RESPONSE OF WHEAT (*TRITICUM AESTIVUM* L.), CANOLA (*BRASSICA NAPUS*) AND MEDIC (*MEDICAGO*) TO A ONCE-OFF MOULDBOARD AND DEEP TINE TILLAGE IN THE SWARTLAND SUB-REGION OF THE WESTERN CAPE

Johannes Geldenhuys van Zyl

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Supervisor: Dr Johan Labuschagne

Co-supervisor: Prof André Agenbag

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Declaration

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Abstract

The study was done (2014 = year 1 and 2015 = year 2) at the Langgewens Research Farm of the Western Cape Department of Agriculture near Moorreesburg (33°17'00" S, 18°42'00" E; 191 m). The aim of this study was to evaluate the effect of a once-off strategic tillage operation with a mouldboard plough or tine implement within different crop rotation systems on mineral-N levels of soils, soil moisture content, biomass production, chlorophyll content of leaves, stomatal conductance, light interception, initial and final root mass, reproductive components, seedling survival, weed seed bank, grain yield and grain quality of spring wheat *(Triticum aestivum L)* and canola (*Brassica napus).* Medic (*Medicago)* biomass and root mass was recorded during year 2.

The experimental design was a split-plot employed as a randomised complete block design. Three cropping sequences namely: medic/clover-wheat-medic/clover-wheat (McWMcW), wheat-lupin-wheat-canola (WLWC) and lupin-wheat-canola-wheat (LWCW) were allocated to main plots and replicated four times in year 1. The same plots were used during year 2 but due to crop rotation the cropping sequences were WMcWMc, WCWC and LWCW. The last letter in the sequence represents the crop on the field at the time of data collection. Tillage treatments were allocated to subplots namely: (a) continuous no-till (NT), soil left undisturbed until planting, (b) non-inversion tillage, with a tine (DT) to a depth of 400 mm and (c) inversion tillage with a mouldboard plough (MP) to a depth of 250 mm. The seed were planted with a tined no-till planter with knife openers. Plant and soil samples were collected every 30 days from a day before planting until harvesting and the relevant parameters determined. The study area was managed as a no-till system under the cropping systems mentioned above since 2000 and no stubble were removed from the research area since 2007.

Soil water content (SWC) and soil mineral nitrogen content (NH_4^+-N + NO_3^- -N) were determined one day before planting and every 30 days thereafter until harvesting. Soil water content in McWMcW was not influenced by tillage at all sampling dates during year 1. Significant differences were however recorded in LWCW with MP and DT that resulted in an increase in SWC during June and July of year 1. During year 2, NT resulted in higher (P=0.05) SWC 90 days after planting in LWCW compared to MP and DT. Soil water content was not influenced by tillage in either WMcWMc or WLWC for both years 1 and 2, 90 days after planting.

Soil mineral nitrogen was not influenced by tillage in McWMcW and LWCW during year 1. There were however significant differences recorded during year 2 with MP and DT increasing mineral nitrogen content 60 and 120 days after planting in LWCW. Tillage did not influence mineral nitrogen content during year 1 in WLWC, however, in year 2 mineral nitrogen content

was significantly increased. Tillage treatments did not resulted in significant differences in mineral nitrogen content during year 2 in WMcWMc. Tillage treatments resulted in a higher amount of mineral nitrogen in McWMcW compared to the other sequences during year 1.

Glomalin content is an indicator of mycorrhizal growth. During year 1 DT significantly increased the glomalin content. It is concluded that a disruptive effect of DT and MP did not have a negative effect on SWC, mineral nitrogen or glomalin content.

During year 1 no significant differences (P=0.05) were recorded for the effect of tillage on light interception (LI), chlorophyll content (CC), stomatal conductance (SC) and initial root mass (IRM) in LWCW and McWMcW. Final root mass (FRM) in LWCW was significantly higher in NT in the 200 – 300 mm depth compared to MP. Tillage did not influence LI, SC or FRD in WLWC during year 1. There were however significant differences in CC between tillage practices in WLWC rotation. Deep tine resulted in significantly lower flag leaf CC compared to MP. Biomass production (BMP) was significantly higher in MP compared to NT for WLWC. IRM was significantly higher in DT compared to MP and NT for WLWC. During year 2 no significant differences were recorded for the effect of tillage on LI, CC, BMP and FRM in LWCW. DT however resulted in a significantly higher IRM compared to MP in LWCW. Tillage did not influence FRM in WLWC during year 2. MP and NT however resulted in significantly higher LI compared to DT in the beginning of the season. Leaf CC was significantly higher in MP, 60 and 120 days after planting compared to NT and DT in WLWC. MP also significantly increased BMP in WLWC compared to NT. The IRM for WLWC increased significantly with DT compared to NT. During year 2 no significant differences were recorded for the effect of tillage on BMP in McWMcW. NT had a significantly higher IRM compared to MP for WMcWMc. The final root mass also showed significant differences in the 100 - 200 mm range. DT significantly increased FRM in this range compared to MP.

During year 1 no significant differences between tillage practices were recorded for seedling emergence and survival rates, ear-bearing tillers per square metre (ear-bearing tillers per m^2), spikelets per ear, kernels per ear, thousand kernel mass (TKM), grain yield, grain protein and hectolitre mass (hl). Significant differences were recorded between crop rotations as grain protein content of wheat was higher in McWMcW compared to LWCW. Canola seedling emergence and survival, number of pods, seeds per pod, seed yield and TKM was not influenced by tillage in year 1. No-till (NT) however resulted in significantly higher seed oil content than MP. During year 2 wheat spikelets per ear and kernels per ear were not influenced by tillage. No-till however, resulted in significantly higher wheat seedling emergence and survival rates, ear-bearing tillers per m^2, grain yield, grain mass, TKM and HI compared to MP. In comparison with DT, NT significantly increased the amount of ear-bearing tillers per m^2 and grain yield. Mouldboard plough and DT however showed a significant increase in protein content compared to NT. There were no significant differences for the effect of tillage on canola seedling emergence and survival, seeds per pod, seed yield, TKM and percentage oil for year 2. DT and MP however had a significantly higher number of pods per plant compared to NT. Medic biomass production was not influenced by tillage during year 2. Strategic tillage resulted in positive and negative effects regarding reproductive components.

Soil samples taken before tillage treatments were applied showed that there were no significant differences in the number of weeds (*Lolium multiflorum*, *Polygonum aviculare* and *Vicia spp*) that germinated between subplots. Data recorded in the field during year 1 showed a significant reduction in the number of *Lolium multiflorum* with a strategic MP tillage compared to NT. During year 2 the number of seeds that germinated under shade net showed that MP tillage the previous year significantly reduced the number of *Lolium multiflorum* seedlings. These results were also recorded in the field study which showed a reduction in the number of seeds that germinated the second year after tillage. During year 2, shade net trials showed that MP significantly reduced the number of *Polygonum aviculare* compared to DT and NT. Tillage had no significant effect on the number of *Vicia spp* and on the number of broadleaf weed species recorded during year 1 and year 2. MP however, reduced the number of unidentifiable weed species during year 1 and year 2. Crop rotation with canola and medic reduced the number of weed plants recorded throughout this study.

The conclusion is that a strategic tillage operation can have positive effects on crop production, but the tillage operation has to be economically viable and improve yield without damaging the environment.

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List of Abbreviations

B	Boron
BMP	Biomass production
°C	Degrees Celsius
C	Carbon
CC	Chlorophyll content
CA	Conservation Agriculture
Ca	Calcium
cm	Centimetre
cm^2	Square centimetre
CT	Conventional till
Cu	Copper
DT	Deep tine
FRM	Final root mass
g	Gram
g^{-1}	Per gram
ha	Hectare
ha^{-1}	Per hectare
hl	Hectolitre mass
IRM	Initial root mass
K	Potassium
kg	Kilogram
kg^{-1}	Per kilogram
kg hl^{-1}	Kilogram per hectolitre
LAI	Leaf area index
LI	Light interception
LWCW	lupin-wheat-canola-wheat
m	Metre
m^{-1}	Per metre
m^2	Square metre
McWMcW	medic/clover-wheat-medic/clover-wheat
Mg	Magnesium
mg	Milligram
mm	Millimetre
Mn	Manganese
MP	Mouldboard plough

N	Nitrogen
Na	Sodium
NH_4^+	Ammonium
NO_3^-	Nitrate
NT	No-till
OM	Organic matter
P	Phosphorus
S	Sulphur
s	seconds
SC	Stomatal conductance
SPAD	Soil plant analysis development
SWC	Soil water content
TKM	Thousand kernels mass
TSM	Thousand seed mass
WLWC	wheat-lupin-wheat-canola
Zn	Zinc

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Chapter 1

Introduction

1.1. Background

Agriculture is one of the main financial contributors to the South African economy (Anon., 2012a). A major activity of agriculture is grain production which is bound to certain regions of South Africa because of the climate and soil quality (Taylor *et al.,* 2012). The Western Cape is one of South Africa's major wheat producing regions and represents 37% of wheat production in South Africa (Anon., 2012a). This study was performed in the Swartland which is a sub-region of the Western Cape and produces wheat, canola and medics. According to Anon (2012), the Swartland has a typical Mediterranean climate and most of the rain occurs during the winter. The long, wet winters and relatively high rainfall makes the region suitable to grow wheat, canola and medics annually (Anon., 2012a). The rainfall during the growing season (April - October) is approximately 300-500 mm with a long-term average of 464.5 mm (Maali & Agenbag, 2006). Soils in the Swartland originates mainly from shales and are shallow and stony with weak structured A horizons (Maali & Agenbag, 2006). The soil is vulnerable to the effects of erosion and the loss of organic carbon (Hobbs *et al.,* 2008). The soil is low in organic carbon content mainly because of the warm, dry summers (Anon., 2012b). In an effort to reduce the negative impact of farming activities on the soil and environment, large proportions of the grain producing areas of the Western Cape have converted to conservation agriculture during the nineties (Anon., 2012a). No-till forms part of conservation agriculture, apart from the numerous benefits (Taylor *et al.,* 2012).

Triplett & Dick (2008), highlight the importance of the effects of tillage, sowing techniques and seedbed preparation on crop establishment as any changes in these factors can be costly for growers and the consequences are not easy to predict. Grain farmers therefore have to apply sound, scientific farming techniques, which reflect a balance between soil preparation activities, conservation agriculture and financial viability.

