Long-term effect of tillage and crop rotation practices on soil C and N in the Swartland, Western Cape, South Africa

By

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DECLARATION

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Abstract

Soil Organic Matter (SOM) is an important indicator of soil quality influencing nutrient availability, water infiltration and retention and soil biological activity. The loss of SOM due to intensive cultivation is a growing concern worldwide. The Swartland is an important small grain production region in South Africa. It is situated in a semi-arid Mediterranean climate and as such has low SOM content (0.75 - 1.5 %). Conservation agriculture is the implementation of reduced tillage and diverse crop rotations and is seen as a possible solution to declining SOM in agricultural soils. The purpose of this study is to observe the effect of three commonly practiced tillage treatments and five different crop rotations on soil C and N stocks in the soil and the two major soil organic matter functional pools, namely, Mineral bound (MB) and Particulate Organic Matter (POM).

The study was conducted on two long term trials on the Langgewens Research Farm, situated near Moorreesberg, Western Cape, South Africa (33°16'34.41" S, 18°45'51.28" E). The climate is semi-arid Mediterranean with an average rainfall of between 275-400 mm with 80% falling in the winter months (April – August). The soils in this region are mainly derived from Malmesbury shale and tend to be shallow and stony. The first trial site (Site A) was a long term tillage study in its 8th year and consisted of three different 4-year crop rotation systems each under three different tillage practices. The three crop rotations included two 100 % crop treatments: Wheat monoculture (WWWW); Wheat-Canola-Wheat-Lupin (WCWL); and one 50 % crop-50 % pasture treatment: Wheat-Medic-Wheat-Medic (WMWM). These treatments were planted under three tillage treatments: No tillage (NT); Minimum tillage (MT); Conventional tillage (CT). The second trial site (Site B) was a long term soil quality trial in its 19th year and consisted of four 4-year crop rotation systems under no tillage conditions. The four crop rotation systems included one 100 % crop system: Wheat monoculture (WWWW); and three 50 % crop-50 % pasture systems: Wheat-Medic-Wheat-Medic (WMWM); Wheat-Medic/Clover-Wheat-Medic/Clover (WMc); Wheat-Medic/Clover-Wheat-Medic/Clover with supplementary grazing on Salt Bush (WMc SB).

No tillage had the highest total C stocks (0-40 cm) under both WWWW and WMWM, 31 Mg C ha^{-1} and 30 Mg C ha^{-1}. These were significantly greater than both the MT, 28 Mg C ha^{-1} and 27 Mg C ha^{-1} respectively, and CT, 22 Mg C ha^{-1} and 21 Mg C ha^{-1}, treatments under the same respective crop rotations. The effect under WCWL differed in that MT (28 Mg C ha^{-1}) preformed significantly better than both NT (22 Mg C ha^{-1}) and CT (13 Mg C ha^{-1}).

Conventional tillage under WCWL had the lowest total C stocks by a significant amount, 15 Mg C ha^{-1} lower than that of MT under the same crop. The two high biomass rotations, WWWW and WMWM have significantly greater total C stocks than that of WCWL. This is evident under both the CT (WWWW, 22 Mg C ha^{-1}; WMWM 21 Mg C ha^{-1}) and the NT (WWWWW 30 Mg C ha^{-1}; WMWMW Mg C ha^{-1}), where WCWL has a lower C stock of 13 22 Mg C ha^{-1} and 22 Mg C ha^{-1} respectively. WCWL however is able to accumulate a much higher total C stock under MT (28 Mg C ha^{-1}), with there being no significant difference between it and WWWWW (28 Mg C ha^{-}1) and WMWM (27 Mg C ha^{-1}).

The majority (55-95 %) of soil C at all sites were found in the MB fraction, while POM contributes a significantly smaller percentage. Under all treatments we can observe the trend of POM-C contribution to total C decreases with depth. There was very little difference found between the MB-C of all tillage and crop rotation treatments. However, there was great variation in the POM-C content of the treatments. Under WMWM, CT had significantly greater POM-C than NT at the 10-20 cm profile, 5.80 g kg^{-1} and 4.92 g kg^{-1} respectively, likely due to deeper incorporation of surface residues under CT. Under WWWW, NT had significantly greater POM-C than CT in the 5-10 cm profile at 2.18 g kg^{-1} and 1.10 g kg^{-1}, respectively. The effect of crop rotation was similarly undefined, there was little significant difference between treatments in the MB-C while the POM-C showed great variation. Under NT in the 5-10 cm profile, WCWL had the largest POM-C, 3.76 g kg^{-1}, significantly greater than both WMWM with 2.91 g kg^{-1}, and WWWW with 1.81 g kg^{-1}. However at the 10-20 cm profile WWWW with 2.18 g kg^{-1}, was significantly larger than both WMWM and WCWL, with 0.75 g kg^{-1} and 0.89 g kg^{-1} respectively.

Tillage was found to have the strongest influence on soil C stocks, with NT having the largest C stocks followed by MT, both being significantly greater than CT. Crop rotation had a lesser, but still significant influence on C stocks, but a larger role in N stocks. WWWW and WMWM had the greatest C stocks, while the reduced grazing on WMc SB also led to greater C stocks. The inclusion of a legume pasture (Medic and Medic-Clover) had a significant increase in N stocks while WCWL had the lowest N stock. The data gathered from this study, highlights the benefits of conservation agriculture through the usage of reduced tillage and high biomass producing leguminous pastures. WMWM and WMc SB under NT had excellent SOM accumulation and provide a diversified production system and would be recommended for this region for these reasons.

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Table of contents

List of figures

List of tables

List of Abbreviations

C	Carbon
CT	Conventional Tillage
ECEC	Effective Cation Exchange Capacity
fPOM	Free Particulate Organic Matter
MB	Mineral Bound
MB-C	Mineral Bound Carbon
MT	Minimum Tillage
N	Nitrogen
NT	No Tillage
OM	Organic Matter
oPOM	Occluded Particulate Organic Matter
POM	Particulate Organic Matter
POM-C	Particulate Organic Matter Carbon
S	Sulphur
SOM	Soil Organic Matter
WCWL	Wheat – Canola – Wheat – Lupins
WMc	Wheat – Medic/Clover
WMc SB	Wheat – Medic/Clover with supplementary grazing on Salt Bush
WMWM	Wheat – Medic – Wheat – Medic
WWWW	Wheat Monoculture

Chapter 1
Introduction

Long term field trials were conducted on Langgewens Experimental Farm near Malmesbury, Western Cape, South Africa. The first trial in its 8th year in 2014 was conducted to evaluate the effect of tillage and crop rotational practices on soil quality. The second trial in its 19th year in 2014 was a crop rotation evaluation trial under no tillage practices. These two trials were used to study the effect of tillage and crop rotational practices on the soil organic matter (SOM) and the soil organic matter functional pools.

Langgewens is located in a semi-arid Mediterranean climate. The average rainfall is between 300-400 mm with 80 % falling in the winter (April – August). This is a limiting factor in the choice of dry land crop selection. The main crops planted are small grains (wheat, barley, and oats), canola oil seed, legumes (lupines) and pastures (medics and clover). While conventional tillage practices are still widely utilised, conservation tillage is beginning to increase in popularity. Under years of intensive farming practices there has been a loss of SOM. This loss can have a negative effect on crop production due to loss of soil fertility, poor structure and reduced water holding capacity. Reduced tillage and inclusion of high biomass yielding crops in believed to lead to an increase in SOM. While this has been widely studied in temperate regions there is less research in semi-arid regions (Lal 2006; Álvaro-Fuentes et al. 2009; Sombrero & de Benito 2010), and even less in a South African context (Smit 2004; Botha 2013; Smith 2014). Although both Smit (2004) and Botha (2013) conducted their studies on the effect of tillage practices on soils in the Swartland, SOM was only a marginal part of their focus and none looked at SOM fractional pools. Smith (2014) conducted his study on the effect of crop rotational practices on the SOM content and SOM functional pools in the Overberg region, however, he did not compare the effect of different tillage methods and the soils were also different. So to the best of our knowledge there is limited data on the effect of management practices on SOM in the winter wheat production regions of South Africa, and no knowledge about the effect of these practices on SOM quality in the Swartland.

Therefore, the first objective of this study was to evaluate the effect of tillage and crop rotational practices on the total C and N stocks in the Swartland region. To further understand the soil C and N stock distribution, selected soil and crop properties had to be evaluated, such as: vertical distribution of SOM, bulk density, soil texture, and residue inputs. This objective was addressed in Chapter 3 of this thesis. The second objective was to evaluate the effect of tillage and crop rotation practices on the distribution of SOM functional pools. This objective was addressed in Chapter 4 of this thesis.

Chapter 2
Literature review

2.1 Introduction

Soil organic matter (SOM) is one of the largest carbon (C) sinks on earth. Lal (2002) estimated that between 1200 and 2200 Gt of C are stored in the earth's soil as organic matter. This compared to 720-750 Gt in the atmosphere and 550-835 Gt in plant biomass. This makes soil organic matter a key tool in sequestering CO_2 from the Earth's atmosphere. However the soil can act as either a C sink or a C source due to SOM being in a complex equilibrium (Lal 2011) This equilibrium is dependent on the rate of SOM inputs and the rate of SOM mineralisation (Johnstone et al. 2009).

Between 1850 and 1995, Lal & Bruce (1999) estimated that 78 Gt of C were lost from the soil due to land use changes and deforestation. This can be attributed to wetland draining, erosion and increased disturbance of the topsoil. With the advent of the Green Revolution there was an increase in land tilled and a greater reliance on inorganic fertilizers placing less importance on SOM. The increased tillage led to greater SOM mineralisation and soil erosion resulting in depletion of SOM and reduction in productivity in certain lands (Rasmussen et al. 1998; Lal 2004; Alvaro-Fuentes et al. 2009).

Soil organic matter not only plays a key role in mitigating climate change but it is of vital importance to food security. Soil organic matter is considered to be a key marker on soil health and sustainable agriculture. It is of growing importance with the trend to move away from reliance on inorganic fertilisers to meet the nutritional needs of crops. An increase in SOM improves many chemical, physical and biological properties of the soil (Haynes 2005). The chemical properties influenced are cation exchange capacity, buffering capacity, metal complexation, and interaction with soluble organic complexes. Physical properties that are influenced by SOM are bulk resistance to compaction, water retention and infiltration, aggregate formation and stability, and thermal modulation. Soil organic matter acts as a matrix for microbes as well as a pool of metabolisable energy. Mineralised SOM is an important source of plant available N, P, and S.

Tillage has one of the greatest effects on the loss of SOM (Magdoff & Weil 2004). During the first two years of cropping virgin land it is estimated that 20 to 30 % of SOM is lost from the soil (Syers & Craswell 1995). In total up to 70 % of SOM can be lost when comparing a cultivated soil to undisturbed forest soils. Vegetation plays an important role in the accumulation of SOM as it directly influences OM inputs. Fallow periods are found to have a lower SOM accumulation than continuous cropped fields (Alvaro-Fuentes et al. 2009; Biederbeck et al. 1994), while the inclusion of a pasture system has the benefit of increased SOM accumulation (Salvo et al. 2014). Soil organic matter turnover is dependent on microbial activity. This in turn is influenced by environmental factors such as the temperature range in the soil, water availability and oxygen availability (Oades 2014). Physical factors of the soil also have an influence such as mineralogy, soil texture and aggregate formation (Martinez et al. 2008). This leads to SOM accumulation and stability varying greatly across climates and landscapes.

Conservation agriculture, the use of reduced tillage and implementation of crop rotation, is currently being heralded as an important method to improve SOM, sequester atmospheric CO_2 and improve crop yields. However much SOM increases are only in the top 10-30 cm of the soil (Alvaro-Fuentes et al. 2009; Sombrero & de Benito 2010), and total C stocks over the entire soil depth vary little between conservation and conventional tillage (Powlson et al. 2011).

Conservation agriculture has been subject to much research over the past decades as an alternative to conventional tillage (Cavalieri et al. 2009; Moussa-Machraoui et al. 2010; Morell et al. 2011). However much of the studies conducted have been in temperate areas. Little data currently exists for semi-arid regions which are agriculturally significant and also low in SOM, therefore sensitive to C loss (Smith 2014). International studies conducted by Alvaro-Fuentes et al. (2009), Sombrero & de Betino (2010) and Sisti et al. (2004) show the effects of tillage on SOM in semi-arid regions. Studies conducted in South Africa by Prinsloo et al. (1990) and Du Toit et al. (1994) looked at the effect of tillage on SOM in the summer rainfall region, while Agenbag & Maree (1989), Botha (2013) and Smith (2014) studied the effects of tillage on SOM in the semi-arid winter rainfall region.

2.2 The effect of tillage on SOM

The disturbance of the soil experienced during tillage has been found to have a significant influence on SOM. Prinsloo et al. (1990) found the loss of SOM under cultivation to be 68%, while du Toit et al. (1994) found the loss to be between 10-75 %. The mixing of residues into the soil increases SOM mineralisation due to greater exposure to microbial decomposers and optimal moisture and temperature regimes (Alvar-Fuentes et al. 2009; Sombrero & de Betino 2010). Soil disturbance by tillage leads to destruction of the protective soil aggregate (Botha 2013). This in turn exposes the labile C occluded in these aggregates to microbial breakdown (Alvaro-Fuentes et al. 2009).

Since the 1970s conservation tillage, including minimum, no and zero tillage have become increasingly popular. This is due to the decrease in working of the land, reducing labour and fuel costs, and the positive effect on the soil quality, i.e.: improved soil structure, better water infiltration and reduced run off, and reduced dry and warming of the soil (Sisti et al. 2004; Sombrero & de Betino 2010). However conventional tillage is still prevalent in many parts of the world.

Conservation tillage can be defined according to the Conservation Information Center (CTIC 2004) as any tillage and planting system that leaves 30 % or more crop residues on the surface after planting. This remaining mulch serves to reduced water loss and erosion compared to conventional tillage. The three main methods of conservation tillage are minimum till, no-tillage and zero tillage. Minimum tillage results in the largest soil disturbance with the soil being lightly scarified or cultivated before planting to produce an even seed bed. No-tillage results in the soil remaining undisturbed until planting which takes place using a no-tillage planter which only disturbs the planting row. Zero-tillage results in the least tillage as the soil remains undisturbed until planting which is done with a zero tillage planter resulting in soil disturbance only around the seed. Conventional tillage involves several workings of the soil including mouldboard ploughs, disking, harrowing and cultivating. This is to control weeds, incorporate crop residues and prepare an even seedbed.

In certain areas of the world it is still common to burn the plant stubble before planting, to ease the ploughing and planting process (Lal 2004; Haynes 2005). Many studies have found that conservation tillage can increase SOM compared to conventional tillage especially in the top 30 cm of the soil (Hao et al. 2001; Six et al. 2004; Alvaro-Fuentes et al. 2009; Sombrero & de Betino 2010). However studies in Semi-arid regions are less definitive, with Alvaro-Fuentes et al. (2009) and Sombrero & de Betino (2010) showing an increase, but Sisti et al. (2004) showing no significant difference. A review by Powlson et al. (2011) concluded that when examining the total C stock of the soil down to 1 m, that there is no significant difference between conventional and conservation tillage (Fig. 2.1), this was also found in studies by Sisti et al. (2004) and Sombrero & de Betino (2010). It was found that the there was a significant difference above 30 cm with conservation tillage building up a stratified layer of plant residues, while at deeper depths the mixing effect of conventional tillage accumulated a greater amount of mineral-associated SOM.

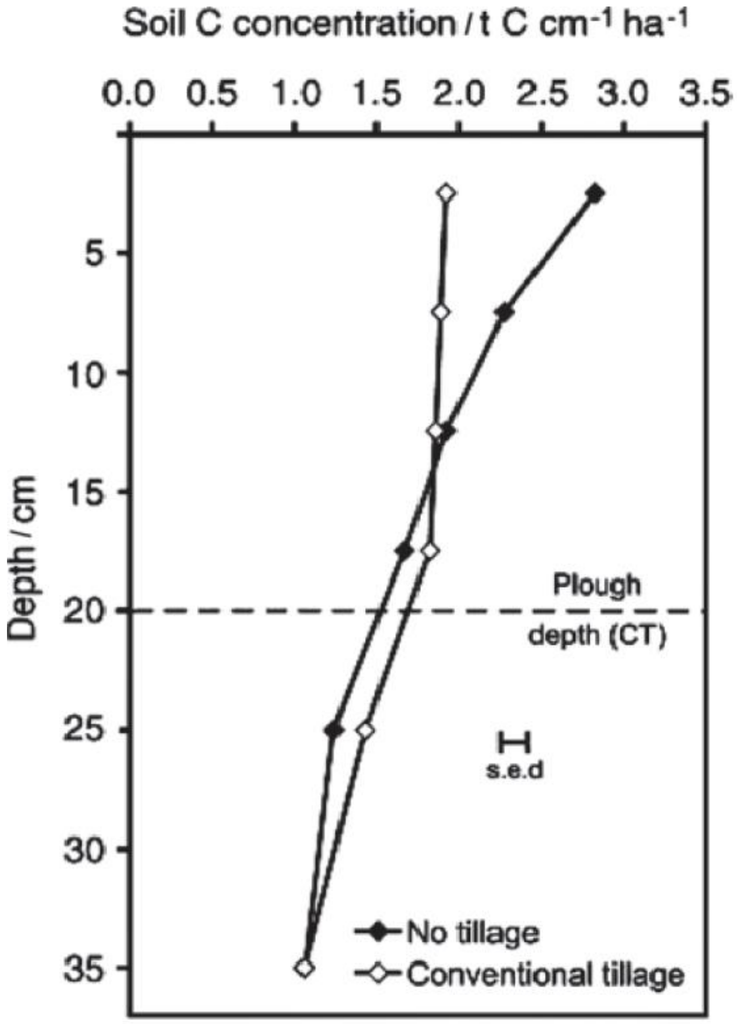


Figure 2.1. The effect of tillage on Soil Organic Matter Distribution (Powlson et al. 2011)

2.3 Effect of crop rotation on SOM

The choice of crop chosen to be grown on a site plays an integral role in the SOM balance as the crops influence the C inputs into the soil. Different crops produce biomass of differing quantities and qualities (Johnstone et al. 2009). Crops that produce a large amount of biomass, such as wheat or pastures, will lead to a greater addition of OM to the soil, compared to crops with a low biomass such as canola or beans. While leaves and stalks provide a large addition of OM to the topsoil, roots also play an important but poorly understood role (Van Vleck &

King 2011; Smith 2014). Rasse et al. (2005) found that roots can contribute as much as twice the amount of stable C to the soil as above ground residues.

The quality of crop residues are determined by the C:N ratio. Residues with a low C:N ratio are regarded as high quality, and will mineralise rapidly, allowing for faster access to essential nutrients such as N, P and S. Low quality residues with a high C:N ratio will mineralise at a slower rate and will therefore have a longer residual time in the soil. A C:N ratio below 25:1 will lead to mineralisation of N into the soil (Sparks 2005). It is then obvious that the inclusion of legumes into a crop rotation will have a positive effect in the mineralisation of OM. Schmidt et al. (2011) postulated that while the composition of OM plays a role in the residual time in the soil, the soils biotic and abiotic conditions have a much larger influence. Smith (2014) found that the inclusion of a pasture system into a crop rotation led to an increase in SOM over continuous cropping, mainly due to the prolific root system of the pastures and the greater period of time that the soil remains undisturbed. Alvaro-Fuentes et al. (2009) found that continuous cropping to lead to greater SOM accumulation over a crop-fallow system, supporting the trend of having fields under continuous cover, water permitting.

2.4 Soil organic matter functional pools

SOM is a highly variable substance, its composition ranging from fresh plant and microbial residues with a high rate of turn over to humic substances with little anatomical resemblance to its parent material and turnover rate measured in millennia (Haynes 2005; Breulmann 2011). The complex nature of SOM hinders our ability to study the quality of SOM, with many methods focusing on the humic acid, fulvic acid and humin fractions (Brunn et al. 2004). However these fraction differ only marginally in terms of turnover rate and functional pools (Helfrich et al. 2007). Physical fractionation methods have been proposed to overcome these short comings. These methods tend to separate the SOM into two major fractions, labile and stable (Haynes 2005; Helfrich et al. 2007; Manlay et al. 2007; Cerli et al. 2012). The separation between the two fractions is based on their turn over time: labile having the shortest turn over time and stable having the longest turn over time ranging from decades to centuries (Helfrich et al. 2007).

The labile fraction can also be referred to as the particulate organic matter (POM) fraction. This fraction is an intermediate between plant litter and humified substances. It has the shortest turn over time ranging from a couple of months to decades (Haynes 2005). This fraction is the most sensitive to cultivation but is also the most important for plant nutrition. POM can be further broken up into two different groups, free particulate organic matter (fPOM) and occluded particulate organic matter (oPOM). The fPOM fraction is present mainly in the upper layers of the soil and is not associate with the mineral fraction. The oPOM fraction is surrounded by the mineral fraction affording it a degree of protection from microbial decomposition.

The stable fraction also referred to as the mineral bound (MB) fraction is composed of organic C compounds that are tightly bound or sorbed to the mineral fraction of the soil. This is the more stable fraction with a turn over time of decades to centuries, it is also the larger fraction accounting for the majority of the SOM present in the soil (Haynes 2005; Helfrich et al. 2007; Manlay et al. 2006). This fraction is important in C sequestration and in increasing the aggregate stability of the soil.

2.5 Conclusions

Soil organic matter plays and important role in sustainable agriculture by improving certain soil parameters such as nutrient availability, water retention and infiltration, physical resilience and biotic activity. No agriculture system can be expected to be sustainable and continuously productive under management practices that lead to SOM loss. However, agriculture inevitably leads to a loss of SOM from the natural undisturbed system and methods need to be assessed to limit this.

According to the literature, conservation tillage increases the total SOM in the top 30 cm of the soil compared to conventional tillage, however shows little difference over the total C stock. The reduced disturbance of conservation tillage leads to a reduced loss of SOM to mineralisation. The inclusion of a high biomass crop rotation with conservation tillage practices will lead to an effective accumulation of SOM. The inclusion of a legume into this rotation will not necessarily lead to an increase in SOM but will improve the quality of it and the availability of essential nutrients.

By studying SOM fractional pools, as opposed to simply SOM quantity, we can gain a greater understanding of the quality of the SOM. This will give us a greater understanding of the proportion of labile and stable fractions of the SOM, giving a clue to the sustainability and productivity on the soils. Semi-arid regions are historically low in SOM and are susceptible to greater loss of SOM due to poor management. It is important to introduce improved farming methods such as conservation tillage and crop rotation into these major crop producing regions, to ensure continuous food production.

Chapter 3

The effect of tillage and crop rotation practises on soil C and N and selected soil properties

3.1 Introduction

In the Swartland, climate is the largest limiting factor in the accumulation of SOM. With a rainfall of between 400-500 mm, plant growth is limited to the wet winter season. This limits the amount of crop residues added to the soil as plant growth is limited. High temperatures also lead to a high microbial activity and the loss of SOM. The Swartland is an important grain producing area, accounting over 30 % of wheat production in South Africa along with Ruens (ARC 2010), however the semi-arid climate and the conversion of fynbos into heavily cultivated wheat fields have led to historically low SOM levels. This is of great concern as SOM is considered to be one of the most important indicators of the sustainability of an agricultural system (Lal 2004). SOM contributes positively to many soil properties such as nutrient exchange and availability, water infiltration and retention, physical resilience and biotic activity (Lal 2004; 2006; 2011). The loss of SOM will lead to loss of agricultural production, increased run off and erosion, reduced biological activity in the soil and an increase in atmospheric CO_2 increasing the risk of food insecurity (Lal 2004).

There has been a great interest in the effects of tillage and crop rotational practises on SOM in recent years. However much of the studies conducted have been in temperate areas as opposed to semi-arid regions and very little in the South African context. Semi-arid regions have historically low SOM due to low rainfall leading to a low production of biomass to be incorporated into the soil. It is because of this low SOM content that semi-arid regions are considered to be highly susceptible to SOM losses (Alvaro-Fuentes et al. 2009). Carbon sequestration is greatly influenced by climatic and mineralogical conditions and is therefore site dependent (Sisti et al. 2004).

The adoption of sustainable agricultural practices is imperative to promote C sequestration. Conservation agriculture is one of these methods, where reduced tillage is combined with crop rotation and the leaving of residues on the surface of the soil. Alvaro-Fuentes et al. (2009)

found that conservation agriculture can lead to an increase in C sequestration in semi-arid regions. Sisti et al. (2004) found that the adoption of no-tillage in isolation will not necessarily lead to a universal increase in C sequestration. The adoption of reduced tillage with a diverse high biomass crop rotation will lead to an increase in C sequestration (Lal & Bruce 1999). The increased OM inputs of the high biomass crops together with the reduced mineralisation of SOM under reduced tillage will lead to a positive SOM accumulation. However due to the slow rate of SOM accumulation it takes a number of years (± 10 years) for any stable effects on the SOM to be observed (West & Post 2002; Sombrero & de Benito 2010).

The main objective of this study was to observe the long term effects (one trial in its 8th year, the other in its 19th year) of tillage practises and crop rotations on the stocks of C and N in the soil. It involved understanding the influencing factors such as soil texture, bulk density, and residue inputs.

3.2 Materials and methods

3.2.1 Study area

The study was conducted on the Langgewens Research Farm (Fig. 3.1), situated near Moorreesberg, Western Cape, South Africa (33°16'34.41" S, 18°45'51.28" E). This forms part of the Swartland region, an important winter grain area on the western coast of South Africa. Small grains are grown under dry land conditions. The climate is semi-arid Mediterranean with an average rain fall of between 275-400 mm with 80 % (ARC-ISCW 2013) falling in the winter months (April – August) (Table 3.1). Summers tend to be warm and dry.

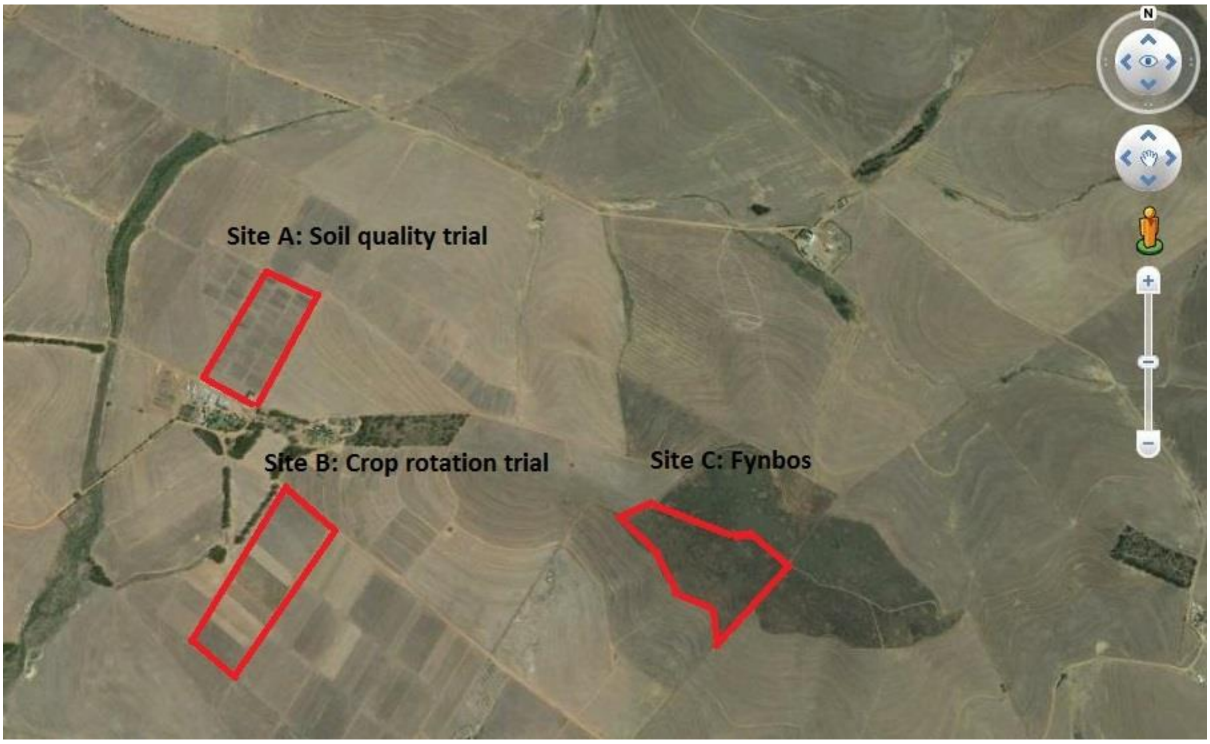


Figure 3.1. Location of Langgewens Experimental Farm and Trial sites

Table 3.1 Long-term monthly climate data for Langgewens Research Farm (ARC-ISCW 2013)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Maximum temperature (̊C)	30.5	30.2	28.8	24.9	20.6	18.1	17.0	17.8	20.2	23.7	27.3	29.0	288.1
Minimum temperture (̊C)	16.3	16.9	15.8	13.6	11.1	9.3	8.0	8.2	9.1	11.0	13.5	15.1	147.9
Evaporation (mm)	319.0	288.0	245.0	171.0	105.0	75.0	71.0	84.0	120.0	198.0	267.0	313.0	2257.0
Rainfall (mm)	8.1	10.6	15.4	30.5	58.3	64.4	58.2	61.7	36.8	24.3	15.0	12.0	395.3
Raining days	2.3	2.3	3.0	5.6	8.8	9.1	9.5	10.0	7.9	5.7	3.3	2.9	70.4

The soils in this region are mainly derived from Malmesbury shale and tend to be shallow and stony. The dominant soil forms are Swartland, Oakleaf and Glenrosa (Soil Classification Working Group, 1991). The maximum working depth of the soil ranged from 30-60 cm and are composed of 40-60 % coarse fragments and have a clay content of 10-15 % sandy loam. The C content range is 0.5-2.0 %.

3.2.2 Experimental site layout

The study was conducted on two long-term trials at the Langgewens Research Farm, Site A was a soil quality trial in its 8th year where the effect of both crop rotation and tillage were studied. Site B was a cropping system trial in its 19th year. Only the effect of crop rotation under no-tillage was studied on this site. An adjacent site (Site C) of natural fynbos was used as a comparison with the agricultural systems.

3.2.2.1. Site A trial description

Site A was on a mid-slope with a gradient of less than 5 % (Fig. 3.2). The dominant soil form at the trial area was Swartland (Orthic A – Pedocutanic B) (Soil Classification Working Group 1991) (Fig. 3.2). The working depth of the soil was 20-40 cm and was of a sandy loam texture.

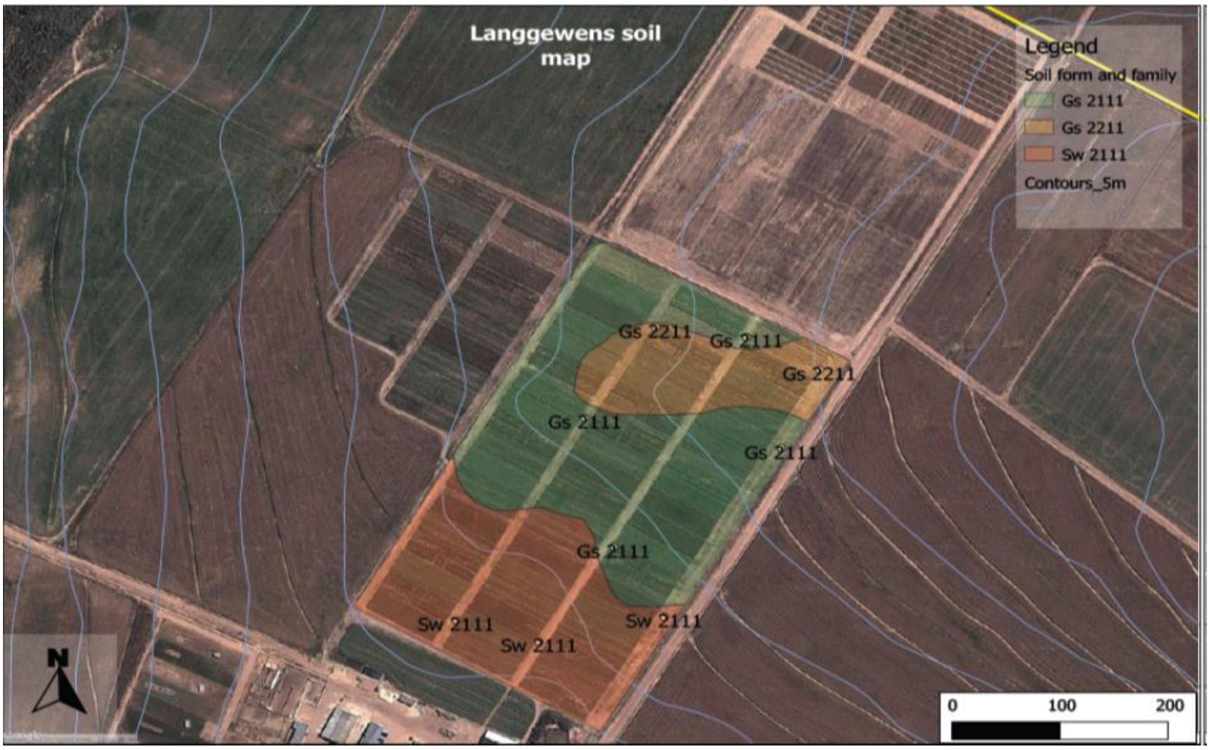


Figure 3.2 Soil map of Site A at Langgewens

The Site A trial (8th year) consisted of three different 4-year crop rotation systems each under three different tillage practices. Each crop rotation treatment (30 x 30 m) was replicated four times. Each crop rotation replicate was sub-divided into three 10 x 30 m sub-plots for each tillage practise. The crops used in the various rotation systems were: wheat (*Triticum* spp.), canola (*Brassica napus*), lupins (*Lupinus* spp.) and barrel medics (*Medicago truncatula*). The three crop rotation systems that were studied were:

Two 100% crop rotations consisting of:

- Wheat monoculture (WWWW)
- Wheat-Canola-Wheat-Lupin (WCWL)

One 50% crop and 50% pasture rotation consisting of:

- Wheat-Medic-Wheat-Medic (WMWM)

The three tillage treatments were:

- Conventional Tillage (CT)
- Minimum Tillage(MT)
- No tillage (NT)

Conventional Tillage involved scarifying the soil to a depth of 100-150 mm with a tine cultivator in late March followed by ploughing with a mouldboard to a depth of 150-200 mm a few days before planting. Minimum Tillage involved scarifying the soil to a depth of 100-150 mm with a tine cultivator in late March. In the NT treatment there was no disturbance of the soil prior to planting. All crops were planted with a NT planter (Ausplow with knife openers and presswheels) in late May, with the exception of Medic which was allowed to re-establish itself from the soil seed bank without replanting. None of the treatments at Site A were ever grazed during the trial period.

