality parameters and their effect on maize grain yield as affected by the rainfall. Maize was harvested manually and the grain yield for different tillage treatments and nitrogen fertilizer application rate was measured in each plot for the whole trial just after harvest.

5.3.1 Statistical data analysis

Statistical analyses of yield data were carried out using GenStat® statistical software (GenStat®, 17th edition, VSN International, UK) and means were separated using Tukey's least significant difference (LSD) at 5% level of significance. The principal component analysis was performed out using The Unscrambler® X chemometric software (The Unscrambler® X v10.5, CAMO SOFTWARE AS, Oslo Science Park, NORWAY).

5.4 Results and discussion

5.4.1 Effect of N fertilizer rates and rainfall on maize yield

On average yield was 12.3, 12.4 and 11.8 t/ha in NT, RT and CT treatments, respectively under high N fertilizer application rate (200 kg/ha) across the years (Table 1). In medium N fertilizer application rate (100 kg/ha) it was 10.6, 11.3 and 11.4 t/ha in NT, RT and CT, respectively while in 0 kg/ha N fertilizer application rate it was 6.6, 7.6 and 8.3 t/ha in NT, RT and CT, respectively.

Moreover, significant yield ($p < 0.05$) variation and non-variation ($p > 0.05$) was observed in tillage × N fertilizer application rate in tillage treatments within and across the years (Table 1). In the first three years, there were no significant yield variation ($p > 0.05$) in tillage × N fertilizer application rate. This may be ascribed to the fact that the whole farm where the trial was conducted was under no-till since 1990 hence there were no much differences and disturbances in terms of nutrient distribution across the soil profile in different N fertilizer application rate treatments. From 2006/07 growing season to 2009/10 growing season, significant yield variation ($p < 0.05$) was observed in tillage × N fertilizer application rate with the higher N application rate (200 kg/ha) yielding higher maize yield (in most cases) than mid-rate (100 kg/ha) and no N application (0 N kg/ha), respectively. This was due to that N is the most required nutrient by plants and from a management point of view applying 200 kg/ha of N may be ideal to achieve a higher yield. Srivastava et al. (2018) also reported similar results that higher amount of N increases maize yield but also pointed out that it can also cause serious environmental problems. In such cases, the authors suggested the reduction of N fertilizer input and improved N use efficiency which is crucial for the sustainable production of maize crop.

In this study, variation in yield across the years seemed to be mostly influenced by the amount of rainfall received and its distribution during the growing season (Fig. 1). When rainfall received during the season was low (less than or equal to 400 mm/year) for example in season 2006/07, 2014/2015 and 2015/16, the average grain yield in 200 kg/ha N fertilizer application rate was 9.13

t/ha, 7.96 t/ha and 7.00 t/ha in NT, RT and CT, respectively. However, when the average rainfall was above 600 mm/year, yields averaged at 13.3 t/ha, 13.7 t/ha and 13.5 t/ha in no-till, rotational tillage and conventional tillage in 200 kg/ha N fertilizer application rate. Although there was no much variation in yield between the tillage treatments, what was most apparent and interesting is that yield improved in reduced tillage treatments (NT and RT) during the period of drought, in 2014/15 and 2015/16 growing season than CT treatment after eleven years of trial establishment. However, this is contrary to what was observed in 2006/07 growing season where yield was lower under NT treatment during the period of drought. This may be attributed to low resilient characteristics of reduced tillage treatments during early staged of implementation.

These results agree with the meta-analysis study conducted by Rusinamhodzi et al. (2011) which showed that yield under conservation agriculture was high when the mean annual rainfall was low, < 600 mm. This can be attributed to higher infiltration and the residue cover (Chapter 3) which enhances moisture conservation in conservation agriculture during the period of drought. Hussain et al. (1999) also reported that yield was 10-100% higher in CA in relatively dry seasons than in CT treatments. The temporary yield fluctuation is mainly influenced by environmental factors with rainfall having the strongest effect (Mallory and Porter 2007; Grover et al. 2009).

Furthermore, specific responses of yield to CA is also dependent on soil type. In the current study with clay loam soil (Ferralsols Haplic), although difficult to assess overtime because of the complex interaction of various CA components and the environment, it can be argued that yield under CA improves due to improved soil physio-chemical properties such as soil organic carbon and N, pH, aggregate stability, infiltration, bulk density and soil important nutrients under CA

(Chapter 3 and 4). Rusinamhodzi et al. (2011) reported no differences in maize grain yield between NT and CT treatments on silt clay loams over time but found improvements on sandy and loamy soil. In heavy clay poorly drained soil, Dick and Van Doren (1985) found that a reduction in maize associated with reduced tillage treatments or no-till and suggested crop rotation as a possible cause. Other authors, however, have reported that maize yield are insensitive to tillage over a wide range of soil textures, climate conditions and the duration of the experiment as long as adequate weed control and equal plant densities are maintained (Van Doren et al., 1976). In poorly drained soils, yield reduction has been reported (Yakle and Cruse 1984) and improvements in yields on well-drained soil have also been reported (Griffith et al. 1986). This was attributed the efficient use of water and improved physical conditions of the soil in well-drained soil.

Nitrogen is the most limiting input in maize production in sub-Saharan Africa (Edmonds et al., 2009). Our results have shown yields improvements in NT under high N rate (200 kg/ha) than CT treatment (Fig. 3). However, this advantage diminished with the decrease in N rates. These results are in line with the study conducted semi-arid sub-humid region which showed that yields were more increased by N fertilization than tillage (Diaz-Zorita et. al., 2002). This indicates that CA is input intensive and requires the application of the correct proportion of fertilizer to improve yield (Rusinamhodzi et al., 2011.

Table 1: Maize grain yield observed from 2003/2004 growing season to 2016/2017 growing season. The LSD shown is for tillage × nitrogen rate at 5% level of significance.

season	N applied (kg/ha)	NT	RT	CT	LDS $_{(0.05)}$
2003/04	0	12.50	13.81	13.16	NS
	100	12.86	13.25	13.45	
	200	13.23	13.53	13.74	
2004/05	0	10.35	11	10.3	NS
	100	11.89	11.06	10.88	
	200	11.92	11.33	11.24	
2005/06	0	8.85	10.43	11.01	NS
	100	10.24	11.95	12.78	
	200	12.16	13.26	13.04	
2006/07	0	3.73	4.36	5.46	0.88
	100	6.63	7.18	7.39	
	200	7.09	7.26	7.18	
2007/08	0	5.41	6.31	8.85	1.32
	100	10.93	11.96	14.21	
	200	16.36	16.53	15.48	
2008/09	0	4.63	6.87	6.29	0.8
	100	10.68	12.07	12.11	
	200	13.93	14.53	13.64	
2009/10	0	6.38	7.63	7.65	1.06
	100	10.92	11.55	10.97	
	200	12.94	12.19	10.06	
2010/11	0	5.42	6.5	8.31	NS
	100	9.35	10.17	13.43	
	200	12.81	14.38	15.07	
2011/12	0	7.55	8.3	9.54	1.06
	100	12.49	12.56	12.49	
	200	13.24	13.35	12.4	
2012/13	0	5.61	6.17	7.54	NS
	100	9.7	9.67	10.94	
	200	10.22	9.79	11.1	
2013/14	0	6.53	8.75	8.78	1.54
	100	14	14.87	15.37	
	200	17.06	17.28	16.41	
2014/15	0	3.94	4.46	4.01	1.03
	100	8.81	8.89	7.56	
	200	8.83	8.19	7.04	
2015/16	0	5.4	5.53	5.76	0.68
	100	8.6	8.35	7.06	
	200	9.46	8.43	6.78	
2016/17	0	6.11	6.4	8.77	1.02
	100	11.08	11.04	11	
	200	12.59	12.97	11.84	
Average	Low	6.6	7.6	8.3	
	Medium	10.6	11.0	11.4	
	High	12.3	12.4	11.8	