1.2. Problem statement

The high prices of farm land together with the high input and running costs poses an increasing challenge to wheat, canola and medic farms (Hobbs & Gupta, 2003). In order to maintain highly productive grain farming and combat the increasing costs of herbicides, fertiliser, machinery and labour which have reduced profit margins, farmers and researchers are forced to develop new strategies to increase yield (Anon., 2012a).

Different tillage practices have been used since the beginning of commercial farming in the Swartland region. Conventional tillage (CT) leaves soil vulnerable to the effects of erosion and the loss of organic carbon (Hobbs *et al.,* 2008). Soil losses are one of the critical issues in sustainable agricultural production with increased significance in the future (Anon., 2012b). The introduction of conservation agriculture (CA) not only reduced the negative effects of erosion and loss of organic carbon, but crop yield also improved (Montgomery, 2007). No-till, under normal circumstances resulted in increased organic matter, water infiltration and improved aggregate stability in the top 5 cm of the profile (Quincke *et al.*, 2007).

Contrary to numerous benefits, major challenges consequented from conservation agriculture (CA) for example: the stratification of certain elements; effective weed control and an increase in pests, which limited the adoption of conservation tillage systems (Thomas *et al.,* 2007). Continuous no-till resulted in less favourable soil conditions such as the stratification of nutrients and an increase in bulk density (Taylor *et al.,* 2012). Taylor *et al.,* (2012) also found that no-till in the 50-350 mm soil layer in a clay loam, increased penetration resistance with a build-up of organic carbon in the top 50 mm of the soil profile. In a study by Katsvairo *et al.,* (2002), on maize-soybean systems in silt loam soils, a higher water infiltration rate was reported with mouldboard tillage and chisel tillage compared to no-till. There is evidence that crop residues may also serve as habitat for pests and diseases that help negatively influence seedling survival and crop performance (Tebruègge *et al.,* 1991). The increase in residue cover, especially where no livestock is allowed to utilize the stubble or fodder, may also interfere with the planting process (Wilhelm & Mielke, 1988).

1.3. Aim

This study was aimed to explore, some of the negative effects of long term no-till practices. A single deep tine and mouldboard plough tillage practice were implemented on no-till fields to evaluate crop performance. The study was performed in the Swartland region of the Western Cape and data was collected over a period of two years. Data obtained from this study will serve to help make informed decisions and recommendations on the effect of deep tine tillage and mouldboard tillage as a management tool in wheat, canola and medic. The study acknowledges the positive effects of the no-tillage practice as part of conservation agriculture and strives to promote scientifically sound farming practices with optimum crop yield.

1.4. Literature review

The main reasons of tillage are for mixing fertiliser into the soil, seedbed preparation, weed control, soil loosening and management of crop residues (Hobbs *et al.,* 2008). The different methods of tillage influence the soil's physical, biological and chemical properties (Hillel, 1998) and it influences the amount of available nutrients, soil water and thus effect plant growth (Tebruègge *et al.,* 1991). Hillel (1998), reported on the effects of environmental management of cropped fields, identifying soil-water balance as a determinant for crop performance. Parameters such as runoff, drainage, deep percolation and the evaporation from the soil surface can be calculated in order to estimate the soil-water balance (Hillel, 1998). Different management practices can be implemented to improve water storage for example tillage, residue management, fertilisation and crop rotation (Wilhelm & Mielke, 1988).

The production of wheat, canola and medic in the Swartland region is mostly under rain fed conditions. The performance of the plant is largely influenced by the amount of available soil water (Agenbag & Maree, 1991). Soils in these areas have relatively low water storage capacity and seasonal rainfall has an influence on wheat yield and wheat quality (Wilhelm & Mielke, 1988). Conservation agriculture increases water availability for crops by reducing soil water evaporation. This will allow better growth of root systems by preventing soil compaction (Lithourgidis *et al.,* 2006). The availability of water to the plant is a principle factor that influence crop performance and dry mass production (Garabet *et al.,* 1998).

Nitrogen is an essential plant nutrient and is the mineral element required in the largest quantities for crop development and growth (Govaerts *et al.,* 2007). The amount of nitrogen uptake by the plant is linked to different growth stages, thus, the more available nitrogen to the plant at these critical times, the better the plant could perform (van Biljon, 1987). Nitrogen uptake depends on soil mineral nitrogen availability and root distribution (Gastal & Lemaire, 2002). The use of crop rotation systems, altering wheat with lupin/medic has shown an increase in yields of wheat, compared to wheat monoculture. This higher yield of wheat in rotation with nitrogen-binding legume may be a result of a higher amount of available nitrogen content in the soil (Lopez-Bellido *et al.,* 2000). Increased available nitrogen throughout the growing season of wheat will benefit the quality of the yield (Chan & Heenan, 1996). Stockfish *et al.,* (1999) reported that a strategic tillage operation in minimum-tillage system caused the degradation of organic matter that had been accumulated for 20 years, but slightly increased plant available nitrogen in the soil profile. Periodic ploughing should redistribute soil mineral nitrogen and other nutrients layered by NT (Gastal & Lemaire, 2002). Tarkalson *et al.,* (2012) however reported that tillage resulted in decreased available nitrogen in sugar beet which contributed to a decrease in growth rate as well as crop yields specific in sugar beets. As reported by Chan and Heenan (1996), Galantini *et al.,* (2000) and Maali & Agenbag (2006). Soil disturbance through tillage, may therefore reduce the positive effect of crop rotation - whereby N-binding legumes are included in different annual cycles to increase the mineral nitrogen content in the soil. According to López-Bellido, *et al*. (2007), the application of nitrogen, when water is sufficient, will improve the crop yield and protein content of wheat.

Maali & Agenbag (2006) reported a lower protein content in wheat which was grown after canola, compared to the protein content of wheat on soil after peas. The use of crop rotation systems with canola and lupin has shown an increase in yields of wheat compared to wheat monoculture (Chan & Heenan 1996). More available nitrogen throughout the growing season of wheat will benefit the quality of the yield (Galantini *et al.,* 2000).

Rillig *et al.,* (2003) reported that glomalin content could be used as a sensitive indicator of soil C changes produced by land use. The hyphae of all members of arbuscular mycorrhizal fungi produce glomalin (Wright & Upadyaya, 1996). Soils that are more resistant to erosive forces (well-aggregated soils) with better water infiltration and aeration will increase heterogeneous protected C microhabitats which enhances microbial activity (Palma *et al.,* 2000) and diversity (Lupwayi *et al.,* 1998).

Energy for photosynthesis is provided by solar radiation interception by the plant (Rieger *et al.,* 2008). Crop productivity is determined by the ability of foliage to capture photosynthetically active radiation (PAR), the efficiency with which biomass is produced and the accumulation of dry matter in competitive sinks especially during grain filling (Hemmat & Eskandari, 2006). Leaf area index (LAI) is the ratio of green leaves to the ground area and is used as a parameter to characterise a crop's ability to capture PAR (Hulugalle *et al.,* 2005). Optimum LAI must be established as early as possible, through expansion of leaf area and by maintaining green leaf area for continuous and abundant dry matter production throughout the growing season. Environmental stresses and ageing of leaves will cause a reduction in dry matter production (Yeo *et al.,* 1991). An increase in leaf area can however increase water loss through transpiration and subsequently result in water stress during anthesis and grain filling during relatively dry years (Hulugalle *et al.,* 2005).

The rate of photosynthesis is associated with the amount of leaf water; a deficit in the amount of leaf water will contribute to stomatal closure (Sperry *et al.,* 2002). The photosynthesis rate can also be affected by a smaller leaf area which will give an indication of leaf inhibition and increased abscission (Kozlowski & Pallardy, 1997). Increased mechanical resistance of soil can influence water uptake in plants and will contribute to stomatal closure (Caird *et al.,* 2007).

Photosynthetic capacity can be measured by the amount of biomass produced. Growth conditions have a direct impact on grain yield, and by measuring biomass of plants the effects of the different growth conditions can be studied (Alizadeh & Allameh, 2015). High biomass production ensures better competition with weeds (Balyan *et al.,* 1991), however it may create a favourable microclimate which will cause plants to be more susceptible to diseases (Olesen *et al.,* 2004). Increase in biomass production are associated with taller stems, larger leaves that stay greener for longer and a higher amount of ear-bearing tillers per m^2 (Borghi, 1999) and an increase in water use of plants (Hulugalle *et al.,* 2005).

Soil physical, chemical and biological characteristics will be influenced by the degree of soil disturbance and these changes influence vegetative development (Montgomery, 2007). Light interception (LI) increase with incorporation of tillage and lower LI resulted in a smaller plant population (Uppal & Gooding 2013).

Soil structure and organic carbon are influenced by tillage; this will have an effect on the amount of plant available water. Plant available water is the principle factor that influence crop performance and dry mass production (Garabet *et al.,* 1998).Alizadeh and Allameh (2015) reported that tillage method had a significant effect on plant height. The maximum height was recorded with MP. Root biomass and penetration increased deeper into soil because of tillage practices and produced considerably more vegetative growth (Jamshidian & Khajehpour, 1999). Initial canola root growth is sensitive to poor seedbed establishment, this will decrease the biomass of roots effecting yield (Fooladivand *et al.,* 2009). Seedling emergence may be slow due to greater root penetration resistance of drier soil (Jamshidian & Khajehpour, 1999).

Braunack & Dexter (1989) reported an increase in the number of seedlings that germinated in plots that received tillage treatment. Rieger *et al.,* (2008) supported these findings and reported that lower numbers of seedlings were observed in no-till treatments compared to conventional treatments. Alizadeh and Allameh (2015) found that seedling emergence and survival were positively influenced by an increase in seed soil contact found in tilled plots. Shallow tillage with a tine implement increased the amount of crop residues on and in the surface layers resulting in an improved seedling survival rate of medic (Mannering *et al.,* 1975). Hemmat and Eskandari (2005) however recorded significantly higher seedling survival rates with no-till treatments. By increasing the sowing depth of medic from 10 to 50 mm, Carter and Challis (1987) reported a decrease in seedling emergence of 5% to 80%. Kotzé *et al.*, (1997) reported that deep-disc and mouldboard plough treatments removed between 40% and 68% of seeds respectively from the soil surface and placed them deeper than 150 mm below the surface which influenced seedling survival negatively.