Fertilizer was applied at planting at the following rates

- At planting
  - Wheat & Canola: 2:1:0 (29) + S @ 129 kg/ha
  - Lupins: Single superphosphate @ 143 kg/h
- Top dressings: single top dressing @ 40 days after emergence with 27%N + 3%S
  - Wheat: 40 kg N/ha
  - Canola: 50 kg N/ha

3.2.2.2. Site B trial description

Site B was located on a lower slope with a gradient of between 5-10 % (Fig. 3.3). The dominant soil forms present were Glenrosa (Orthic A – Lithocutanic B), Klapmuts (Orthic A – E Horizon

– Pedocutanic B) and Swartland (Orthic A – Pedocutanic B) (Soil Classification Working Group 1991) (Fig. 3.3). The working depth was 40 – 60 cm and was of a sandy loam texture.

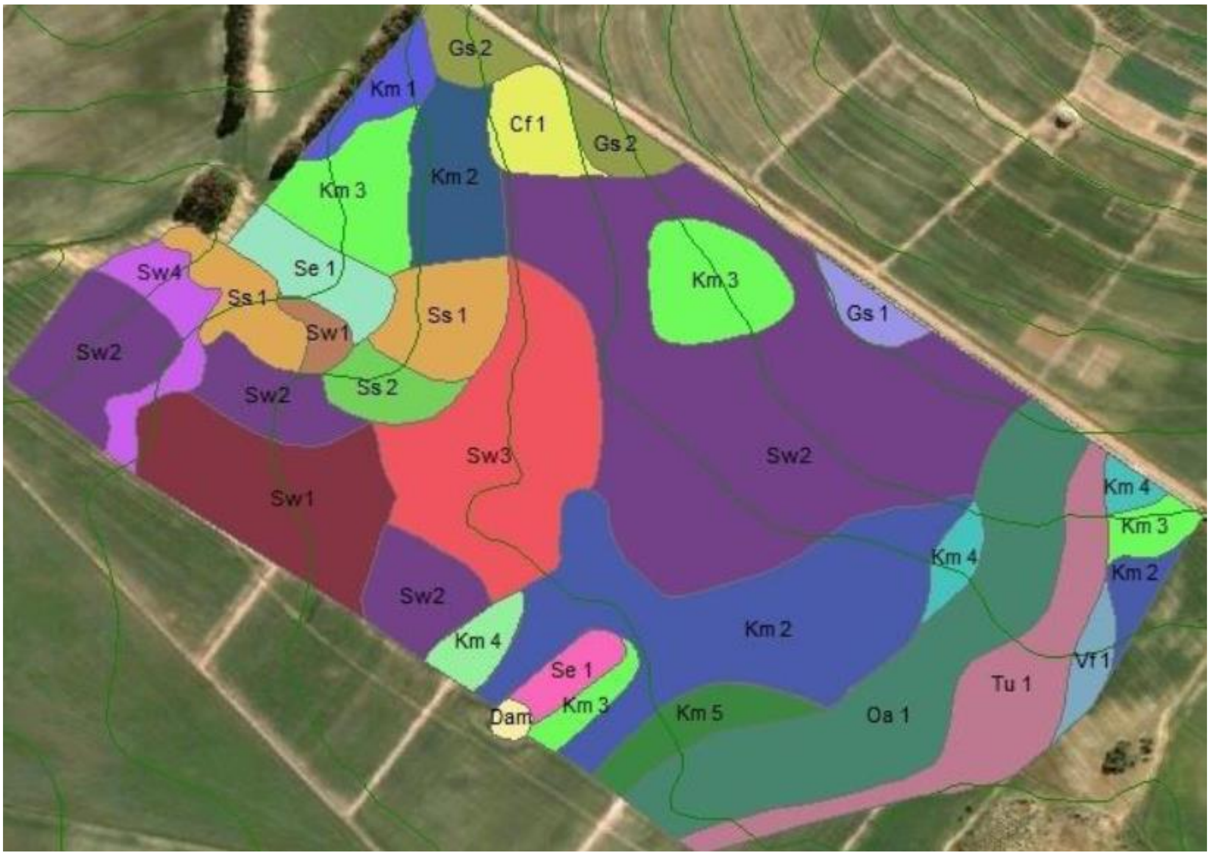


Figure 3.3 Soil map of Site B on Langgewens

The Site B trial (19th year) consisted of four different 4-year crop rotation systems all under NT. Each crop rotation treatment (0.2 ha) was replicated four times. The four crop rotation systems that were studied were:

One 100 % crop rotation consisting of:

- Wheat monoculture (WWWW)

Three 50 % crop 50 % pasture rotations consisting of:

- Wheat – Medic – Wheat – Medic (WMWM)
- Wheat – Medic/Clover – Wheat – Medic/Clover (WMc)
- Wheat – Medic/Clover – Wheat – Medic/Clover that was less grazed due to supplementary grazing of the sheep on salt bush (WMc SB)

All treatments were planted with a No tillage planter (Ausplow with knife openers and presswheels). The barrel medics and clover were allowed to re-establish from the soil seed bank. The pastures rotations were grazed throughout the year by sheep, but in the WMc SB treatment, the sheep were initially grazed on salt bush (*Atriplex nummularia)* camps early in winter to allow the Medic to thoroughly establish itself before grazing. The wheat stubble was also grazed after harvest.

The fertilizer application was as follows:

- At planting
    - Wheat: 2:1:0 (29) + S @ 129 kg/ha
- Top dressings: single top dressing @ 40 days after emergence with 27%N + 3%S
    - Wheat: 40 kg N/ha

3.2.2.3. Site C description

Site C was located at a nearby natural undisturbed fynbos site. This site was on a midslope with a gradient of 10-20 %. Due to the higher-lying location of the site, the soil differed from the cultivated Site A and B in terms of texture, being a sandy loam. The soil was also a Swartland form with a maximum depth of 20-30 cm. Site C was populated predominantly with renosterbos (*Elytropappus rhinocerotis)* with some parts being overrun with rye grass.

3.2.3 Soil sampling and preparation

Soil samples were collected in late June to mid-July 2014. This was 2-4 weeks after emergence of the wheat. All sites sampled were under wheat rotations at the time. Soil samples were taken from three replicate sites of each of the 14 selected treatments. These were taken to a depth of 40 cm at increments of 0-5 cm, 5-10 cm, 10-20 cm and 20-40 cm. Twenty five soil cores (3-4 kg) were taken per replicate using a steel pipe (4 cm diameter) in a 10 m radius in the field, samples were taken both on and in-between the crop row. Samples from each depth were bulked and mixed in a marked plastic bags. After air-drying all soil samples were sieved through a 2 mm sieve. An undisturbed (not sieved) soil sample was kept aside from each treatment for aggregate stability analysis. All analyses was conducted on dry sieved soil samples unless otherwise stated.

3.2.4 Quantification of coarse fragments

Usually the quantification of coarse fragments takes place during the sieving process of sample preparation. The samples are gently pre-crushed in a mortar and pestle to break up large clods before passing through a 2 mm sieve. This will separate it into a fine fraction (<2 mm) and a coarse fraction (>2 mm). However, because these shallow soils were derived from shale saprolite they could not be pre-crushed as this would have crushed the shale fragments altering both the chemical and physical properties of the soil. Due to the fact that the samples were taken in a wet state and then dried, a large amount of fine material remained bound to the coarse fragments. This led to an overestimation of the coarse fragment content mass and unrealistic figures such as 80-90% of the soil sample.

To correct for this overestimation, a representative 100 g sub-sample was taken from the coarse fragments and placed in an Ultrasonic bath (UR 1, Retsch Gmbh & Cokg., Germany) for 5 minutes to disperse and remove the fine soil adhered to the coarse fragments. The samples were then wet sieved (2 mm) to separate the coarse and fine fractions and oven dried overnight. Once dry the samples were weighed, and a correction factor was calculated to accurately determine the coarse fraction of the soil samples.

3.2.5 General soil characterization

3.2.5.1 Mineralogical composition

The clay mineral composition of the soils was determined using clay separation and X-ray diffraction (Whittig & Alladice 1986). Two sub soil samples were analysed, one from Site A and one from Site B, to give an indication of the clay mineral composition and site variation. The clays were separated using Calgon solution and Ultrasonic bath to disperse the clay. They were then saturated with $CaCl_2$ to ensure Ca saturation. The clay samples were dialysed to remove excess salts and ground lightly. They were then analysed using X-ray diffraction at 45 kV and 30 mA using Cu Kα radiation (Whittig & Alladice 1986).

3.2.5.2 pH

Soil pH was measured on all 5-10 cm samples in both water and 1M KCl at a 1:2.5 soil to solution ratio. Samples were shaken for 30 min on a reciprocating horizontal shaker and then allowed to stand for another 30 min before the pH was measured.

3.2.5.3 Exchangeable cations

Exchangeable basic cations and exchangeable acidity was determined on all 5-10 cm soil samples. Exchangeable basic cations (Ca, Mg, Na and K) were extracted using the 1M Ammonium Acetate (NH_4OAc) (pH 7) extraction method (Thomas 1982). The cations were determined using Atomic Absorption Spectroscopy. Exchangeable acidity was determined using the 1 M KCl extraction method according to Thomas (1982). The effective cation exchange capacity (ECEC) was calculated from the sum of the exchangeable acidic and basic cations.

3.2.5.4 Total C and N analysis

Total C and N was determined on all soil samples from all depths. Total C and N was determined using a dry combustion Eurovector Elemental Analyser (Eurovector Instruments & Software, Italy). Dry combustion is considered to be one of the more accurate methods as it ensures complete combustion of organic C. As there was no free carbonates present, the total C can be considered to be entirely organic. Samples were ball milled prior to analysis to ensure complete and instantaneous combustion.

3.2.5.5 Particle size

The pipette and sieve methods were used to determine the texture of all soil samples (Gee & Bauder 1986). Forty grams of soil were pre-treated with 35 % H_2O_2 to remove all organic matter. Once all organic matter had been removed the sample were dispersed with 10 ml of Calgon solution, the samples were stirred and then left overnight. Once dispersed the sample was passed through a 0.053 mm sieve to separate the sand fraction from the silt and clay fractions. The sand fractions were dried and then sieved into their respective grades. The clay and silt fractions were determined using a sedimentation cylinder and a Lowry pipette.

3.2.5.6 Bulk density

Field bulk density was determined using the clod method according to Grossman & Reinsch (2002). Samples were taken in November after harvest at all sites at depths of 5-10 cm, 10-20 cm and 20-40 cm. Sample pits were dug using an excavator due to the hard setting of the dry ground. The face of the pit was then cleared with a shovel and clods removed using a rock hammer. Duplicate clods were taken for each site to ensure accurate determination. The clods were air-dried for several weeks in the lab at 30 ^{0}C. The samples were then broken into manageable sizes and weighed. The clod was then dipped into molten paraffin wax (70 ^{0}C), ensuring the sample is completely covered. After drying it was dipped again into the wax to ensure no pores remained open. The mass of the clod and wax was recorded before the clod was completely submerged in water and its displacement recorded. As the density of the wax and water were know, the density of the clod was able to be calculated.

Due to the large proportion of coarse fragments in the clod, the bulk density had to be corrected so as to give an accurate representation of the bulk density of the soil (less than 2 mm). This was achieved by calculating the mass and volume of a representative sample of coarse fragments per site and subtracting these from the mass and volume clod sample, leaving only the density of the fine fraction.

3.2.6 Plant residue inputs

Above ground samples of all crops were taken in November after harvest. The above ground material was determined (kg m^{-3}) by removing all plant material at ground level from a determined area. These samples were returned to the lab to be oven dried (60 ^{0}C) for 48 hours before recording their mass. Due to the hard setting nature of the soil root samples could not be taken and existing data from a similar study in the Southern Cape was used (Smith, 2014). Oven-dried plant samples were then finely milled and the C and N content was analysed using a dry combustion Eurovector Elemental Analyser (Eurovector Instruments & software, Italy).

3.2.7 Statistical analysis

Statistical differences between treatments were distinguished at the $P < 0.05$ level using Tukey's Studentized Range test. A one-way ANOVA was used for this completely randomized design.

3.3 Results and discussion

3.3.1 General soil characterisation

3.3.1.1 Soil chemical and mineralogical properties

The topsoil (5-10 cm) pH of the sites was mildly acidic to neutral with a minimal variation; Site A had a pH range of 6.0 to 6.4, while Site B had a range between 5.6 and 6.2. Both sites were within the optimal pH range for crop production (Appendix A - Table A-1). The topsoil (5-10 cm) base saturation for both sites was high ranging from 95 to 99 %. Site A topsoil (5-10 cm) samples had an ECEC between 3.8 and 5.4 cmolckg^{-1}, while Site B was between 5.0 and 6.3 cmolc kg^{-1} (Appendix A – Table A-1). Generally, the total C content of all sites was low with the top soil having a range between 6.4 and 27.3 g C kg^{-1}, while the lower horizons had a range of 3.7 to 5.3 g C kg^{-1}. This was to be expected for the semi-arid area. The natural fynbos site had an overall lower C content in the topsoil of 16 g C kg^{-1} and a higher content in the subsoil of 7.2 g C kg^{-1} compared to the test sites.

X-ray diffraction analysis identified muscovite and kaolinite as the dominant clay minerals (Appendix A - Fig. A-1). Both of these are low activity clay minerals, with kaolinite having a CEC of between 2 – 5 cmolc kg^{-1} and muscovite between 10 – 40 cmolc kg^{-1} (McBride 1994).

3.3.1.2 Coarse fragments

Soil coarse fragment content are generally determined by the location of a site, being a product of parent material and landscape position, etc. However, it is known that tillage practices can significantly affect coarse fragment content, especially in shallow, saprolitic soils. In this study it was found that tillage did significantly affect the distribution of coarse fragments in the soil. At site A, the WMWM and WCWL under CT had a significantly greater coarse fragment content across all depths (Fig 3.4 b and c), this was less defined under WWWW (Fig. 3.4 a). It is assumed that the deeper tillage of the mouldboard plough is shattering the larger rock fragments deeper in the horizon. The mixing action of the mouldboard would also allow for these fragments to be mix throughout the horizon, and therefore effecting all depths.

The larger area which comprises Site B under NT was bound to have a greater variation in coarse fragment content (Fig. 3.5). Here the coarse fragment content appears to be influenced mainly by the position in the landscape. The WMWM and WMc treatments contain the greatest coarse fragment contents which is reflective of their positions on the upper mid slope and crest of the slope.

Coarse fragments constitute an in-active part of the soil matrix and thus an increase in coarse fragments will serve to dilute the SOM stocks of the soil by reducing the volume of the fine soil. To remove the influence of soil coarse fragment content on soil C and N stocks, the bulk density (Appendix A – Figs. A-2 and A-3) used to calculate these stocks reported later in this chapter have been corrected for coarse fragment content as described in the material and methods section 3.2.5.6.

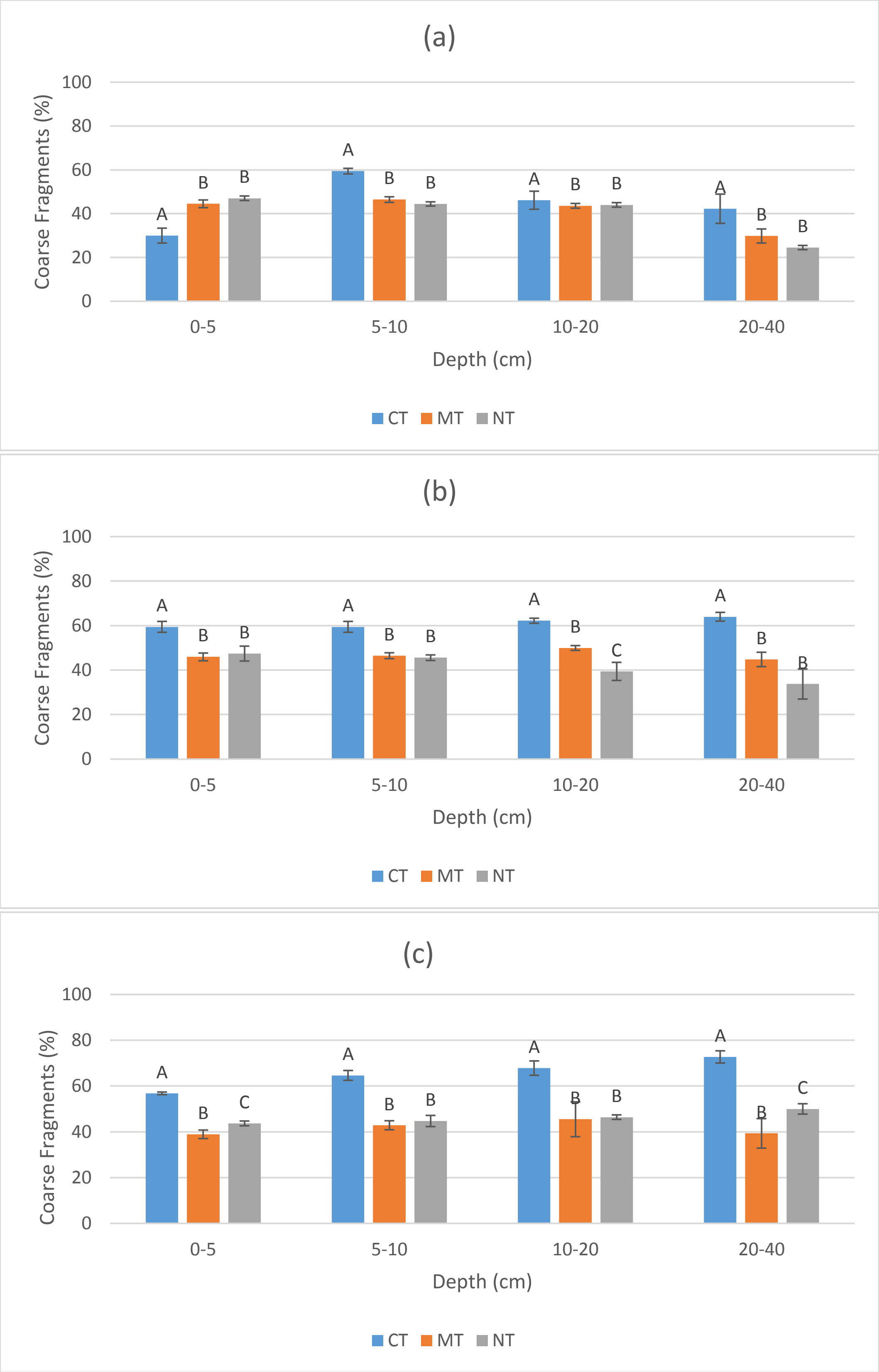


Figure 3.4 The effect of tillage on soil coarse fragment content of (a) WWWW, (b) WMWM and (c) WCWL treatments at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at $\alpha = 0.005$. Similar letters indicate lack of significant difference

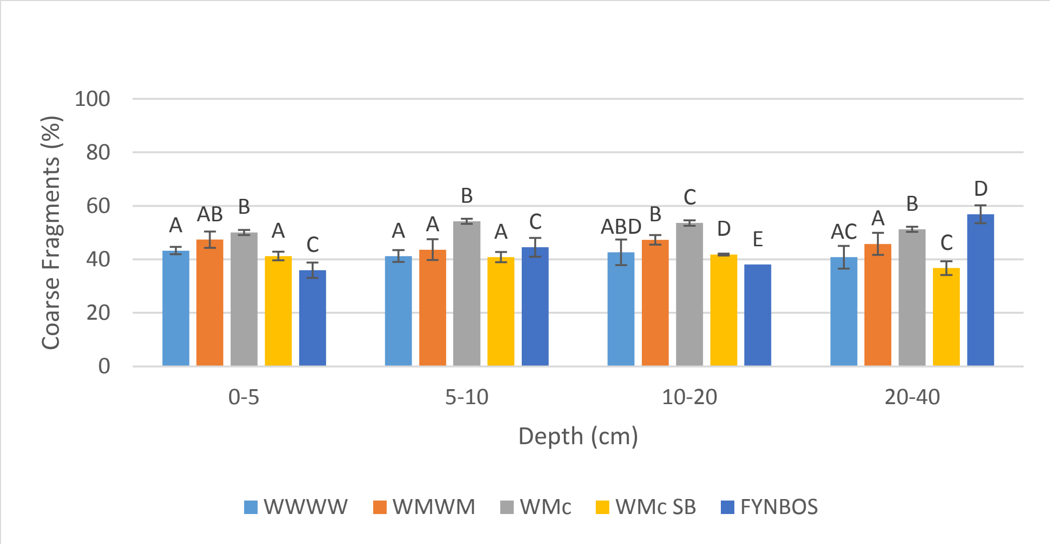


Figure 3.5 Coarse fragments content under NT of soils at Site B and Fynbos at Site C

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

3.3.1.3 Soil texture

The soil texture of most sites was classified as sandy clay loam (Table 3.2-3.5). While clay content at sites was generally similar, there were some treatments that showed substantially higher clay contents, and this could play a role in the C content. Particularly, at site B, the WWWW treatment had 10 - 15 % more clay than the pasture treatments (Table 3.5). Clay content is known to affect C content of the soil as clay can act as a stabilising mechanism, especially if the clay minerals are poorly crystalline (Kalbitz et al. 2005). A higher clay content should also lead to an increase in aggregate stability, which in turn should help protect the SOM from decomposition by forming a protective barrier around the SOM (Kolbl & Koegel-Knabner 2004). However, an insignificant positive correlation ($R^2 = 0.058$) was found between clay content and total C content of the soil at all sites (Appendix A- Fig. A-4). This weak correlation indicates that other factors such as tillage and crop rotation could have a significant effect on soil C content.

Table 3.2 Average soil texture properties of Site A WWWW treatment

Treatment		Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture Class
WWWW	CT	0-5	19.7	13.7	64.8	Sandy Clay Loam
		5-10	21.6	11.7	64.9	Sandy Clay Loam
		10-20	29.7	8.4	61.5	Sandy Clay Loam
		20-40	59.9	17.0	23.1	Clay
	MT	0-5	18.7	10.7	70.1	Sandy Clay Loam
		5-10	20.2	14.6	65.2	Sandy Clay Loam
		10-20	29.2	10.7	60.1	Sandy Clay Loam
		20-40	62.8	9.6	27.6	Clay
	NT	0-5	19.6	13.1	67.3	Sandy Clay Loam
		5-10	21.0	14.1	64.9	Sandy Clay Loam
		10-20	25.9	10.7	63.5	Sandy Clay Loam
		20-40	61.4	12.0	26.5	Clay

Table 3.3 Average soil texture properties of Site A WMWM treatment

Treatment		Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture Class
WMWM	CT	0-5	16.5	2.5	80.9	Sandy Clay Loam
		5-10	16.7	4.0	79.2	Sandy Clay Loam
		10-20	18.3	8.4	74.0	Sandy Clay Loam
		20-40	24.9	16.9	61.1	Sandy Clay Loam
	MT	0-5	14.0	16.3	69.7	Sandy Clay Loam
		5-10	16.8	7.1	76.2	Sandy Clay Loam
		10-20	19.1	8.5	72.4	Sandy Clay Loam
		20-40	34.7	4.4	60.9	Sandy Clay Loam
	NT	0-5	16.2	15.8	68.1	Sandy Clay Loam
		5-10	17.6	14.1	68.3	Sandy Clay Loam
		10-20	23.4	14.5	62.1	Sandy Clay Loam
		20-40	41.6	14.3	47.4	Clay Loam

Table 3.4 Average soil texture properties of Site A WCWL treatment

Treatment		Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture Class
WCWL	CT	0-5	22.4	11.6	65.9	Sandy Clay Loam
		5-10	12.0	9.6	78.4	Sandy Clay Loam
		10-20	17.9	12.2	69.9	Sandy Clay Loam
		20-40	39.2	12.4	48.4	Sandy Clay
	MT	0-5	12.8	12.5	74.8	Sandy Clay Loam
		5-10	14.0	12.5	73.5	Sandy Clay Loam
		10-20	21.5	18.8	59.7	Sandy Clay Loam
		20-40	41.5	13.1	37.5	Sandy Clay
	NT	0-5	13.0	13.4	73.6	Sandy Clay Loam
		5-10	14.6	12.9	72.5	Sandy Clay Loam
		10-20	15.5	24.8	59.7	Sandy Clay Loam
		20-40	26.4	19.1	54.4	Sandy Clay Loam

Table 3.5 Average soil texture properties of Site B and C treatments

Treatment	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture Class
WWWW	0-5	23.9	20.1	56.1	Sandy Clay Loam
	5-10	29.1	5.0	65.6	Sandy Clay Loam
	10-20	29.5	15.8	54.6	Sandy Clay Loam
	20-40	42.6	15.1	42.3	Clay Loam
WMWM	0-5	16.5	14.9	68.6	Sandy Clay Loam
	5-10	11.1	17.8	71.1	Sandy Clay Loam
	10-20	22.2	12.9	65.0	Sandy Clay Loam
	20-40	23.8	13.9	62.3	Sandy Clay Loam
WMc	0-5	13.3	11.7	71.7	Sandy Clay Loam
	5-10	15.1	34.7	51.1	Sandy Clay Loam
	10-20	20.5	10.5	61.8	Sandy Clay Loam
	20-40	31.7	15.4	53.8	Sandy Clay Loam
WMc SB	0-5	14.4	17.3	68.4	Sandy Clay Loam
	5-10	18.2	9.2	71.3	Sandy Clay Loam
	10-20	21.4	10.9	66.6	Sandy Clay Loam
	20-40	34.0	13.8	52.1	Sandy Clay Loam
FYNBOS	0-5	12.0	14.0	74.3	Sandy Clay Loam
	5-10	12.6	11.0	76.4	Sandy Clay Loam
	10-20	11.3	8.8	79.8	Sandy Clay Loam
	20-40	9.0	12.4	73.8	Sandy Clay Loam

3.3.2 Crop residue inputs

Crop residues play an important part in the SOM cycle. Above and below ground residues contribute directly to the SOM as it is their decomposition that forms SOM (Haynes 2005). While it is easy to observe the additions of above ground crop residues as they form a blanket on the soil surface and are easy to quantify at the end of the season, the below ground are equally, if not more important and are substantially more difficult to determine. There are also difficulties in understanding the removal of biomass from grazing of pastures. The crop residue data from this study is used simply as an estimate of inputs and is in no way a thorough investigation. The above ground inputs were measured by biomass measurements of mature crops at the end of the season, while the below ground inputs data was used from a previous study under similar conditions (Smith 2014).

Lupins had significantly greater above ground C inputs than any other crop (Fig. 3.6a); at 2583 kg C ha^{-1} it almost double that of medic, 1431 kg C ha^{-1} and medic/clover kg C ha^{-1}. There was no significant difference between the medic and medic/clover pasture systems, with the inclusion of clover to the mix having no change to the C inputs. Wheat had the second highest C inputs at 1747 kg C ha^{-1}, followed by canola, 1692 kg C ha^{-1}. However these were not significantly greater than any other treatment. The discrepancies between C inputs and C content or C stocks could be motivated by the fact that above ground residues form a blanket on the surface and with the exception of CT, are not incorporated. Below ground C inputs would play a larger role in SOM formation. In the similar study conducted by Smith (2014) in the Southern Cape it was found that canola, lupins and medic had greater root densities than wheat in the top 10 cm, however these were not statistically significant (Table 3.6). Wheat had greater root densities than all the three remaining crop rotations from 10–30 cm, however these were again not significant. The N fixation ability of medic, medic/clover and lupins were noticeable, with all three having larger N inputs than both canola and wheat, however only lupins was significantly greater than wheat, with no significant difference between any of the other treatments (Fig 3.6b).

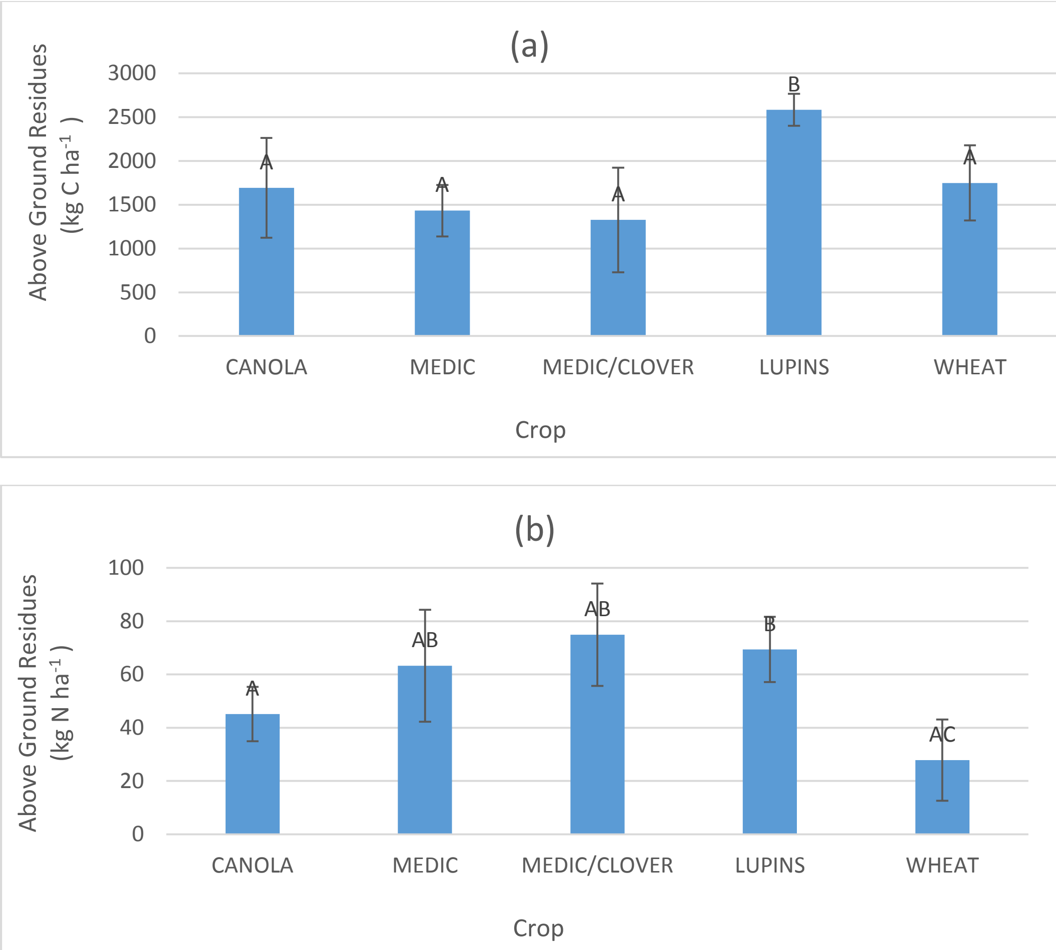


Figure 3.6 Average above ground crop residues (a) C and (b) N inputs (kgha^{-1}) across at all sites.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

Table 3.6 The root density by depth of selected crops reported by Smith (2014)

Crops	Root density by depth (kg m^{-3})			
	0-5 cm	5-10 cm	10-20 cm	20-40 cm
Canola	7	5	3	2
Medic	6	6	2.5	2
Lupins	6.5	4.5	2.5	2.5
Wheat	5	4.5	3	3

The quality of the crop residues will determine the rate at which they will degrade, as well as the amount of C and N contributed to the soil for every kg of residue. There was very little variation between crops in C content (Fig 3.7a). All crops had a C content between 40-46%. Wheat had the highest C content at 46 %, while lupins had the lowest at 41 %. The only significant difference in C content was medic, 45 %, being significantly greater than both medic/clover, 44 % and lupins 41 %.

The N content of the residues had a more telling pattern (Fig 3.7). Medic/clover (2.9 %) was significantly greater than all other treatments. Medics (2.0 %) was significantly greater than canola (1.2 %), lupins (1.1 %) and wheat (0.8 %). Wheat had a significantly lower N content than all other residues. However this was expected due to the high cellulose content of wheat straw. Lupins had a N content significantly lower than both medic pasture systems.

The C:N ratio predictably was the inverse of the N content (Fig 3.7c). Medic/clover had a significantly lower ratio than all other crops with a ratio of 15. This was closely followed by medic which was significantly lower than all remaining crops with a ratio of 23. There was no significant difference between lupins and canola, both having a ratio of 38. Wheat (53) had a significantly higher ratio than any other crop.

Canola's root system has a significantly higher C:N ratio than all other treatments at 110 (Table 3.7). Wheat also has a recalcitrant root system, having a C:N ratio of 70. The two legumes had lower C:N ratios of 20 and 50 for medic and lupin respectively. This would add substantial N to the SOM, but will be readily decomposed by microbes.