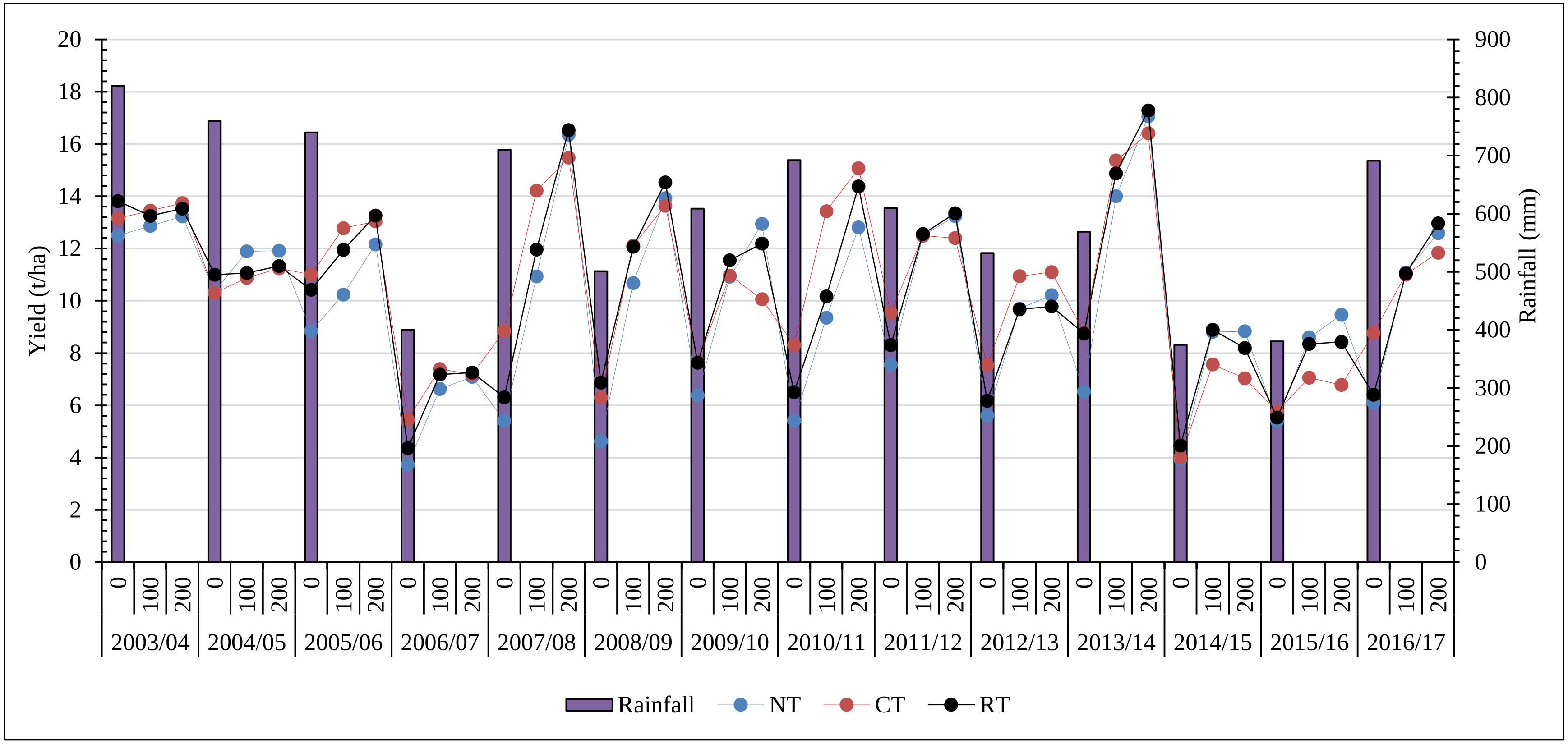

Fig. 1: Maize grain yield trends as affected by rainfall from 2003/04 growing season to 2016/17 growing season. Note: 0 = 0 kg/ha N-fertilizer, 100 = 100 kg/ha N-fertilizer and 200 = 200 kg/ha N-fertilizer.

5.4.2 Principal component analysis (PCA) models

The principal component analysis was performed to compare maize grain yield (t/ha) in different tillage treatments (Fig. 2). The distribution of PCA score plots of grain yield showed different clusters between the different tillage treatments although there were some overlap in clusters, particularly in NT and RT treatments. No-till (NT) and Rotational tillage (RT) showed wide variation in clusters while in conventional tillage (CT) treatments the distribution of clusters was much reduced. The PCA score for the first two PCs explained 88% of the total variability, PC1 explained 81% of the total variance and PC2 explained 7% of the variance. The overlap in clusters for NT and RT treatments indicates that the grain yield between the two was more similar and different to that of CT treatments.

The principal component analysis was also performed to assess some of the soil physical, chemical and biological properties that contributed to maize grain yield (Fig. 3). The PCA score for the first two PCs also explained 81% of the total variability with PC1 contributing 81% of the total variance and PC2 contributing 7% of the total variance. However, there was no parameter that seemed to be related to maize yield. This was attributed to the complex interaction of bio-physio-chemical parameters with the environment. Dam et al. (2005) reported that maize yields after 11 years were not affected by tillage and residue, which affect soil physical, chemical and biological properties, but climate-related differences seemed to have a greater influence on yield variation.

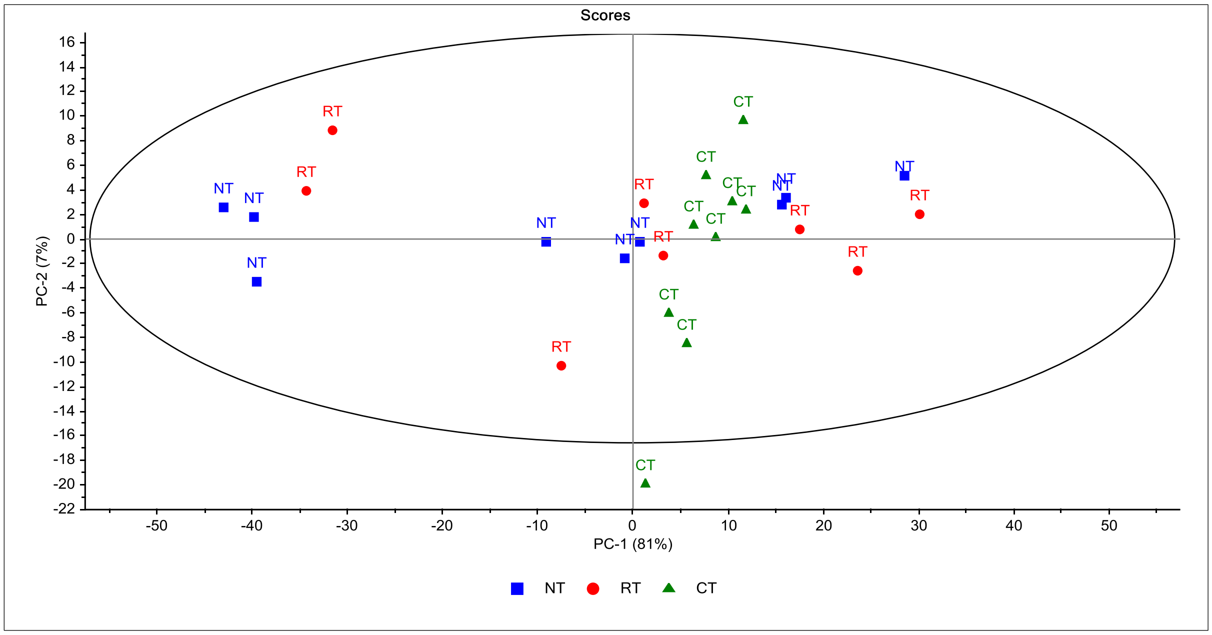

Fig. 2: Principal component analysis (PCA) similarity map for the first two principal components (PCs) showing yield variation in different tillage treatments. Note: NT = no-till, RT = rotational tillage and CT = conventional tillage.

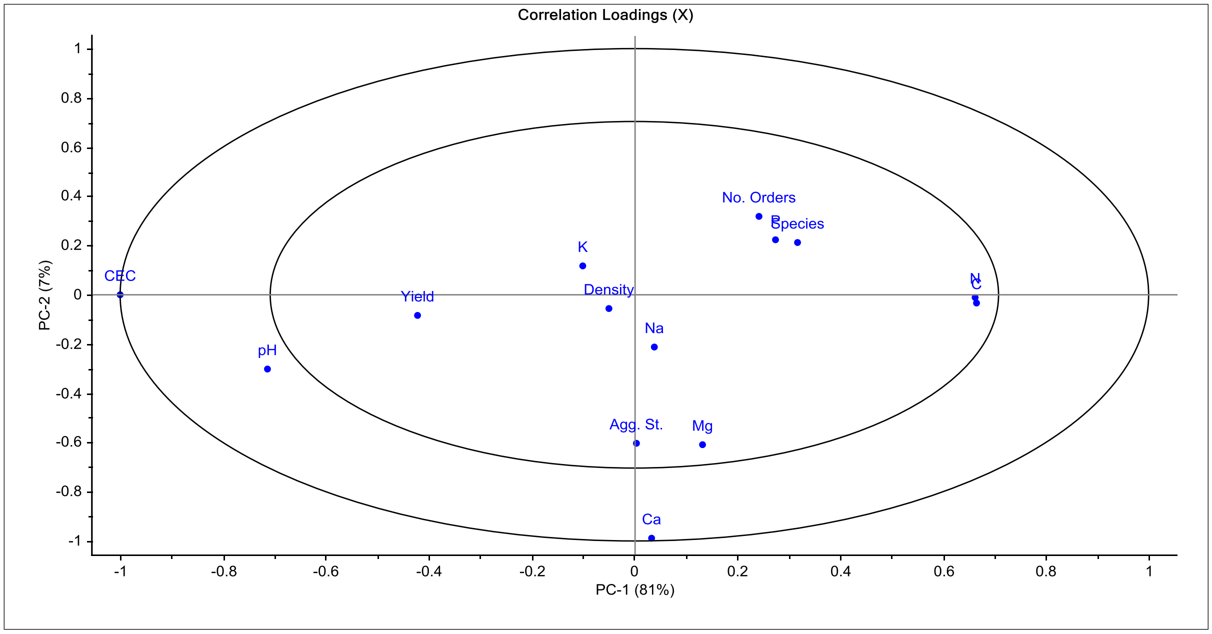

Fig. 3: Principal component analysis (PCA) similarity map for the first two principal components (PCs) showing.