Tillage may influence soil characteristics in the root zone through altering soil porosity and strength (Lipiec *et al.*, 2006), -aggregation (Keller *et al.*, 2007), -water content (Osunbitan *et al.*, 2005), -soil temperature (Dardanelli *et al.*, 1994) and -aeration (Shaxson, 2003). The use of tillage to prepare seedbeds and the subsequent benefits are well documented. However, the degree of soil disturbance and soil physical quality that is required to ensure good crop establishment received less attention (Braunack & Dexter, 1989). As a result of tillage root beds may therefore differ in physical properties depending on the size of the aggregates, thus influencing the suitability of a seedbed for germination, emergence and root development, by influencing factors such as intra- and inter-aggregate aeration (Liebig *et al*., 2004). Swanepoel *et al*., (2016) evaluated once-off tillage of previously no-tillage pastures in the southern Cape. They found that most changes in soil quality indicators as a result of soil tillage were observed shortly after tillage and occurred mostly only in the shallow soil layers. Few of these effects were still visible one year after tillage. Microbiological indicators changed most in response to tillage, but unlike the chemical and physical indicators, microbial soil indicators did not influence production directly.

Heer and Krenzer (1989) found that no-till had the potential to increase the soil water content in continuous wheat production. However, after two years of the three year study, wheat yield obtained with a conventional tillage system was significantly higher than those obtained with a no-till system. After conducting a four year winter wheat study, Davidson and Santelmann (1973) had similar results, and reported that average grain yields were lower in the minimum or no-till treatments than in the clean or ploughed treatments and concluded that the grain yield was inversely related to the amount of straw residue on the soil surface before planting. Bauer and Black (1992) also reported that grain yields were consistently higher in mouldboard ploughed treatments compared to no-till plots. Yield decreases as a result of preserving mulches related to the primary causes of root diseases such as take-all, *Pythium* root rot and *Rhizoctonia* root rot (Cook & Veseth, 1991). Surface residue provides an environment for numerous microbes that can include some wheat pathogens such as tan spot which hamper yield (Williams & Goldman, 1985). Some microbes produce secondary compounds that may be toxic to wheat in wetter regions. Contributing to higher yields is the use of more effective chemical weed control as well as more intensive tillage systems. Increased weed pressure would be expected to result in increased competition and lower wheat yields (Cast, 1987).

Reproductive components such as the number of ear-bearing tillers, spikelets per ear, number of kernels per spikelet and mean kernel mass can be influenced by tillage (Norwood, 2000). Hemmat and Eskandari (2005) reported that tillage reduced the amount of ears per square metre significantly. Previous studies concluded that tillage had no significant effect on either the number of spikelets per ear (van Biljon, 1987), or the mean kernel mass (Rieger *et al.,* 2008). Significant differences were however reported between cropping sequences which included a legume crop. Lopez-Bellido *et al.,* (2000) and Alijani *et al.,* (2012) recorded an increase in reproductive components when a N-binding legume crop was included in rotation with wheat and corn respectively.

Less intensive cultivation practices have become more popular in the past 10 years (Llewellyn *et al.,* 2012). These cultivation practices consist of reduced, minimum- or no-till, and are known to save time and money (Triplett & Dick, 2008). Different degrees of soil disturbance may have a major impact on the composition of weed species and their competiveness with commercial crops (Thomas *et al.,* 2007). The knowledge of weed composition shifts is important for effective weed control, which is a major problem in no-till practices (Kirkegaard *et al.,* 2014). Due to reduced tillage and soil disturbance, weeds can become an important variable in crop production, both ecologically and economically. Production practices such as the tillage system, herbicide use and inner row cultivation reduces weeds (and weed seed bank) density and distribution (Ma *et al.,* 2009).

However, studies by Swanton *et al.,* (1993) proved that tillage had no effect on weed flora, instead changes in weed communities were influenced by location and year (Derksen *et al.,* 1993). Chauhan & Preston (2006) found that no-till increased the total number of weeds compared to minimum and conventional tillage. Herbicide application and inner row cultivation reduced the total weed seed numbers (Schreiber, 1992). Seeds were vertically distributed by tillage (McGillion & Storrie, 2006).

Nokes *et al.,* (1997) concluded that rotating crops can help to prevent the build-up of problem weeds. The reservoir of various weed species seeds (seed bank) in the soil can exceed billions per hectare. Under favourable conditions many of these seeds remain viable to germinate (Dang *et al.,* 2014). Tillage can promote the amount of weed seeds that geminate, because it creates a favoured seedbed for weeds as well as crops (Chauhan *et al.,* 2006). Many researchers (Dang *et al.,* 2014 and Kirkegaard *et al.,* 2014) have reported that pre-plant tillage is necessary for weed control and that weeds can be effectively controlled by the use of appropriate herbicides as well as strategic tillage practises.

Different tillage practices had more influence on weed populations than nutrient source (McCloskey *et al.,* 1996). Many weed species found in conventional tillage, rely only on a single regenerative strategy. This strategy consists of germination from a persistent, large soil seed bank. These seed banks are persistent because most seeds are buried by mouldboard ploughing (Ball *et al*., 1999). Seeds in conventional tillage will remain viable and can germinate in subsequent years when returned to a suitable depth by tillage. Seeds in undisturbed soil remain on or near the surface with conservation tillage and can germinate quicker and thus be controlled more effectively (Mohler, 1993). Weed control aboveground may cause seeds present in the upper layer of soil to diminish within a few years (Jan & Faivre-Dupaigre, 1977). Seed bank species relying on regeneration may become less of a problem in conservation tillage systems (Clements *et al.,* 1994).

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Chapter 2

Material and methods

The influence of a strategic once-off tillage (mouldboard plough and deep tine) operation on the response of wheat, canola and medic in the Swartland area of the Western Cape was studied.

2.1. Experimental layout and treatments

The experimental layout was a randomised complete block design with a split-plot treatment replicated four times (Snedecor & Cochran, 1967). Tillage practices namely; continues no-till (NT), deep tine to depth of 400 mm (DT) and mouldboard plough (MP) were applied to sub-plots in year 1 (Table 2.1).

Tillage treatments was only applied to sub-plots before planting during 2014 (year 1) and not during 2015 (year 2) (Table 2.1). Data was collected on the same sub-plots during both years, to study the effect of a strategic once-off tillage over a two year time frame.

The influence of a once-off tillage operation was tested on two crop rotation systems allocated to main plots namely: lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) (Table 2.1). During year 1 crop rotation systems were in three different sequences (last symbol in sequence represents crop measured) namely: lupin-wheat-canola-wheat (LWCW), wheat-lupin-wheat-canola (WLWC) and medic/clover-wheat-medic/clover-wheat (McWMcW) (Table 2.1). During year 2 crop rotation systems were in three different sequences (last symbol in sequence represents crop measured) namely: wheat-lupin-wheat-canola (WLWC), lupin-wheat-canola-wheat (LWCW) and wheat-medic/clover-wheat-medic/clover (WMcWMc) (Table 2.1). The study area was managed as a no-till system under the cropping systems mentioned above since 2000 and no stubble were removed from the research area since 2007.

The experimental gross plot size was 60 m x 15 m. Each plot was divided into 3 sub-plots, 60 m x 5 m of which one half (30 m x 5 m) was used for destructive sampling (soil and root sampling). The remaining 30 m x 5 m was used to evaluate crop growth (non-destructive), yield and grain quality.

Table 2.1: Table illustrating tillage practices and crop rotation during 2014 (year 1) and 2015 (year 2).

Trial	2014	2015
Year	1	2
Tillage	Once-off tillage treatments	No tillage treatments
Tillage practice	MP	NT
	DT	NT
	NT (Control)	NT
Cropping sequences	McWMcW	WMcWMc
	LWCW	WLWC
	WLWC	LWCW
Crop on field	wheat	medic/clover
	wheat	canola
	canola	wheat

wheat-lupin-wheat-canola (WLWC), lupin-wheat-canola-wheat (LWCW), medic/clover-wheat-medic/clover-wheat (McWMcW), no-till (NT), deep tine (DT), mouldboard plough (MP)

2.2. Locality

This research was done during 2014 (year 1) and 2015 (year 2) at the Langgewens Research Farm, near Moorreesburg (33°17’00” S, 18°42’00” E; 191 meters above sea level) in the Western Cape Province of South Africa.

2.3. Soil

Soil at the Langgewens Research Farm derived mainly from Malmesbury and Bokkeveld shales. These are shallow sandy-loam soils with a clay content of 14.9 - 16.4 % (Table 2.2). Effective rooting depth is estimated to vary between 30 - 90 cm. Shale layers cause vertical drainage to be poor giving rise to rapid saturation of low-lying areas. High stone content and relatively shallow soil result in low water retention capacity. These soils have a high production potential for wheat, canola and medic yields in the Swartland sub-region (Anon. 2012a).

Table 2.2: Particle size composition in cropping sequences during year 1 in the 0-300 mm soil depth before tillage was applied at Langgewens (adapted from Leygonie, 2015).

Crop rotation					
	Coarse sand:	Medium sand:	Fine sand:	Silt:	Clay:
	2 – 0.5 mm	0.5 – 0.25 mm	0.25 – 0.106 mm	0.05 – 0.002 mm	< 0.002 mm
WLWC	17.6	4.9	51.9	10.6	15.0
LWCW	18.9	5.7	51.1	8.9	15.4
McWMcW	22.7	5.6	47.7	8.9	15.3

wheat-lupin-wheat-canola (WLWC), lupin-wheat-canola-wheat (LWCW), medic/clover-wheat-medic/clover-wheat (McWMcW), no-till (NT)

Tables 2.3 and 2.4 summarise the chemical composition of the trial site before tillage was applied (adapted from Leygonie, 2015). Except for relatively low sulphur (S) and boron (B) values, all mineral nutrients were at levels that ensured high crop productivity. In order to ensure optimum availability of sulphur and boron, these elements were included in the fertiliser mixture at seeding as well as the use of sulphur containing nitrogen source.

Table 2.3: The macro element (P, Ca, Mg, K, Na and S) and pH in cropping sequences during year 1 in the 0-300 mm soil depth before tillage was applied (adopted from Leygonie, 2015).