Wheat straw would be the most recalcitrant of all the crop residues taking a long time to break down even if it was incorporated into the soil. While the medic systems would be broken down the quickest releasing their nutrients to be available for the next crop, however their SOM could be lost rather quickly.

Table 3.7 The root C and N composition of selected crops reported by Smith (2014)

Crops	C (%)	N (%)	C:N
Canola	40	0.5	110
Medics	40	2.0	20
Lupins	40	1.0	50
Wheat	35	0.5	70

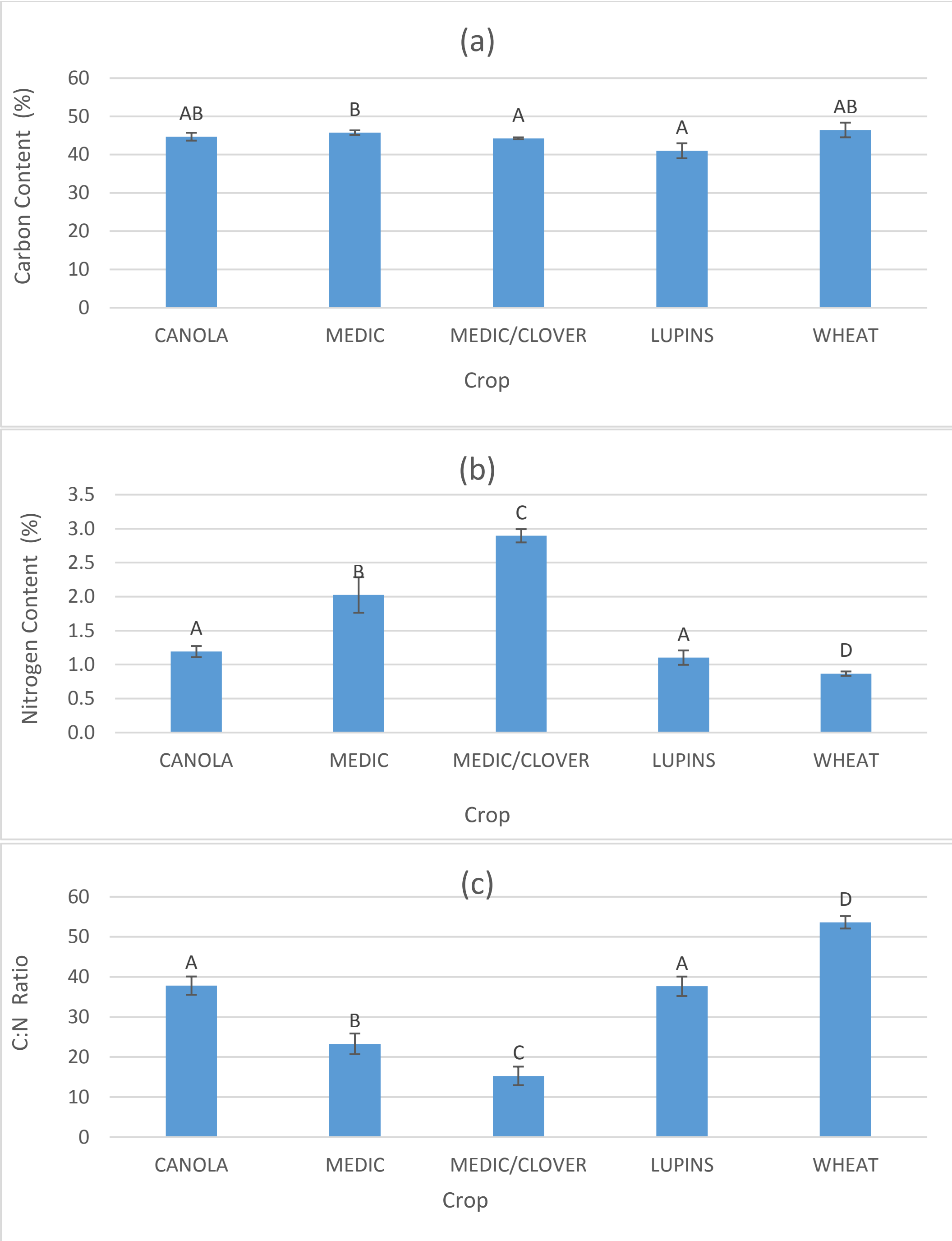


Figure 3.7 Average above ground crop residues: (a) C content, (b) N content and (c) C:N ratio at all sites.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

3.3.3 Effect of tillage on soil C and N

3.3.3.1 Vertical distribution of soil C and N content at Site A

At site A, the effects off tillage were most distinct in the top 10 cm of the soil profile (Fig 3.8), being the zone of greatest physical disturbance. The reduced disturbance of both the NT and MT treatments compared to the CT treatment is evident in the C content of the top 10 cm (Fig 3.8). The C content under NT and MT is significantly higher than CT in the 0-5 cm depth under all crop rotations. The greatest difference being under WMWM, NT (1.80 %) and MT (1.70 %) being at least 0.80% higher than CT (0.90 %). Under WWWW NT (1.40 %) was significantly greater than both MT (1.10 %) and CT (0.70 %). The WCWL treatment had no significant differences between NT (1.30 %) and MT (1.20 %), however both were significantly higher than CT (0.60 %).

At 5-10 cm depth, the C trend is already less pronounced (Fig 3.8). Only under WCWL were both NT and MT greater than CT, with 1.0 % for both compared to 0.6 % for CT. NT was significantly higher than CT under WWWW, 0.80 % vs 0.67 % respectively. There was no significant difference between MT (0.70 %) and either of the other treatments. Under WMWM, MT (1.1 %) was significantly higher than both NT and CT, both having 0.9 % C.

At depths greater than 10 cm CT has a higher C content or at least equal to the other treatments. Under WWWW, CT at 0.63 %, is significantly greater than both NT and MT at 10-20 cm depth, at 0.53 % and 0.55 % respectively. Under WMWM there is no significant difference between any of the treatments, however CT is higher than both at 10-20 cm, at 0.77 %, compared to NT, 0.54 % and MT, 0.65 % respectively. Under WCWL, CT was significantly higher than NT in the 10-20 cm at 0.67 % and 0.51 % respectively. However it was not significantly higher than MT at 0.55 %.

At 20-40 cm the trend is less consistent with NT (0.52 %) being significantly greater than CT (0.39 %) under WWWW. There was no significant difference under WMWMW, however CT (0.64 %) was higher than both MT (0.54 %) and NT (0.53 %), and MT (0.54 %) being significantly higher than both NT (0.44 %) and CT (0.47 %) under WCWL.

Overall, NT had greatest accumulation of C, followed by MT and then CT which had the greatest extent of soil disturbance, and predictably the lowest C contents. The soil C patterns observed here are similar to those found by Alvaro-Fuentes et al. (2009). His trials conducted on three sites in the semi-arid regions of Spain found that both NT and reduced tillage had higher SOC accumulation than conventional tillage. He also found that the greatest difference was in the top 10 cm of the soil, with very little variation between 10-35 cm. Sombrero & de Benito (2010) also conducted trials comparing NT, reduced tillage and conventional tillage in the semi-arid area of Spain. Their study, conducted under five different crop rotations also found that NT and reduced tillage resulted in significantly greater SOC compared to conventional tillage.

Nitrogen content follows a similar trend to that of C content, with the reduced disturbance treatments resulting in higher N contents and the greatest difference taking place in the top 10 cm of the profile (Fig 3.9). In the upper 0-5 cm horizon, NT resulted in significantly higher N contents than CT under all crop rotations (Fig 3.9). Under WWWW, there was no significant difference between NT (0.10 %) and MT (0.09 %), which were both greater than CT (0.05 %). Under WMWM NT (0.16 %) was significantly greater than both MT (0.13 %) and CT (0.07 %). NT (0.1 %) was significantly greater than both MT (0.05 %) and CT (0.05 %) under WCWL.

There was no significant difference between any of the treatments under WWWW at 5-10 cm, all with an N content of 0.05 %. Under WMWM both NT (0.09 %) and MT (0.09 %) were significantly higher than CT (0.07 %). Minimum tillage N content (0.10 %) was significantly greater than both NT (0.06 %) and CT (0.05 %) under WCWL. The only significant difference between treatments at 20-40 cm was under WMWM, with CT (0.08 %) being significantly higher than both NT (0.06 %) and MT (0.05 %)

The effects of tillage on N content was expected to follow a similar pattern to that of C stocks, as the loss of SOM due to disturbance would affect both similarly. The effects of tillage possibly having a greater effect on the N content as the more recalcitrant residues are lower in N and composed mainly of cellulose. However it has been shown that plant residues higher in N result in greater passive (mineral bound) SOM pools in the long-term (Haynes & Beare 1997).

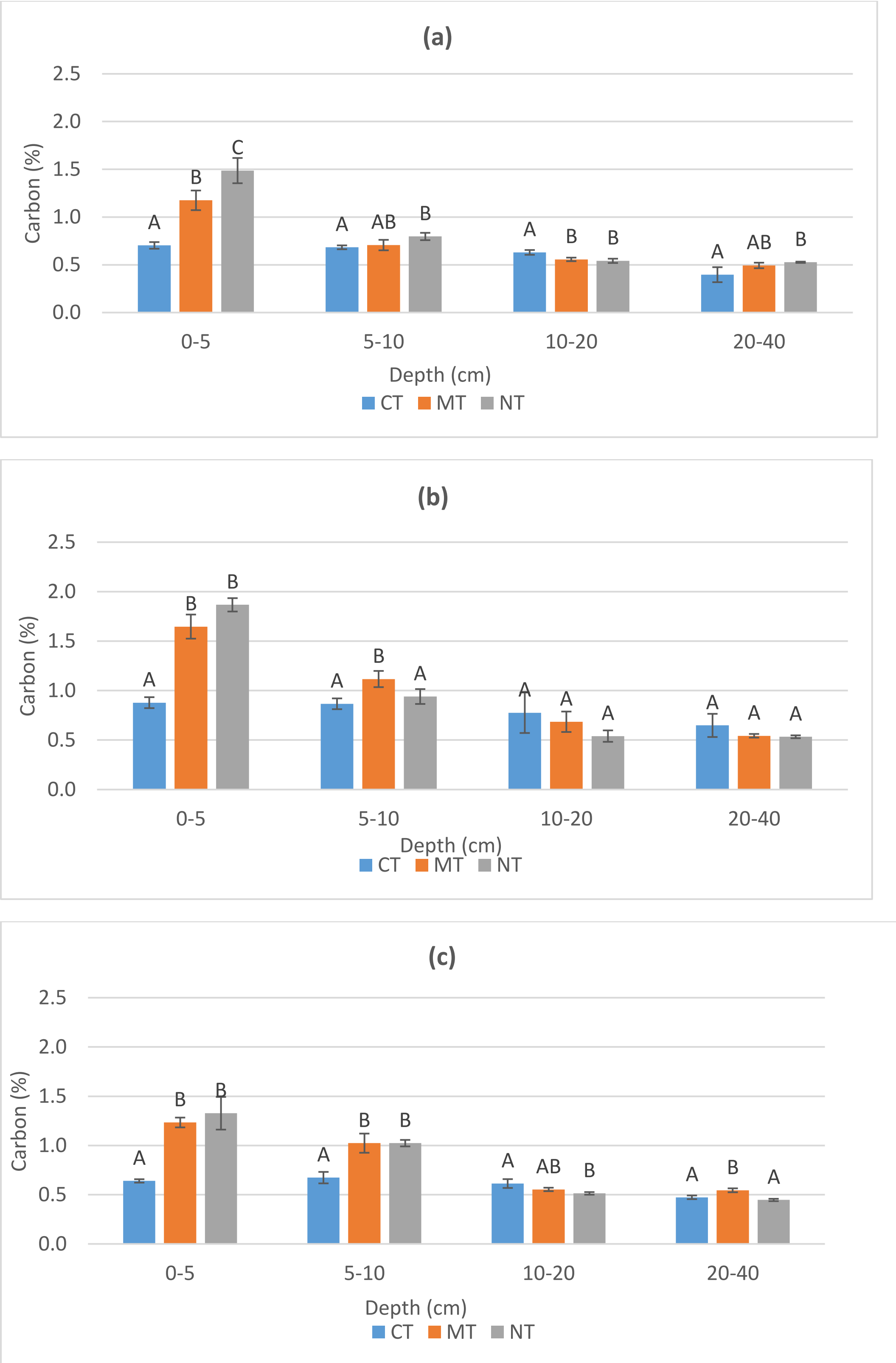


Figure 3.8 Effect of tillage on vertical distribution of soil C (%) in the (a) WWWW, (b) WMWM and (c) WCWL rotation treatments at Site A.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

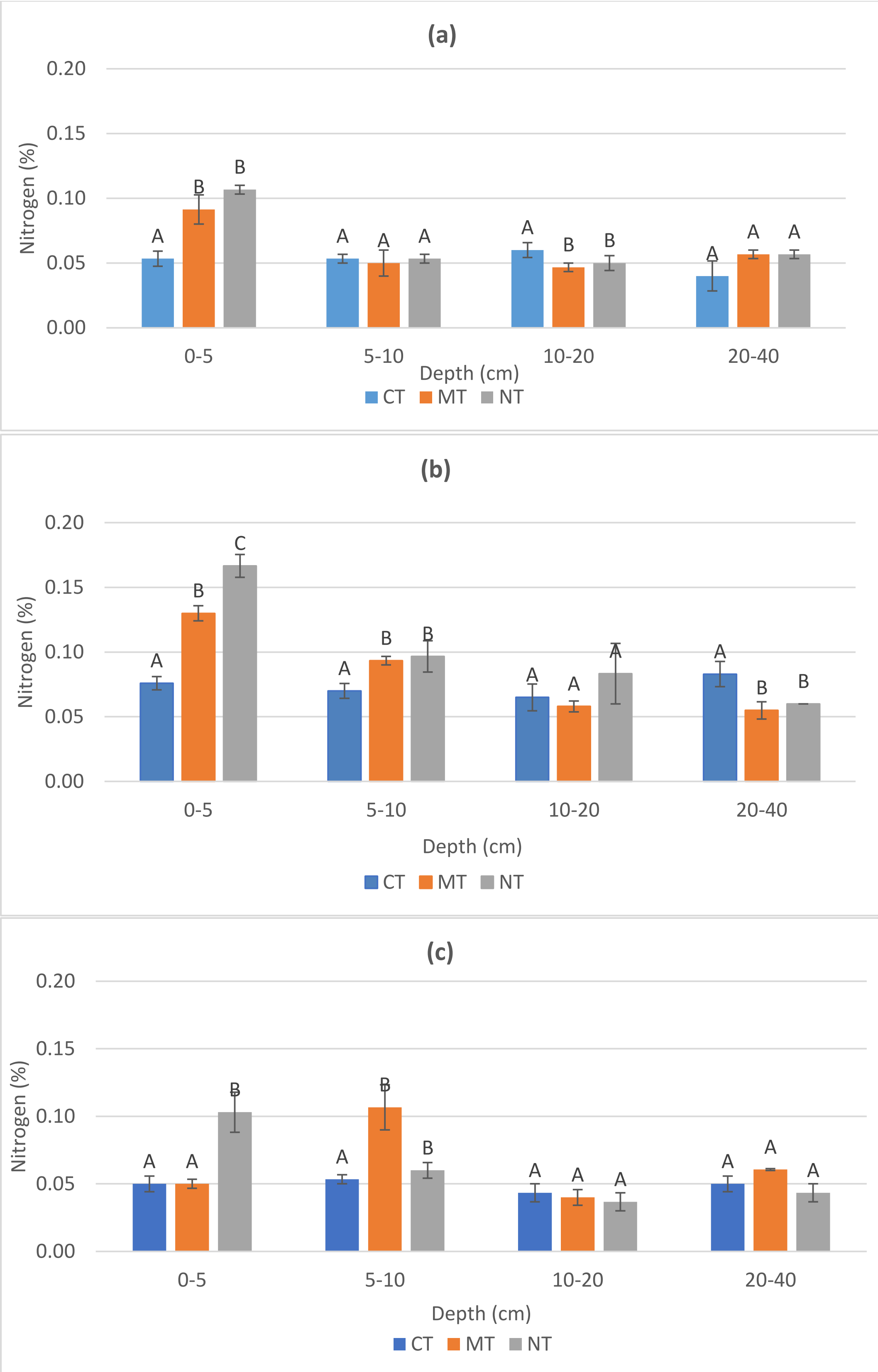


Figure 3.9 Effect of tillage on vertical distribution of soil N (%) in the (a) WWWW, (b) WMWM and (c) WCWL rotation treatments at Site A.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

3.3.3.2 Soil C and N stocks at site A

The trend of total C stock follows that of C content, with reduced disturbance leading to significantly greater total C stock (Fig 3.10a). NT had the highest total C stock under both WWWW and WMWM, 31 Mg C ha^{-1} and 30 Mg C ha^{-1}. These were significantly greater than both the MT, 28 Mg C ha^{-1} and 27 Mg C ha^{-1} respectively, and CT, 22 Mg C ha^{-1} and 21 Mg C ha^{-1}, treatments under their respective crop rotations. The effect under WCWL differed in that MT (28 Mg C ha^{-1}) preformed significantly better than both NT (22 Mg C ha^{-1}) and CT (13 Mg C ha^{-1}). CT under WCWL had the lowest total C stock by a significant amount, 15 Mg C ha^{-1} lower than that of MT under the same crop.

Total N stock follow a similar trend to total C stock, however less pronounced (Fig 3.10b). In general the reduced tillage treatments have increased N stock compared to CT, however this is not the case for WMWM, where there is no significant difference between CT (2.1 Mg N ha^{-1}) and MT (2.5 Mg N ha^{-1}). NT is significantly greater than both of these treatments at 3.6 Mg N ha^{-1}. Under WWWW both NT and MT, at 2.7 Mg N ha^{-1} each, were greater than CT (2.1 Mg N ha^{-1}). Under WCWL we observed the same trend as the total C stocks with MT (2.6 Mg N ha^{-1}) being significantly higher than both CT (1.1 Mg N ha^{-1}) and NT (1.8 Mg N ha^{-1}), however NT was still significantly greater than CT.

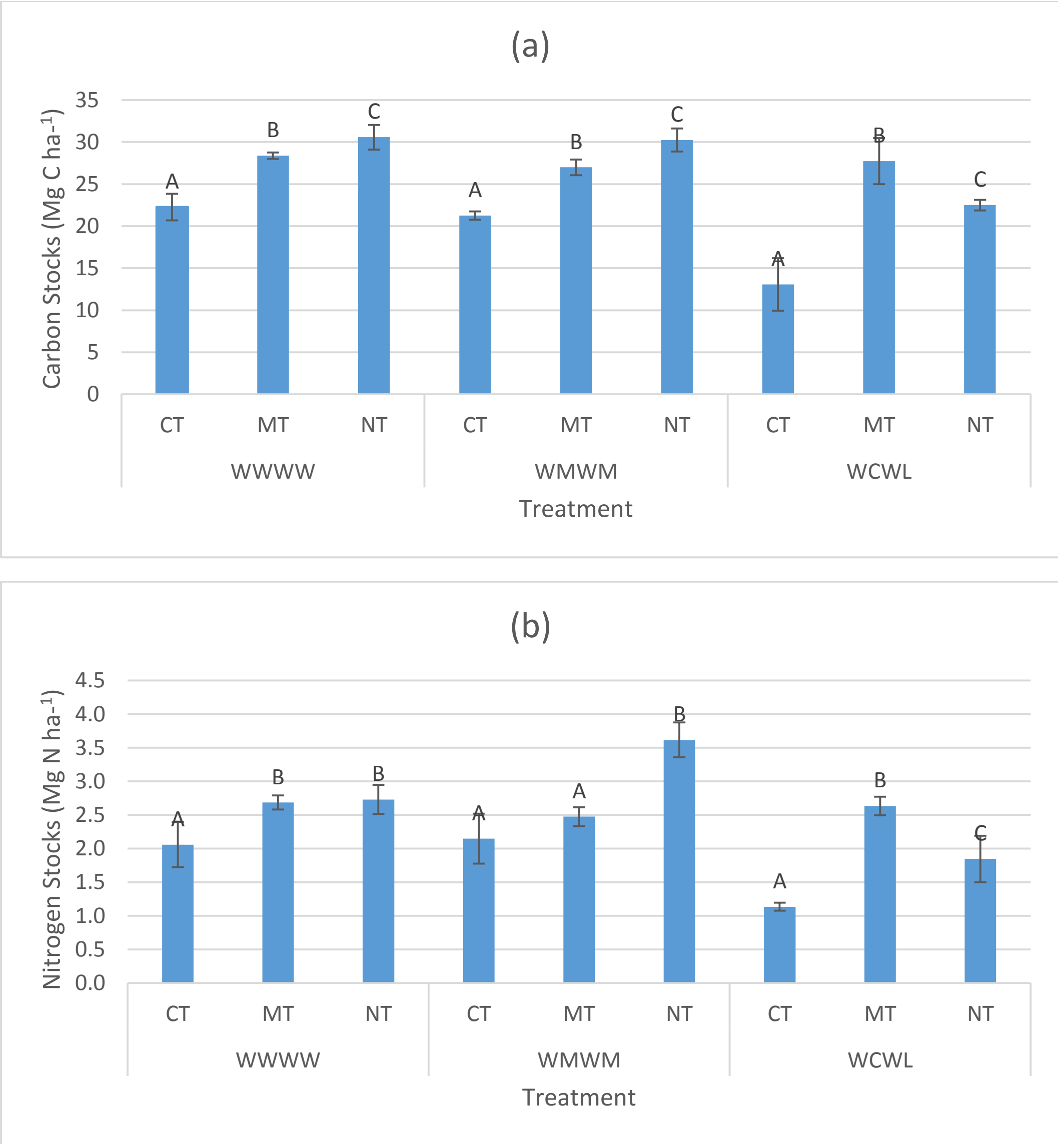


Figure 3.10 Effect of tillage on total soil (a) C and (b) N stocks (0-40 cm) for all crop rotation treatments on Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

When C stocks are examined by depth the trend of reduced tillage leading to an accumulation of C continues (Fig 3.11). In the top 0-5 cm profile under WWWW, both NT (7.3 Mg C ha^{-1}) and MT (5.6 Mg C ha^{-1}) were significantly higher than CT (3.6 Mg C ha^{-1}), while there was no significant difference between either NT or MT. The same trend is visible under WMWM with NT (9.8 Mg C ha^{-1}) being significantly higher than both MT (6.9 Mg C ha^{-1}) and CT (3.8 Mg C ha^{-1}). Both NT and MT, at 6.2 Mg C ha^{-1} and 6.1 Mg C ha^{-1} respectively, where significantly higher than CT at 2.6 Mg C ha^{-1}. As the depth increases the trends becomes less significant and defined. At 5-10 cm NT and MT are significantly greater than CT under all crop treatments, however there is no significant difference between the two of them.

In both the 10-20 cm and 20-40 cm intervals under WCWL the trend becomes more similar to the total C stocks. MT has the greatest C stocks at 10-20 cm at 5.5 Mg C ha^{-1}, significantly higher than both NT (5.2 Mg C ha^{-1}) and CT (3.3 Mg C ha^{-1}). This was again true for 20-40 cm where at 11 Mg C ha^{-1} MT was significantly higher than both NT (7.0 Mg C ha^{-1}) and CT (4.9 Mg C ha^{-1}). Noticeable in all crop rotations was that in the 10-40 cm depths CT was not significantly higher than either NT or MT as was expected. Under both WWWW and WCWL it was in fact significantly lower than both of these treatments.

Two studies conducted in the semi-arid regions of Spain by Alvero-Fuentes et al. (2009) and Sombrero & Benito (2009) also found that reduced tillage lead to a significant increase of total C stocks compared to CT. No tillage led to the greatest increase in both studies, with Sombrero & de Benito (2009) reporting a 7.1 Mg C ha^{-1} increase under NT when compared to CT tillage. Chen et al. (2009) found a much smaller increase in total C stocks between NT and CT of only 3 Mg C ha^{-1} on the Loess plateau in China. However, Sisti et al. (2004) reported no significant difference between CT and NT under soya-bean wheat rotation. A review by Powlson et al (2011) concluded that when examining the total C stocks of the soil down to 1 m that there is generally no significant difference between conventional and conservation tillage. It was found that there was a significant difference above 30 cm with conservation tillage building up a stratified layer of plant residues, while at deeper depths the mixing effect of CT accumulated a greater amount of mineral associated SOM. However, this was not observed in the present study, with NT having greater stocks across all soil depths. It was initially believed that the burying effect of CT might increase C stocks at depths below 20 cm, however this was not observed here. This could possibly due to the shallow, saprolitic nature of the soils at Langgewens experimental farm, that could prevent this subsoil C enriching effect under CT.

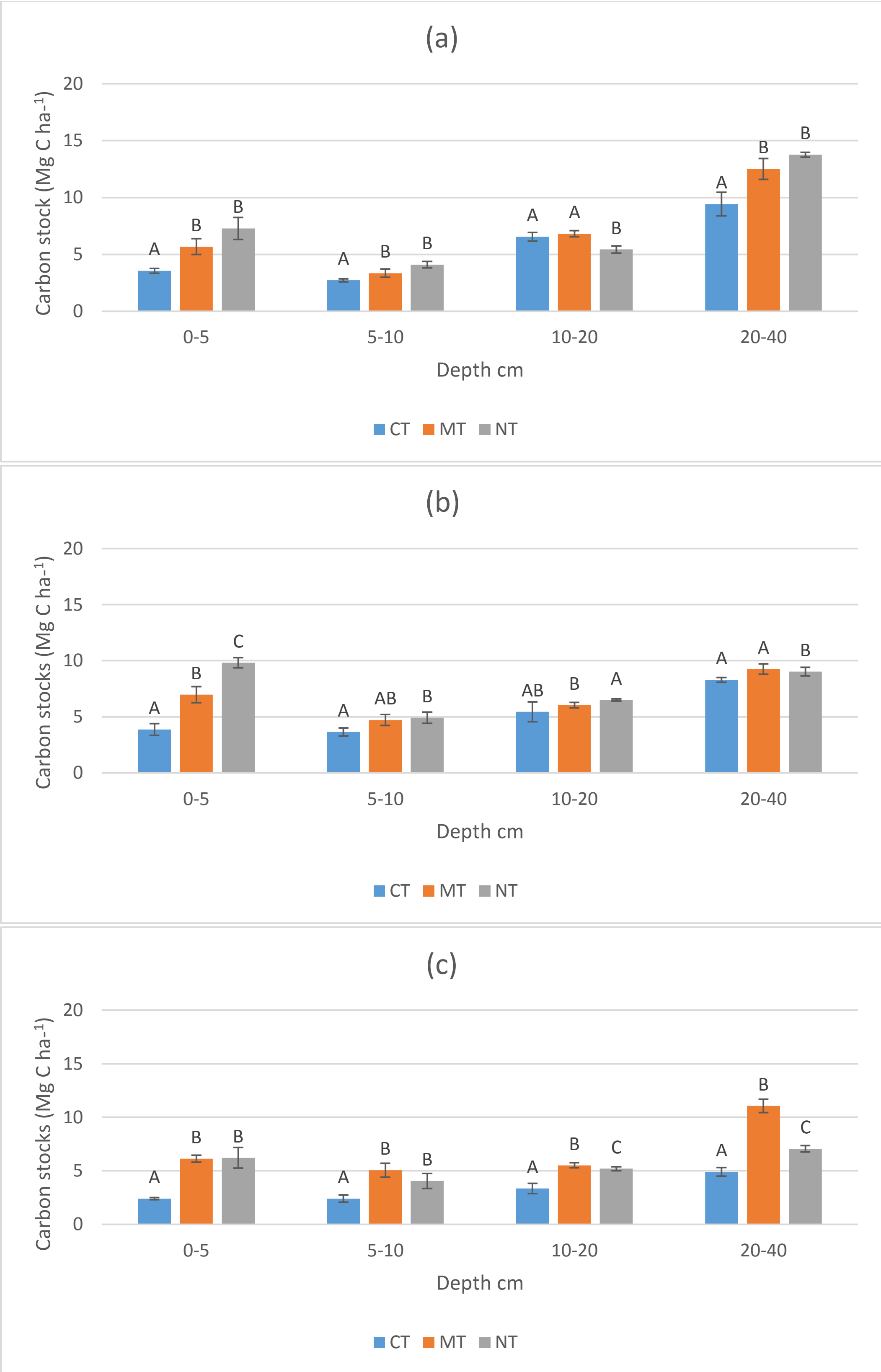


Figure 3.11 Effect of tillage on vertical distribution of soil C stocks (Mg C ha^{-1}) in the (a) WWWW, (b) WMWM and (c) WCWL rotation treatments at Site A.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

On observation of the N stocks at 0-5 cm it is shown that CT was significantly lower than the other treatments under all crop rotations (Fig 3.12). Under WWWW Both NT (0.5 Mg N ha^{-1}) and MT (0.4 Mg N ha^{-1}) were higher than CT (0.2 Mg N ha^{-1}). Under WMWM NT (0.9 Mg N ha^{-1}) was three times as high as CT at 0.3 Mg N ha^{-1}. Under WCWL both NT and MT, 0.5 Mg N ha^{-1} each, were significantly greater than CT at 0.2 Mg N ha^{-1}.

At 5-10 cm both NT (0.5 Mg N ha^{-1}) and MT (0.4 Mg N ha^{-1}) were significantly greater than CT (0.29 Mg N ha^{-1}) under WMWM. MT (0.5 Mg N ha^{-1}) is significantly greater than both NT (0.3 Mg N ha^{-1}) and CT (0.2 Mg N ha^{-1}) under WCWL, following the same trend observed in total N stocks. At the 10-20 cm horizon only WMWM had any significantly difference with NT at 0.7 Mg N ha^{-1} being greater than both MT and CT, 0.5 Mg N ha^{-1} and 0.4 Mg N ha^{-1} each.

There was no significant difference in the 20-40 cm horizon under WWWW, while under WMWM NT was significantly higher than MT at 1.2 Mg N ha^{-1} and 1.0 Mg N ha^{-1} respectively. Under WCWL we again see the trend of MT (1.3 Mg N ha^{-1}) being significantly higher than both NT (0.6 Mg N ha^{-1}) and CT (0.5 Mg N ha^{-1})

Sisti (2004) found only one treatment where N stocks were significantly higher under NT than conventional tillage. However two out of three treatments showed an increase in N for NT below 30 cm. Chen et al. (2009) found no significant difference between NT and CT at all depths down to 30 cm.

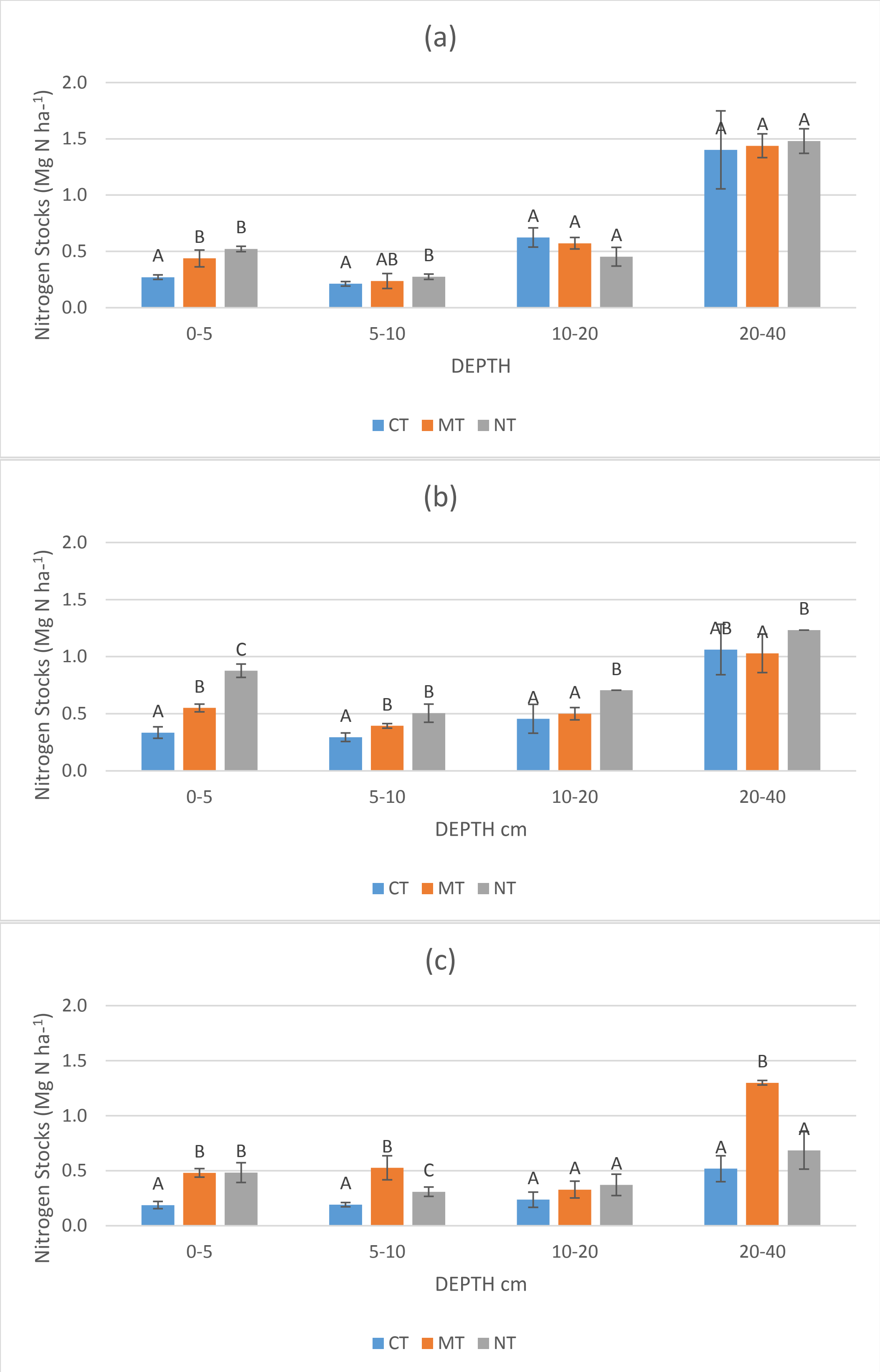


Figure 3.12 Effect of tillage on vertical distribution of soil N stocks (Mg N ha^{-1}) in the (a) WWWW, (b) WMWM and (c) WCWL rotation treatments at Site A.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

3.3.4 Effects of crop rotation on soil C and N

3.3.4.1 Vertical distribution of soil C and N at Site A

It is evident from the top 10 cm that the crop – pasture rotation leads to an increase in C content in the top soil (Fig 3.13). In the 0-5 cm horizon WMWM was significantly higher than both WWWW and WCWL under all tillage treatments. Under CT WMWM had a C content of 0.8 % compared with 0.7 % for WWWW, while WWWW was significantly greater than WCWL (0.6 %). Under MT, WMWM (1.6 %) was significantly greater than both WWWW (1.1 %) and WCWL (1.2 %). NT had the same trend with WMWM (1.9 %) being significantly greater than both WWWW (1.5 %) and WCWL (1.2 %).