5.5 Conclusion

The results of this study showed a significant variation of yield within and across the years and across the tillage treatments. Rainfall received during the growing season and its distribution was identified as the main factor that influences the variability of yield as compared to bio-physio-chemical characteristics of the soil which are difficult to assess due to the complex interaction of various CA components with climate. In the long-term, > 10 years, yield was found to improve under conservation agriculture and this was more apparent during the drought period experienced in 2014/15 and 2015/16 growing seasons. The results also showed that successful application of conservation agriculture requires the application of the high rate of N fertilizer.

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CHAPTER 6

Spectral models for rapid assessment of soil organic carbon and nitrogen: VIS-NIRS application to Feralsols Haplic from the sub-tropical region of South Africa

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Abstract

In this study, the use of visible to near infrared spectroscopy (VIS-NIRS) was explored as a technique to predict soil organic carbon (SOC) and soil organic nitrogen (SON) in soils collected from different tillage management practices. Tillage treatments were no-till (NT), rotational tillage (RT) and conventional tillage (CT). The reflectance spectra of samples from 0-10, 10-20 and 20-30 cm depths were acquired from all tillage treatments using a laboratory bench-top monochromator NIR Systems Model XDS spectrometer. Partial least square regression (PLSR) models were developed using the leave-one-out cross validation method. The models were then tested on independent samples (54) randomly selected from the total 324 samples. Principal component analysis (PCA) was used to differentiate SOC in different tillage treatments. The best prediction model was observed for SOC with the coefficient of determination (R^2) = 0.993, root mean square error of prediction (RMSEP) = 0.157% and residual predictive deviation (RPD) = 2.55 compared with R^2= 0.661, RMSEP= 0.019%, RPD= 2.11 for SON. Clusters of SOC distribution in the PCA for different tillage treatments showed slight differences in SOC stock between the treatments with NT having quite different stock than CT treatment. Therefore, considering the predictive statistics and accuracy created by the model in SOC prediction, VIS-NIRS can be recommended as a fast, accurate technique for SOC determination in Feralsols Haplic. This will reduce cost significantly associated with SOC and SON analysis for researchers and farmers.

Key words: VIS-NIRS, SOC, chemometrics, PLSR, RPD

6.1 Introduction

Soil organic carbon (SOC) is widely recognised as a principal indicator of soil quality because of its influence on various processes linked to physical, chemical and biological soil properties. Its decline in soil due to management practices such as tillage which breaks soil stable aggregates leads into slacking, soil erosion and eventually, soil degradation. There has been an increased interest in studies of SOC in recent years. This is caused by its predicted effects on climate change (Guerrero et al., 2016). The amount of SOC varies spatially due to natural soil variability, climate and management practices. Thus, measurements of SOC require a large number of samples to hold high statistical robustness, otherwise, they would be limited by huge uncertainties causing misleading inferences (Muukkonen et al., 2009). Furthermore, quantification of SOC is expensive, and requires the use of chemical reagents (Walkley, 1947; Jackson, 1973) and recently, the use of sophisticated laboratory instruments (Matejovic, 1996; Leco Corporation, 2012). Therefore, there is an urgent need for a rapid and accurate approach for measurements of SOC allowing huge analysis of samples within a short period of time, low effort and budget, and for precision agriculture.

The application of visible to near infrared radiation spectroscopy (VIS-NIRS) for assessing SOC is arguably the best technique than mid infrared (MIR) for example, possessing the afore-mentioned requirements (Guerrero et al., 2016). Reportedly, the use of MIR is more suitable than VIS or NIR, however, this method has proven to be more expensive and complex than using VIS-NIRS (Viscarra Rossel et al., 2006a). VIS-NIRS technique requires the only collection of samples at preparation and provides accurate information of several soil properties from one spectral reading (Vohland and Emmerling, 2011). Application of VIS-NIRS collects large information about soil physical, chemical and biological properties of a sample and therefore, permits measurements of many soil properties from the single measurement (Minasny et al., 2011). The VIS-NIRS technology has been used successfully in many industries, for several decades, such as pharmaceuticals, petrochemicals, crop production and food processing (Minasny et al., 2011). It reflects structural and compositional information of molecules as absorptions at spectral wavelengths between 350 and 2500 nm (Nawar et al., 2016). The absorptions are associated with the stretching and bending of bonds forming the OH, NH and CH groups (Clark, 1999; Viscarra Rossel and Behrens, 2010). Several authors (Brown et al., 2006; Viscarra Rossel et al., 2006b; Viscarra Rossel and Behrens, 2010) have reported that different wavelengths and spectral ranges can be responsible for prediction of SOC content. For example, Sudduth and Hummel (1991) pointed out that NIR (near-infrared region) reflectance data provided a better prediction of SOC than VIS (visible region). On the other hand, Islam et al. (2003) examined the ability of reflectance spectroscopy to predict numerous soil properties, including SOC, in the UV, VIS and NIR ranges and they found that overall prediction was better with the whole spectral range (VIS-NIRS) than VIS or NIR.

A number of studies that have been conducted at global, continental, national, regional and local scale field scale using VIS-NIR spectroscopy to analyse SOC have shown that estimates of SOC have been with the substantial range of accuracy (Milos and Bensa, 2017). Most studies were done in heterogeneous soil samples with respect to soil forming factors and the possible factors of relatively large differences that relate to accuracy of estimation relates to factors such as parent material, heterogeneity of soil type, high SOC variability, land uses and size of the sampling area

(Milos and Bensa, 2017). More homogenous soils and geographically closer soil samples with similar characteristics have resulted in better model predictions (Wijewardane et al., 2016). Vis-NIR spectroscopy techniques have also been applied and expanded to the analysis of SOC and N fractions, assessment of SOC and N of different management practice such as tillage type and the analysis of these in different soil depths. Hence the successful application of this technique in soil properties can significantly reduce the cost and time needed in sample preparation for wet chemistry chemical analysis.

This study explored the accuracy of using VIS-NIR spectroscopy for the prediction of SOC and N of the soil samples that are similar in soil type but differing in management practices. Therefore, the objective of this study was to assess the accuracy of using VIS-NIR spectroscopy, in a long-term trial, for the prediction of SOC in soil (Feralsols Haplic) that has been managed under no-till, rotational tillage and conventional tillage.

6.2 Materials and methods

6.2.1 Soil samples

Soil samples used in this study were collected in Bergville, Winterton (28°55'26.83"S, 29°33'38.64"E, 1038 asl), KwaZulu-Natal Province, South Africa, at the end of the 2015/2016 growing season in the trial that was established in 2003/2004 growing season. This area has a sub-tropical humid climate, characterized by cold dry winters (May to August) and warm rainy summers (October to March). The mean annual rainfall is 643 mm/year receive mostly during the summer months. The soil was classified as Ferralsols Haplic (FAO, 2006) equivalent to Hutton non-swelling with clay loam soil texture (Soil Classification Working Group, 1991). Previously, the trial site has been managed under no-till since 1990 under dryland-maize commercial production in rotation with soybean until the establishment of the trial in the 2003/2004 growing season. Since the beginning of the experiment, the trial site has been planted to dry maize continuous monocrop in summer and left fallow during the winter months. The average pH (KCl) of the top 30 cm of the trial was 6.62. A total of 324 soil samples from no-till (NT), rotational tillage (RT, which consists of conventional tillage after every four season of NT) and conventional tillage (CT, which consists of annual ploughing with moldboard plough to a depth of 30 cm, followed by disking to a depth of 1 cm) treatments in the 0-10 cm, 10-20 cm and 20-30 cm depths were taken to the laboratory at the University of KwaZulu-Natal for Vis-NIR analysis and for stand chemical analysis.