Crop rotation	**pH (KCl)**	**P** (mg kg^{-1})	**Ca** (mg kg^{-1})	**Mg** (mg kg^{-1})	**K** (mg kg^{-1})	**Na** (mg kg^{-1})	**S** (mg kg^{-1})
WLWC	4.61	51	1056.9	315.9	153.37	24.50	5.22
LWCW	5.23	55	951.6	269.1	147.90	27.12	9.50
McWMcW	5.16	69	1275.3	409.5	209.93	24.12	4.86

wheat-lupin-wheat-canola (WLWC), lupin-wheat-canola-wheat (LWCW), medic/clover-wheat-medic/clover-wheat (McWMcW), no-till (NT), mouldboard plough (MP), deep tine(DT)

Table 2.4: The micro element (Cu, Zn, Mn and B) analysis in cropping sequences during year 1 in the 0-300 mm soil depth before tillage was applied at Langgewens (adopted from Leygonie, 2015).

Crop rotation	**Cu**	**Zn**	**Mn**	**B**
	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})	(mg kg^{-1})
WLWC	1.36	7.25	158.04	0.22
LWCW	1.25	4.38	163.79	0.45
McWMcW	1.37	7.48	157.44	0.24

wheat-lupin-wheat-canola (WLWC), lupin-wheat-canola-wheat (LWCW), medic/clover-wheat-medic/clover-wheat (McWMcW)

2.4. Climate

The climate at Langgewens is a typical Mediterranean climate with a long-term average (15 years) of 464.5 mm of rain per year. The total monthly rainfall recorded for year 1 and year 2 is presented in Figure 2.1. The total rainfall recorded for year 1 and year 2 growing seasons (April-October) were 296 mm and 175 mm respectively. In season rainfall was 31% and 55% lower than the long-term average (387.79 mm) in year 1 and year 2 respectively (ARC-ISCW, 2015).

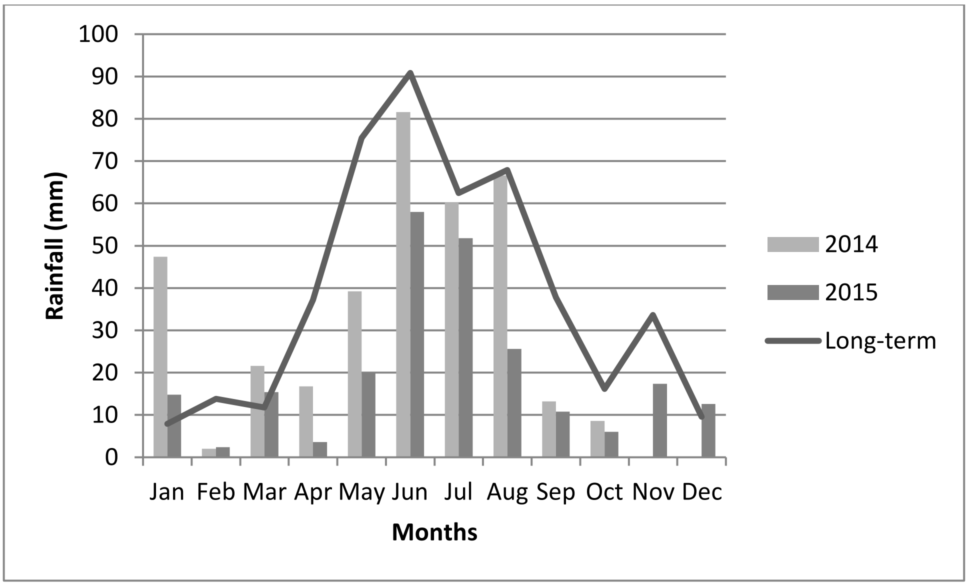

Figure 2.1: The long-term average rainfall compared to 2014 (year 1) and 2015 (year 2) rainfall at the Langgewens Research Farm (ARC-ISCW, 2015).

Rainfall recorded for both 2014 (year 1) and 2015 (year 2) in April, May, June and July were below average. This could have had an effect on wheat tiller survival rate. Anthesis (flowering) and seed set of both wheat and canola could have been restricted as a result of the relatively low rainfall recorded in September and October, especially in year 2.

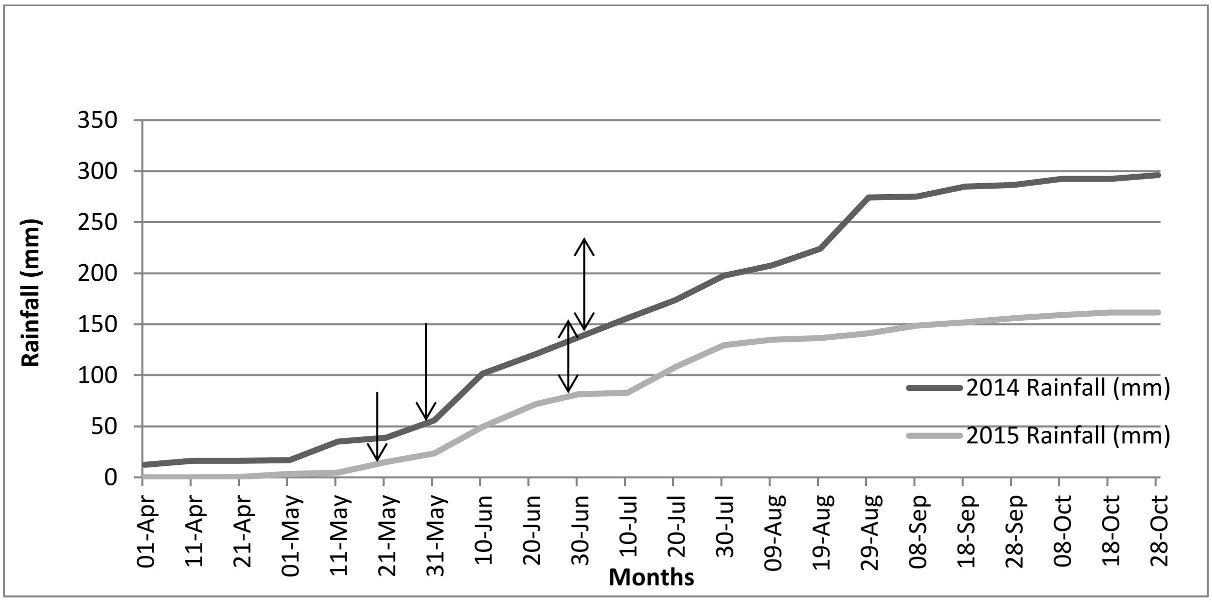

Figure 2.2: Accumulation of rainfall during 2014 (year 1) and 2015 (year 2) growing season (1st of April to 31st of October) on the Langgewens Research Farm. (Planting date: ↓; Top dressing: ↕) (ARC-ISCW, 2015).

Once-off tillage treatments were done on 29 May 2014. During the year 1 and year 2 growing seasons 38.8 mm and 15.2 mm rain was received before planting (30 May 2014 and 20 May 2015 respectively) (Figure 2.2). Ten days after planting wheat and canola plots received a further 20 mm (year 1) and 8.4 mm (year 2) of rain. Top dressing was applied on 30 June 2014 and 28 June 2015 with relatively low follow-up rainfall.

Mean daily maximum temperatures for 2014 (year 1) and 2015 (year 2) growing seasons remained between 10 °C and 20 °C from planting until early October, followed by an increase towards harvesting (Figure 2.3 and Figure 2.4).

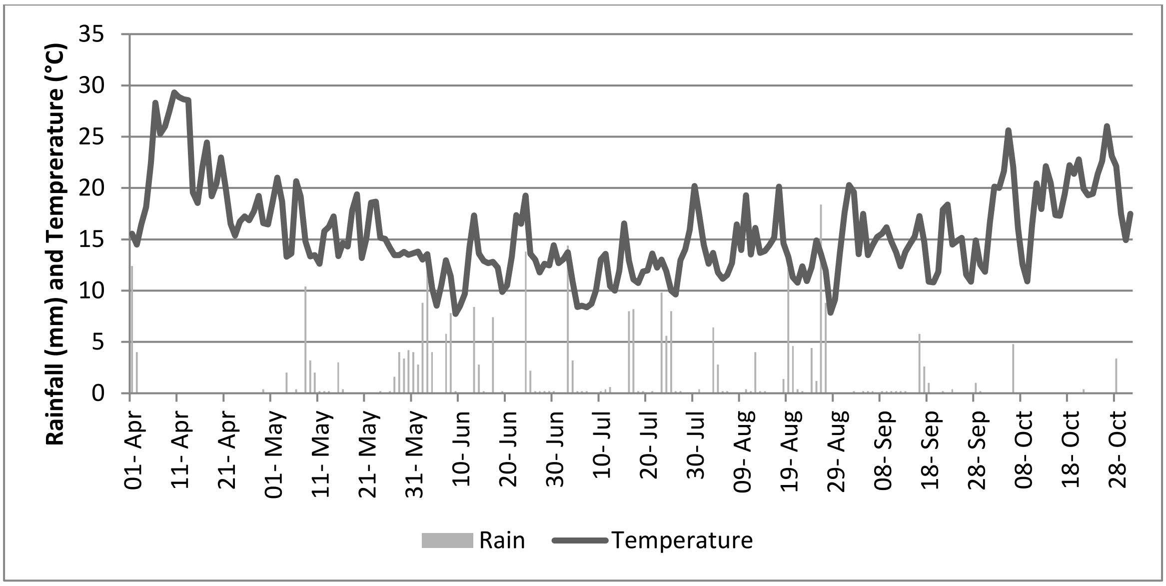

Figure 2.3: Daily rainfall (mm) and mean daily maximum temperatures (°C) recorded for the period April to November 2014 (year 1) at Langgewens Research Farm (Data from the ARC-ISCW).