At 5-10 cm under CT, WMWM (0.9 %) was again significantly greater than both WWWW (0.7 %) and WCWL (0.7 %). Under MT both WMWM (1.1 %) and WCWL (1.0 %) were greater than WWWW (0.7 %). Under NT the trend was less defined with WCWL (1.0 %) being significantly greater than WWWW (0.8 %) while WMWM (0.9 %) was not significantly different to either. There was no significant difference between treatments at 10-20 cm, however WMWM was greater than both other treatments under CT and MT. At 20-40 cm WMWM (0.5 %) was significantly higher than both WWWW (0.4 %) and WCWL (0.4 %) under CT. Under NT WCWL (0.4 %) was significantly lower than both WWWW (0.5 %) and WMWM (0.5 %).

Smith (2014) found that in the Southern Cape the inclusion of a high biomass pasture system such as a four year Medic-Medic-Wheat-Wheat rotation led to a significant increase in C content over wheat monoculture. He also observed the trend of decreasing C content with depth. The increase in C content of WMWM in the top 10 cm of the soil is most likely due to the bulk of the roots forming topsoil as medic pasture has lower aboveground inputs than the other crops (Fig 3.6a). Medics are known to have a very dense fibrous root system, especially when compare to canola and lupins (Smith 2014). However at Site A the medic pastures were not grazed but only mown, this led to a larger SOM accumulation than in a commercial setting. The poor performance of the WCWL system, even though canola and lupins were both strong producers of above ground residues, is most likely due to the single taproot of the canola, while the leaf matter on the soil surface was observed to disappear rapidly compared to the cover provided by the wheat stubble and straw, and medic. The lupins crop had poor growth performance under the climatic conditions in the area leading to lower biomass yields. This highlights the important role that roots play in SOM accumulation.

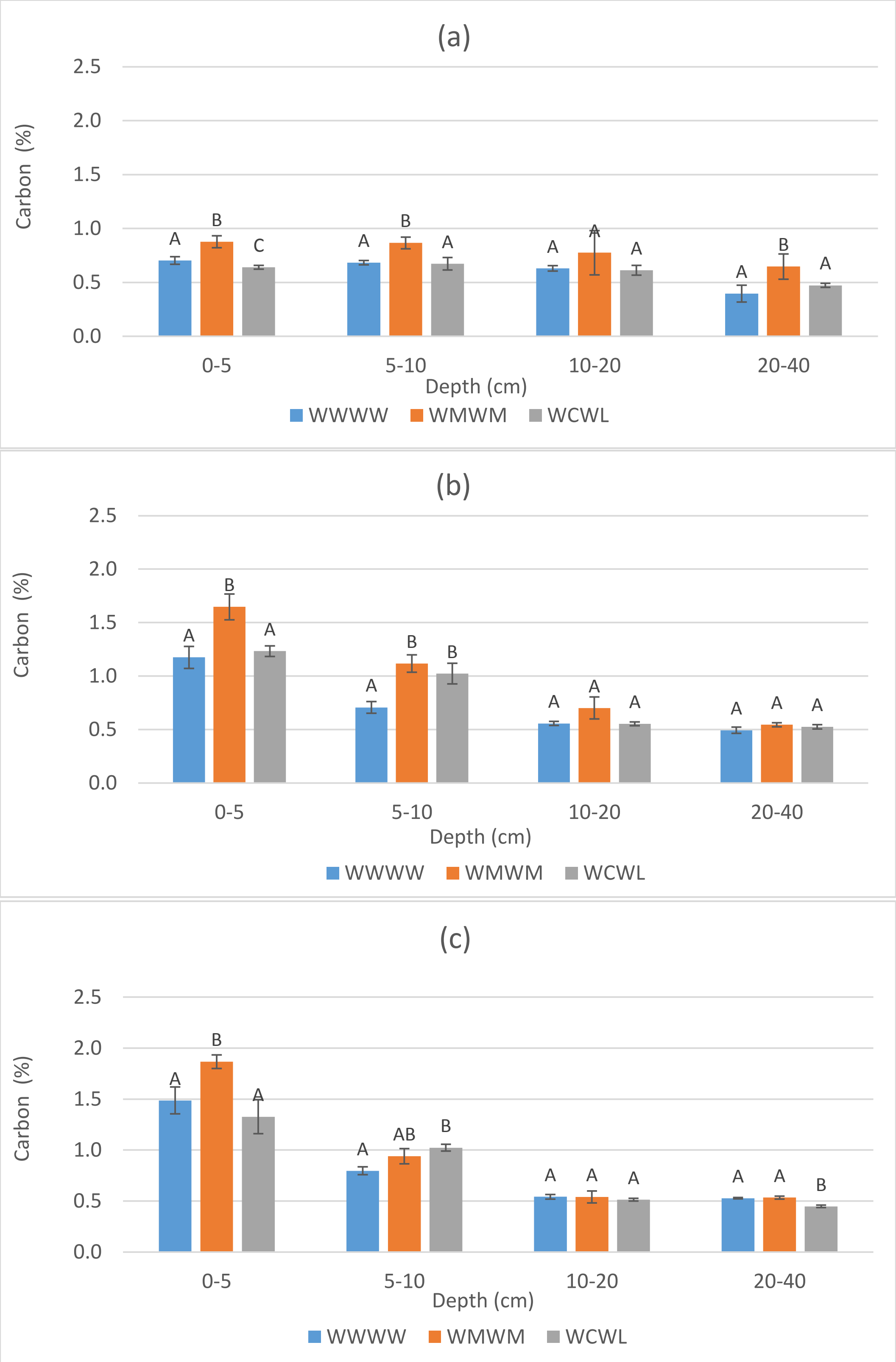


Figure 3.13 Effect of crop rotation on vertical distribution of soil C content (%) in the (a) CT, (b) MT and (c) NT tillage treatments at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

Examining N content across all depths it is immediately noticeable that the strong N fixation of medic plays a significant role (Fig 3.14). Under almost all treatments WMWM had the highest N content in the 0-20 cm depths, with the most significant being the top 10 cm under NT.

At 0-5 cm WMWM was significantly higher than all other crop rotations. Under CT, WMWM has an N content of 0.08 % compared to the WWWW at 0.05 % and WCWL at 0.05 %. Under MT, WMWM had an N content of 0.13 %, while WWWW was significantly greater than WCWL at 0.09 % and 0.05 % respectively. WMWM under NT had the highest N content out of all treatments at this depth at 0.17 %, while this was significantly greater than both WWWW (0.11 %) and WCWL (0.1 %), the latter two had no significant difference to each other.

This trend continues in the 5-10 cm horizons, with the only exception being WCWL (0.1 %) under MT, being greater but not significantly different to WMWM (0.09 %). Both rotations were significantly greater than WWWW (0.05 %). WMWM (0.07 %) was significantly greater than both WWWW (0.06 %) and WCWL (0.04 %) under CT. Under NT WMWM (0.1 %) was significantly greater than both WWWW (0.05 %) and WCWL (0.06 %), being more than double that of the former. At 10-20 cm, both WWWW (0.06 %) and WMWM (0.07 %) were significantly higher than WCWL (0.04 %) under CT. WMWM (0.06 %) was significantly greater than both WWWW (0.05 %) and WCWL (0.04 %) under MT. The same was observed under NT with WMWM (0.1 %) being significantly higher than both WWWW (0.05 %) and WCWL (0.04 %). The only significant differences at 20-40 cm was under CT, where WMWM (0.06 %) was significantly higher than both WWWW (0.04 %) and WCWL (0.04 %), and under NT where WCWL, at 0.04 % was significantly lower than both WWWW and WMWM at 0.06 % each.

The beneficial properties of legumes becomes obvious when examining the N content of WMWM. WMWM was significantly higher than WWWW under all treatments up to 20 cm depth, with the exception of CT. The N fixing nodules in the roots directly adding to soil N once the plants die. WCWL generally performed poorly even though it contained lupins as a legume in the rotation. However lupins has shown to be a weaker N fixing crop than medic, and was only included for one year of the four year rotation compared to two for medics. Wheat also received an additional top dressing of 40 kg N per ha^{-1}, while the lupins crop received none.

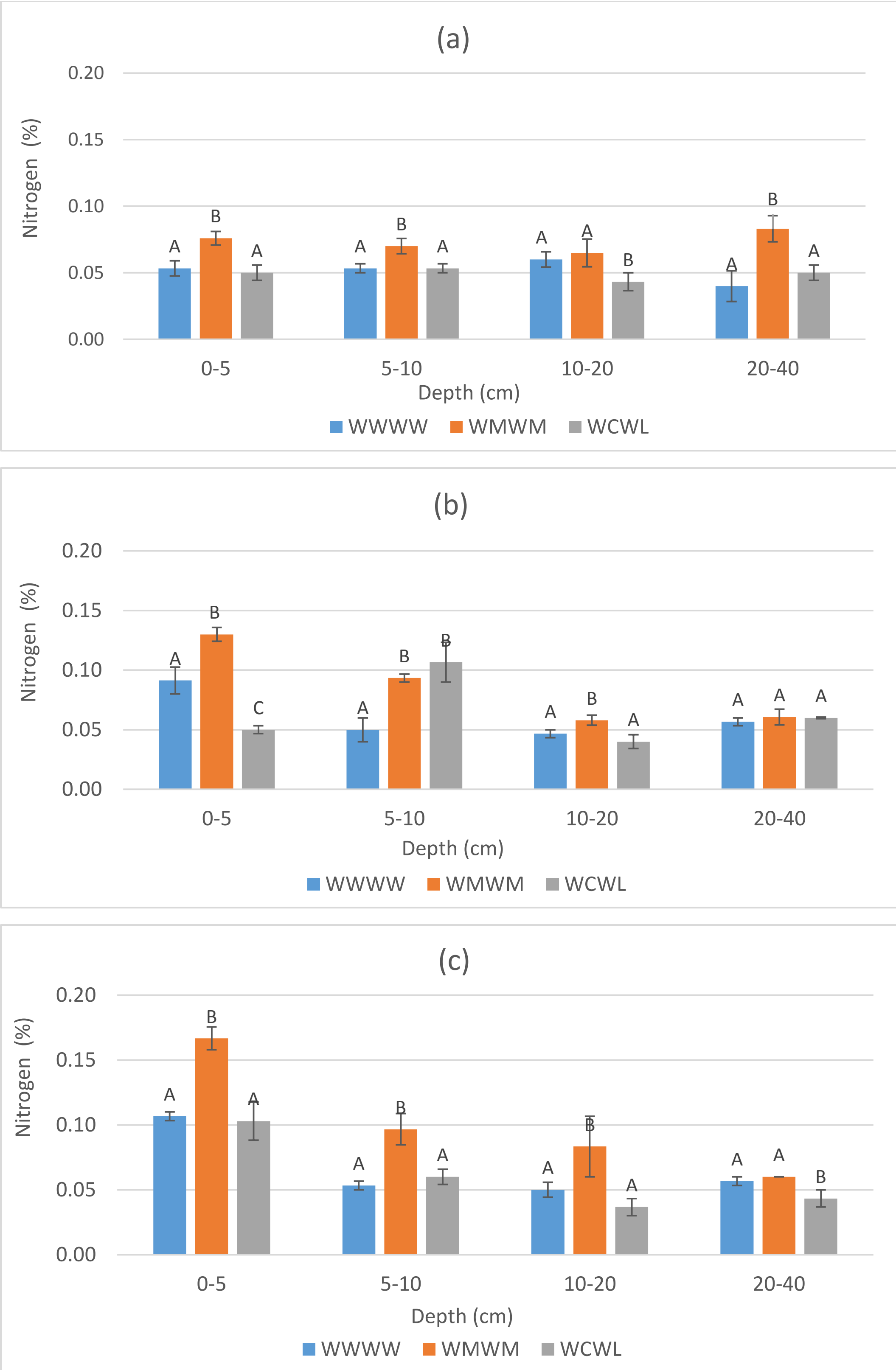


Figure 3.14 Effect of crop rotation on vertical distribution of soil N content (%) in the (a) CT, (b) MT and (c) NT tillage treatments at Site A.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant differenc

3.3.4.2 Soil C and N stocks at Site A

On examining the effect of crop rotations on total C stocks at Site A (Fig. 3.15a), it can be seen that WWWW and WMWM rotations, have significantly higher total C stocks than that of WCWL. This is evident under both the CT (WWWW, 22.3 Mg C ha^{-1}; WMWM 21.3 Mg C ha^{-1}) and NT (WWWW 30.6 Mg C ha^{-1}; 30.3 WMWM Mg C ha^{-1}), where WCWL has a lower C stock of 13.1 Mg C ha^{-1} and 22.5 Mg C ha^{-1} respectively. However, under MT, the WCWL rotation, was able to accumulate a much higher total C stock (27.7 Mg C ha^{-1}); although not significantly different from WWWW (28.3 Mg C ha^{-}1) and WMWM (27.0 Mg C ha^{-1}).

Total N stocks show a less decisive picture than N content (Fig. 3.15b). The WMWM is only significantly higher than the other rotations under NT, its total N stocks of 3.6 Mg N ha^{-1} compared to WWWW (2.7 Mg C ha^{-1}) and WCWL (1.9 Mg C ha^{-1}). WCWL was also significantly lower than WWWW. Under CT WCWL (1.1 Mg C ha^{-1}) was significantly lower than both WWWW and WMWM both with a total N stocks of 2.1 Mg C ha^{-1}. Under MT WWWW (2.7 Mg C ha^{-1}) was significantly higher than both WMWM (2.5 Mg C ha^{-1}) and WCWL (2.6 Mg C ha^{-1}).

The higher C stocks of WWWW that we observed are most likely due to wheat being a high biomass producer, while the low N content of the straw means that it will be more resistant to decomposition than the legumes. It has already been stated that the lupins generally performed poorly under these climatic conditions. Smith (2014) found a significant increase in total C stocks when comparing wheat-medic crop-pasture systems compared to 100 % crop Wheat-Barley-Lupin-Canola rotation. In his study Wheat-Medic systems yielded between 70.2 – 74.7 Mg C ha^{-1}, this in comparison to wheat monoculture with 54.7 Mg C ha^{-1}.

There was little significant difference in C stocks in the 0-5 cm horizon (Fig. 3.16). Under CT, WMWM (0.35 Mg C ha^{-1}) was significantly higher than WWWW (0.27 Mg C ha^{-1}), which was in turn significantly higher than WCWL (0.19 Mg C ha^{-1}). There was no significant differences under MT and NT, however WMWM was the highest for both, having an N stock of 0.55 Mg C ha^{-1} under MT compare to 0.44 Mg C ha^{-1} for WWWW and 0.48 Mg C ha^{-1} for WCWL. Wheat monoculture had higher C stocks below 10 cm than both other treatments (Fig. 3.16). This could be a results of wheat's deep dense root system, while canola and lupins had a shallower tap root.

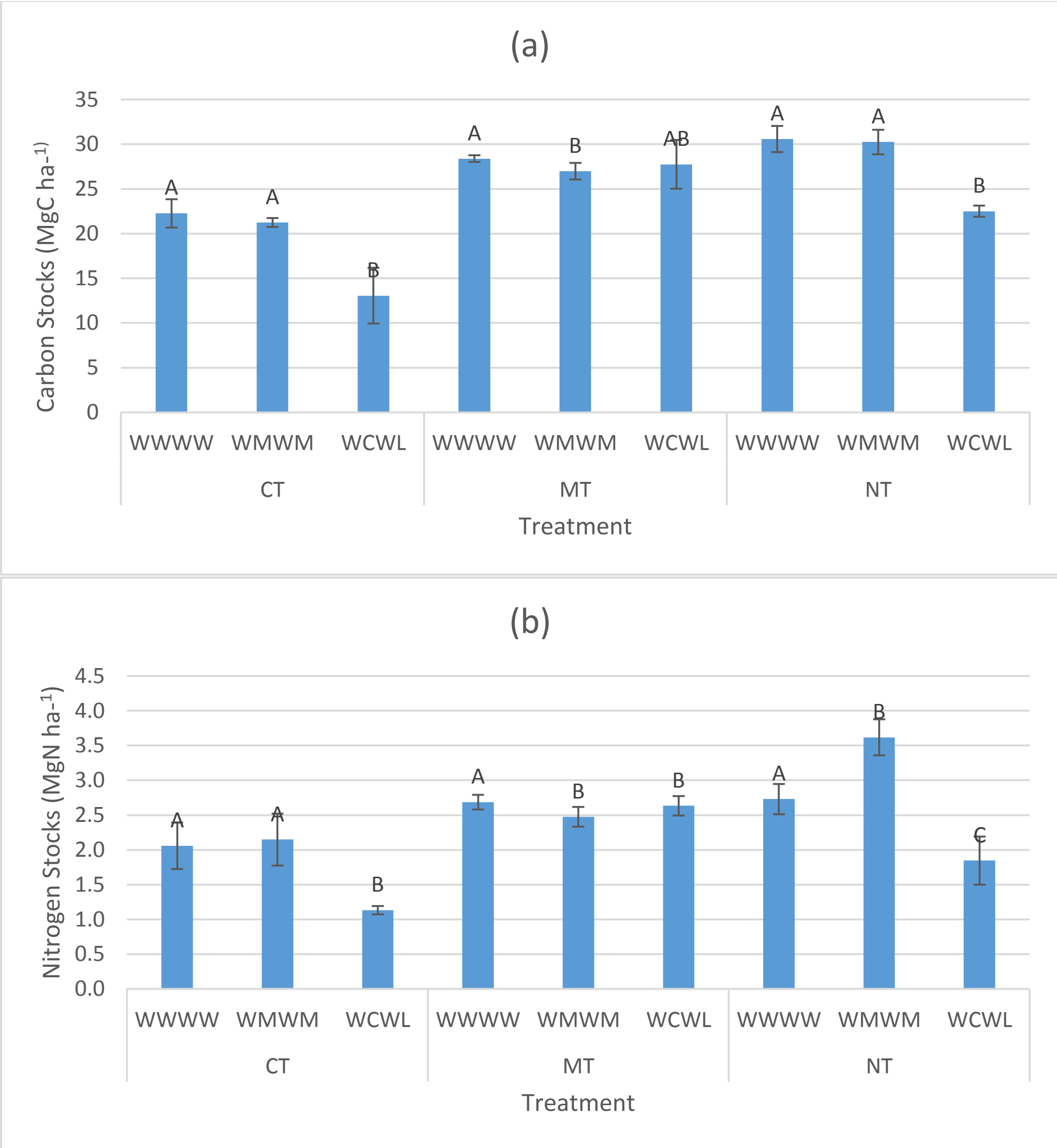


Figure 3.15 Effect of crop rotation on total soil (a) C and (b) N stocks (0-40 cm) for all treatments on Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

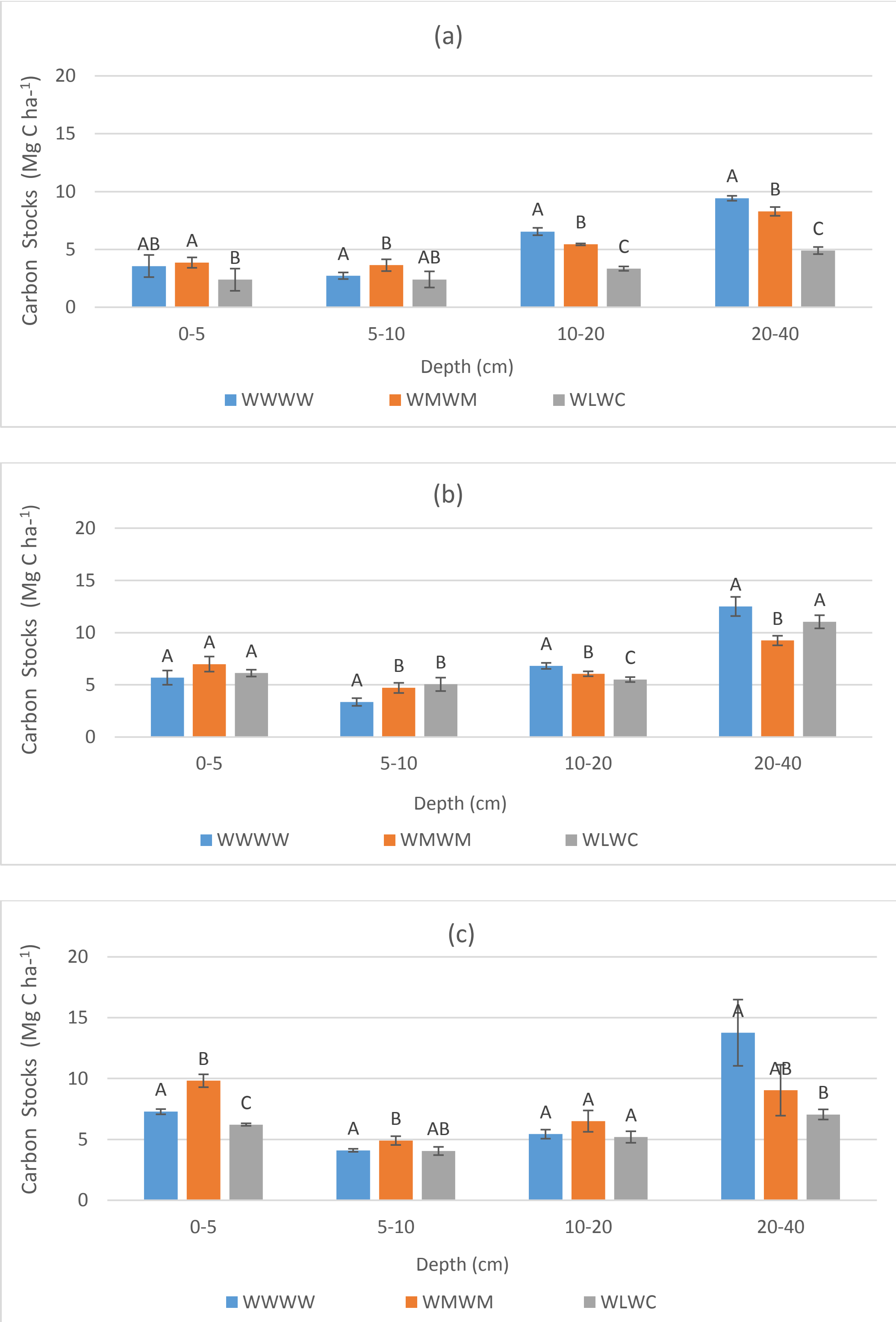


Figure 3.16. The effect of crop rotation on the soil C stocks under (a) CT, (b) MT and (c) NT at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

The N fixation of both medics and lupins was noticeable in the 0-10 cm horizon under both MT and NT (Fig 3.17). At 5-10 cm, under MT both WMWM (0.39 Mg N ha^{-1}) and WCWL (0.53 Mg N ha^{-1}) were significantly greater than WWWW (0.24 Mg N ha^{-1}). WCWL (0.52 Mg N ha^{-1}) was the highest under NT at 5-10 cm, being significantly higher than WWWW (0.27 Mg N ha^{-1}) but not WMWM (0.40 Mg N ha^{-1}). At 5-10 cm under CT WMWM (0.29 Mg N ha^{-1}) was significantly higher than both WWWW (0.21 Mg N ha^{-1}) and WCWL (0.19 Mg N ha^{-1}).

WWWW had a higher N stock in the 10-40 cm range compared to both WMWM and WCWL. At 10-20 cm it was significantly higher (0.62 Mg N $ha^{-1)}$ than WCWL (0.28 Mg N ha^{-1}), and was higher than WMWM (0.54 Mg N ha^{-1}) but not significantly. Under MT, both WWWW (0.57 Mg N ha^{-1}) and WMWM (0.50 Mg N ha^{-1}) were significantly higher than WCWL (0.33 Mg N ha^{-1}), while there was no significant difference between any treatment under NT.

WWWW had the highest N stock under both MT and NT at 20-40 cm. Under MT WWWW (1.44 Mg N ha^{-1}) was significantly higher than both WMWM (1.03 Mg N ha^{-1}) and WCWL (1.30 Mg N ha^{-1}). WCWL was in turn significantly greater than WMWM. Under NT both WWWW (1.48 Mg N ha^{-1}) and WCWL (1.39 Mg N ha^{-1}) were significantly higher than WMWM (1.03 Mg N ha^{-1}). WMWM (1.0 Mg C ha^{-1}) was significantly higher than WCWL (0.51 Mg N ha^{-1}) under CT, while WWWW (0.95 Mg N ha^{-1}) was not significantly different to either.

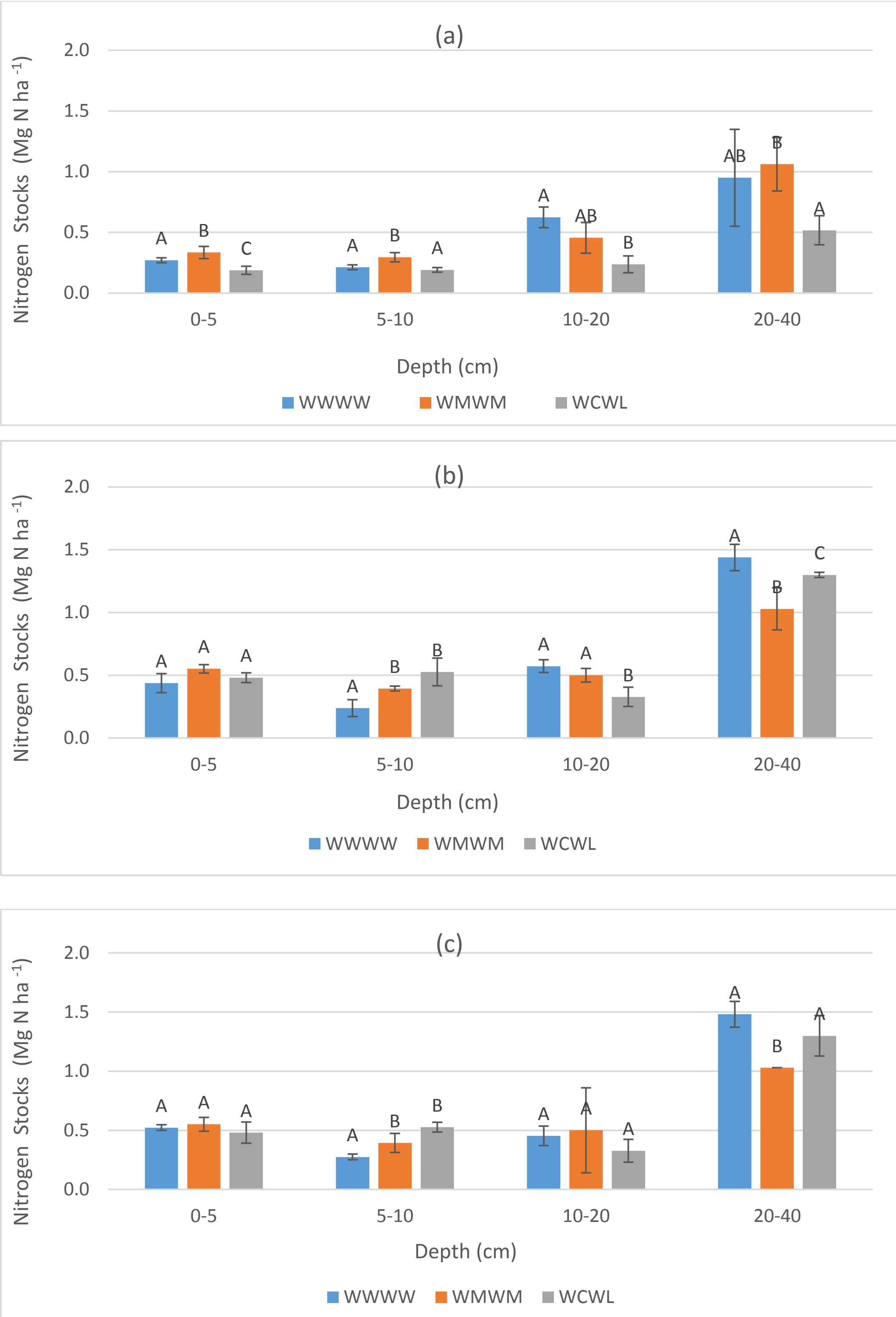


Figure 3.17. The effect of crop rotation on the soil N stocks under (a.) CT, (b) MT and (c.) NT at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

3.3.4.3 Vertical distribution of soil C and N at Site B

From Fig 3.18a we can see WWWW again has a high C content across all depths, being significantly higher in the 5-10 depth than all other crop rotations. This is a similar trend to that observed on Site A. The two rotations with the medic/clover mix, WMc and WMc SB were both higher than the WMWM rotation, being significantly so in the 0-5 cm, WMWM (1.5 %) compared to WMc (1.9 %) and WMc SB (1.9 %), at 5-10 cm, WMc (0.9 %) compared to WMWM (0.7 %) and 20-40 cm, WMc SB (0.6 %) compared to WMWM (0.4 %).

Again WWWW showed a strong ability to accumulate C in the soil, being significantly higher than WMWM in the 5-10 cm depth. However 0-5 cm the two medic/clover rotations (WMc, WMc SB) were significantly higher. WMWM had the lowest C content at all depths at this site, however this may have something to do with having a lower clay content. Although WMc SB was grazed less heavily than WMc, there seems to be no difference between the two rotations.

N content favours the legume pasture systems, where we can see the effect of N fixation, especially in the top 5 cm. Both WMc (0.16 %) and WMc SB (0.17 %) were significantly higher than the WWWW (0.12 %) and WMWM (0.12 %). This is less noticeable in the 5-10 cm with only WMc (0.1 %) not being significantly higher than WWWW (0.1 %), while WMc SB (0.08 %) is significantly lower.

In the 10-40 cm depths there is no longer any significant difference between any of the treatments. Fynbos had significantly high N content compared to all treatments under 10 cm, while it was higher than all treatments at 0-5 cm there was no significant difference to WMc and WMc SB. This could be attributed to the specialised root system of the fynbos. While there was no application of N to the fynbos site it is evident that the lack of removal of biomass and the lack of disturbance, allowing root system to fully develop, has a significant effect on N content.