6.2.2 VIS-NIR spectroscopy collection

The reflectance spectra from the soil samples were measured in the laboratory using a laboratory bench-top monochromator NIR Systems Model XDS spectrometer (FOSS NIR Systems, Inc.; Maryland, USA) equipped with a quartz halogen lamp and lead sulfide (PbS) detector. The spectrometer was calibrated by scanning a 100% white reference tile before scanning the first sample and at 30 minutes intervals during scanning of samples to reduce baseline shift of spectral response. The full VIS-NIR (450-2500 nm) spectra were collected from the soil samples. Each spectrum was the average of 32 scans recorded using Vision software (Vision TM, version 3.5.0.0, Tidestone Technologies Inc., KS, USA).

6.2.3 Chemical analysis of Carbon and Nitrogen from soil samples

Soil organic C and N were analysed by an automated Dumas dry combustion method using a LECO CNS-2000 (Leco Corporation, Michigan, USA) (Leco Corporation, 2012). Briefly, air-dried soil samples were passed through a 0.5 mm sieve size, then a 0.5 g sample was then measured and put into the LECO for analysis of C and N. The procedure was based on dry combustion of air-dried samples in crucibles, subjected to a 1350 °C furnace temperature for about 7 minutes.

6.2.4 Data analysis

6.2.4.1 Chemometric analysis

To observe normality of the collected spectra, exploratory analysis of spectra was done by plotting all spectra and seeing if they followed a similar trend. Chemometric analysis of data was carried out using The Unscramble® X chemometric software (The Unscrambler® X v10.5, CAMO Software AS, Oslo Science Park, Norway). The collected spectral data was subjected to different pre-processing techniques to improve its dependence on chemical data. Pre-processing techniques tested included smoothing and transformation of spectral data using Savitzky-Golay algorithms, area normalization, standard normal variate transformation and selection of wavelength band that reflected best results on models performance. Outlier samples were selected based on F-residuals and Hotelling T^2 outlier detection at 5%. No outliers were observed and 75% of data was used for calibration whilst 25% was assigned to an independent test set. Kernel algorithm was used to develop partial least square regression (PLS) models, the most improved regression technique for

VIS-NIRS models (Naes et al., 2002; Nicolai et al., 2007; Davey et al., 2009, Cozzolino et al., 2009).

The optimum chemometric conditions of each PLS model was based on the ability of a model to obtain high regression coefficient during cross validation (R^2_{cv}; Eq. 1) and low root mean square error of cross validation (RMSECV). The R^2_p -value and ratio of performance deviation (RPD; Eq. 2) as well as low unfairness contribution of each sample (Bias; Eq. 3) and root mean square error of prediction (RMSEP; Eq. 4) were used as a measure of models accuracy in predicting the independent test set.

$$R^2 = 1 - \frac{\sum (y_{cal} - y_{ref})^2}{\sum (y_{cal} - y_{mean})^2} \tag{1}$$

$$RPD = \frac{\mathrm{SD}}{\mathrm{RMSEP}} \tag{2}$$

$$Bias = \frac{1}{n}\sqrt{\sum (y_{pred} - y_{ref})^2} \tag{3}$$

$$RMSEP = \sqrt{\sum (y_{pred} - y_{ref})^2 / n} \tag{4}$$

y_{cal} -calculated value; n-number of samples used in calculation; y_{ref} - actual value measured by chemical method; y_{mean}- average value of predicted data; y_{pred} - value predicted by Vis-NIRS, and *SD*- standard deviation of measured data values.

6.2.4.2 Statistical data analysis

Statistical analyses of chemical soil data were carried out using GenStat® statistical software (GenStat®, 17th edition, VSN International, UK). The coefficient of variation (CV%) was calculated as the ratio of the standard deviation to the mean, multiplied by 100 and reported as a percentage.

6.3 Results and discussion

6.3.1 Spectra-based PCA models

Principal component analysis (PCA) was performed on VIS-NIRS spectra to compare the effect of tillage system and N-fertilizer application rate on SOC (Figs. 1-4). This grouping was only possible with spectra transformed using Savitzky Golay second derivatives pre-processing method (Fig. 1-4). The distribution of the PCA score plot of soil spectra showed an overlap in clusters between NT and RT, while CT was slightly different from the two (Fig. 1). The PCA scores for the first two PCs (Fig. 1) show slight SOC variation in different tillage treatments. The first two PCs explained 76% of the total variability, PC1 explained 52% of the variance and PC2 explained 24% of the variance. This was similar to what was observed in soil chemical analysis which showed marginal differences in total SOC between the tillage treatments (Chapter 3). Spectral data collected in soil samples which were subjected to different N-fertilizer application rate were also subjected to similar analysis. The distribution of PCA score plots of soil spectra acquired in different tillage treatments showed three slight distinctive clusters corresponding to three N-fertilizer application rates (Fig. 2-4). The first two PCs accounted for the 89% of the total variability, PC1 explained 55% of the variance while PC2 explained 34% of the variance (Fig. 2). Variation in SOC under RT treatment (Fig. 3) was clearly observed with RT (0N) dominating the positive side of PC1 while RT (100 kg N) and RT (200 kg N) were clustered along the negative side of PC1. The first two PCs accounted also for 89% total variability. Lastly, the separation of clusters in CT treatment with respect to N-fertilizer application rate was observed (Fig. 4). In this case, the two components explained 94% of the total variability, PC1 explained 77% of the total variance and PC2 explained 17% of the total variance. This indicates the potential power of VIS-NIRS base technology in predicting SOC in the soil.

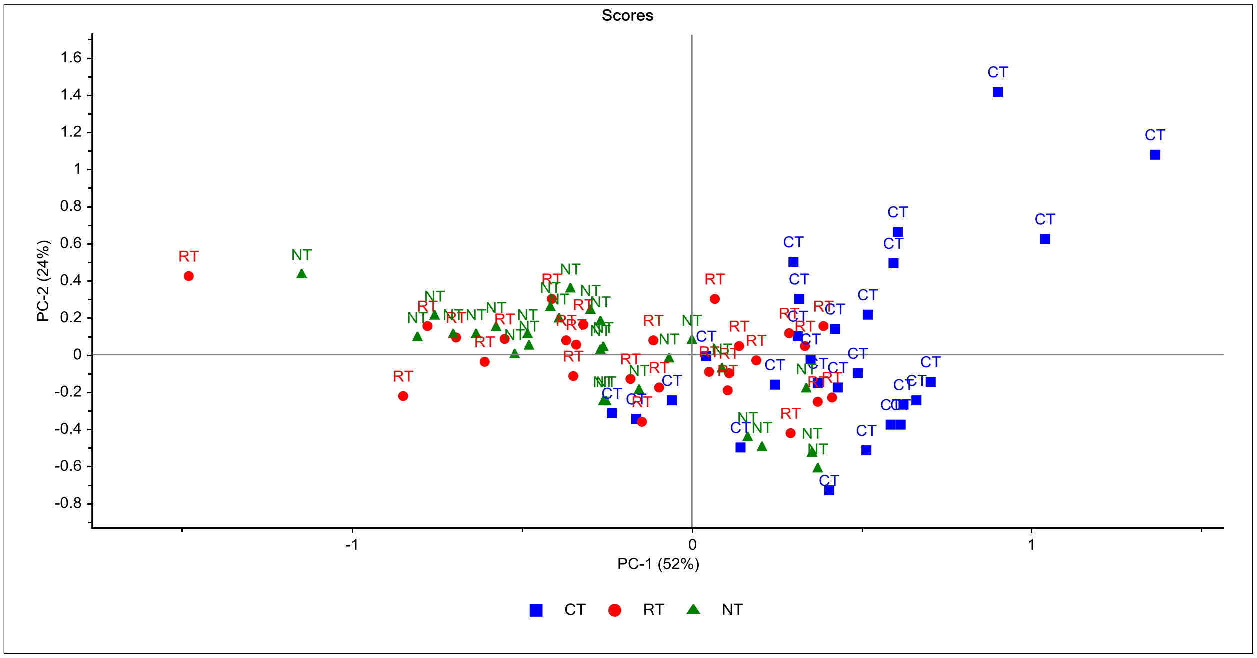

Fig. 1: Principal component analysis (PCA) similarity map for the first two principal components (PCs) showing soil organic carbon (SOC) variation in different tillage treatments (CT = conventional tillage, RT = rotational tillage and NT = no-till).