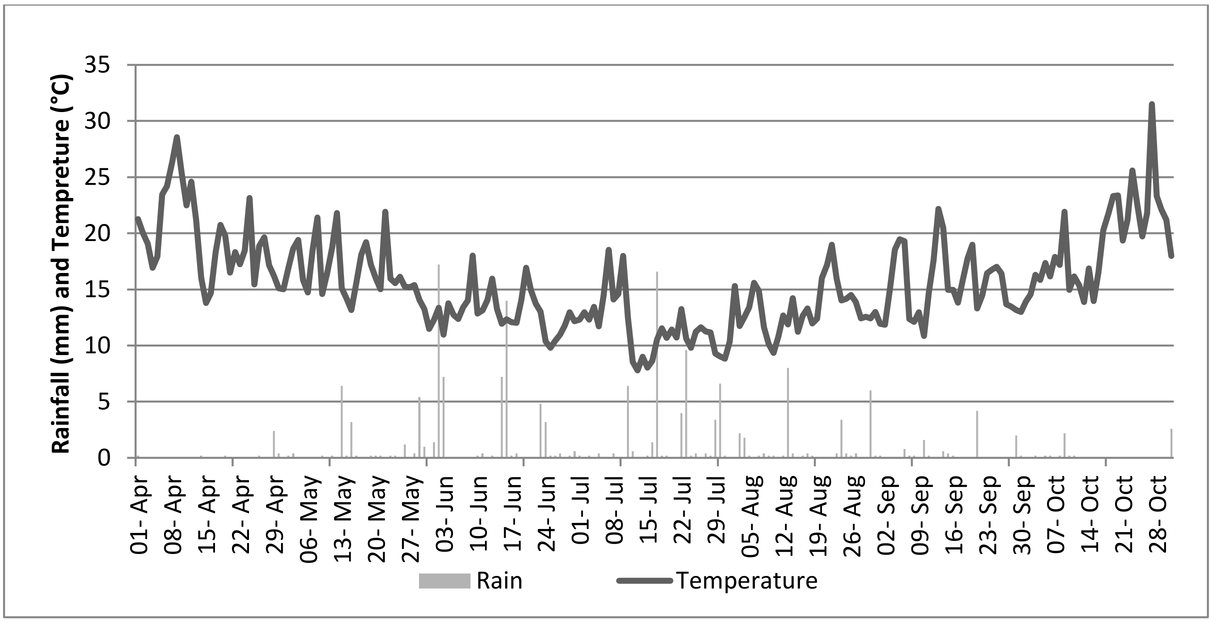

Figure 2.4: Daily rainfall (mm) and mean daily maximum temperatures (°C) recorded for the period April to November 2015 (year 2) at Langgewens Research Farm (Data from the ARC-ISCW)

2.5. Maintenance of experimental plots

General management of the experimental site was in accordance with the protocol as prescribed by the Langgewens Technical Committee, that includes experts covering all aspects of crop production.

Wheat, cultivar SST 027 and canola cultivar Hyola 555TT was planted, using a no-till Ausplow, fitted with knife-openers and press wheels with an inter-row spacing of 300 mm. The medic/clover mixture is a regenerating crop, and was not newly established.

2.6. Data collection

2.6.1. Soil moisture

Soil moisture content during year 1 was obtained from the soil water study done by Leygonie (2015). The water content for year 1 growing season was measured electromagnetically (Diviner 2000 device) at weekly intervals to a depth of 800 mm during the growing season (only 0 – 300 mm used). During the first readings, the Diviner 2000 was calibrated at volumetric soil water content at 100 mm depth increments. Soil water measurements were taken weekly during the growing season (May – October during year 1).

During year 2 soil samples were collected at 30 day intervals, only 0 - 300 mm deep, starting one day before planting until harvesting. Four samples were collected per treatment combination. From these four samples a sub-sample was collected and placed in a sealed bag. Wet mass of each sample was recorded before oven dried, and dry mass recorded after oven dried at 60 ˚C drying. Gravimetric water content was calculated using the formula: Gravimetric water content = (soil wet mass – soil dry mass) / soil dry mass) x 100 (Brady & Weil, 1999). Gravimetric water content was then converted to volumetric soil water content: Volumetric soil water content = (gravimetric water content / 100) x (bulk density / density of water). The saturated water content to a depth of 300 mm was calculated using results obtained from the soil study (Leygonie, 2015). From these values the bulk density for each treatment was calculated. (NT=1560 kg m^{-3}, DT=1537 kg m^{-3}, MP=1484 kg m^{-3}). Volumetric water content was used because it is a numerical measure of soil moisture. It is simply the ratio of water volume to soil volume.

2.6.2 Soil mineral nitrogen

During year 1 and year 2 soil samples were collected at 30 day intervals, 0 - 300 mm deep, starting one day before planting until harvesting. Four sub-samples were collected per treatment combination. Ammonium- and nitrate nitrogen (NH_4^+-N and NO_3^--N) were extracted from soil with 1N KCl. Ammonium-N (NH_4^+-N) was determined colorimetrically on a SEAL AutoAnalyzer 3 after reaction with a sodium salicylate, sodium nitroprusside and sodium hypochlorite solution that was buffered at a pH of 12.8 to 13.0. Nitrate-N (NO_3^--N) concentration in the extract was also determined colorimetrically on a SEAL AutoAnalyzer 3 through reduction of NO_3^- to NO_2^- using a copper-cadmium reduction column, whereafter the nitrate reacted with sulfanilamide under acidic conditions, using N-1-naphthylethylenediamine dihydrochloride (Bemlab, 2014).

2.6.3 Glomalin content (0 – 300 mm)

Glomalin content, an indicator of mycorrhizal growth in the soil (Palma *et al.,* 2000) and was recorded during heading stage of wheat and flower initiation of canola for year 1 (year of tillage). Four samples were collected per treatment combination to a depth of 300 mm. Glomalin extraction utilises sodium pyrophosphate at a higher concentration and pH level to extract glomalin (AgriLASA, 2004)

2.6.4. Light interception (LI)

The amount of light intercepted by plants reflects on the crop growth rate and biomass production (Olesen *et al.,* 2004). Light interception combined with plant chlorophyll content can be used as an indication of the photosynthetic potential during different growth stages (Olesen *et al.,* 2004). Data were collected at 30 day intervals, starting 30 days after planting for year 1 and 60 days after planting for year 2. During year 1 it was noted that plants were still too small at 30 day after planting and the decision was made to delay the first reading during year 2. Final LI was recorded 120 days after planting. Light interception was measured using an AccuPAR LP-80 PAR/LAI ceptometer. The light intensity was measured in sets, five readings directly above the wheat and canola canopy accompanied by five readings directly below the canopy on ground level to determine the total light intercepted by the canopy as a whole in wheat and canola.

2.6.5. Chlorophyll content

Chlorophyll content (CC) can be used as an indication of the photosynthetic potential during different growth stages (Olesen *et al.,* 2004). Data were collected at 30 day intervals, starting 30 days after planting and ending 90 days after planting for year 1 and year 2. A portable chlorophyll meter (Minolta SPAD 502 chlorophyll meter) was used to record the chlorophyll content of the uppermost full leaf. Thirty readings per treatment combination were logged and the mean value noted. Readings were taken one third of the leaf's length from the stem and the midrib was avoided in wheat and canola.

2.6.6. Stomatal conductance

Stomatal conductance (SC) estimates the rate of gas exchange and transpiration through the leaf stomata as determined by the degree of stomatal aperture. It is a function of the density, size and degree of opening of the stomata; with more open stomata allowing greater conductance, and consequently indicates that photosynthesis and transpiration rates are potentially higher. A leaf porometer was used to record stomatal conductance. The same procedure as described for recording chlorophyll content was followed, and five readings per treatment combination were recorded. Data is only available for year 1 season in wheat and canola due to technical difficulties with the leaf porometer in year 2.

2.6.7. Biomass production

Wheat and canola biomass production (BMP) of each sub-plot was determined one week before harvest by the collection of fifteen rows of one metre each that were cut at soil level and placed in bags. Bags were then placed in a 60 °C oven to dry for one week after which each bag was weighed and the total biomass in kg ha^{-1} determined. Total biomass for wheat and canola (kg ha^{-1}) = total biomass (kg m^{-1}) row length x (10000)/ (0.3). Twelve 0.25 square m quadrants instead of rows were used to determine medic biomass production. Total biomass for medics (kg ha^{-1}) = total biomass (average 0.25 m^2) x 40000.

2.6.8. Initial root mass

Initial root mass (IRM) samples were collected six weeks after seedling emergence for wheat, canola and medic. Five sets of 110 mm diameter soil cores were sampled by placing the pipe directly over the plants and then sampled it into a depth of 300 mm. Cores were washed over a 2 mm sieve, dried and root mass was determined. Root mass (g m^{-3}) = mass of roots in core x 350.877. ($core\ volume = \pi$ r^2 x h).

2.6.9. Final root mass (FRM)

Soil cores (50 mm diameter) were taken at 0-100,100-200 and 200-300 mm depth respectively. Each was sampled in five replicates, one in the row and 2 directly adjacent between rows on both sides of the in-row sample (150 mm on each side of the row). These samples were collected at the end of the growing season for wheat, canola and medic. This was replicated 3 times per treatment combination. Cores were washed over 2 mm sieve and root mass recorded for canola and wheat. Root mass (g m^{-3}) = mass of roots in core x 5092.96 ($core\ volume = \pi$ r^2 x h).

2.6.10. Seedling emergence and survival

The number of seedlings per m^2 was determined three weeks after crop emergence by counting the number of seedlings per metre row length. Seedlings in fifteen 1 m rows per treatment combination were counted and mean number per meter calculated using the equation: Seedlings per m^2 = (mean seedlings per meter row length) x (3.33). The same procedure as described for seedling survival was used to determine the number of wheat ear-bearing tillers per m^2, and the number of canola plants per m^2 at harvest. The canola plants were cut at soil level, and the wheat tillers and canola plants counted.

2.6.11. Reproductive components

From the samples used to determine the number of ear-bearing tillers, 20 wheat ears were randomly selected and spikelets per ear, number of kernels per spikelet and mean kernel mass recorded. Reproductive components for canola were determined by selecting 100 pods from final plant count samples and counting the number of seeds per pod as well as mean seed mass.

2.6.12. Final yield

A plot harvester was used to harvest wheat and canola. Yield was calculated using the equation: Grain yield = (kg sample mass x 10 000) ÷ area harvested per m^2. Medic yield production was determined by calculating medic dry matter production. Medic yield was expressed as herbage production (see 2.6.7).