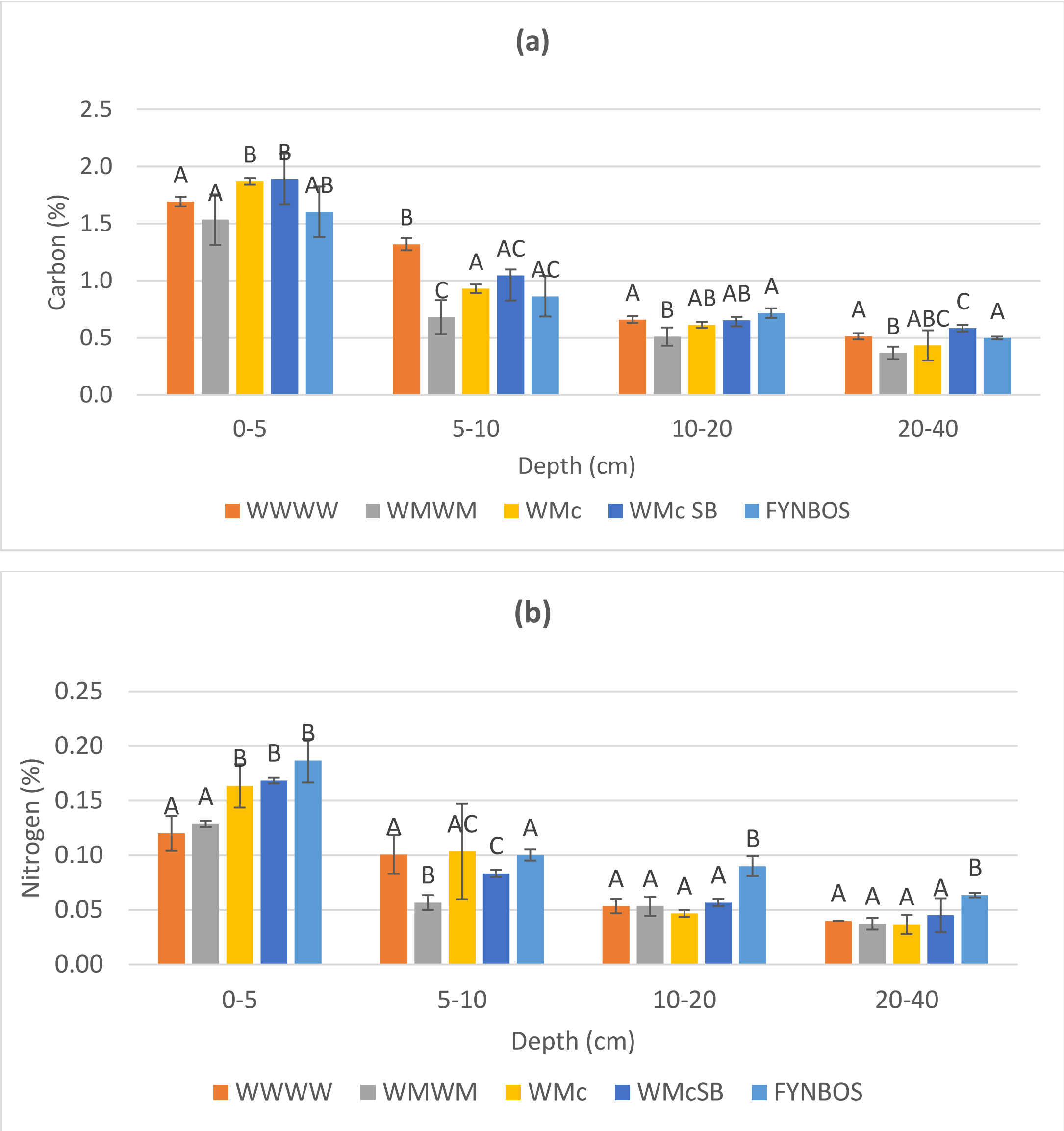


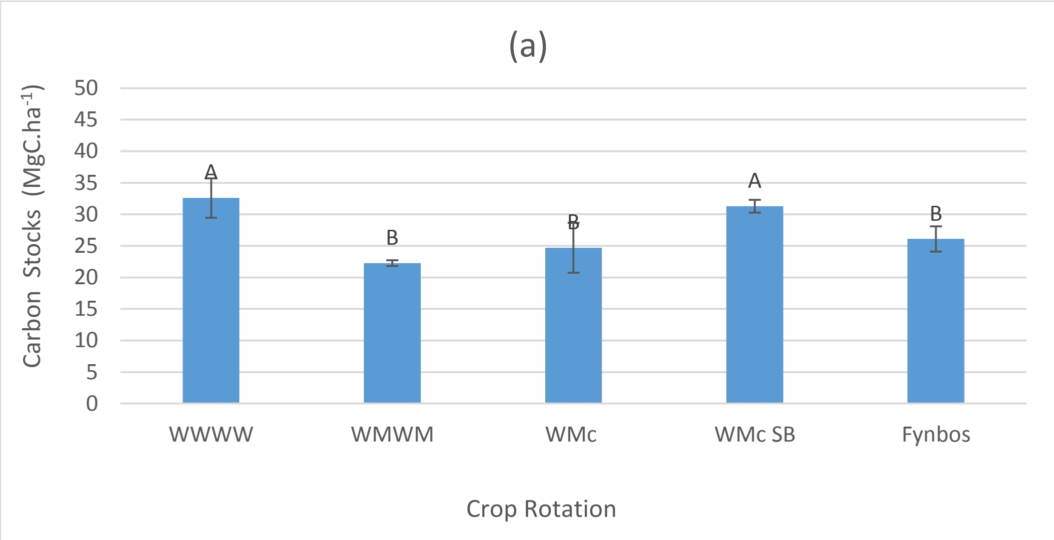
Figure 3.18 Effect of crop rotation on vertical distribution of soil (a) C and (b) N content (%) under NT tillage treatments at Site B.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

3.3.4.4 Soil C and N stocks at Site B

WWWW had higher total C stocks than all other treatments except WMc SB (Fig 3.19a). There was no significant difference between WMWM and WMc, however WMc SB was significantly higher than both.

Total N stocks (Fig. 3.19b) show that WWWW (2.5 Mg N ha^{-1}) had the 2^{nd} highest total N stocks out of all the treatments while WMc SB (2.7 Mg N ha^{-1}) had the highest. Both of these were significantly higher than WMWM (2.1 Mg N ha^{-1}) and WMc (2.2 Mg N ha^{-1}) but not to each other. Fynbos was able to accumulate a larger total N stock than all of the cultivated treatments, highlighting the loss of fertility in these soils compared to the natural veld.



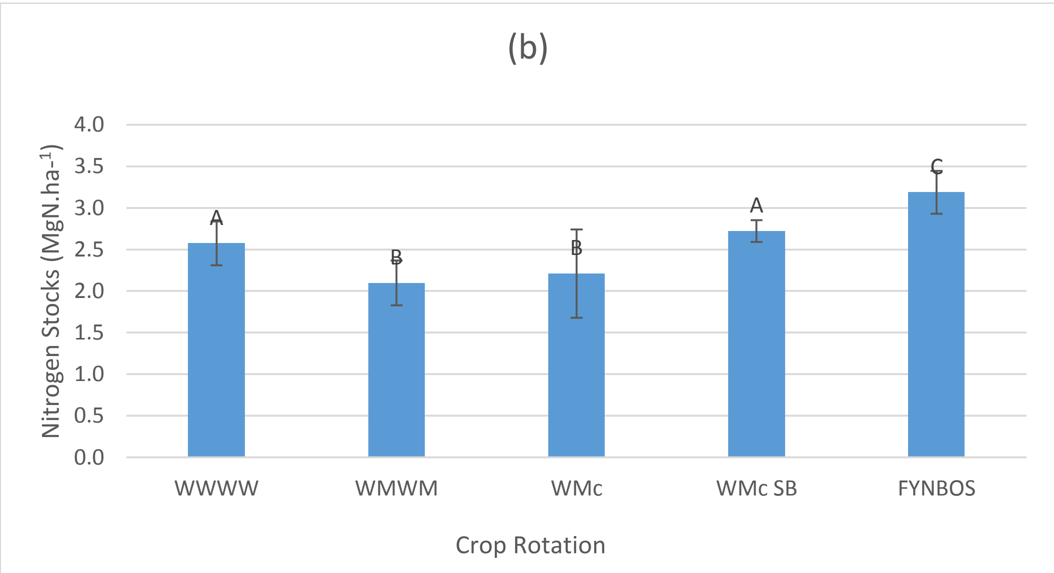


Figure 3.19 Effect of crop rotation on total soil (a) C and (b) N stocks (0-40 cm) for all treatments on Site B.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

At 0-5 cm WWWW (8.5 Mg C ha^{-1}) was significantly greater than all other treatments (Fig 3.18). WMWM, which had a lower C content than the other pasture systems, WMc and WMc SB, had a significantly higher C stock than both, 7.6 Mg C ha^{-1} compared to 6.7 Mg C ha^{-1} and

7.2 Mg C ha^{-1} respectively. These trends continued for all depths with WWWW having the highest C stock and WMWM having the 2^{nd} highest.

WWWW had the highest C stocks out of all rotations on this site across all depths. However there was no significant difference between WWWW and WMc SB on total C stocks. WMWM had higher C stocks than both WMc and WMc SB at all depths, this is in contrast to C content where it was a poor performer. This may be due to variation in the site. WMc SB was significantly higher than WMc at all depths except 10-20 cm. This could be due to the reduced removal of biomass due to reduced grazing. This would also allow the pasture to establish a stronger root system before grazing when compared with the WMc.

WMc SB had a higher N stock across all depths compared to WMWM and WMc. However it was only significant for WMWM at 0-5 cm, 0.8 Mg N ha^{-1} vs. 0.5 Mg N ha^{-1}, and 5-10 cm. 0.3 Mg N ha^{-1} vs. 0.4 Mg N ha^{-1}. WMc was significantly smaller at 10-20 cm, 0.3 Mg N ha^{-1} vs. 0.6 Mg N ha^{-1} and 20-40 cm, 0.7 Mg N ha^{-1} vs. 0.9 Mg N ha^{-1}.

There was not a lot of significant difference between N stocks on this site. WMWM being significantly lower than both WMc and WMc SB in 0-10 cm depths. This could illustrate benefits of including clover into the pasture system, however there was no significant difference between treatments below 10 cm. WWWW did not have significantly lower N stocks to any treatment at any depth. While Wheat has no N fixation ability it does receive a significant application of inorganic N fertilisers.

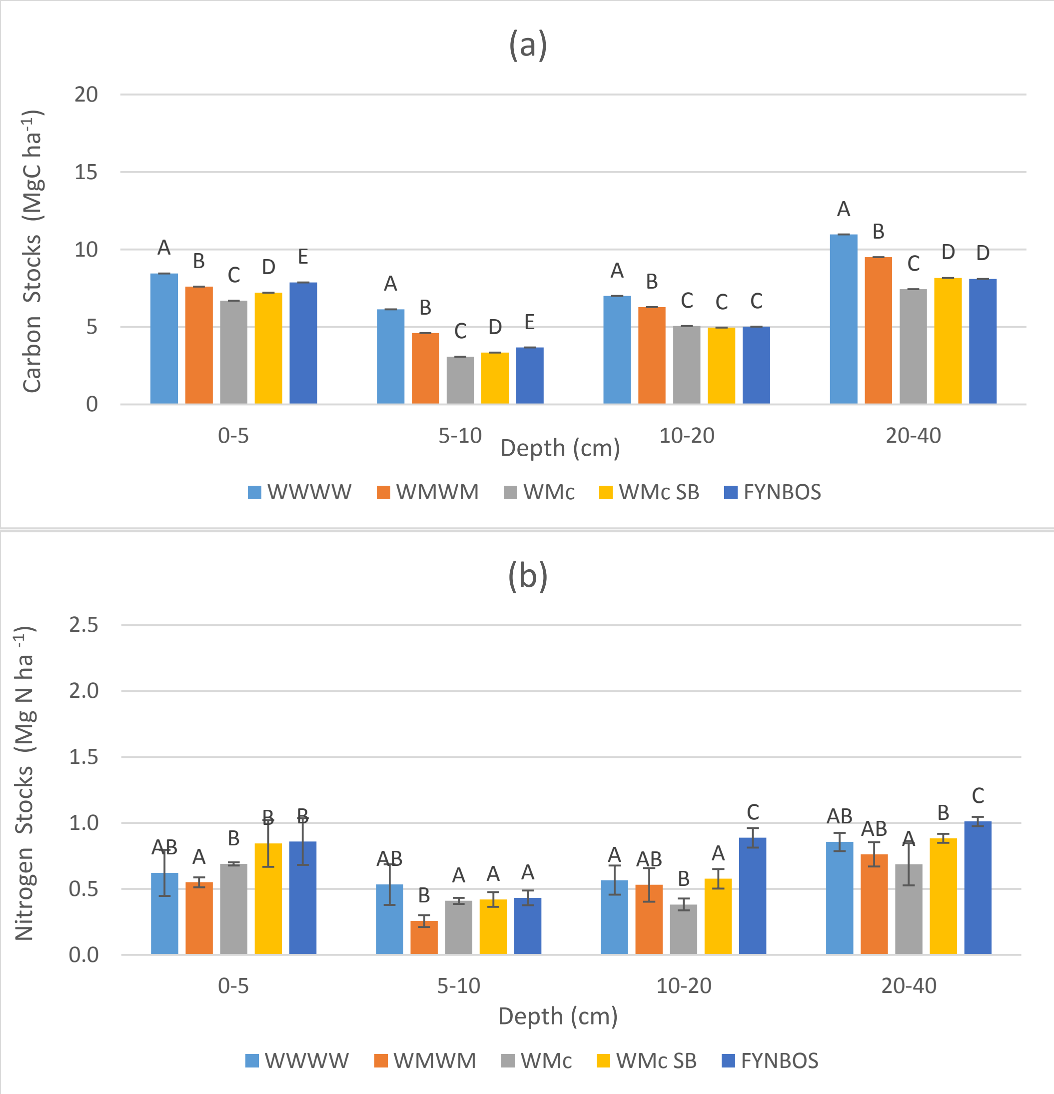


Figure 3.20 Effect of crop rotation on vertical distribution of soil (a) C stocks (Mg C ha^{-1}) and (b) N stocks (Mg N ha^{-1}) in the NT treatments at Site B.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

3.4 Conclusions

It was found that repetitive ploughing with a mouldboard plough under CT led to a significant increase in the coarse fragment content of the soil compared to the reduced tillage systems. When comparing the average above-ground C inputs of the various crops used in the rotations systems, it was found that lupins (2853 kg C ha^{-1}) had significantly higher inputs than all the other crops. Wheat had the second highest C inputs (1748 kg C ha^{-1}), while medic (1432 kg C ha^{-1}) and medic/clover (1326 kg C ha^{-1}) had the lowest C inputs. However, medic/clover had the highest N inputs (75 kg N ha^{-1}), whereas, wheat had the lowest N inputs (28 kg N ha^{-1}). The legumes, medic and medic/clover had significantly higher N content, 2 % and 3 % respectively, than that of wheat (0.8 %) and canola (1 %). This in turn meant that they had a significantly lower C:N ratio which favours the microbial decomposition of the residues and the conversion of the nutrients into plant available form.

From examining the effects of tillage at Site A, it was clear that reduced tillage led to an increase in soil C content over conventional tillage. No tillage had the greatest soil C content in almost all treatments, the highest being under WMWM at 1.8 %. Minimum tillage was consistently the second strongest treatment under all crop rotations with its highest C content under WMWM at 1.7 %. Conventional tillage had significantly lower C content in the 0-10 cm horizons under all treatments. However the difference was less marked with an increase in depth. The greatest difference in C content between treatments was observed in the top 10 cm of the soil. This was in accordance to what was previously found in the literature. Soil N content followed a similar pattern to C content with NT and MT having higher N content than CT. The highest was in the 0-5 cm horizon under WMWM with NT having 0.16 % and MT 0.13 %. In comparison, CT had 0.07 % in the same horizon. The greatest difference in N content was again most prevalent the top 10 cm, with little or no difference below this depth. The higher N content under NT and MT can also be attributed to the greater retention of crop residue due to lower soil disturbance.

Total C stocks for both NT and MT were significantly higher than CT, with the highest being NT under WWWW at 30.6 Mg C ha^{-1} and the lowest being CT under WCWL at 13.0 Mg C ha^{-1}. This is contrary to previous literature, where Lal (2006) and Powlson et al. (2011) found there was no significant difference in total soil C stocks between conventional tillage and conservation tillage, due to deeper incorporation of surface residues by CT leading to higher C stocks below 15 cm. It is possible that the shallow, saprolitic nature of the soils at the experimental site could avert this subsoil C enriching effect under CT. Total N stocks showed NT had the highest stocks under WMWM at 3.6 Mg N ha^{-1} while MT had the highest stocks under WCWL at 2.6 Mg N ha^{-1}. Conventional tillage had the lowest N stocks for all treatments, the lowest being 1.1 Mg N ha^{-1} under WCWL. Again the greater loss of SOM due to greater soil disturbance under CT is demonstrated here.

Crop rotations on Site A, although only in their 8th year, showed that the WMWM rotation resulted in the highest soil C content; the highest C content being under NT at 1.9 % for the 0-5 cm horizon. There was little significant difference in C content between the WWWW and

WCWL treatments. The WMWM rotation also performed best with regards to soil N content, demonstrating the positive effect of incorporating a legume into the rotation, especially a strong legume such as medic. On site A, WMWM was significantly higher than all other treatment, the greatest under NT at 0.17 % in the 0-5 cm horizon. WCWL did not have a significant increase in N over WWWW except under MT where WCWL had 0.1 % and WWWW 0.5 % in the 5-10 cm horizon. The greater weed control under MT compared to NT could explain why this treatment showed better performance under WCWL

Among the Site A crop rotations, the WWWW rotation, although not the strongest performer in soil C content, was able to build up the largest total soil C stocks; achieving the highest stocks of 30.6 Mg C ha^{-1} under NT. This is attributed to the relatively high above ground C inputs of the wheat, and the recalcitrant nature of wheat straw due to its relatively high C:N above 50. The total C stocks produced by the WMWM rotation were generally only slightly lower than that of WWWW at Site A; achieving the highest C stocks of 30.3 Mg C ha^{-1} under NT at Site A. The WCWL rotation resulted in the significantly lowest total C stocks, except under MT where it performed similarly to WMWM and WWWW. This could be attributed to the poor performance of lupins under the present climatic conditions and low root density of canola when compared to wheat and medic. Similar to the N content results, WMWM had significantly higher total N stocks compared to the other rotations at Site A; the greatest N stocks being 3.6 Mg N ha^{-1} under NT.

At Site B, despite being a more mature trial in its 18^{th} year, the distinction between crop rotation treatments was not as clear due to the larger variation in soil conditions due to the much larger size of the experimental plots, thus it is more difficult to draw solid conclusions from this study site. There was also a greater variation in landscape position on this site, WWWW being located near the valley floor. Similar to Site A, WWWW resulted in the highest C stocks of 32.6 Mg C ha^{-1} among the crop rotation treatments, however this could be attributed to the greater clay content on this plot, allowing greater SOM stabilastion. There was no significant difference between WMWM and WMc, showing no noticeable benefit for the incorporation of clover into the pasture. However the reduced grazing on WMc SB is shown as a benefit over the more intensely grazed WMWM and WMc. The highest N stocks were obtained in the WMc SB (2.7 Mg N ha^{-1}) rotation. There was no significant difference between WMWM and WMc, showing no noticeable benefit for the incorporation of clover into the pasture. The much stronger performance of WWWW compared to the pasture systems on Site B can be partially attributed to the recalcitrant nature of the wheat biomass but also due to the much higher clay content on the wheat experimental plots.

This study shows that there is definite benefit to the adoption of conservation agricultural practices such as reduced tillage and high biomass crop rotations with a legume. These practises directly led to a significant increase in SOM content and stocks, with the greatest effect coming from the adoption of reduced tillage. Adoption of legumes into the rotation led to greater N stocks, especially strong legumes such as medic. From this study it can be recommended that NT be implemented in the Swartland, especially in conjunction with WMWM and WMc SB, the reduced grazing of this last treatment having a positive effect on SOM. While WWWW proved a strong rotation for SOM accumulation, its recommendation is not forthcoming due to the problem of pest and weed persistence in a monoculture system. If it is desired to grow canola and lupin it is recommended that this be done under MT as this proved effective in SOM accumulation under the WCWL rotation and affords better weed control.

Chapter 4
The effect of tillage and crop rotation practices on soil organic matter functional pools

4.1 Introduction

Soil Organic Matter (SOM) is a highly variable substance, its composition ranging from fresh plant and microbial residues with a high rate of turn over to humic substances with little anatomical resemblance to its parent material and turnover rate measured in millennia (Haynes 2005; Bruelmann 2011). It is because of this variability it is not enough to simply know the quantity of organic matter in the soil but also its quality. SOM quality is influenced by both the quality and quantity of the residue inputs in the soil and by the rate of decomposition in the soil (Lutzow et al. 2006). Residue quantity and quality is dependent on which crops are planted in rotation and the amount of residues allowed to remain on the field. The inclusion of legumes and high biomass producing crops leads to a higher quality SOM (Sisti et al. 2004). Decomposition of the residues has a more complex set of influences: climate, mineralogy and management practices all contributing to the stability of SOM. Interaction between SOM and sorptive minerals is one of the most important C stabilisation mechanisms, as tightly sorbed SOM is inaccessible to the microbes (Baldock & Skjemstad 2000). This is influenced by the mineralogy and texture of the soil and is beyond the influence of management practices. However management practices can influence soil aggregation which acts as a stabilisation mechanism by physically occluding the SOM. No-tillage systems reduced the disturbance and destruction of soil aggregates therefore reducing the exposure of the SOM to microbial decomposition (Chen et al. 2009; Qin & Huang 2010). The reduced decomposition of SOM under No-tillage not only increases the quantity of SOM but also the quality. According to Arshad et al (1990) no-tillage treatment led to an increase in the carbohydrates, amino acids and amino sugars retained in the SOM.

Most studies on the quality of SOM focus on the quantity of humic acid, fulvic acid and humin fraction in the soil (Brunn et al. 2006). However these fractions differ only marginally in terms of turnover rate and functional pools (Helfrich et al. 2007), giving us a limited idea on the available labile C and recalcitrant C. Physical fractionation methods have been proposed to overcome these short comings. These methods tend to separate the SOM into two major fractions, labile and stable (Haynes 2005; Manlay et al. 2006; Helfrich et al. 2007; Cerli et al. 2012). The separation between the two fractions is based on their turn over time: labile having the shortest turn over time and stable having the longest turn over time ranging from decades to centuries (Helfrich et al. 2007).

The labile fraction can also be referred to as the Particulate Organic Matter (POM) or light fraction. This fraction is an intermediate between plant litter and humified substances. It has the shortest turn over time ranging from a couple of months to decades (Haynes 2005). This fraction is the most sensitive to cultivation but is also the most important for plant nutrition. POM can be further broken up into two different group, free Particulate Organic Matter (fPOM) and occluded Particulate Organic Matter (oPOM). The fPOM fraction is present mainly in the upper layers of the soil and is not associated with the mineral fraction. The oPOM fraction is occluded within soil aggregates, affording it a degree of protection from microbial decomposition. The stable fraction also referred to as the Mineral Associated Organic Matter, or Mineral Bound (MB) is composed of organic C compounds that are tightly bound or sorbed to the mineral fraction of the soil. This is the more stable fraction with a turn over time of decades to centuries, it is also the larger fraction accounting for the majority of the SOM present in the soil (Haynes 2005; Helfrich et al. 2006; Manlay et al. 2006). This fraction is important in C sequestration and in increasing the aggregate stability of the soil. Due to its more humified nature, it also contributes the most to important soils properties such as pH buffering and CEC (Haynes 2005).

Dungait et al. (2012) and Sollins et al. (1996) propose that the effect of tillage has the greatest effect on the distribution of C in the soil. Greater disturbance leads to a greater loss from the POM fraction as the aggregate is destroyed and oPOM is exposed for microbial consumption, while the effect of mixing brings residues into greater contact with microbes. Crop rotation is thought to have a smaller influence of the distribution of C into different fractions. Crop rotations have an influence on the composition and mass of residue inputs. While the mass of residue inputs will directly influence soil total C and should therefore lead to variation in the MB fraction, it is the composition of these residues that will influence the POM as they will influence the recalcitrant nature of the OM. Biedersbeck et al. (1994) found that the POM-C had a strong response to a change in crop rotation, particularly a strong increase in continuous cropping compared to the inclusion of a fallow. Salvo et al. (2010) found a significant increase in POM when a pasture system was included in the rotation compared to continuous cropping. As previously stated, there is currently no information available on the effect of tillage and crop rotation practices on SOM functional pools in the Swartland region.

Thus, the purpose of this experimental chapter is to examine the long-term effect of tillage and crop rotation practices on the POM and MB functional pools at selected sites A and B at Langgewens. A further aim is to examine the relationship between the POM and MB functional pools and soil quality parameters, such as aggregate stability and ECEC.

4.2 Materials and methods

4.2.1 Soil sampling

Soil samples were taken in late June to mid-July 2014. The soil sampling and preparation process is described in detail in Chapter 3. Due to the expensive and time-consuming nature of the physical density fractionation procedure, only selected treatments and depths were analysed. At site A, samples were taken from the Conventional Tillage (CT) and No Tillage (NT) plots for WWWW, WMWM and WCWL. At site B on the WWWW, WMc an WMc SB rotations were sampled. Site A samples were taken at 5-10 cm, 10-20 cm and 20-40 cm to show the effect of the tillage treatments on SOM fractions depth distribution. Only the 5-10 cm samples were compared at site B. The 0-5 cm samples were not used to eliminate the effect of crop litter.

4.2.2 Soil organic matter functional pool fractionation procedure

The SOM functional pool fractionation method used was a density fractionation method based on the procedure proposed by Sohi et al. (2005) and Cerli et al. (2012). The goal was to separate the SOM into the major labile and stable functional fractions using density separation and physical disruption and density fractionation. Two different fractions were isolated, namely the labile particulate organic matter (POM), which consisted of the pooled fPOM and oPOM fractions, and the stable mineral bound organic matter (MB). It was decided to pool the fPOM and oPOM fractions as the oPOM fraction was found to be almost negligible in the case of these Swartland soils.

A Sodium Iodide (NaI) solution of 1.6 g cm^{-3} density was used for fractionation. The reason for using 1.6 g cm^{-3} was that most SOM has a density of or less than 1.5 g cm^{-3}. This would allow the OM to float on the surface while the heavier mineral particles would sink allowing for separation (Golchin et al. 1995). This density was also found to be the most effective by Cerli et al. (2012). A representative 5 g soil sample was taken from each treatment replicate and suspended in 25 ml of NaI (1:5 soil to solution ratio). The samples were gently shaken by hand to separate the fPOM, and then allowed to stand for 1 hour to allow settlement before being centrifuged at 5600 g for 20 min. The fPOM was removed from the surface of the solution and transferred to a Millipore filtration funnel fitted with 0.45 um membrane filter under vacuum. This process was repeated three times to ensure removal of all fPOM from the sample. The fPOM fraction was then thoroughly rinsed using deionised water to until the rinse water had a conductivity of less than 50 uS cm^{-1} to ensure the removal of all remaining NaI. Samples were then air dried below 40 °C for several days before weighing. Samples were then ground using a pestil and mortar until a fine consistency was reached, this was to ensure an even analysis of the sample. A similar process was used to isolate the oPOM fractions. The remaining soil sample was suspended in a fresh 25ml NaI solution. The oPOM was then exposed by dispersing the soil aggregates by sonification. A sonic probe (Qsonica Sonicators, Newton, USA, probe size 13.8 cm x 1.3 cm) was inserted into the sample to a depth of 15 cm. 200 J ml^{-1} of ultrasonic energy was used to disrupt the soil aggregate and expose the oPOM (Cerli et al. 2012). The same procedure as for fPOm was then followed to isolate the oPOM from the mineral fraction. Due to the small size of the collected oPOM fraction, it was combined with the fPOM fraction for further analysis. The remaining mineral fraction was then placed in dialysis tubing and left to stand in a container of deionised water for several days to remove the remaining NaI. The water was changed regularly until it tested free of salts using 0.1 mg $AgNO_3$. It was then oven dried at 40 °C for 72 hours and then ball milled. All dried, weighed and ground/milled samples were sent for CN analysis using dry combustion (EuroVector elemental analyser).

4.2.3 Soil quality indicators

4.2.2.1 Aggregate stability

Aggregate stability was determined on all soil samples (depths 0-10 cm, 10-20 cm and 20-40 cm). The wet sieve technique was used according to Kemper & Rosenau (1986). It is assumed that stable aggregates will be more difficult to breakdown in water than unstable aggregates. Four grams of soil were weighed out and placed in a sieve of the wet sieve apparatus (Eijelkamp Agrisearch Equipment, Netherlands). The sieves (0.250 mm) were then lowered repeatedly into container of distilled water for 3 minutes. The unstable aggregates disintegrated and passed into the distilled water in the container. The remaining sample in the sieve was then lowered repeatedly into a container of Calgon solution for 10 minutes or until all the sample had disintegrated. Both containers were then oven dried overnight and the mass of the sample in each one determined.

4.2.2.2 Soil respiration rate (CO_2 flux)

Soil respiration rate is a useful way to determine the loss of C from the soil from root and microbial respiration, with microbes composing the greatest amount (Keith & Wong 2006). The soda lime method was chosen due to its ease of application and low cost. This method was derived from Keith & Wong (2006) and involves suspending a sample of soda lime (NaOH and $Ca(OH)_2$) inside a PVC chamber that is sealed to the atmosphere but open to the soil below (Fig 4.1). These traps are left in the field for 30 days allowing the soda lime to absorb the CO_2 released from the soil. The change in mass is then measure to determine the respiration rate. A correction factor of 1.69 was (Grogan 1998) was used to account for the formation of water when the soda lime absorbs CO_2.

$$2NaOH + CO_2 > Na_2CO_3 + H_2O$$

$$CaOH + CO_2 > Ca_2CO_3 + H_2O$$

A sample of ± 10 g of soda lime was placed in perforated tubes and before being oven dried at 80 ^{0}C for 24 hours. The dry mass was recorded and the tubes placed in sealed bags for transport to the site. At the site the tubes were suspended in PVC chambers with a 12 cm diameter hole in the base. These were pushed ± 4 cm into the soil at the sampling site. The traps were placed in early June shortly after the emergence of the wheat, and were kept in the field for 30 days. After 30 days the traps were removed and the soda lime was placed in sealed bags for transport. Once returned to the lab the soda lime was oven dried at 80 ^{0}C for 24 hours before the dry mass was determined. The change in mass was then used to determine the daily respiration rate of the soil. Unfortunately due to the heavy rain during this period the CT plots at Site A remained in a water logged state and the ensuing respiration rate was unusually low.

Figure 4.1 Soda Lime trap in field, showing main chamber with CO_2 scrubber on breather hole

4.2.2.3 Exchangeable cations

Effective cation exchange capacity (ECEC) was calculated for the 5-10 cm profile using the methods according to Thomas (1982) as described in 3.2.5.3. A 1M Ammonium Acetate extraction was used for the extraction of basic cations (Ca, Mg, Na and K). Exchangeable acidity was determined using 1M KCl extraction method. Basic cations and exchangeable cations were used to calculate the ECEC.

4.3 Results and discussion

4.3.1. C content of SOM functional pools

4.3.1.1 The effects of tillage practices on the C content of SOM fractions at Site A

Under WWWW we can observe very little variation between the tillage treatments with regard to MB-C content (Fig 4.2). NT (6.15 g kg^{-1}) was significantly higher than CT (4.9 g kg^{-1}) in the 5-10 cm profile. However there was no significant difference between the treatments at the other two depths. There was a trend of decreasing C content with depth, NT under WMWM (Fig 4.2b) decreasing from 6.15 g kg^{-1} at 5-10 cm to 4.82 g kg^{-1} at 10-20 cm. This is again observed with CT under WCWL (Fig 4.2c), with 5.64 g kg^{-1} at 5-10 cm, decreasing to 4.10 g

kg^{-1} at 10-20 cm. This pattern was also observed with the total C content. That NT had a high MB-C than CT at 5-10 cm was expected as this was also observed in total C, however by a smaller amount. However CT was significantly higher at 10-20 cm for total C, while for MB-C there was no significant difference, nor was there for 20-40 cm where total C was significantly higher for NT.

MB-C content under WMWM was more variable than that of WWWW, with no discernible trend showing between the NT and CT treatments (Fig 4.2b). However there was no significant difference between any of the treatments. At 5-10 cm NT had a higher C content (4.92 g kg^{-1}) compared CT (4.48 g kg^{-1}), a similar trend was observed for total C. At 10-20 cm CT (5.80 g kg^{-1}) was higher than NT (5.05 g kg^{-1}) while at 20-40 cm NT (6.69 g kg^{-1}) was again the highest compared to CT (4.99 g kg^{-1}), however CT had a higher total C at his depth. There was no decreasing trend over depth, with NT being lowest in the 10-20 cm horizon and CT having its highest C content in the same horizon.

MB-C content under WCWL was more uniform trend than that of WMWM, with no significant difference between any treatment but a steady decrease in C content with depth (Fig 4.2c). At 5-10 cm NT and CT are near identical at 5.65 g kg^{-1} and 5.64 g kg^{-1} respectively. At 10-20 cm CT was greater than NT at 4.55 g kg^{-1} and 4.10 g kg^{-1} respectively. At 20-40 cm both treatments were near identical with NT at 4.07 g kg^{-1} and CT at 4.05 g kg^{-1}. The lack of any variation in the MB-C was surprising as WCWL had the strongest response to tillage for total C. 5-10 cm NT had significantly higher total C compared with CT, however for MB-C they were near identical. At 10-20 cm CT had a significantly higher total C than NT, however for MB-C, although higher for CT, it was not significant.

Dou et al. (2008) found that trends in MB-C closely followed that of total C, and that NT had a higher MB-C in the top soil (0-10 cm) while CT had a larger MB-C under 30cm. Basile-Doelsch et al. (2009) found significant reduction in MB-C when under tillage compared to a non-tilled soil.