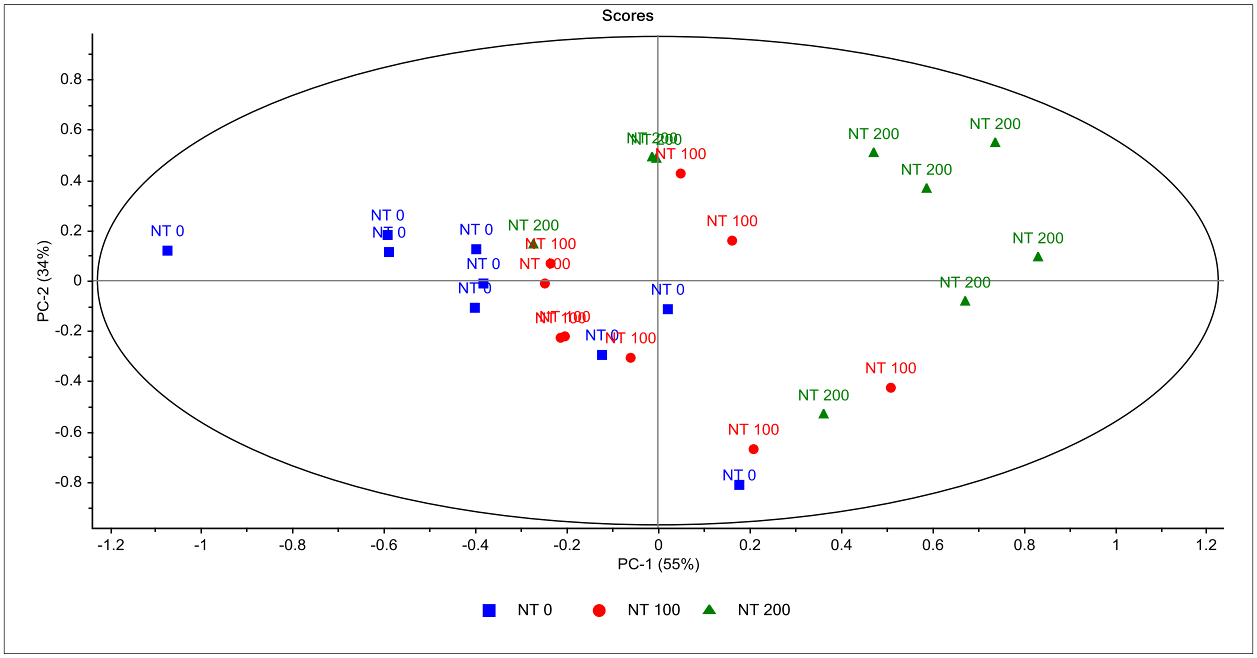

Fig. 2: Principal component analysis (PCA) similarity map for the first two principal components (PCs) showing soil organic carbon (SOC) variation with N-fertilizer level (0, 100 & 200) in NT (no-till) treatment. Note: 0 = no fertilizer applied, 100 = 100 kg/ha nitrogen applied and 200 = 200 kg/ha nitrogen applied.

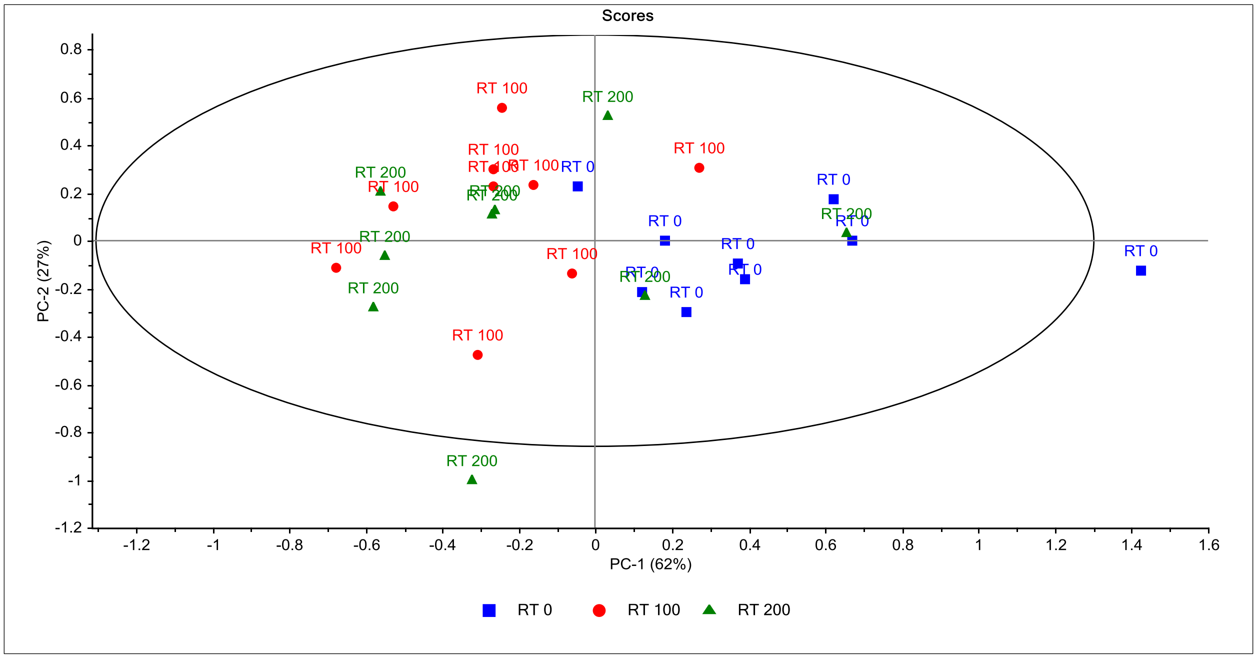

Fig. 3: Principal component analysis (PCA) similarity map for the first two principal components (PCs) showing the variation on soil organic carbon (SOC) with N-fertilizer level (0, 100 & 200) in RT (rotational tillage) treatment. Note: 0 = no fertilizer applied, 100 = 100 kg/ha nitrogen applied and 200 = 200 kg/ha nitrogen applied.

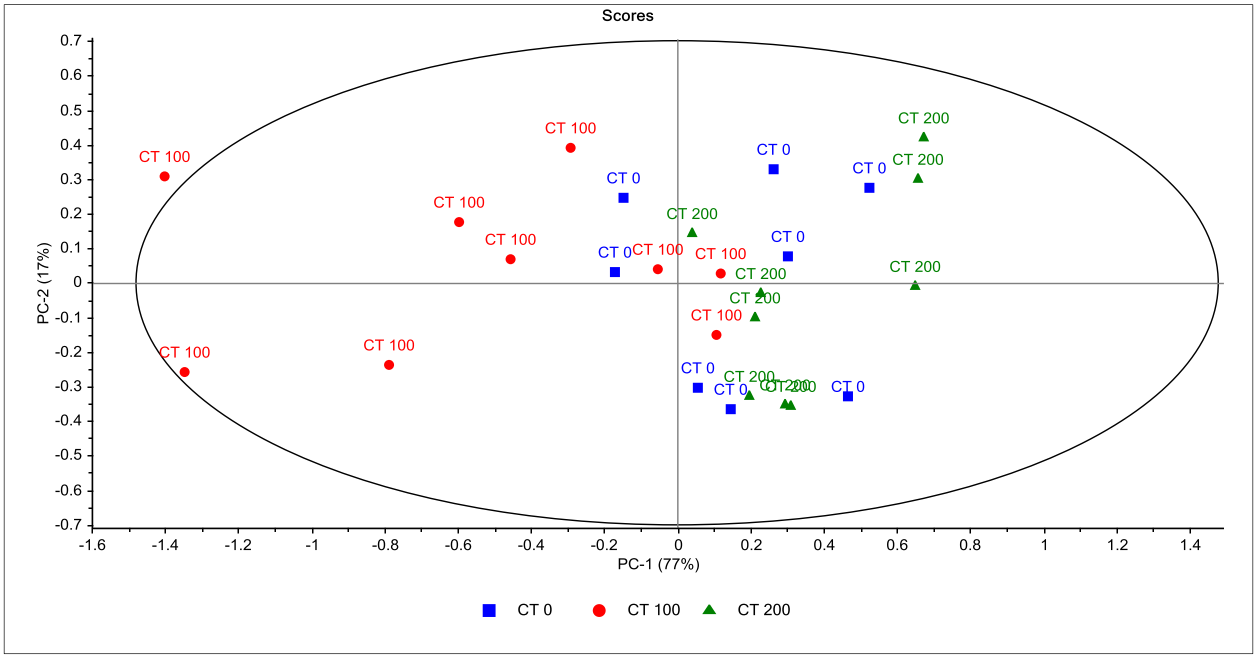

Fig. 4: Principal component analysis (PCA) similarity map for the first two principal components (PCs) showing variation in soil organic carbon (SOC) with N-fertilizer level (0, 100 & 200) in CT (conventional tillage) treatment. Note: 0 = no fertilizer applied, 100 = 100 kg/ha nitrogen applied, and 200 = 200 kg/ha nitrogen applied.