2.6.13. Grain /seed quality

Grain samples were collected from each treatment combination and subjected to quality analyses. Protein content (%), thousand kernel mass (g), falling number (s) and hectolitre mass (kg hl^{-1}) were determined for wheat and percentage oil for canola.

2.6.14. Weed seed bank study

A shade net trial was done to record the number of weeds that germinated in different crop rotations as well as the effect of soil disturbance caused by the tillage treatments throughout the growing season without any herbicide application.

Ten sets of 50 mm soil cores to depths of 50 mm were collected one day before tillage in year 1 and one day before planting in year 2. These soil samples were placed in plastic trays with sand in to ensure effective germination of seeds and left to grow under shade net at Langgewens research farm. Sand used in trays was sterilised and free of weed seeds before trial. Weeds that germinated and could be identified were counted and removed to determine the number of weeds in plots. Samples were left in greenhouse for five months to allow all weeds to geminate and be counted. Weed population (m^2) = $\pi \times 0.5^2$

Three weed species could be identified namely: *Lolium multiflorum* (ryegrass), *Polygonum aviculare* (knottgrass) and *Vicia sativa* (vetch) for they were the most problematic.

2.6.15. Weed field study

The field study was done to determine the weed population established after a once-off tillage, within different crop rotations.

Four quadrants (0.25 square m) per treatment combination were counted to determine the number of weed seedlings three weeks after planting before normal weed terminating herbicides were sprayed. Since weeds collected in field is relatively small, identification was a problem. Weeds collected in field were therefore divided into three categories namely: *Lolium multiflorum*, broadleaved (all broadleaved species) and other (unidentifiable plant species) weeds.

2.6.16. Statistical analyses

An analysis of variance (ANOVA) was performed on data using PROC GLM procedure of SAS software Version 9.3 of the SAS System for Windows (SAS Institute, 2012). Shapiro-Wilk test was performed to test for non-normality (Shapiro & Wilk, 1965). A Fisher t-test with Least Significant Difference was calculated at 5% significance level to compare treatment means (Ott & Longnecker, 2001). The main plot factors were cropping sequences and the sub-plot factors were tillage practices. Observations over time (dates/month) were combined in a split-plot analysis of variance with dates/months as the sub-sub-plot factor (Little & Hills, 1972). (Main plot factor: rotation systems; subplot factor: tillage practices and sub-subplot factor dates/months). Soil depth was added to the model as a sub-sub plot factor. The root observations on the initial and final dates were analysed separately.

2.7. References.

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Chapter 3

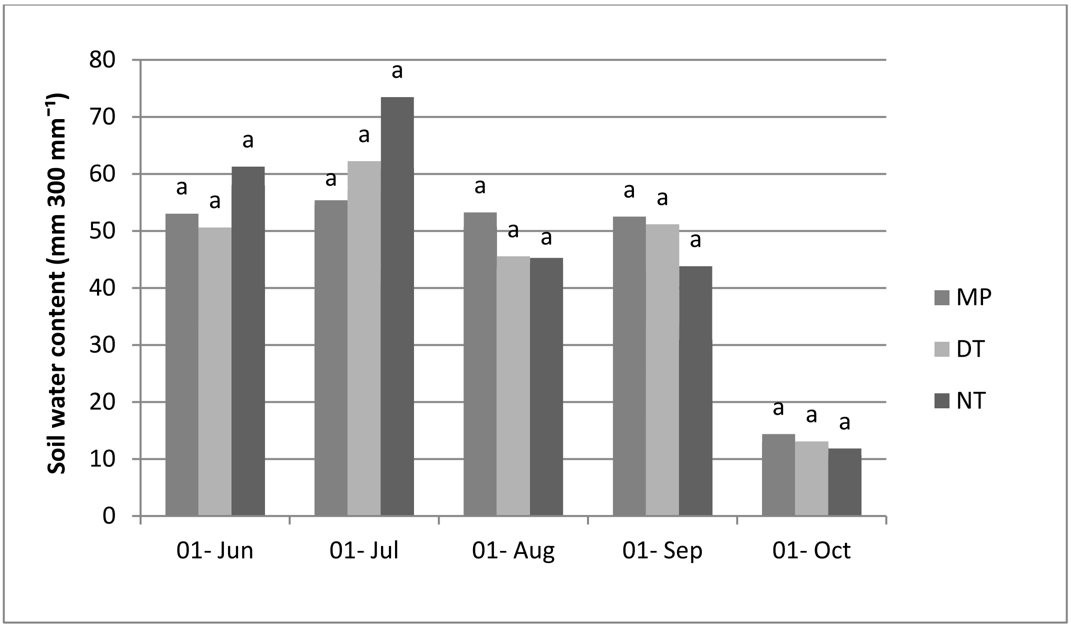
Results and discussion

3.1. Soil water content, soil mineral nitrogen and glomalin content

3.1.1. Soil water content (SWC)

Wheat sequences

Tillage did not influence SWC during year 1 in medic/clover-wheat-medic/clover-wheat (McWMcW) (Figure 3.1.1). Soil water content during germination (1 June) was slightly higher although not significantly so for no-till (NT). Rainfall recorded during the last week of June (Figure 2.1) caused a sharp increase in SWC. SWC decreased when rainfall decreased and temperatures increased at the start of October (Heading). Plants started using more water during heading and grain filling as they reached maturity. Mouldboard plough (MP) resulted in a slight increase in SWC, although not significantly, compared to NT and deep tine (DT) towards the end of the growing season. One of the reasons could be because of lower competition of weeds in MP since fewer weeds was observed in MP. Year 1 also had a below average rainfall during this critical stage (September - October) in plant production and this can be seen in the low amount of SWC available to plants.

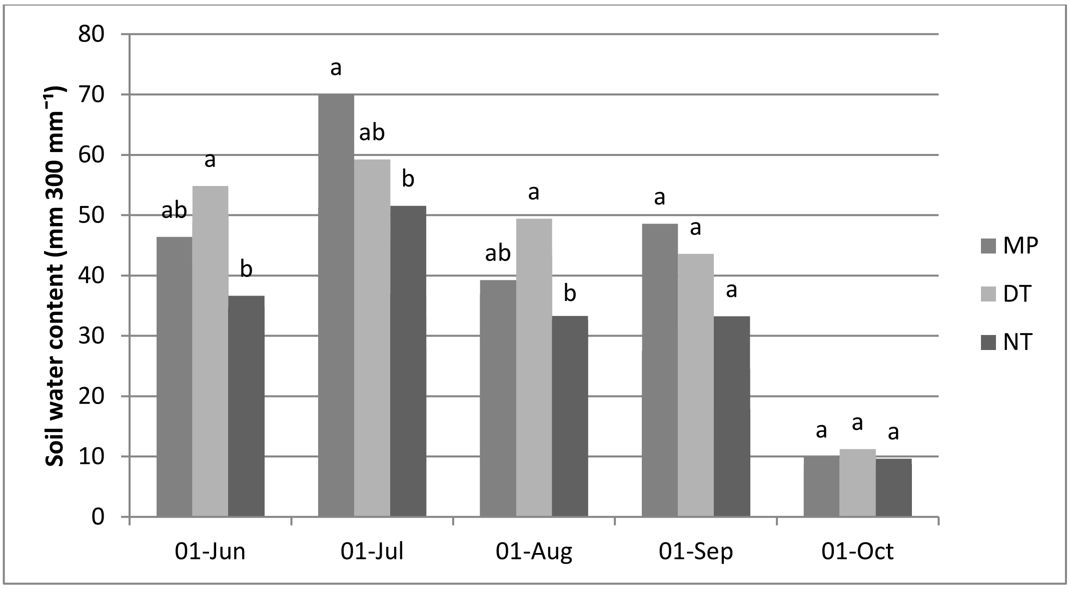


	1-Jun	1-Jul	1-Aug	01-Sep	01-Oct
CV %	15.7213	57.3742	51.4331	34.5015	50.0406
LSD	5.1066	27.9180	27.5470	13.6690	10.9270

Figure 3.1.1: Soil water content (mm 300 mm^{-1}) in the 0 – 300 mm soil profile in a medic/clover-wheat-medic/clover-wheat (McWMcW) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 1 growing season at Langgewens Reseach Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

The effect of a once-off strategic tillage on soil water content in lupin-wheat-canola-wheat (LWCW) (year 1) is summarised in Figure 3.1.2. The SWC remained between 30 and 70 mm (0 – 300 mm) until 1 September 2014. NT resulted in lower soil water content compared to DT and MP during year 1 in LWCW, however significantly so only from planting until stem elongation (1 Aug). No significant differences were recorded between MP and DT during year 1. Fabrizzi *et al.,* (2005) reported similar results and recorded higher bulk densities and penetration resistance in the 0 - 50 mm soil profile with NT compared to conventional tillage which could cause a reduction in infiltration as well as an increase in the amount of water runoff, although similar results were not recorded in McWMcW (Figure 3.1.1). In contrast to these findings, Osunbitan *et al.,* (2005) found that higher macroporosity as a result of non-disturbance of root channels and pore spaces created by root growth and soil biological activities from previous years caused higher SWC found under NT conditions. The amount of SWC reduced dramatically at the end of September as plants started reaching maturity and rainfall decreased.