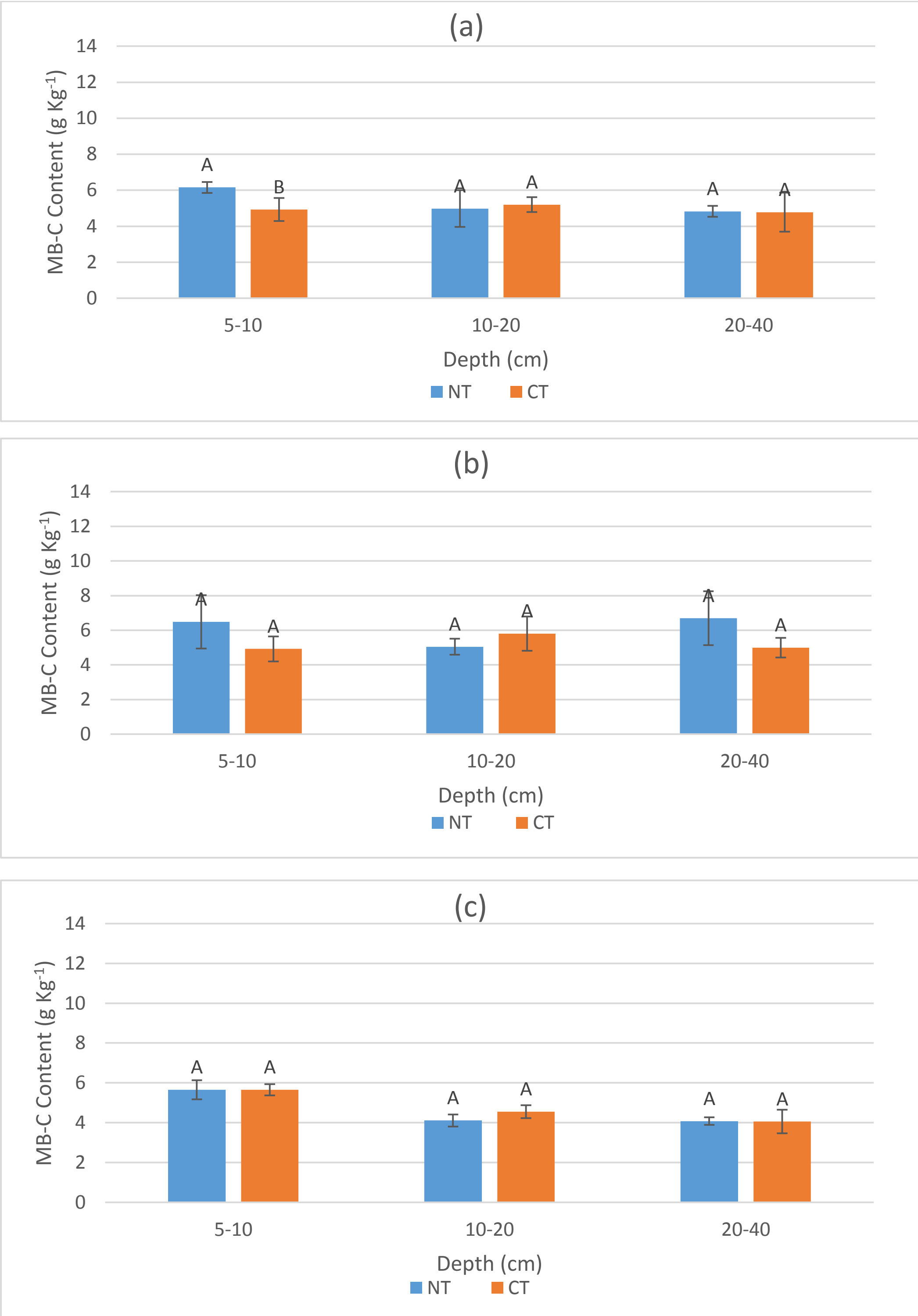


Figure 4.2 The effect of tillage on the MB-C distribution under (a) WWWW, (b) WMWM and (c) WCWL at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

POM-C is expected to show the greatest change due to tillage with Alvaro-Fuentes et al. (2009), Plaza-Bonilla et al. (2010), Carter (1992), Chen et al. (2009) and Dou et al. (2008) reporting a significant increase in liable C with a reduction in the soil disturbance.

However there was no significant difference between treatments, except at 10-20 cm under WWWW (Fig 4.3a), where NT (2.18 g kg^{-1}) was significantly higher than CT (1.10 g kg^{-1}). The C content decreased with depth from 1.81 g kg^{-1} (NT) and 1.71 g kg^{-1} (CT) in the 0-5 cm profile to 0.44 g kg^{-1} (NT) and 0.69 g kg^{-1} (CT) in the 20-40 cm profile, this was similar to the trend observed for total C and MB C content.

POM-C content had a more definite trend than MB-C under WMWM (Fig 4.3b). CT had the highest POM-C content at all depths with 3.37 g kg^{-1} at 5-10 cm horizon decreasing down to 3.12 g kg^{-1} at 10-20 cm and 1.87 g kg^{-1} at 20-40 cm. These were all significantly higher than NT except at 5-10 cm where there was no significant difference. NT had a POM-C content of 2.91 g kg^{-1} at 5-10 cm before rapidly dropping to 0.75 g kg^{-1} and 0.20 g kg^{-1} at 10-20 cm and 20-40 cm respectively. This was unexpected at 5-10 cm as the greater exposure of residues at the surface would have led to greater loss. The trend of CT having a larger POM-C fraction at depth was also found by Dungait et al. (2012) and Dou et al. (2008) but not as shallow as 10-20 cm. This increase in depth of POM-C under CT could possibly be due to the recent movement of a large amount of medic residues from the surface to a greater depth during the recent ploughing, where as NT the residues remain on the surface as a blanket.

NT had a significantly higher POM-C content at 5-10 cm under WCWL than CT (Fig 4.3c), at 3.75 g kg^{-1} compared to 1.08 g kg^{-1} respectively. This fits well the trend of total C as CT was significantly lower. At the other two depths CT has a higher POM-C content than NT although not significantly.

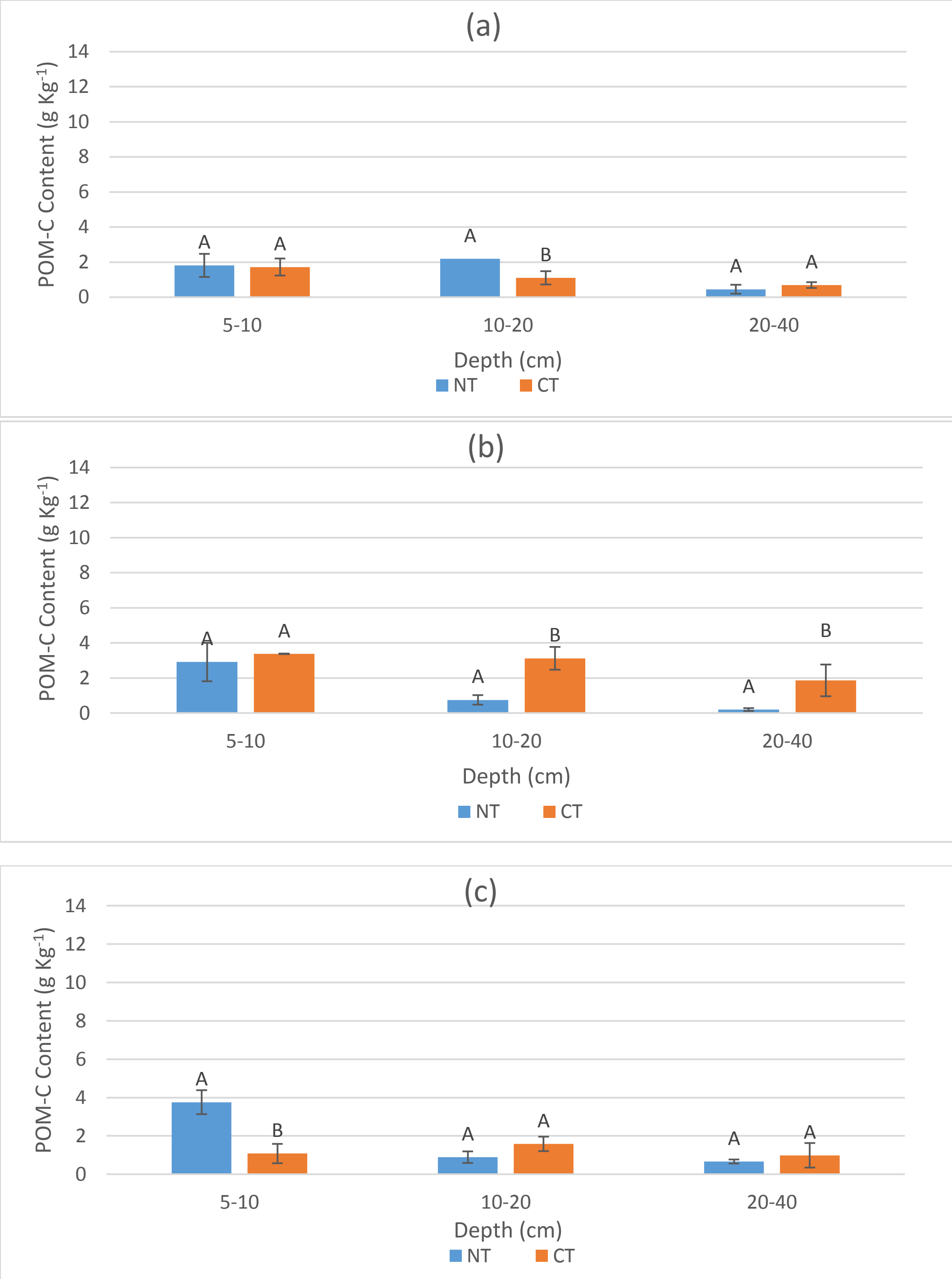


Figure 4.3 The effect of tillage on the POM-C distribution under (a) WWWW, (b) WMWM and (c) WCWL at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.1.2 The effects of crop rotation practices on the C content of SOM fractions at Site A

There was no significant difference for MB-C content between any treatments under CT (Fig 4.4a). At 5-10 cm WCWL had the highest MB-C content at 5.64 g kg^{-1} compared to 4.93 g kg^{-1} for WWWW and 4.92 g kg^{-1} for WMWM. This was unexpected as WCWL had significantly lower total C than WMWM. At 10-20 cm WMWM had the highest MB-C content at 5.80 g kg^{-1} compared to 5.20 g kg^{-1} for WWWW and 4.55 g kg^{-1} for WCWL. At 20-40 cm WMWM was again the highest with 4.99 g kg^{-1} compared to 4.77 g kg^{-1} and 4.05 g kg^{-1} for WWWW and WCWL respectively. WMWM had the highest total C for all depths.

WMWM had the highest MB-C content at all depths under NT (Fig 4.4b). At both 10-20 cm and 20-40 cm WMWM was significantly higher than WCWL, with 5.04 g kg^{-1} and 4.10 g kg^{-1} respectively at 10-20 cm and 6.69 g kg^{-1} and 4.07 g kg^{-1} respectively at 20-40 cm. WWWW was also significantly higher than WCWL at 20-40 cm with 4.82 g kg^{-1} compared to 4.07 g kg^{-1} for WCWL. The trend observed for MB-C is consistent with that observed for total C. WMWM having a constantly higher total C than both WWWW and WCWL.

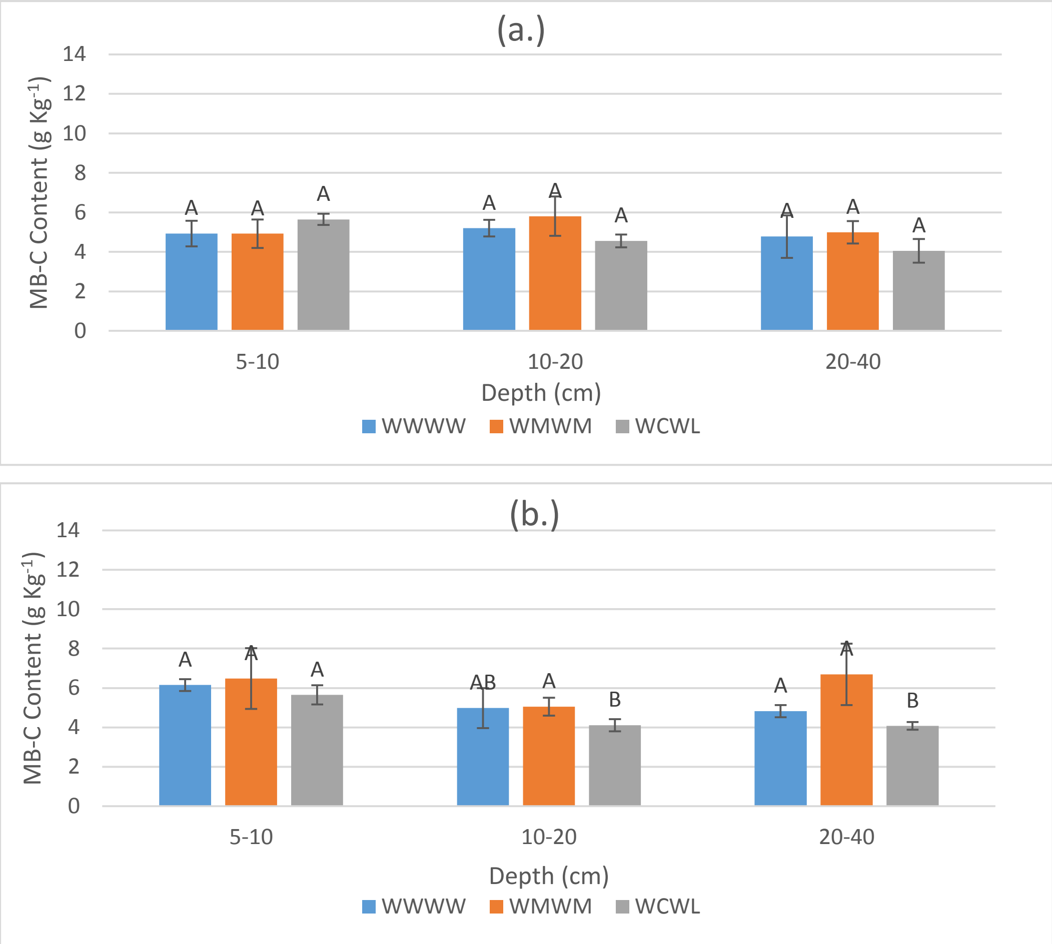


Figure 4.4. The effect of crop rotation practices on the MB-C under (a.) CT and (b.) NT at Site A.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

WMWM had significantly higher POM-C content than all other treatments under CT (Fig. 4.5a), except WCWL at 20-40 cm. At 5-10 cm WMWM had a POM-C content of 3.37 g kg^{-1} compared to 1.72 g kg^{-1} and 1.08 g kg^{-1} for WWWW and WCWL respectively. At 10-20 cm WMWM had a POM-C content of 3.12 g kg^{-1} compared to 1.10 g kg^{-1} and 1.58 g kg^{-1} for WWWW and WCWL respectively. At 20-40 cm WMWM had a POM-C of 1.87 g kg^{-1}, this was significantly high than WWWW, at 0.69 g kg^{-1} but not WCWL, at 0.98 gkg^{-1}. This concurs with the findings of Salvo et al. (2010) that the inclusion of a pasture increases the POM fraction. This significant increase in POM-C for WMWM at depth under CT could be attributed to the incorporation of a large amount of fresh residue during tillage. As these sites are not grazed a large blanket of medic litter forms on the surface. The reduced tillage of only ploughing every second year under the pasture system could also lead to an increase in long term POM-C stability.

A more variable trend is observed from the POM-C content under NT (Fig 4.5b). At the 5-10 cm profile WCWL has the highest POM-C content at 3.76 g kg^{-1}, followed by WMWM at 2.91 g kg^{-1} and lastly WWWW with 1.81 g kg^{-1}, which is significantly lower than WCWL. However at 10-20 cm WWWW had the highest POM-C content at 2.18 g kg^{-1}, significantly higher than both WMWM at 0.75 g kg^{-1} and WCWL 0.89 g kg^{-1}. This resilience of WWWW at depth could be due to the more recalcitrant nature of WWWW residues, the higher proportion of cellulose and lower C:N ratio compared with medics and lupins. At 20-40 cm there was no significant pattern among the treatments.

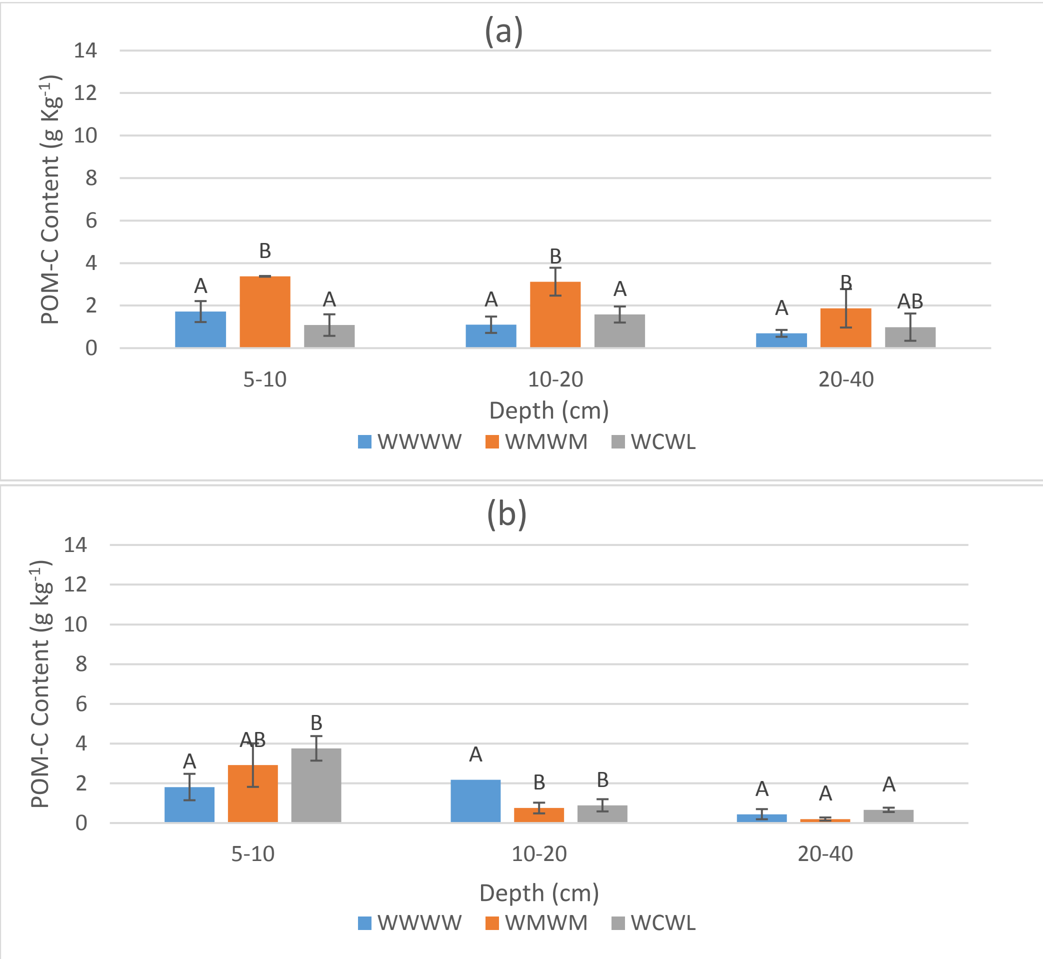


Figure 4.5 The effect of crop rotation on POM-C under (a.) CT and (b.) NT at site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.1.3 The Effects of crop rotation practices on the C content of SOM fractions at Site B

There was no significant differences in the MB-C content or POM-C content at 5-10 cm depth at Site B (Fig 4.6). WWWW had the highest MB-C content at 10.21 g kg^{-1} compared to 8.10 g kg^{-1} and 8.66 g kg^{-1} for WMc and WMc SB. This could be related to the higher clay content at the WWWW sites (Table 3.5). There is very little difference between the POM-C content for all three treatments with WWWW having 2.11 g kg^{-1} followed by WMc with 1.90 g kg^{-1} and WMc SB with 1.81 g kg^{-1}. It was expected that the reduced tillage and higher quality of residue under the crop/pasture systems should be positively contribute to the POM fraction. The greater maturity of Site B has allowed for a longer time of C stabilisation, and perhaps showing that there is a less significant influence of crop rotation on POM-C than expected.

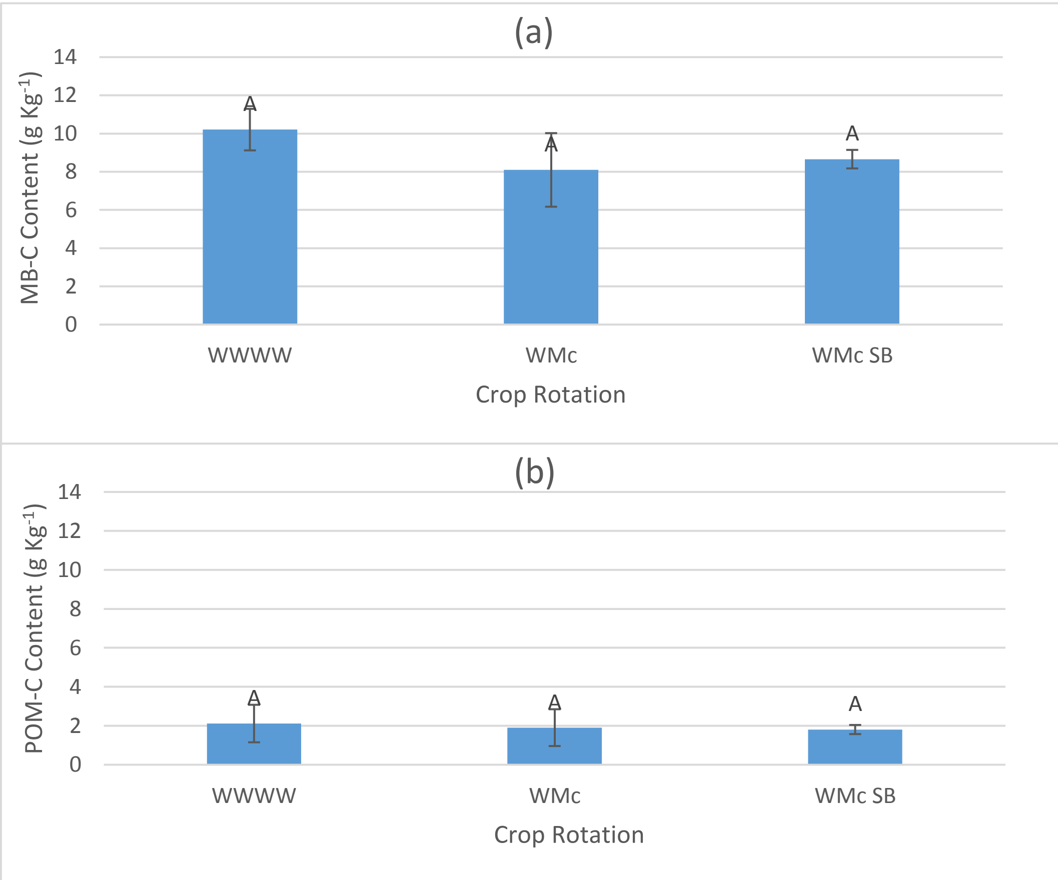


Figure 4.6. The effect of crop rotation on (a) MB-C and (b) POM-C (5-10 cm) under NT at Site B.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.2. The relative distribution of C in the SOM functional pools

4.3.2.1 The effect of tillage practices on the distribution of C in SOM functional pools at Site A

The majority of soil C is found in the MB fraction (approximately 60-95 %) while POM-C contributes a significantly smaller percent (Fig 4.7). Under all treatments we can observe the trend of POM-C contribution to Total C decreases with depth. This is most obviously represented by WCWL under NT (45 % and 14 % for topsoil and subsoil respectively) and WMWM under NT (31 % and 3 % respectively), this is more noticeable under NT as there is no mixing of fresh residues down to the lower horizons. Basile-Doelsch et al. (2009) found that the MB fraction contributed between 25 % and 98 % of Total C in his studies in Reunion, while Dou et al. (2008) found that the POM-C fraction contributed between 1-20 % of the total C in Texas wheat fields. Judging by these studies our data is within reason, even though we have a larger variation.

WWWW had the smallest difference between tillage treatments in both the topsoil and subsoil with 26 % for CT and 23 % NT in the topsoil, and 13 % for CT and 9 % for NT in the subsoil. Under WMWM CT had a larger POM-C fraction than NT at both topsoil and subsoil. In the topsoil CT had a POM-C fraction of 41 % compared to NT 31 %. In the subsoil NT had a vastly reduced POM-C fraction of only 3 % compared to 27 % for CT. WCWL is the only crop rotation where NT had a larger POM-C fraction than CT, at 45 % in the topsoil this is substantially higher than CT 16 %. However in the subsoil CT again has a larger POM-C fraction at 20 % compared to 14 % for NT. The variation observed here could be attributed to the relative young age of the trial on this Site A as there was limited variation in the texture of these sites. Plaza-Bonilla et al. (2013) found that C accumulation and stabilisation of SOM fractions to happen after 11 years, this site is only in its 8th year and is yet to stabilise.

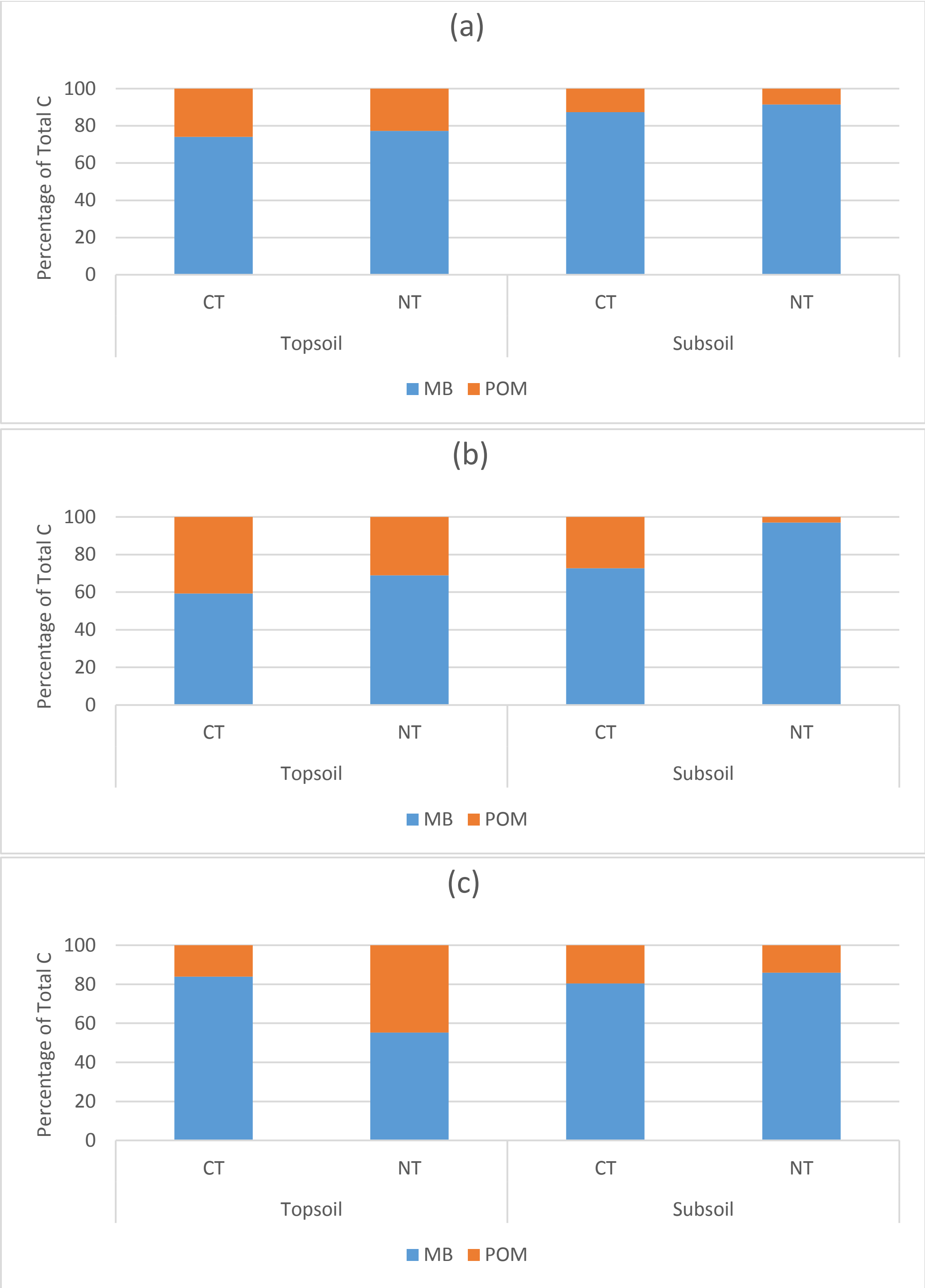


Figure 4.7 The effect of tillage on the relative contribution of MB and POM C to Total C under (a) WWWW, (b) WMWM and (c) WCWL at Site A (Topsoil = 5-20 cm and Subsoil = 20-40 cm).

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.2.2 The effect of crop rotation practices on the distribution of C in SOM functional pools at Site A

The effect of crop rotation was found to be highly variable across the two trials with the trends observed under CT not necessarily being observed under NT (fig 4.7).

Under CT WMWM had the largest POM-C fraction in the topsoil at 41 %, followed by WWWW at 26 % and WCWL at 16 %. Under NT WCWL had the largest POM-C fraction in the topsoil at 44 % followed by WMWM at 31 % and WWWW at 23 %.

The subsoils had a markedly smaller POM-C fractions than the topsoils with an equally poorly observed trend. Under CT WMWM had the largest POM-C fraction at 27 % followed by WCWL at 20 % and WWWW at 13 %. Under NT WCWL had the largest POM-C fraction at 14% followed by WWWW at 8 % and WMWM at 3 %.

It was not expected to observe a large variation in POM-C between crop rotations as it is believed that tillage plays a larger role in POM-C distribution (Balesdent et al. 2002; Dou et al. 2008; Basile-Doelsche et al. 2009). Crop rotation plays a large role in the recalcitrant nature of the SOM, however Dongait et al. (2012) found that it was access to SOM and not the complex nature of SOM that dictates turn over, indicating a larger role of tillage. Basile-Doelche et al. (2009) found that while POM-C was strongly influenced by crop rotation, its contribution to total C distribution was insignificant. Smith (2014) found a much smaller variation under NT in the Southern Cape with MB-C contributing between 84 – 95 % of total C.

The young nature of these sites could be the cause of the variation as there is limited variation in the texture of the sites. Plaza-Bonilla et al. (2013) found that C accumulation and stabilisation of SOM fractions to happen after 11 years, this site is only in its 8th year and is yet to stabilise.

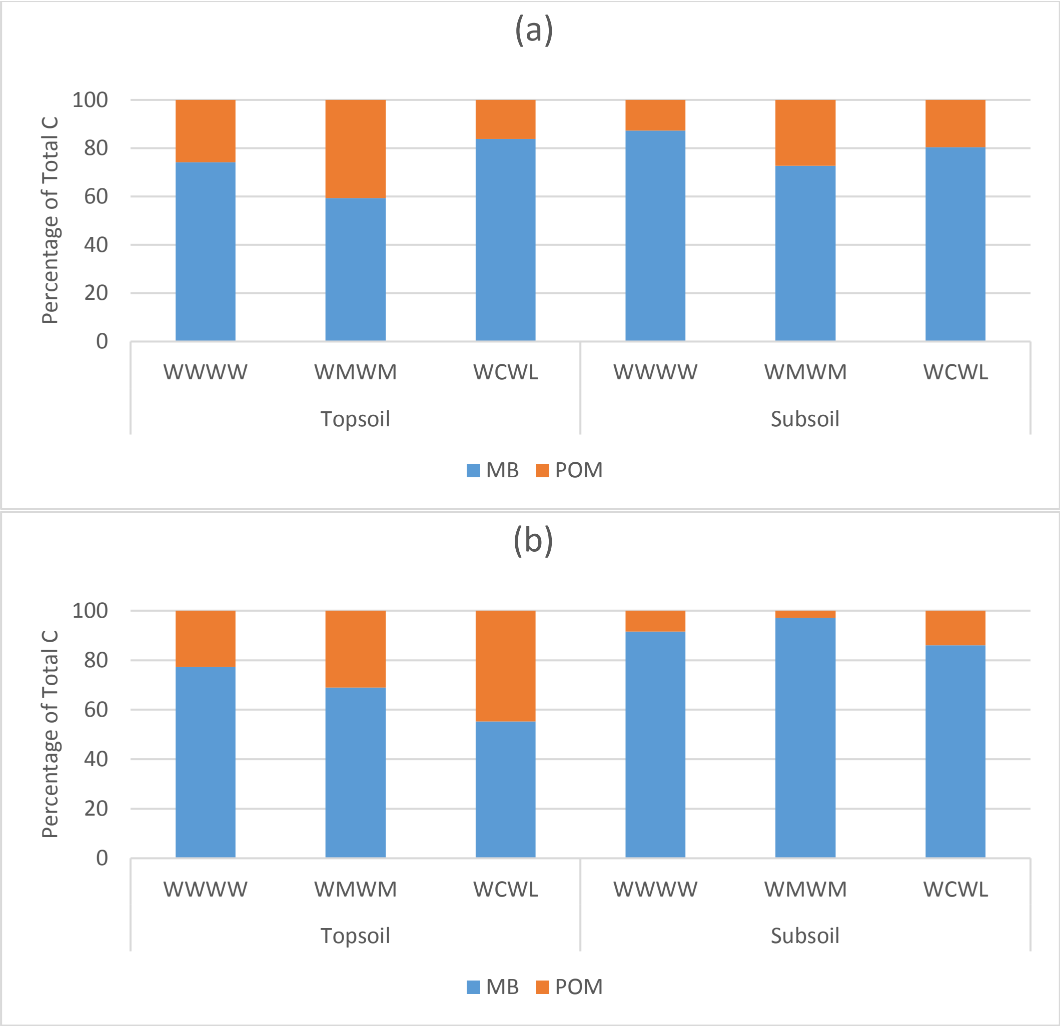


Figure 4.8 The effect of crop rotation on the relative contribution of MB-C and POM-C to Total C under (a) CT and (b) NT at Site A. (Topsoil = 5-20 cm and Subsoil = 20-40 cm).

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.2.3 The effect of crop rotation practices on the distribution of C in SOM functional pools at Site B

Site B showed much less variation in POM-C fractions under NT reflecting the greater age of the site (Fig 4.9). WMc had the largest POM-C fraction at 19 % in the topsoil while WWWW and WMc SB both had 17 %. The variation here of with 2 % shows the stabilisation of POM fractions over a period greater than 10 years.