6.3.2 Description spectra

The graph presented in Fig. 5A shows the typical spectra obtained in soil under different tillage systems. The different spectral lines represent the mean spectra obtained from all tested samples and the reflectance spectrum varied from 400 to 2500 nm. Spectral features obtained such as reflectance picks were similar to those obtained by Milos and Bensa (2017). The beginning of the spectrum (450-700 nm) was characterized by noise and hence was removed before calibration. Strong absorption band around 740-1100 nm, 1100-1660 nm, 1700-2140 nm and 2180-2280 nm were observed. According to Sherman and Waite (1985) and Ben-Dor et al. (1999) wavelengths from 740-1100 nm spectral region are associated with organic carbon and chromophorous constituents (iron oxides) mainly goethite and haematite. The spectral range from 1100-2500 nm is characterized by the features of absorption bands around 1400, 1700, 1860, 2150, 2300 and 2240 nm. These absorption bands are associated with overtones and combination absorptions of C=O, C-H, N-H and O-H (Clark, 1999; Viscarra Rossel and Behrens, 2010) and as a result contains information about the spectral response of SOC for soil samples (Milos and Bensa, 2017). The absorption picks observed at 1400 and around 1860, on the other hand, are associated with the absorption of water and OH^- (Milos and Bensa, 2017). Other authors (Sarkhot et al., 2011; Magwaza et al., 2014) has also reported the same trends of high contributing wavelengths of water adsorption features at these picks. Moreover, the spectrum also has the highest picks around 2200 nm (maximum pick at 2220 nm), 2240 nm, 2300 nm (maximum 2340 nm) and 2500 nm. This may indicate the contribution of these wavelengths in SOC predictions. Many authors have also reported that the wavelengths contributing most to SOC predictions are around 2200 and 2300 nm (Ben-Dor and Banin, 1995; Stenberg et al., 2010; Viscarra Rossel and Behrens, 2010). This is due to Al-OH bends plus O-H stretch combinations that are diagnostic absorption features in clay mineral identification (Clark et al., 1990).

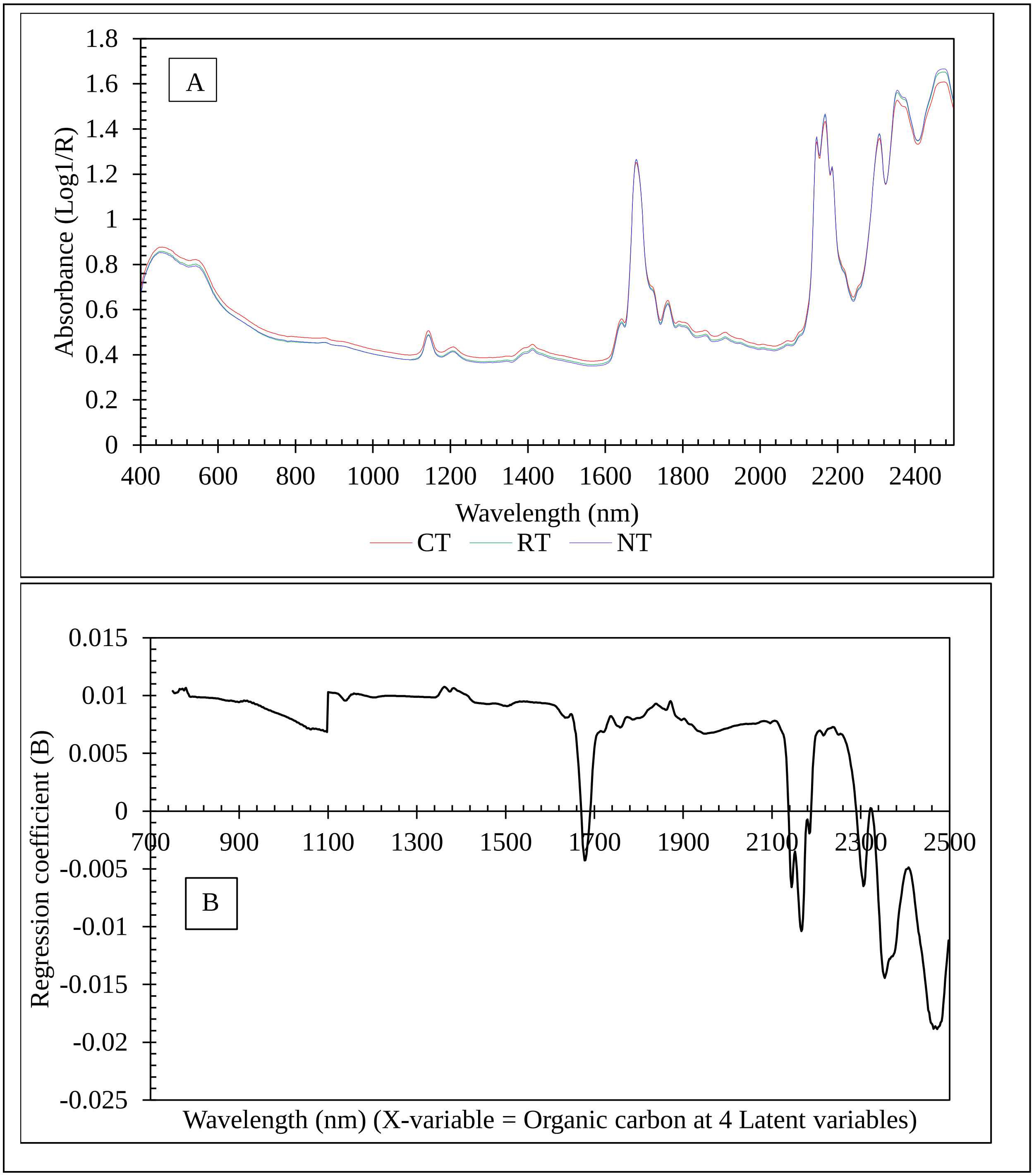

Fig. 5: A typical average VIS-NIRS (400-2500 nm) absorbance intensity spectra and regression coefficient curve of soil organic carbon (SOC) model of different tillage treatments and NIR spectral range of 700-2500 nm.

6.3.3 VIS-NIR models for accurate determination of SOC and N from soil samples

The prediction statistics for the best model developed for SOC and SON predictions are presented in Table 1. The models were most accurate in predicting SOC ($R^2 = 0.993$, RMSEP = 0.157%, RPD = 2.55) than predicting soil organic N ($R^2 = 0.661$, RMSEP = 0.019%, RPD = 2.11). Scatter plots of the relationship between NIR and conventionally measured SOC and SON are presented in Fig. 6 and 7, respectively. High regression coefficient ($R^2 = 0.993$) between SOC measured by Leco and predicted by VIS-NIRS was observed (Fig. 6). Low regression coefficient ($R^2 = 0.661$) between SON measured and predicted was also observed (Fig. 7). The means of both parameters were predicted with a substantial range of accuracy, with minor differences of < 0.05 between them (Table 2). The standard deviation of the predicted data was slightly lower than that of the reference data for both SOC and SON. This means that these values were closer to the mean when compared to the reference data. This implies that there were low chances of predicting a sample as an outlier if its actual value was close to the mean (Ncama et al., 2017). Moreover, according to the interpretation given by Viscarra Rossel (2006b), the RPD values obtained for SOC (2.55) and SON (2.11) indicate excellent model prediction and very good quantitative model predictions, respectively.

The SOC prediction model in this study was more accurate than what has been usually observed in other studies (Table 1) with higher R^2 value. Leone et al. (2012) obtained R^2 values ranging from 0.84-0.93 and RPD values ranging from 2.36-2.53 from local soil predictive models. On the other hand, Gras et al. (2014), Wijewardane et al. (2016) and Knadel et al. (2012) obtained R^2 values of 0.82, 0.83 and 0.81 and RPD of 2.40, 2.41 and 2.40, respectively. Other studies by Kuang and Mouazen (2012) have shown a very wide range of R^2 and RPD, 0.12-0.96 and 1.07-4.95, respectively. Those studies were conducted at a farm scale in four European countries. Milos and Bensa (2017) highlighted that the differences in accuracy of predicting SOC relate to high soil variability, heterogeneity of soil types, parent material, land uses and size of sampling area which could not be easily identified. In this study, therefore, based on high R^2 value, it can be concluded that the soil studied was more homogenous than what has been observed in other studies.

Table 1: Calibration and validation results of soil organic carbon and soil organic nitrogen (SON) models at 450-2500 nm spectral range.

	Calibration Set (n = 270)				Test Set (n = 54)				
	Latent variables	R^2cv	RMSECV	Slope	R^2p	RMSEP	Slope	Bias	RPD
Soil organic C (%)	4	0.998	0.015	0.997	0.993	0.157	0.981	-0.135	2.55
Soil organic N (%)	6	0.694	0.018	0.693	0.661	0.019	0.653	0.003	2.11

Table 2: Statistical description of the soil organic carbon content (%) for the reference (chemically analysed) and NIR predicted values.