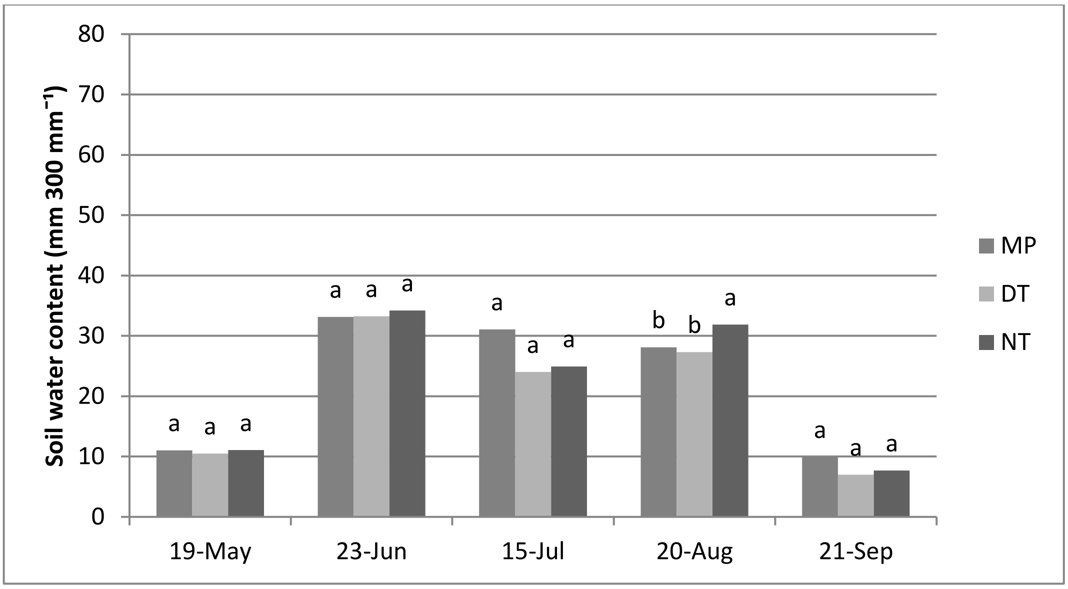


	1-Jun	1-Jul	1-Aug	01-Sep	01-Oct
CV %	**14.3630**	**12.5191**	**13.0565**	**34.5015**	**32.2973**
LSD	**11.4180**	**9.1291**	**8.5652**	**13.6690**	**11.265**

Figure 3.1.2: Soil water content (mm 300 mm^{-1}) in the 0 – 300 mm soil profile for a lupin-wheat-canola-wheat (LWCW) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 1 growing season at Langgewens Reseach Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

During year 2 no significant (P=0.05) differences in SWC were recorded between tillage treatments except for 20 August in LWCW (Heading) (Figure 3.1.3). NT resulted in significantly higher water content compared to MP and DT on this date. Although Fabrizzi *et al.,* (2005) as well as Sayre & Hobbs (2004) reported that the amount of residue cover and better infiltration will increase water content, it was not found in this study as MP did not differ from NT and DT. Roper *et al.,* (2013) reported that during drier seasons the amount of crop residues can have a major role on improving rainfall interception.



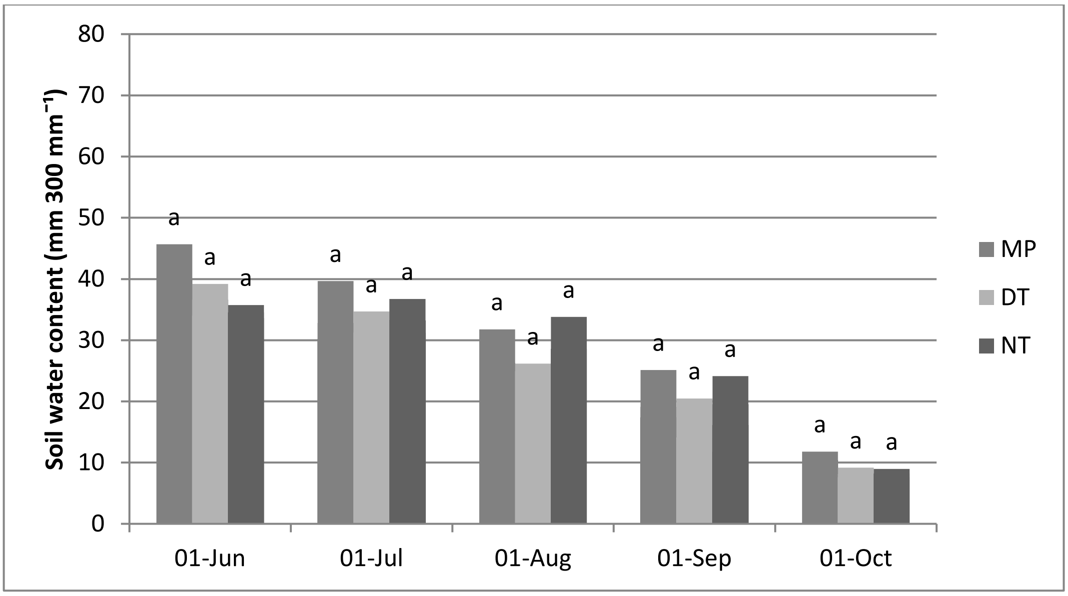
	19-May	23-Jun	15-Jul	20-Aug	21-Sep
CV %	22.9276	9.6158	19.2449	6.8068	17.3658
LSD	4.2181	5.4678	9.9586	3.3925	8.3360

Figure 3.1.3: Soil water content (mm 300 mm^{-1}) in the 0 – 300 mm soil profile for a lupin-wheat-canola-wheat (LWCW) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Canola sequences

Soil water content during year 1 for wheat-lupin-wheat-canola (WLWC) is illustrated in Figure 3.1.4. The SWC were between 8 and 45 mm (0 – 300 mm) soil profile throughout the growing season. There was no significant differences (P=0.05) between the tillage treatments. The amount of SWC reduced at the end of September (Pod and Seed Development stage) as plants reached maturity and as rainfall decreased. The amount of SWC for the WLWC tended to be lower (Figure 3.1.4) than LWCW (Figures 3.1.2 and 3.1.3). The reason could be that canola has a higher water demand compared to wheat as reported by Nielsen (1997). However, the cumulative evapotranspiration reported by Leygonie (2015) showed no significant differences between crop sequences.

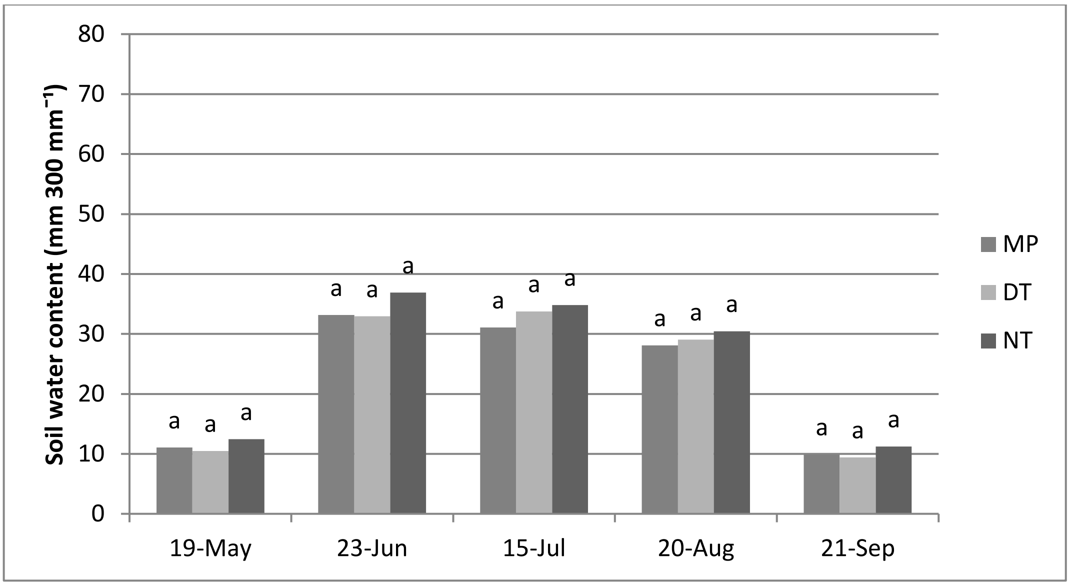


	1-Jun	1-Jul	1-Aug	01-Sep	01-Oct
CV %	27.4562	31.8186	37.9556	41.7930	30.1593
LSD	17.4590	19.7920	17.7400	16.8150	5.9440

Figure 3.1.4: Soil water content (mm 300 mm^{-1}) in the 0 – 300 mm soil profile for a wheat-lupin-wheat-canola (WLWC) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 1 growing season at Langgewens Reseach Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

During year 2 no significant differences (P=0.05) in SWC for WLWC were recorded throughout the growing season (Figure 3.1.5). SWC increased in the beginning of the season as precipitation increased (Figure 2.3) and decreased towards the end of the season (Pod and Seed Development) as rainfall decreased. Plaza-Bonilla *et al.,* (2014) reported that NT improved soil water infiltration, increasing SWC. Sharma *et al*., (2011) reported that NT had a greater soil water holding capacity due to the increased soil hydrophilic compounds including organic matter.



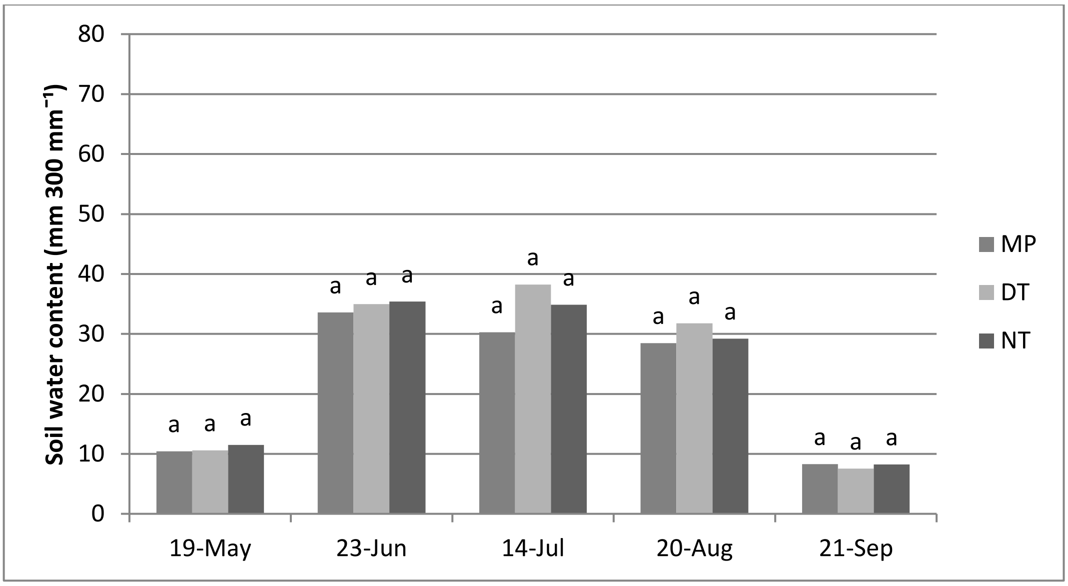
	19-May	23-Jun	15-Jul	20-Aug	21-Sep
CV %	11.7967	11.6813	7.1225	5.5487	10.1229
LSD	2.3096	6.9365	4.0942	2.8041	2.3353

Figure 3.1.5: Soil water content (mm 300 mm^{-1}) in the 0 – 300 mm soil profile for a wheat-lupin-wheat-canola (WLWC) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 2 growing season at Langgewens Reseach Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Medic sequences

Soil water content in wheat-medic/clover-wheat-medic/clover crop rotation the medic crop (WMcWMc) was only measured in year 2. No significant differences were recorded between tillage treatments (Figure 3.1.6). WMcWMc tended to result in higher SWC (51.3 mm 300 mm^{-1}) compared to LWCW (43.5 mm 300 mm^{-1}). These results could be because of a higher amount of residues on surface during the medic year as well as less implement traffic over soils every second year. Arvidsson *et al.,* (2009) recorded similar results with increase in SWC with reduced implement traffic. Volumetric water content tended to decrease for all tillage treatments and crop rotations from planting date until harvesting. Lower rainfall at the end of year 1 growing season (August) caused a sharp decrease in soil water content for all tillage and crop rotations studied. During year 2, drier conditions caused an overall decrease in SWC throughout the growing season compared to year 1.