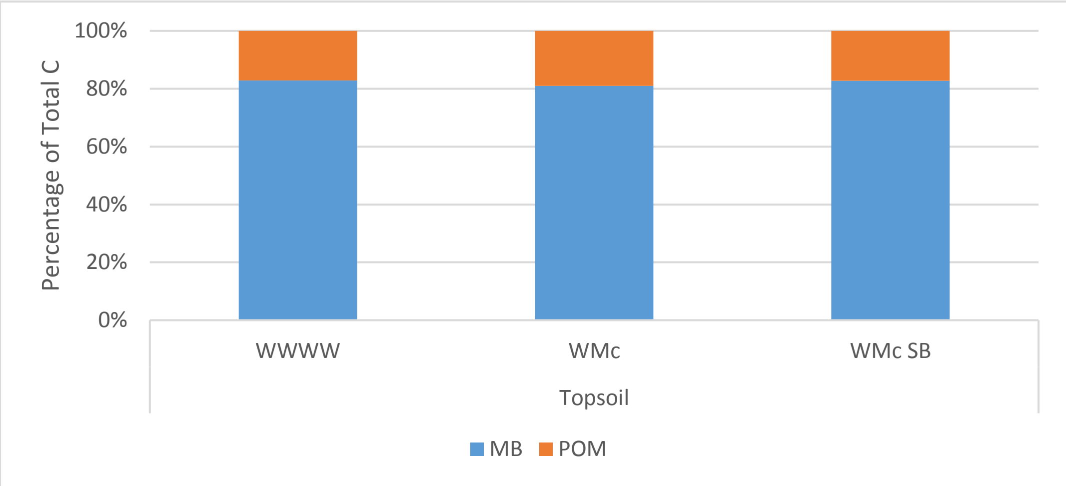


Figure 4.9 Relative contribution of MB and POM C to Total C under NT at 5-10 cm depth at Site B

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.3 SOM functional pools quality

4.3.3.1 The effect of tillage practices on SOM function pools C:N ratio at Site A.

There was little difference between C:N ratios of the Mineral Bound fraction under the two tillage treatments, with no significant difference between any of them except under WCWL, at a 20-40 cm. There was a general decrease in the ratio with depth (Fig 4.10). This follows a similar trend found by Smith (2014) where MB C:N decreased with depth, while Grünewald et al. (2006) did not find a trend over depth. There was no consistent trend with one treatment having a higher C:N ratio under one crop rotation, and another being higher under a different crop rotation. This is shown when examining the 5-10 cm profile. Under WWWW CT had a higher C:N ratio at 10:1 compared to NT at 9.8:1. While under WMWM there was no difference with both treatments having a ratio of 11:1. NT had the highest C:N ratio under WCWL at 10:1 compared to 9:1 for CT. The only significant difference observed was under WCWL in the 20-40 cm profile, NT at 8:1 was higher than CT at 7:1 cm. MB C:N should be more resistant to the effects of tillage than POM C:N as its association with the mineral particles acts as a stabling effect.

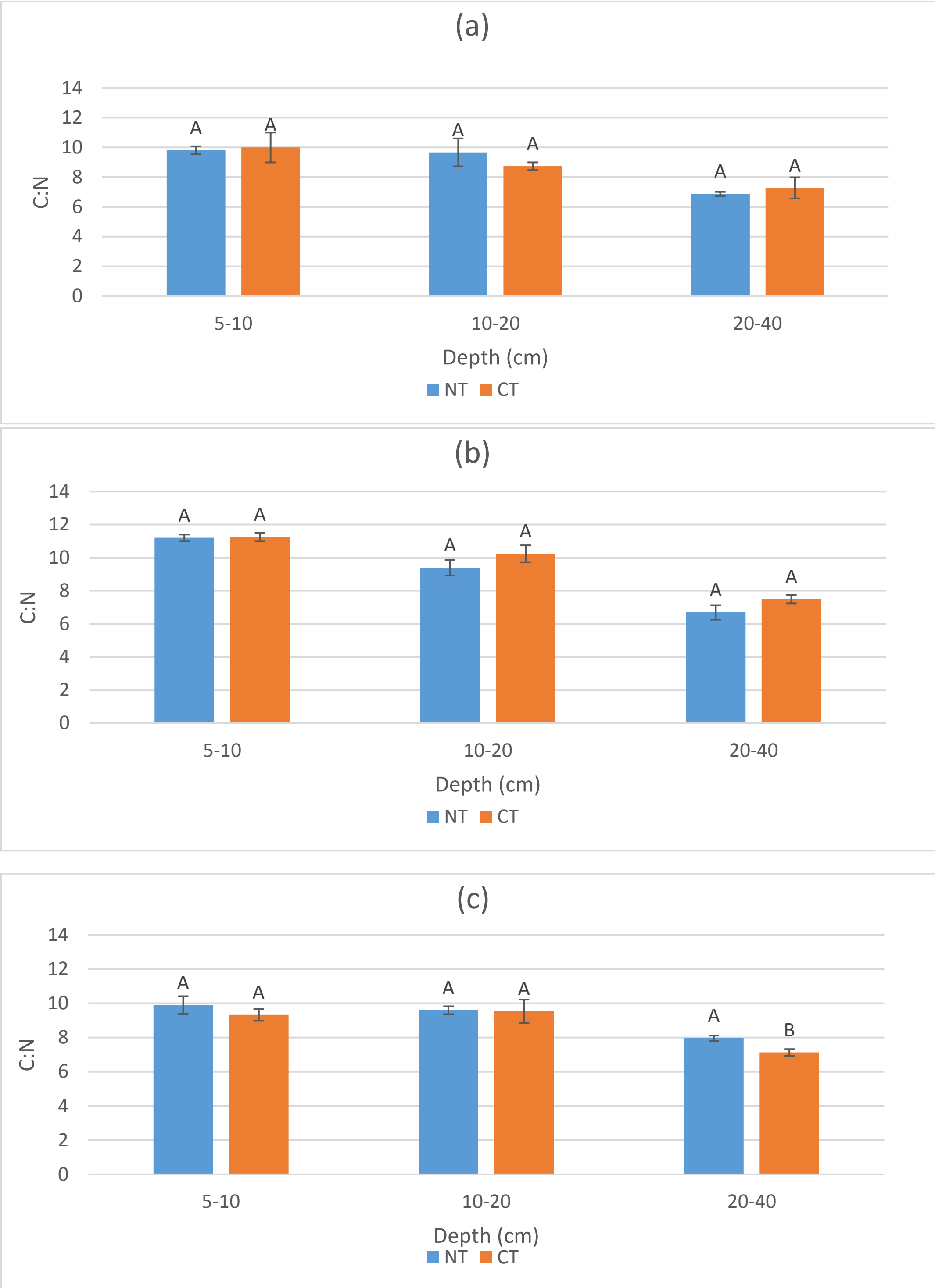


Figure 4.10 The effect of tillage on the C:N of the Mineral Bound fraction under (a) WWWW, (b) WMWM, and (c) WCWL at Site A.

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

As was expected there was a much larger variation in the C:N ratio of the POM fraction (Fig 4.11), as POM fraction is very susceptible to tillage, and the disturbance will lead to greater microbial activity. There were however some unexpected results. The first noticeable trend is the decrease in the C:N with depth. This could be attributed to the fact that the SOM at depth is older than the fresh residues at the surface had have had a chance to undergo greater microbial decomposition, leading to a lower C:N ratio (Stevenson and Cole 1999).

Under WWWW, NT had a higher C:N ratio than CT in the 5-10 cm profile, 42:1 and 30:1 respectively. This is reversed at 10-20 cm profile with CT having a C:N of 81:1 compared to NT at 55:1. In the 20-40 cm profile CT has a C:N ratio of 17:1, significantly higher than NT with a C:N ratio of 4:1. Under WMWM CT had a significantly higher C:N than CT at all depths. At 5-10 cm CT was had a C:N ratio of 12:1 compared to 8:1 for NT. At 10-20 cm CT had a C:N ratio of 39:1, more than 10 times greater than that of NT at 3:1. At 20-40 cm CT had a C:N of 15:1 compared to NT of 3:1.Under WCWL, NT had significantly higher C:N ratios than NT at both 5-10 cm, 81:1 and 47:1 respectively and 10-20 cm, 61:1 and 22:1 respectively. At 20-40 cm there was no significant difference. Tan et al. (2007) found that NT had a positive effect on the light SOM fractions compared to CT in the top 10 cm. Below 10 cm however CT had a lower C:N than NT.

The C:N ratio of MB SOM is significantly lower than that of the POM SOM, with the MB having a range of 6:1 to 11:1 while the POM SOM had a range of 3:1 to 80:1. This was also observed by Grunewald et al. (2006), Smith (2014) and Tan et al. (2007), however not to such a large degree. This could be attributed to the fact that MB fractions have gone through a greater degree of microbial decomposition, with microbes being N rich, and C consumed by the microbes, (Stevenson & Cole 1999) leading to a lower C:N. The greater variability in this site could be attributed to the age of the site, as the sites used for Grunewald and Smith were older sites, allowing for a stabilising of the SOM fractions, and perhaps less collection of crop litter.

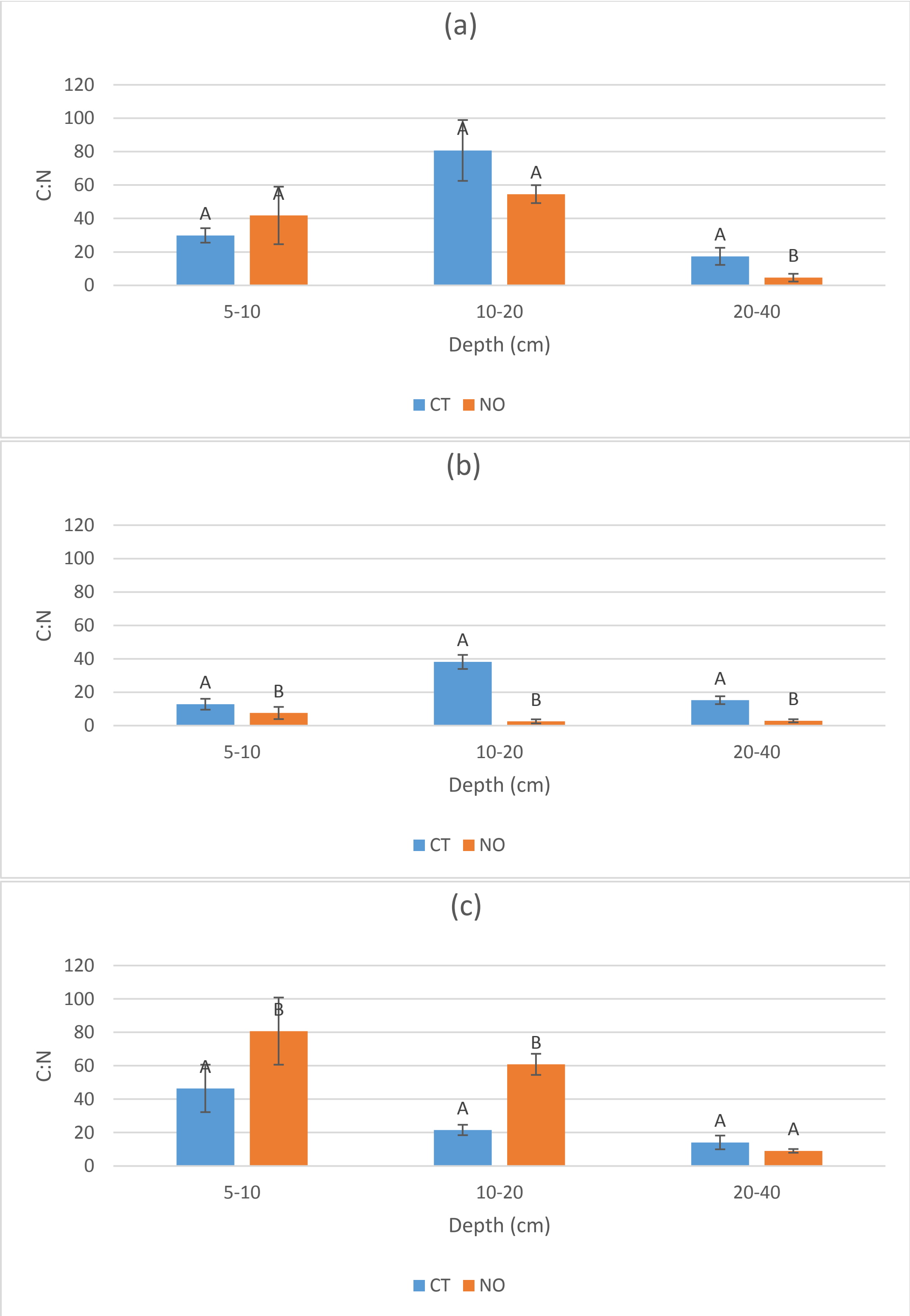


Figure 4.11 The effect of tillage on the C:N of the Particulate Organic Matter fraction under (a.) WWWW, (b.) WMWM and (c.) WCWL at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.3.2 The effect of crop rotation practices on SOM function pools C:N ratio at Site A.

The effects of crop rotation seem to have a larger influence on the C:N of the Mineral Bound fraction than does tillage (Fig 4.12). This is expected as the inclusion of legumes into the rotation should decrease C:N. However this is not necessarily the case WMWM which has the strongest legume in rotation has the highest C:N ratio at all depths under CT and in the 5-10 cm profile under NT. Under CT, WMWM (11:1) had a significantly higher C:N than WCWL (9:1) while WWWW (10:1) was not significantly different to either. At 10-20 cm WMWM (10:1) and WCWL (10:1) were both significantly greater than WWWW (9:1). There was no significant difference between treatments at 20-40 cm with all treatments between 7:1 and 8:1.

Under NT (Fig. 4.12b) WMWM had the highest CN ratio at 5-10 cm at 11:1, significantly higher than both WWWW (10:1) and WCWL (10:1). At 10-20 cm there was no significant differences between treatments, WWWW (10:1) having the highest C:N ratio followed by WCWL (10:1) and WMWM (9:1). At 20-40 cm WCWL had the highest C:N ratio at 8:1, significantly higher than both WWWW and WMWM at 7:1.

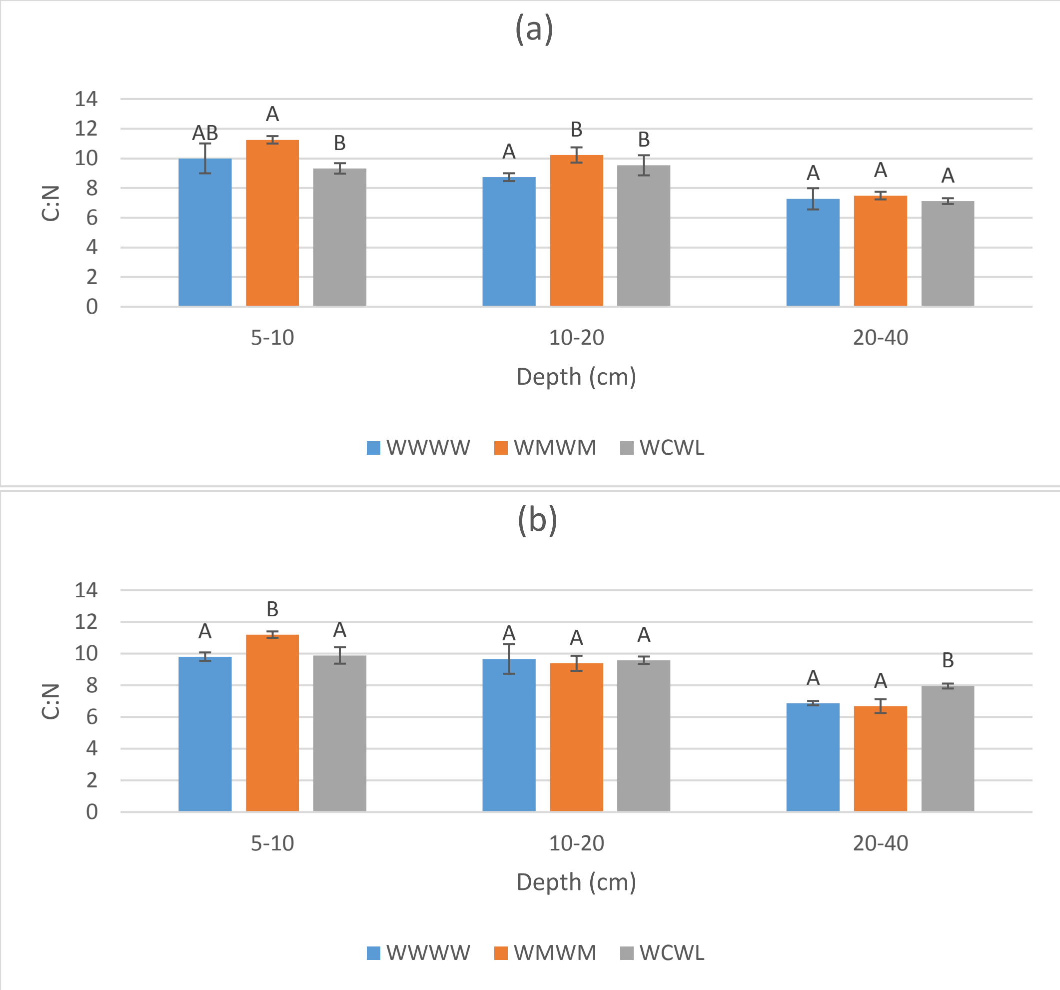


Figure 4.12 The effect of crop rotation on the C:N of Mineral Bound fraction under (a) CT and (b) NT at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

Once again the C:N ratio of POM fractions shows a great degree of variation, with no strong trends showing in the different treatments (Fig. 4.13). Under CT (Fig. 4.13a) WCWL had the largest C:N ratio at 5-10 cm, 47:1, followed by WWWW, 30:1. Both were significantly higher than WMWM at 13:1. At 10-20 cm WWWW had the highest C:N ratio of all POM fractions at 81:1. This was significantly higher than both WMWM at 38:1 and WCWL at 22:1. There was no significant differences in the 20-40 cm profile.

Under NT (Fig. 4.13b) WMWM had significantly low C:N ratio across all depths. At 5-10 cm WCWL had a very large C:N ratio of 81:1 which was significantly greater than WWWW at 42:1 and 10 times larger than WMWM at 8:1. At 10-20 cm both WWWW, at 55:1, and WCWL, at 61:1, were significantly higher than WMWM at 3:1. There was no significant difference at

20-40 cm with WWWW and WCWL, 5:1 and 9:1 respectively, having C:N ratios more comparable to that of WMWM, 3:1.

While there was a great variability across the sites, WMWM had significantly lower C:N ratio than WWWW under all treatments above 20 cm. This illustrates the positive effect the legume Medics has on the POM, especially under NT. Smith (2014) recorded similar results where rotations including Medics and Lucerne pastures had lower C:N than 100% crop rotations.

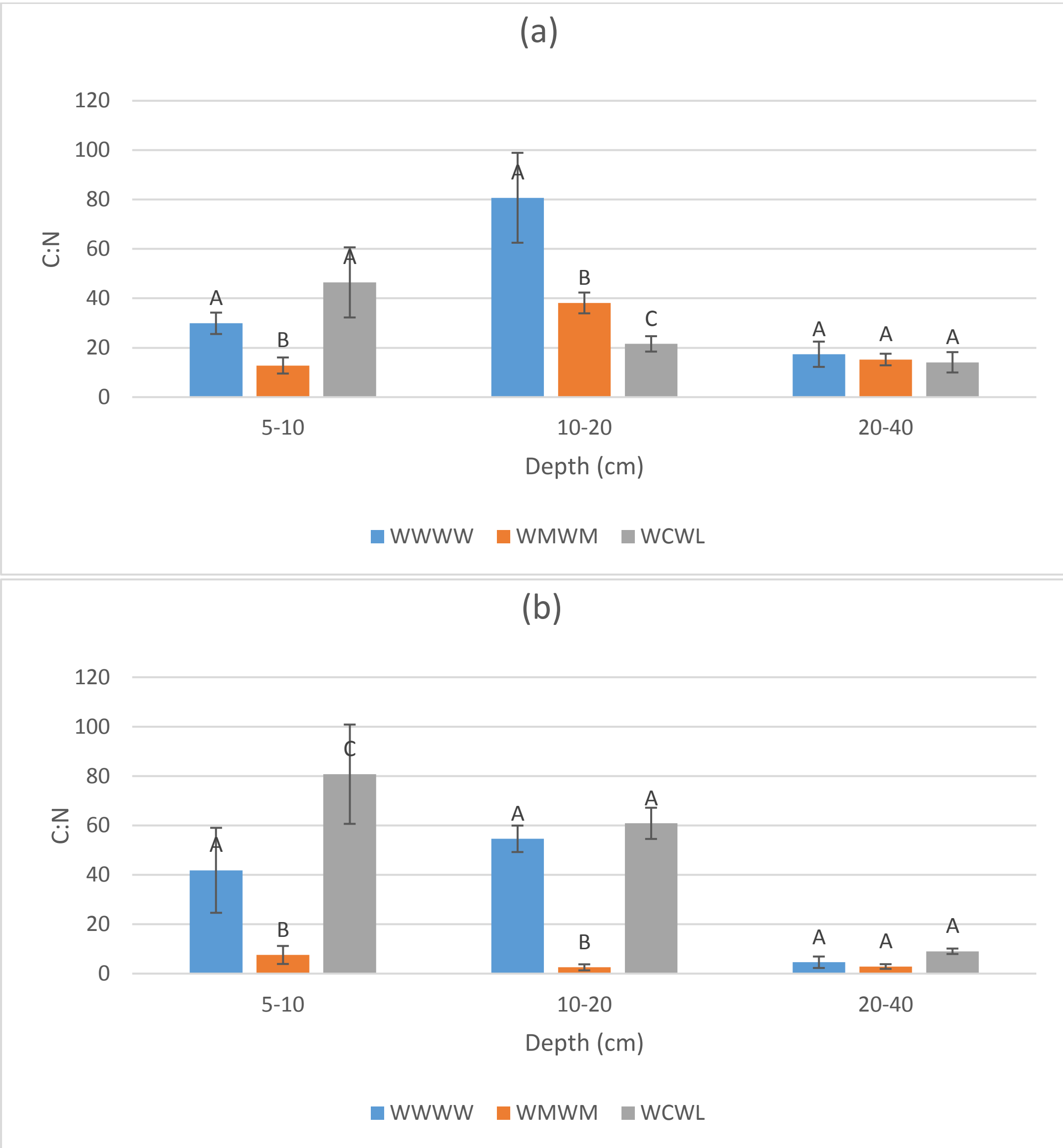


Figure 4.13 The effect of crop rotation on the C:N of Particulate Organic Matter fraction under (a) CT and (b) NT at Site A

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at α= 0.005. Similar letters indicate lack of significant difference

4.3.3.3 The effect of crop rotation practices on SOM function pools C:N ratio at Site B

There was no significant difference in the C:N ratio of the MB fractions at Site B (Fig. 4.14a), this was in common with all other treatments on Site A at this depth (Fig. 4.13). WWWW had the highest C:N ratio at 11:1 followed by WMc SB at 10:1 and WMc at 9:1. The C:N of the POM fractions were significantly lower and less variable than Site A due to the maturity of the site (Fig. 4.14b). WMc SB had the highest C:N ratio at 20:1, significantly higher than both WWWW, 11:1 and WMc at 11:1. While WMc was not significantly higher than WWWW, the assumed positive effect of the reduced grazing on WMc SB was not observed as WMc SB had a significantly larger C:N than the other two treatments.

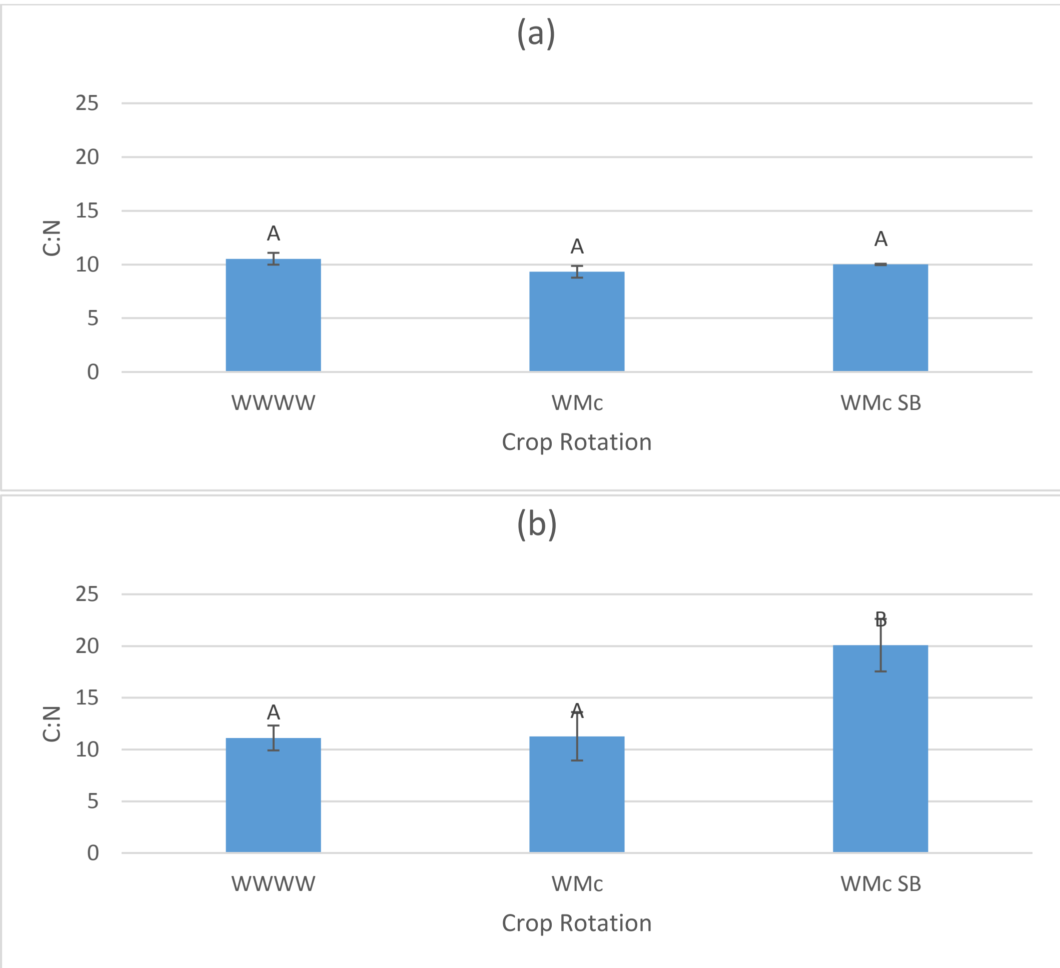


Figure 4.14 The effect of crop rotation on the C:N ratio on the (a) Mineral Bound fraction and (b) Particulate Organic Matter Fraction at Site B

Note: Error bars represent standard error, and alphabetical letters denote statistical differences between treatments according to Tukey's Studentised Range test at $\alpha = 0.005$. Similar letters indicate lack of significant difference

4.3.4 Relationship between SOM functional pools and soil quality parameters

4.3.4.1 Relationship between SOM fractions and CO_2 flux

POM is thought to be a useful indicator of labile C (Janzen et al. 1992) as it is in a non-complexed form and is readily available as a substrate for microbial mineralization of C and N (Haynes 2005). Therefore it is expected to have a positive correlation between POM-C and CO_2 flux, providing a useful infield indicator of the turnover of SOM. However this was unfortunately not the case. A very weak correlation of R^2= 0.007 was observed between POM-C and soil respiration in this trial (Fig. 4-5). This could have been caused by excessively wet conditions during the respiration trials with one site, WWWW, being water logged for the duration of the four week experiment. The C:N ratio of the POM is known to have significant influence on the decomposition rate of the POM, and therefore the CO_2 flux. A SOM C:N ratio of 24:1 or less will lead to a rapid decomposition of the SOM as there will not be a N deficit. However even with a C:N between 8:1 and 15:1 there was no correlation (R^2= 0.004) between a drop in C:N and an increase in CO_2 flux (Fig. A-6). This could again be attributed to the wet conditions during the trial.

4.3.4.2 Relationship between SOM functional pools and ECEC

A weak positive correlation (R^2=0.199) was found between MB-C and ECEC (Fig 4.15). This shows that MB-C does have an influence on ECEC, however in this case the largest influence was clay content (R^2= 0.36) (Fig. 4.16). POM-C was found to have an insignificant influence on ECEC (R^2= 0.005) (Fig. A-7). Krull et al. (2003) also reported that fPOM had an insignificant role in determining ECEC.

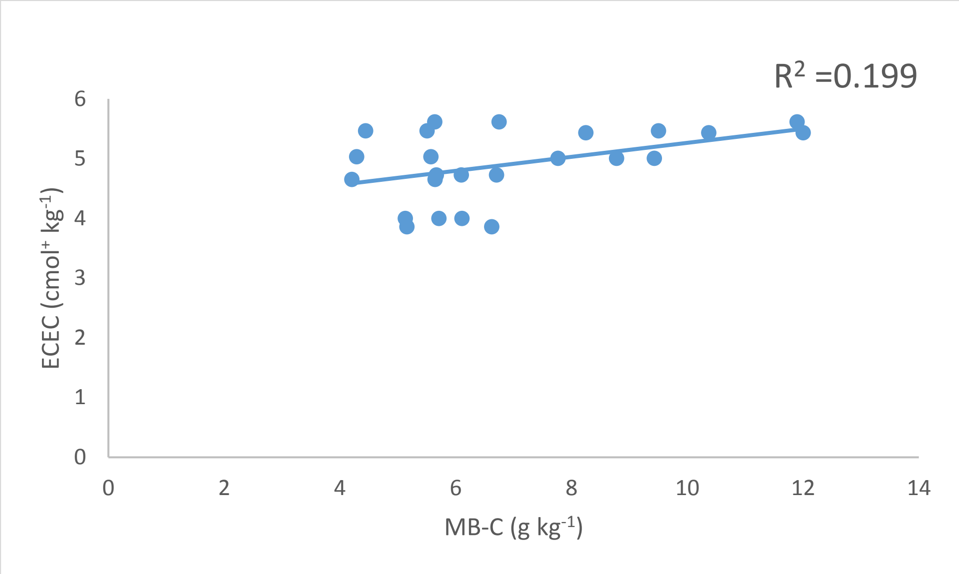


Figure 4.15 Relationship between MB-C content and ECEC

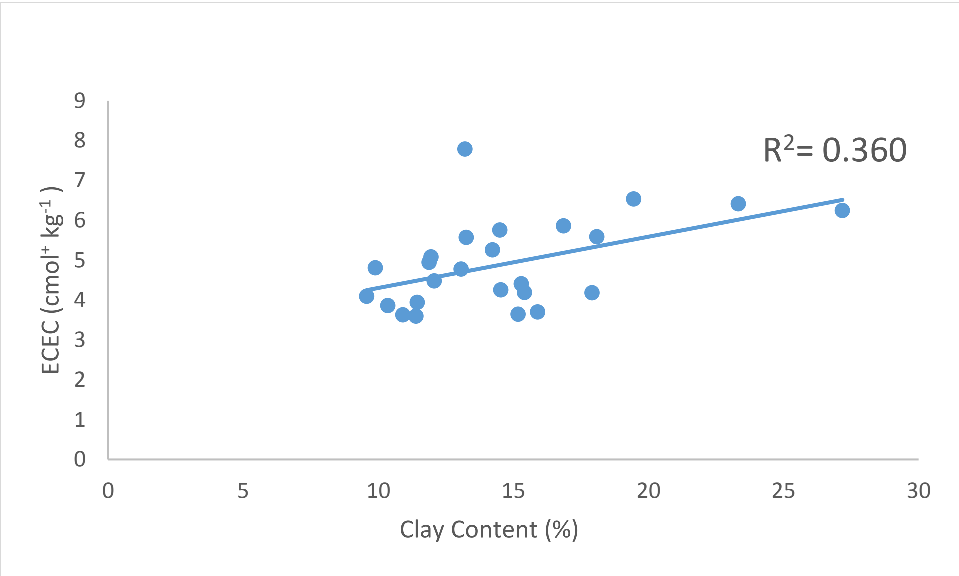


Figure 4.16 Relationship between clay content and ECEC

4.3.4.3. Relationship between SOM functional pools and aggregate stability

The POM fraction can be stabilised by the interactions with the clay fraction and the physical occlusion formed by the aggregates. The POM fraction also serves as the main substrate for microbes, leading to the formation of mucilage which help bind soil particles together leading to the formation of aggregates. However in the case of these soils, the vast majority of the POM fraction was derived from fPOM and not from oPOM. Thus, it is unsurprising that there was an insignificant positive correlation (R^2 = 0.009) between POM-C and aggregate stability (Fig. A-8). There was also a weak positive correlation between aggregate stability and MB-C

(R^2 = 0.16) and total C (R^2 = 0.077) (Fig. A-9). This could indicate that soil organic matter is not playing a very strong role in soil aggregate stability in these saprolitic, shale-derived soils.

4.3.5 Relationship between MB and clay content

An important factor in the long term SOM levels is the stabilisation mechanisms and their relationship with the SOM. For the MB fraction the relationship with the clay content is important as it contains the minerals that interact with the OM. The XRD data (Appendix A – Fig. A-1) shows that the clay mineral composition is mainly kaolinite and muscovite, both low activity, crystalline clay minerals that will tend to bind weakly to SOM (Lutzow et al. 2008). There was a weak positive correlation between MB-C and clay percentage, with a R^2= 0.411 (Fig. 4.17).