	Chemically-analyzed (n = 270)				NIR Predicted values (n = 54)			
	Mean	SD	CV%	Range	Mean	SD	CV%	Range
Soil organic C (%)	1.67	0.40	23.9	3.36	1.64	0.26	15.6	1.49
Soil organic N (%)	0.08	0.04	49.0	0.21	0.09	0.02	26.5	0.14

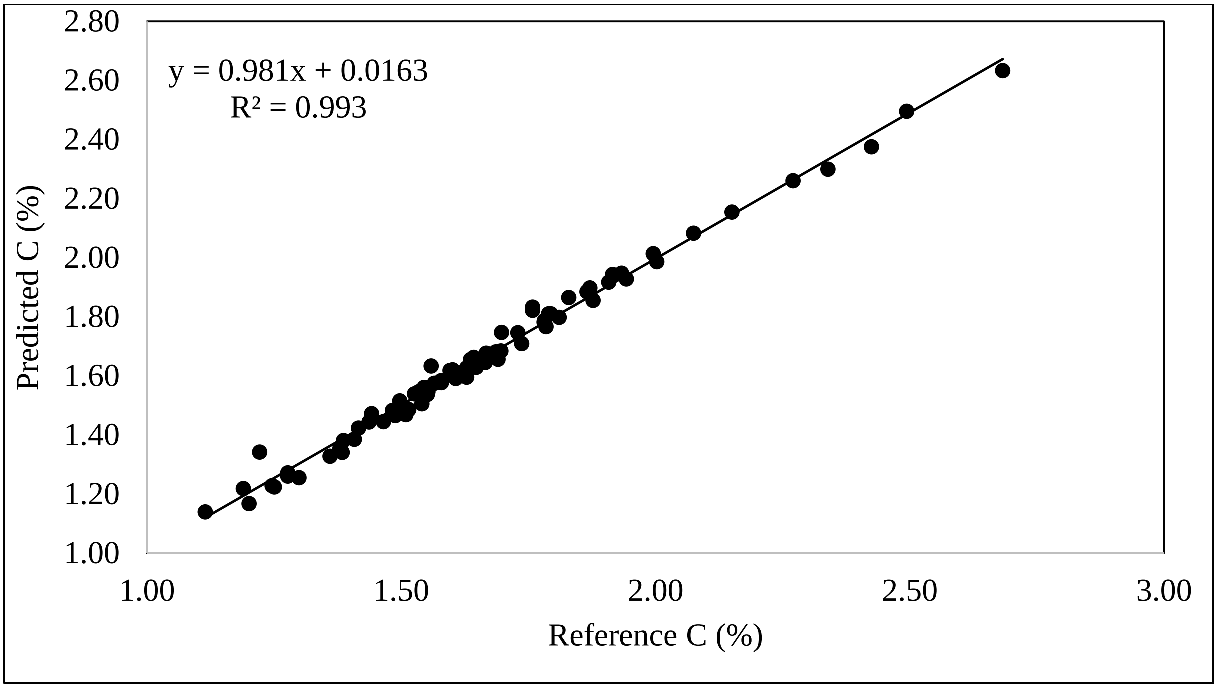

Fig. 6: PLS models showing the capability of VIS/NIR spectral analysis in predicting soil organic carbon (SOC) in soil differing in tillage treatments.

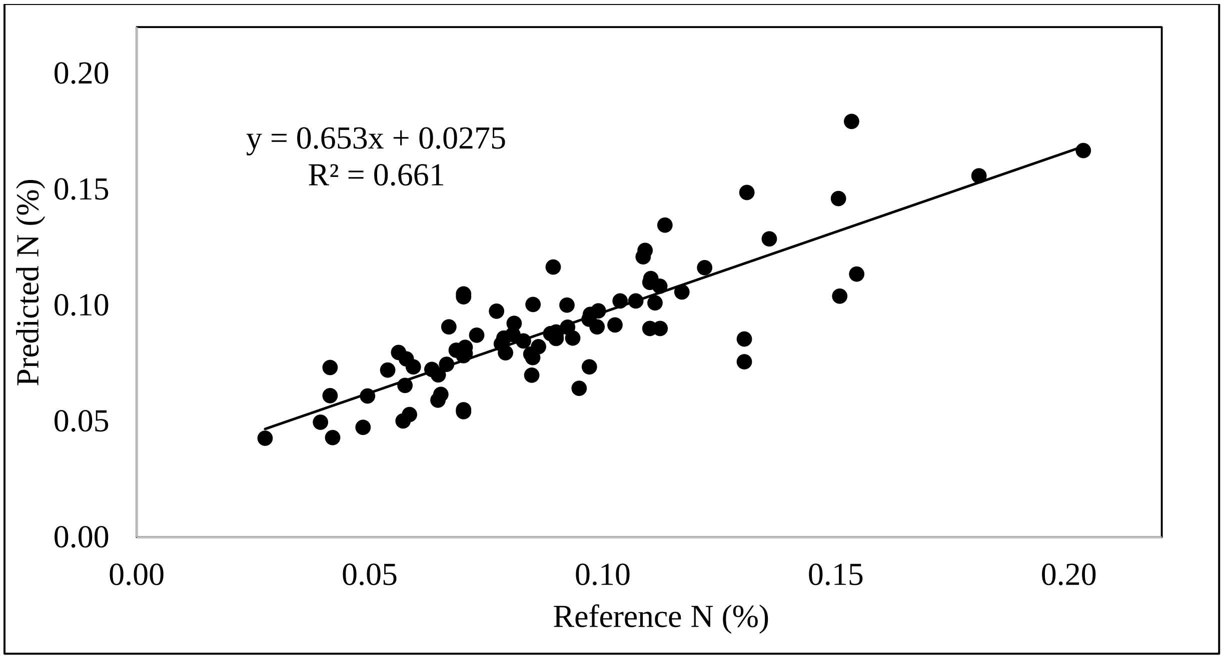

Fig. 7: PLS models showing the capability of VIS/NIR spectral analysis in predicting soil organic nitrogen (SON) in soil differing in tillage treatments.

6.4 Conclusion

The capability of VIS-NIRS together with chemometrics analysis of spectra to predict SOC and SON from soil under different tillage treatments was demonstrated. Spectral range from 700 nm to 2500 nm was found to be optimum in predicting SOC in the studied soil. VIS-NIRS predicted SOC more accurately than SON confirmed by parameters of cross-validated predictions diagnostic such as high R^2 and RPD, and low RMSEP values obtained in SOC than in SON. Therefore, considering the predictive statistics and accuracy created by the models, VIS-NIRS can be recommended as a fast and accurate technique for SOC determination in Feralsols Haplic. This could be a great benefit to researchers and farming community where larger samples of SOC are needed for monitoring and evaluation.

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CHAPTER 7

GENERAL DISCUSSION

The world population is expected to reach a 50 billion mark in the year 2050. This increase is expected to come more from the developing countries particularly in the sub-Saharan Africa region. Therefore, the pressing need to increase the food supply and ensure food security is clear. However, meeting these needs seem impossible because of the high level of human-induced soil degradation. Approximately, 45% of the world arable land is affected by degradation and a larger percentage of this, ~ 68%, is confined to sub-Saharan Africa. In South Africa, about 45% of the arable land is degraded (Bai and Dent, 2007). This combined with water scarcity in the country and the predicted impacts of climate change put more pressure on arable land and in such cases conservation agriculture has been recommended because of its resilience characteristics to land degradation, drought and its effect on water use efficiency. Conservation agriculture is based on three principles i.e. no-till, permanent residue cover and diversified crop rotation. Conservation agriculture permanently covers the soil thus protecting it from erosion, degradation and increase soil organic matter which is important for soil quality. However, the quantification of soil organic matter is very expensive and time-consuming. As a result, experiments aimed at assessing management, climate, soil type and their interaction effects on soil organic carbon may be limited by the lack of resources and therefore, a different cheaper approach has to be explored. Visible to near infrared spectroscopy present such opportunity because it permits the analysis of a large number of samples within a short period, low effort and budget and for precision agriculture.

Moreover, studies on conservation agriculture in South Africa are very scarce and its adoption is very low compared to the developed countries. The majority of the published literature on conservation agriculture comes from temperate cooler environments. The responses of soil quality characteristics in sub-tropical and semi-arid environments may differ from those observed in temperate cooler environments. Brouder and Gomez-Macpherson (2014) concluded that the potential and environmental benefits of conservation agriculture adoption for crops in agroecological region beyond the intensively studied Australia and America remains uncertain and controversial.

Thus, the overall aim of this study was to evaluate the effect of no-till conservation agriculture on soil quality, and maize yield and secondary to this, to explore the use of visible to near infrared spectroscopy as a possible tool for soil organic carbon analysis in the studied soil. The study investigated the effects of no-till with permanent residue cover, rotational tillage with permanent residue cover and conventional tillage with residue removed on selected soil biological, physical and chemical properties. In soil biology, the study investigated the effect of various tillage treatments and nitrogen fertilizer application rates on the abundance and diversity of macrofauna. On the soil selected physical properties, the study investigated the effect of various tillage treatments on soil aggregate stability, infiltration rate, bulk density and aggregate-associated carbon. On selected soil chemical properties, the study investigated the effect of different tillage practices and N-fertilizer application rates on total C and N, P, K, Ca, Mg, Na, pH and CEC. Thereafter, the study investigated the studied soil quality parameters and their association with maize yield. Lastly, the study explored the use of visible to near infrared spectroscopy on soil organic carbon prediction.

The results of the study have indicated that the overall macrofauna population improves under NT conservation agriculture compared to CT. Order Isoptera (termites), Coleoptera (beetles) and Diplopoda (millipedes) were amongst the top three dominant order found in this study. However, there were no significant differences found in diversity and evenness of orders. These results have provided the evidence that mulch-based system and less soil disturbance provide a better condition for macrofaunal settlement through reduction of habitat destruction. Mulch protects these organisms against extreme changes in temperature and humidity and provide organic residues as a source of food thus providing a stable environment for macrofaunal settlement. These organisms, in turn, play a crucial role in ecosystem functioning. Termites for example, through their activities of selecting, transporting, manipulating and cementing soil properties bring an immediate change in soil physical properties such as infiltration and aeration. This was evident in this study as significantly higher infiltration rate was observed under reduced tillage treatments as compared to conventional tillage practice (Chapter 3). The similarity of organisms observed in different tillage treatments provided the evidence of the importance of crop rotation. It appears that the constant supply of similar organic feed over a long-term may have influenced the similar type of organisms which dwell on similar feeds. The review of the literature has shown that crop rotation under NT conservation agriculture influences both the quantity and the quality of the organic material. For example, the rotation of cereal with leguminous crop provide the organic matter with low C/N ratio as compared to the only cereal-based material. This, in turn, influences microbial activities and the development of diverse macrofauna groups which are important in ecosystem functioning such as the recycling of soil nutrients. In addition, it appeared that, due to the low number of earthworms found, termites are mostly found in dry areas as compared to earthworms. This may suggest that earthworms prefer organic feeds input with lower C/N ratio while on the other hand, termites are adopted to feed on organic resources with higher C/N ratio.

Furthermore, soil macrofauna is well known to play a role in soil structural formation with termites and earthworms considered and ecosystem engineers because of their profound contribution in reworking the soil. In this study, it was found that aggregate stability and infiltration greatly improves under reduced tillage treatments (NT and RT) than conventional tillage. However, aggregate stability was only significantly higher in the top soil as compared to the subsoil and this was attributed to the SOC stratification in the top layer of the soil as compared to the subsoil. On the other hand, there were no significant differences in aggregate stability across the tillage depth in conventional tillage treatment and this was attributed to the more even distribution of soil SOC in the soil profile. Soil organic matter is the major binding agent of soil particles and its presence in higher concentration is associated with soil aggregation and more stable aggregates. This, in turn, protects the soil against soil erosion and thus degradation. Higher infiltration observed in reduced tillage treatments was associated with the presence of larger macrofaunal groups in these treatments. With respect to the effect of fertilizer application rate on soil aggregation and aggregate stability, there were no significant correlation trends found in all treatments which can be explained with certainty. Differences were not observed in soil total carbon across the tillage treatments. However, particulate organic carbon decreased with increase in tillage intensity. These particular results indicate that soil organic carbon takes time to change and transform because of the abundant pool in soil and the more sensitive indicator for small changes is particulate soil organic carbon. This pool is minimally transformed and has the fast recycling rate compare to recalcitrant pool associated with minerals which take weeks to months or even years to transform. Moreover, significant differences in soil total carbon were only observed in depth distribution. Soil total carbon was found to be significantly higher in the top 0-10 cm in reduced tillage treatments as compared to the lower depth while in conventional tillage was more uniform. This was attributed to reduced soil mixing in reduced tillage treatments as compared to conventional tillage.

In addition, unlike with what is usually observed in other studies, particularly, those conducted in temperate and cooler regions where soil organic matter usually increases in the long-term trials under NT. This study has shown that the total soil organic carbon takes time to increase in semi-arid area, particularly, in 1:1 low activity clay minerals. However, this slow improvement of total soil organic matter does not put this tillage operation in a disadvantageous position over CT because the soil is permanently protected from erosion and it improves its physical conditions. For example, it was found that yields were significantly improved in reduced tillage treatments than in CT during the period of severe drought (i.e. 2014/15 and 2015/16 growing season). This important feature of CA provides an insight or evidence that yields can be significantly be improved in sub-Saharan Africa if this system can be adopted by both small-scale and commercial farmers. This will ensure the protection of our arable land base and significantly improve food security. The resilient feature of CA to water stress is associated with permanent soil cover which increases moisture conservation of the system than CT. The higher rate of N application was found to increase yield than mid and lower rate. Yields were more reduced in NT in mid and lower rate than in RT and CT treatments because of perhaps immobilization process by microorganisms. The yield was also found to be influenced by climate factors, rainfall, as compared to soil quality parameters. Maize yield increased with an increase in rainfall and the opposite was true. What was most apparent in the study was the resilient effect of reducingd tillage treatments during the period of drought.

The results on soil chemical characteristics found that the pH of the soil was lower under no-till as compared to conventional tillage and rotational tillage. With respect to depth distribution, pH increased with increase in depth under no-till and rotational tillage treatments while in conventional tillage it was relatively uniform. The increase in pH in lower depths in reduced tillage treatment was attributed to slow leaching lime due to the larger pores created by macrofauna while acidity in the soil surface may have been due to greater soil organic matter decomposition which led to acidity. With respect to nitrogen application rates, it remained relatively uniform across the tillage treatments and this was attributed to lime that was applied every second season in each tillage treatment. Furthermore, significant differences were observed in P concentration amongst the tillage treatments with no-till having the highest P concentration than rotational tillage and conventional tillage. Significant differences were also found in tillage × depth interaction where the concentration P in no-till treatment was found to be stratified in the soil surface compared to rotational tillage and conventional tillage where it was relatively uniform across the soil profile. Significant differences were also found between the tillage treatments where no-till was found to contain higher concentration K than rotational tillage and conventional tillage treatments. However, unlike N and P where the stratification in the soil surface was observed, K concentration was uniformly distributed across the treatment depth in all tillage treatments. From a management point of view, these results clearly indicate that conservation agriculture increases the availability of the major nutrients (NPK) in the soil surface. Bearing in mind that crop rotation was not practiced as one of the management strategies to improve soil fertility in the current study, this may suggest that inclusion of the several crops in the rotation such as leguminous crops may have even a bigger impact on the soil in improving fertility. This may also improve the quality of soil organic matter and hence the diversity of macrofaunal population because of the quality and the quantity of different organic input in the soil. In addition, no significant differences were found in Ca concentration across the tillage treatments. The differences were only found across the treatment depths. In reduced tillage treatments, Ca was found to increase with an increase in depth while in conventional tillage treatment, it was found to decrease with increase in depth. This was attributed to lower pH in the soil surface in reduced tillage treatments and higher pH in the underground soil profile. Lower pH in the soil surface may have decreased the availability of Ca and higher pH in the sub-soil may have increased its availability. In Mg concentration, there were no significant differences across the tillage treatments and differences were only observed in the tillage × depth interactions. The concentration of Mg decreased with increase in depth mostly in the in the 0-20 cm depth and this was contrary to what was observed in Ca another divalent cation. Differences in distribution of these nutrients across the soil profile may have been influenced by crop and the weeds nutrient preferences and different root distribution. The uptake of Mg could have been more important than Ca. Moreover, Mg is involved in isomorphic substitution of clay minerals while Ca is not, and this could have influenced the retention of Mg in the upper layers in reduced tillage treatments. Lastly, sodium was found to be uniformly distributed across the tillage treatments and across the treatment depths. Mineralogical nature and climate condition could probably have influenced the distribution of this mineral.

Lastly, VIS-NIRS predicted SOC more accurately than SON confirmed by parameters of cross-validated predictions diagnostic such as high R^2 and RPD, and low RMSEP values obtained in

SOC than in SON. Therefore, considering the predictive statistics and accuracy created by the models, VIS-NIRS can be recommended as a fast and accurate technique for SOC determination in the studied soil. This could be a great benefit to researchers and farming community where larger samples of SOC are needed for monitoring and evaluation.

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