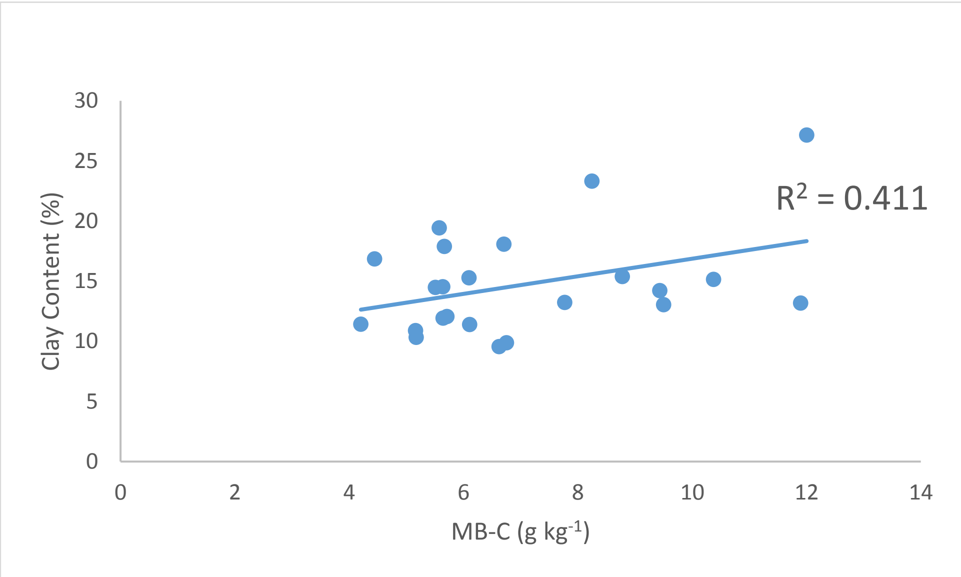


Figure 4.17 Relationship between MB-C and clay content.

4.4. Conclusions

As expected, tillage was found to have little effect on the MB-C content, due to the inaccessible nature of MB-C (Dongait et al. 2012). However the lack of any significant differences in the POM-C due to tillage treatment was not expected; this could be due to the relatively young age of Site A. Plaza-Bonilla et al. (2013) proposed that it takes 11 years for SOM to stabiles after a change in management practices, while Site A is only in its 8th year, it may not yet have had time to stabilise.

NT did not have any significant positive influence on POM-C, with CT often having a higher POM-C at depth. This increase of POM-C under CT could be the incorporation of surface residues into the soil, whereas under NT these residues remain on the surface. This would lead to a short term increase in labile C in the soil soon after tillage, but would be rapidly mineralised.

The effect of crop rotation was found to have a stronger effect on SOM functional pools than tillage. On Site A, there was little significant variation in the MB-C content between the three rotations, however WCWL was found to be significantly lower than both WWWW and WMWM under NT, below 10 cm, this follows the trend of lower total C under this rotation.

There was a greater variation in the POM-C between the different crop rotations. The POM-C content of the WMWM rotations was significantly higher than all treatments under CT on Site A. This could be explained by the incorporation of a large amount of ungrazed medic residues during tillage, however this POM-C would be readily mineralised and would possible decrease latter in the growing season. Crop rotations planted under NT illustrated the importance of root inputs into the POM-C pools. The greatest POM-C was concentrated in the 5-10 cm profile, showing the large concentration of roots in the topsoil, while WWWW was able to have an higher POM-C at depth due to its deep fibrous root system. Site B had no significant variation between any crop rotation for both MB-C and POM-C.

It was found that between 55-97 % of the SOM was in the form of MB-C, with little variation between tillage practises in the topsoil, but CT having the largest POM-C in the subsoil. This can be attributed to the greater soil mixing under CT, caring fresh crop residues to a greater depth. The C:N was found to decrease with depth as found by Stevenson & Cole (1999). Mineral bound SOM had a significantly lower C:N than POM SOM, which is attributed to its greater degree of decomposition (Haynes 2005). The range for MB was between 6:1 and 11:1 while POM was between 3:1 and 80:1. While it was expected that the inclusion of a legume would have an effect on the C:N of POM, the trend was not very pronounced.

There was found to be no correlation between soil respiration and either POM-C or POM C:N due to water-logging at the site during soil respiration measurement. This is unfortunate as this could have proven to be a useful field indicator of SOM turn over. A weak, positive correlation was found between MB-C and ECEC (R^2=0.199), however a stronger correlation was found between clay and ECEC (R^2=0.360) showing that clay was a more important factor in ECEC. No correlations was found between aggregate stability and POM-C, due to the very low oPOM and low aggregate stability of this site. There was found to be a weak positive correlation (R^2= 0.411) between soil clay content and MB-C, showing mineral stabilisation is an important factor in SOM accumulation as MB-C contributes the largest proportion of total C.

While the findings of this section of the study were not conclusive on the effect of tillage and crop rotation practices on the SOM functional pools, it did show that the majority of the SOM is stored as MB-C and remains largely unaffected by management practices, mainly due to its inaccessibility. However further studies need to be conducted to illustrate the effect of management practices on POM-C.

Chapter 5
Conclusions and further studies

5.1 General conclusions

Semi-arid regions often play a crucial role in food production across the globe, in South Africa they are especially important for the production of small grains. Due to their low SOM levels semi-arid regions are susceptible to production decline due to SOM loss. Conservation agriculture is seen as a management strategy with positive results in SOM accumulation and C sequestration. While SOM levels are important, it is equally important that it has a high enough quality to improve microbial activity and increase the availability of plant nutrients. A key indicator that should be included in a SOM analysis is SOM fractions as these provide a greater indication of the proportion of SOM that will provide plant available nutrients and the proportion that will remain stable in the soil and lead to long term C sequestration.

The main objective of this study was to determine the long-term effect of different tillage and crop rotation practices on the distribution of soil C and N in the Swartland region. Reduced tillage had a significant effect on the accumulation of both C and N in the top 30 cm of the soil. Both NT and MT had significantly greater total C stocks than CT, averaging an increase of 48 % in total C stocks. Unlike Lal (2006) and Powlson et al. (2011), it was not observed that CT accumulated greater C stocks than NT below 15 cm. Instead it was found that NT had higher C stocks at almost every depth. This shows that there will be a significant difference between NT and CT on these shallow, saprolitic soils.

Crop rotation had a lesser, but still significant influence on total C stocks, with WWWW and WMWM having the largest total C stocks when planted under NT, having an average increase of 36 % in total C stocks over WCWL, the weakest crop rotation for C accumulation. The positive influence of legumes on the N stocks was noticeable, with the incorporation of medic pastures having a significant increase in total N stock. Under NT, WMWM had 33 % greater total N than WWWW, and 89 % greater total N than WCWL. However under the other tillage treatments, WWWW was not significantly lower than WMWM, but this is heavily influenced by WWWW receiving heavy N fertilizer every year, compared to every alternate year for WMWM.

Both WWWW and WMWM are producers of large amounts of biomass, a large proportion of which is returned to the soil at the season end. The recalcitrant nature of wheat straw, and the continuous addition of it over consecutive years lead to WWWW accumulation a large amount of SOM. While medic is also a producer of large amounts of biomass, the fact that it is able to re-establish itself from the soil seed bank every alternate year also leads to a reduction in soil disturbance under this rotation. However the incorporation of clover into the pasture system showed no significant increase in either C or N stocks.

The effect of grazing intensity was noticeable, with WMc SB having a 40 % increase in total C over WMc, indicating that allowing a pasture to become better established before grazing has a significant increase in SOM accumulation. The treatment with the highest C stocks was WWWW under NT, with 30.6 MgC ha^{-1} to a depth of 40 cm. The lowest total C stocks was WCWL under CT, with 13.0 MgC ha^{-1} to a depth of 40 cm.

The C content decreased significantly with depth with the 20-40 cm profile having a 22 -77 % lower C content than the 0-5 cm profile. NT proved to have the greatest C accumulation in the topsoil, followed by MT. There was no significant difference between treatments below 30 cm showing that there is no influence below the zone of tillage. The greatest concentration of C was found in the top 10 cm of the soil, the region of greatest root density, but also the zone of greatest disturbance.

Vertical distribution of N followed a similar trend to C content where reduced tillage led to an accumulation of N in the topsoil, due to reduced disturbance. NT proved to have the greatest N accumulation out of the three tillage treatments. There was a reduction in N content of up to 63 % between the 0-5 cm and 30-40 cm profiles.

There was found to be an extremely low correlation (R^2= 0.027) between clay content and C content showing that the effects of tillage and crop rotation proved to be a major influence on the C sequestration in the soil.

Tillage was found to have a negligible effect on the MB-C in the soil across all depths. This is due to the mineral bound fraction being closely bound to the mineral surfaces in the soil and is generally inaccessible to the microbes activated by the soils disturbance. The most susceptible fraction to the effects of tillage is the oPOM-C fraction, as this is exposed by the destruction of the soil aggregates that protect them. Unfortunately this fraction was too small to observe independently and had to be studied together with the fPOM-C. Due to the young age of site A (8 years) the POM-C fraction was highly variable with no strong trends observed. Under WWWW there was no significant difference between CT and NT except at 10-20 cm where NT was 98% greater than CT. Under WMWM CT had 316% greater POM-C than NT. This could be accounted for by incorporation of medic residues prior to planting, while under NT they remain on the soil surface. This illustrates the short term variation of the POM-C fraction and the difficulty of long term studies. Site B showed no variation in the POM-C fraction. This was a more mature trial, in its 19th year, and could possibly illustrates that there is less of an influence on POM-C than was expected. It is expected to take between 10 to 30 years for SOM levels to stabilise with the introduction of conservation tillage (Alvaro-Fuentes et al. 2009; Sisti et al. 2004).

The majority of the soil C at the sites was found to be in the more stable MB-C form. This fraction is increased as microbes reduced POM into more stable forms that are then able to bind onto the mineral faces of the soil matrix and become resistant to further decomposition. It was expected that reduced tillage would lead to a greater proportion of C being in the POM-C form, however the variability observed in this fraction leaves no observable trend, with POM-C accounting for 14% to 45% of the total C in the topsoil, POM-C account for 30% of total C on average. There was a significant reduction in the contribution of POM-C to the total C in the subsoil averaging 14% of total C compared to 30% total C in the top soil. This is due to the subsoil being below the zone of tillage and not receiving a fresh incorporation of crop residues from the tillage action. The subsoil is dependent on the slower mixing of SOM by soil fauna and the downward movement of more complex SOM. CT had a larger proportion of POM-C in the subsoil than NT, with CT being 130% larger than NT below 10 cm. The mixing of fresh residues into the lower profile by the mouldboard plough, under CT would account for this increase. Crop rotation had an equally weak influence on the proportion of C in the two respective fractions, with no discernible trends observed.

The data gathered from this study, highlights the benefits of conservation agriculture through the usage of reduced tillage and high biomass producing leguminous pastures. WMWM and WMc SB under NT had excellent SOM accumulation and provide a diversified production system and would be recommended for this region for these reasons. WCWL performed poorly due to low quality inputs from canola and lupins, however canola is an important economic crop in the region and should not be discontinued. If it is to be cultivated, MT would be the recommended tillage treatment. Although WWWW showed positive influence on C and N stocks, the limitations of a monoculture system, in both financial diversification and pest management are too limiting for this rotation to be recommended. Reduced tillage does not only reduce the establishment costs of the crop but also has a positive effect on SOM accumulation and hopefully sustainable food production.

Unfortunately the study into SOM functional pools failed to produce conclusive data but has shown itself to be a useful indicator in other regions and warrants perseverance. A greater understanding of the labile fraction could lead to revised fertilisation recommendations through a greater understanding of plant available nutrients from the SOM.

5.2 Further studies

While Botha (2013) as well as Agenbag & Maree (1989) have conducted studies in this region on the effect of tillage on SOM this was the first study to examine the effects of tillage practices and crop rotation practices on the SOM fractions. Unfortunately the data proved less than conclusive. A further study on a more mature sight might yield greater insight into effects on this valuable indicator, the inclusion of a more representative natural sight would allow a greater understanding on the long term effects of these management practices on these sites. It is recommended to take a larger sample for determination of oPOM and fPOM samples as the oPOM was particularly difficult to isolate due to the small proportion of total C it contributed.

A more in depth study into the quantity and quality of the crop residues would allow for a better understanding of the rate of OM inclusion into the soil, with a particular focus on the root contribution and the effects of grazing intensity of the pastures.

This study showed the benefits of reduced tillage and the inclusion of pasture on the soil C and N content on shallow soil in a semi-arid region. Further studies on SOM in the region would allow for a data base to be compiled of the increased of available of nutrients in the soil due to labile SOM. This would allow for a revision of fertilizer application recommendations, taking into account the increase in nutrients due to management practices increasing labile SOM.

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Appendix A

Additional data

Table A-1. Exchangeable cations and pH values of trial site

Site	SAMPLE	H+ (cmol⁺ kg⁻¹)	Ca (cmol⁺ kg⁻¹)	Mg (cmol⁺ kg⁻¹)	Na (cmol⁺ kg⁻¹)	K (cmol⁺ kg⁻¹)	ECEC (cmol⁺ kg⁻¹)	pH
Site A	WWWW NT	0.02	2.76	0.75	0.45	0.74	4.73	5.23
	WWWW CT	0.01	2.48	0.57	1.38	0.58	5.03	5.36
	WMWM NT	0.02	3.29	0.87	0.44	0.84	5.46	4.98
	WMWM CT	0.01	3.09	0.52	0.44	0.58	4.65	5.39
	WCWL NT	0.02	2.19	0.55	0.55	0.56	3.86	5.00
	WCWL CT	0.01	2.30	0.59	0.58	0.52	4.00	5.30
Site B	WWWW	0.01	3.29	0.87	0.54	0.72	5.43	5.70
	WMc	0.02	3.67	0.68	0.52	0.73	5.62	5.92
	WMc SB	0.02	3.05	0.64	0.54	0.75	5.01	5.64

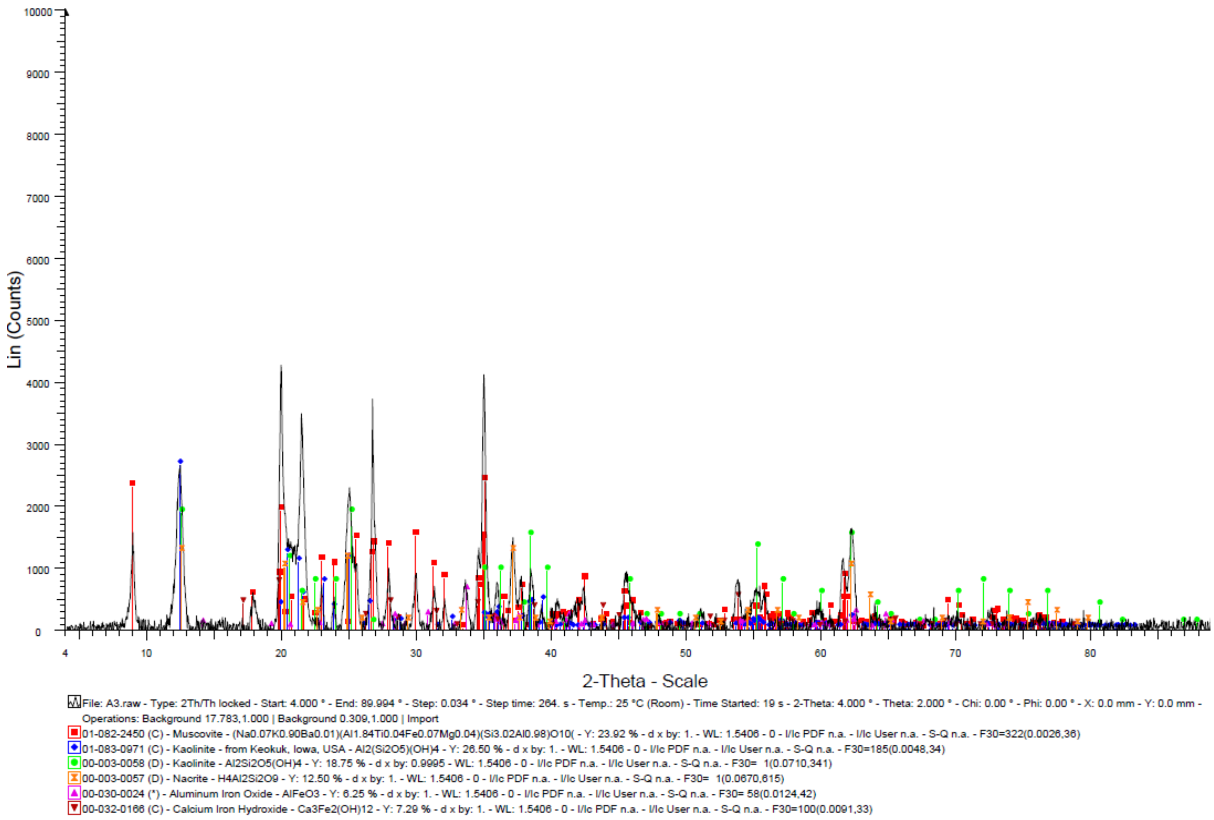

Figure A-1 X-ray diffract gram of selected subsoil clay fraction

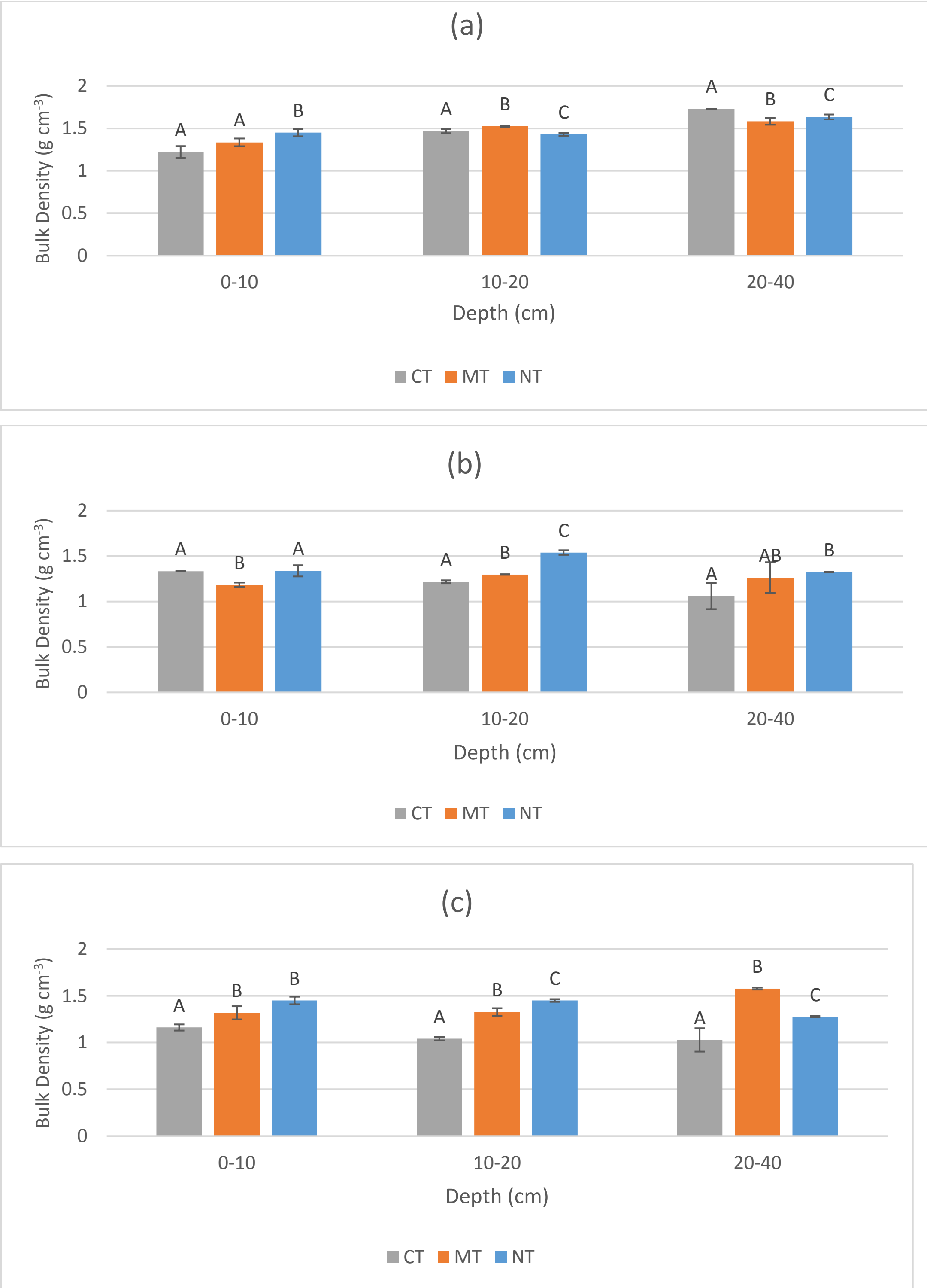

Figure A-2 Corrected bulk density of plots a) WWWW, b) WMWM, and c) WCWL at Site A

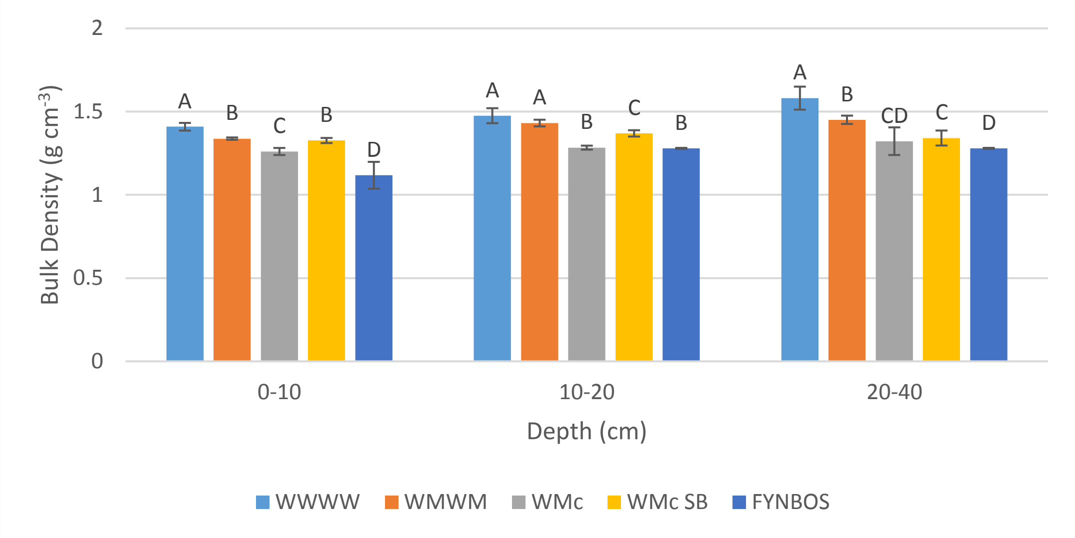

Figure A-3 Corrected bulk density at Site B

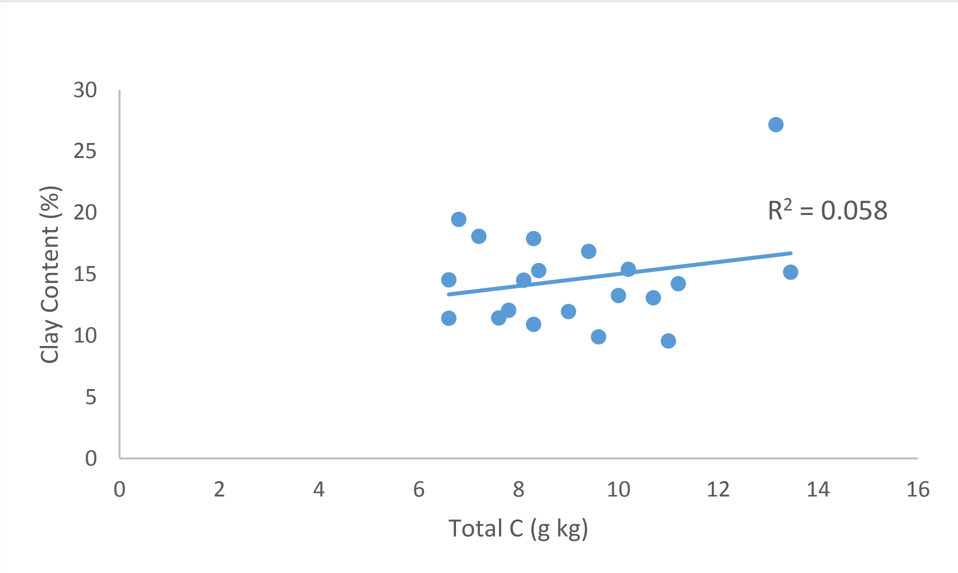

Figure A-4. The relationship between soil total C and clay content at all sites.

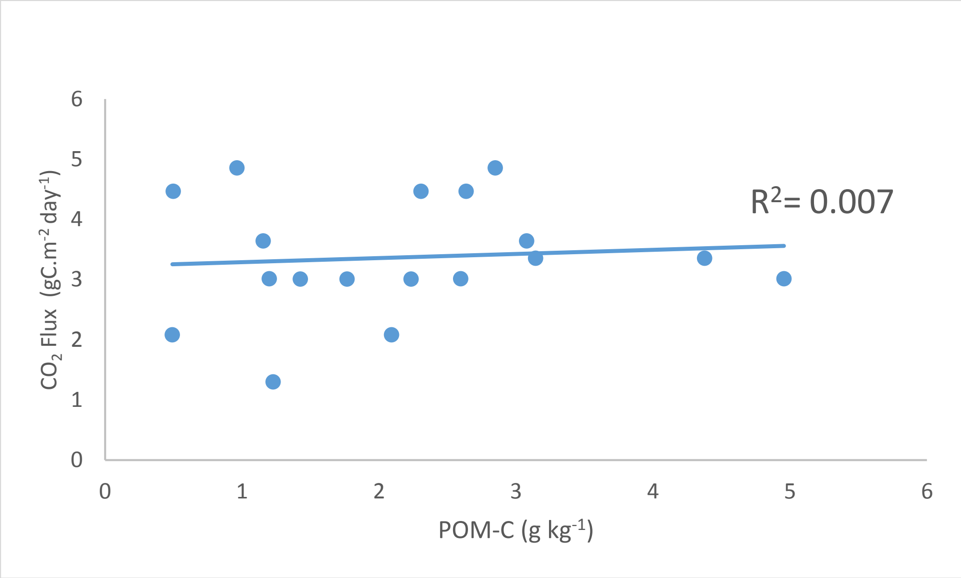

Figure A-5 Relationship between POM-C and soil CO_2 flux on all sites

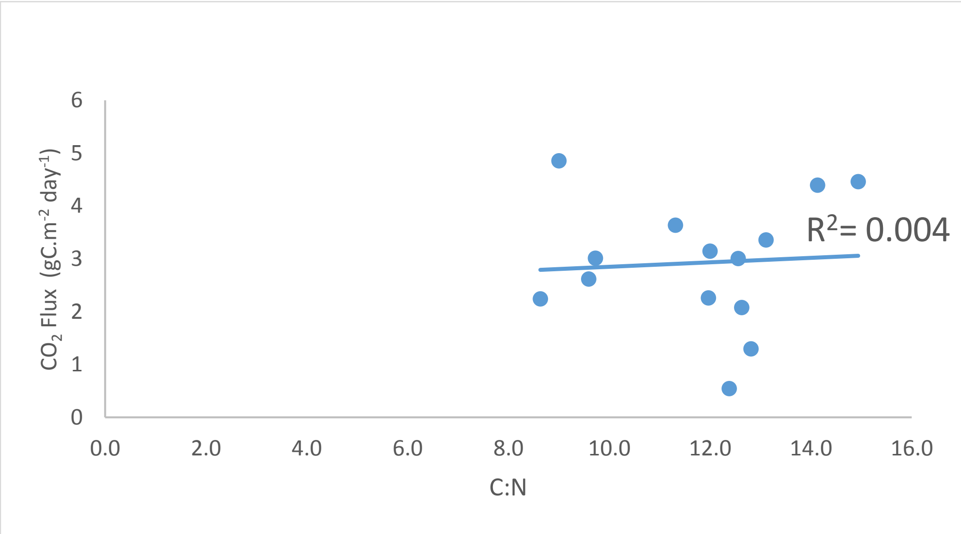

Figure A-6 Relationship between C:N of POM and CO_2 flux at all sites

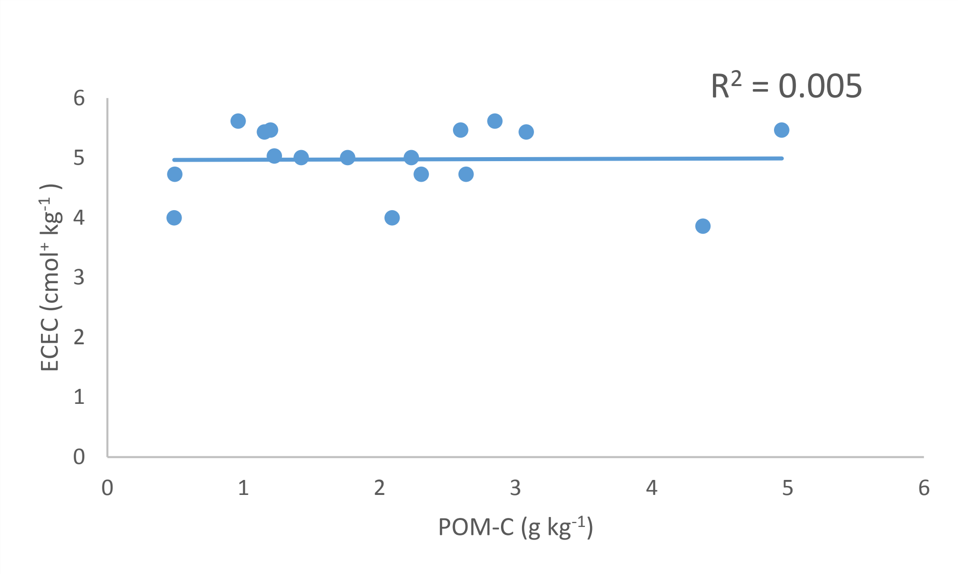

Figure A-7 Relationship between POM-C and ECEC

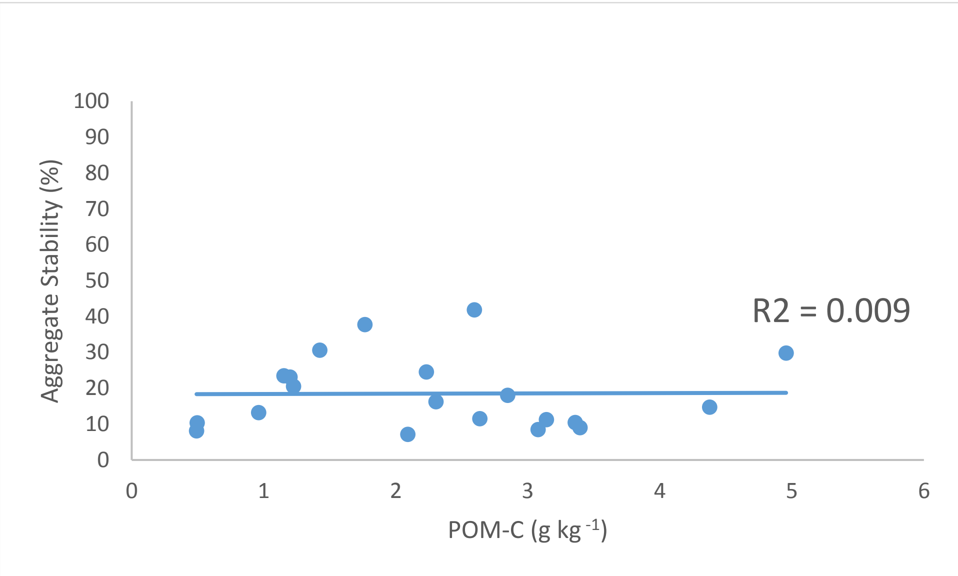

Figure A-8 Relationship between POM-C and aggregate stability

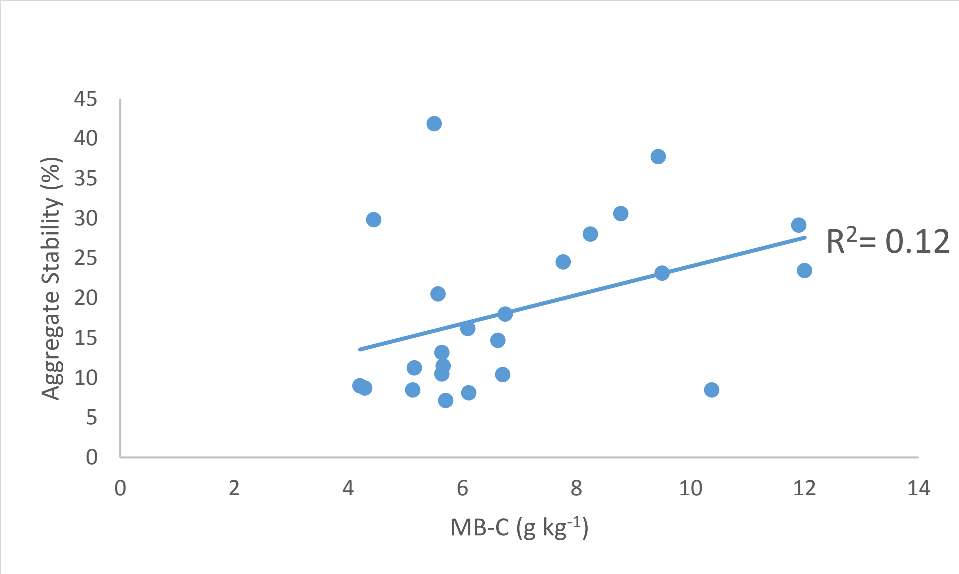

Figure A-9 Relationship between MB-C and aggregate stability