	19-May	23-Jun	15-Jul	20-Aug	21-Sep
CV %	12.3104	5.0172	6.9403	7.9013	15.9444
LSD	2.3091	3.0066	4.7815	4.6893	2.8968

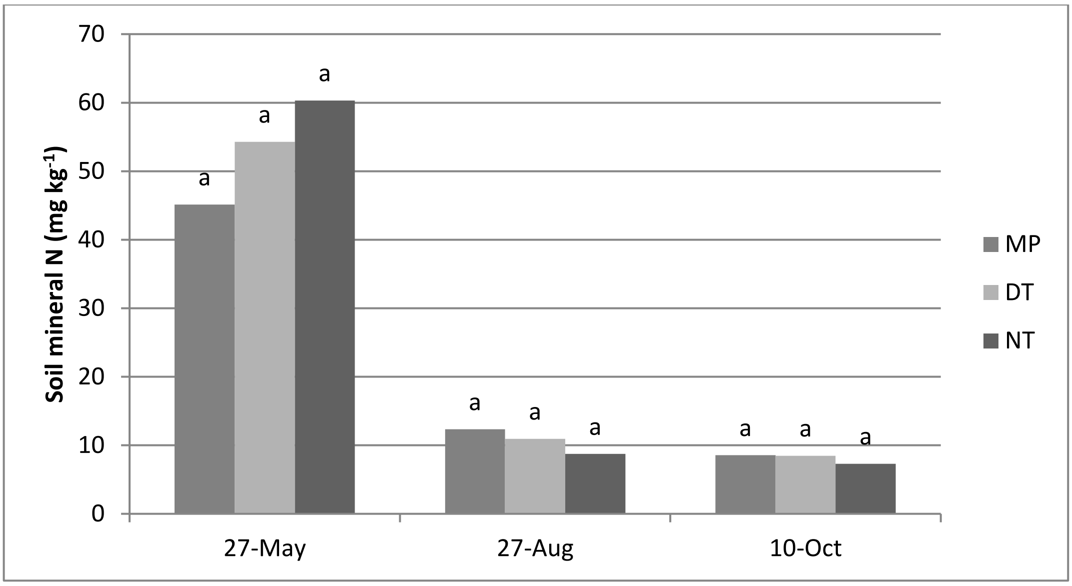
Figure 3.1.6: Soil water content (mm 300 mm^{-1}) in the 0 – 300 mm soil profile in a wheat-medic/clover-wheat-medic/clover (WMcWMc) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

3.1.2. Soil mineral nitrogen content

Wheat sequences

Initial mineral nitrogen for year 1 varied between 42 and 60 mg kg^{-1} in McWMcW (Figure 3.1.7). Tillage treatments did not influence (P=0.05) soil mineral nitrogen content at any sampling date in the McWMcW system. A general decrease (73 – 87 %) in mineral nitrogen content was however observed between planting and 60 days after planting (27 Aug). Similar decreases were also observed by Agenbag (2012).

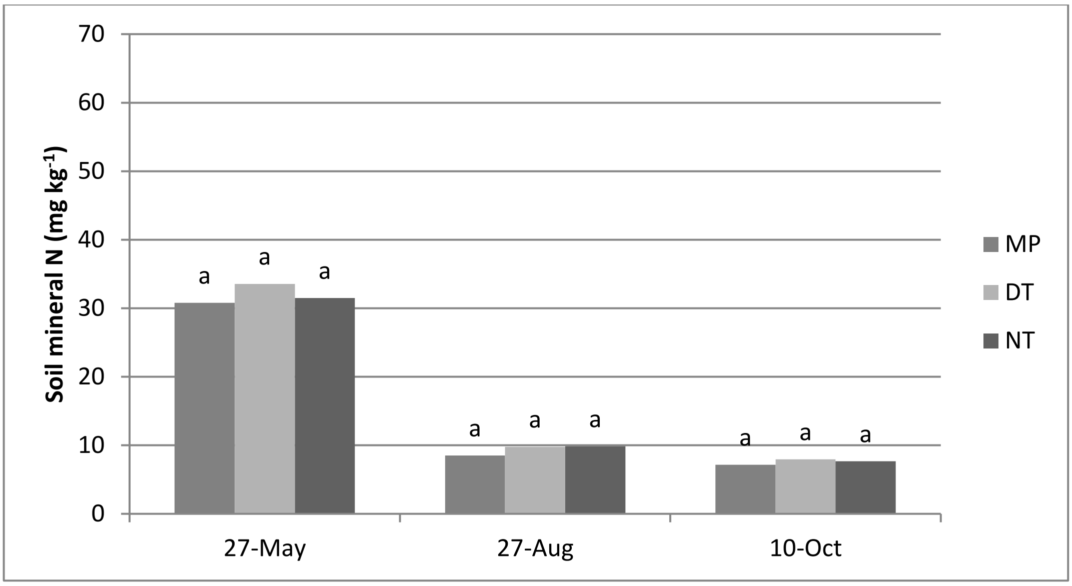


	27-May	27-Aug	10-Oct
CV %	28.5762	24.6250	26.5653
LSD	26.3280	4.5454	19.5682

Figure 3.1.7: Soil mineral nitrogen content (mg kg^{-1}) in a medic/clover-wheat-medic/clover-wheat (McWMcW) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 1 growing season at Langgewens Reseach Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

LWCW also plots showed no significant differences (P=0.05) in mineral nitrogen before tillage in year 1 (Figure 3.1.8). Values for these treatments before tillage were between 30 and 33 mg kg^{-1}. The amount of mineral nitrogen decreased 90 days (Heading) and 120 days (Physiological Maturity) after planting (Figure 3.1.8).

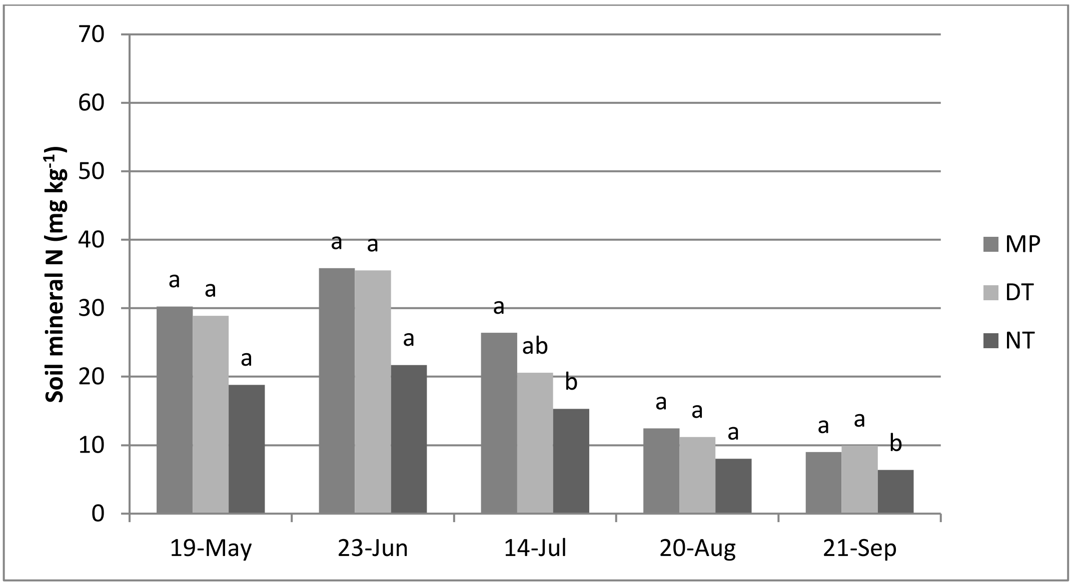


	27-May	27-Aug	10-Oct
CV %	25.7228	11.7119	23.5864
LSD	0.2676	1.0970	0.9852

Figure 3.1.8: Soil mineral nitrogen content (mg kg^{-1}) in a lupin-wheat-canola-wheat (LWCW) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 1 growing season at Langgewens Reseach Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

The general trend regarding mineral nitrogen in LWCW (year 2) showed no differences as a result of tillage treatments tested (Figure 3.1.9). The only exception was on 14 Jul where MP resulted in significantly higher mineral nitrogen compared to NT. The effect of tillage on mineral nitrogen was first recorded during year 2. Varco *et al.,* (1993) reported that the reason for these differences in year 2 and not in year 1 (year of tillage) as expected, could be that tillage was applied during a time when soil temperature and microbial activity were low (end of May). Mineral nitrogen was thus released during year 2 when soil temperature and microbial activity increased and not during year one after tillage (Varco *et al.,* 1993). The crop residues mixed into soil through tillage (MP) could also increases the amount of residual nitrogen released compared to surface-residues in NT systems. Similar results were obtained by (Varco *et al.,* 1993). The amount of mineral nitrogen increased 30 days (23 June - Tillering) after planting, whereafter it decreased towards the end of the season. These increases in the beginning of the season could be the effect of nitrogen applied during the planting of crops. When comparing year 1 to year 2, the amount of mineral nitrogen recorded during year 1 (year of strategic tillage) season was not different from year 2.



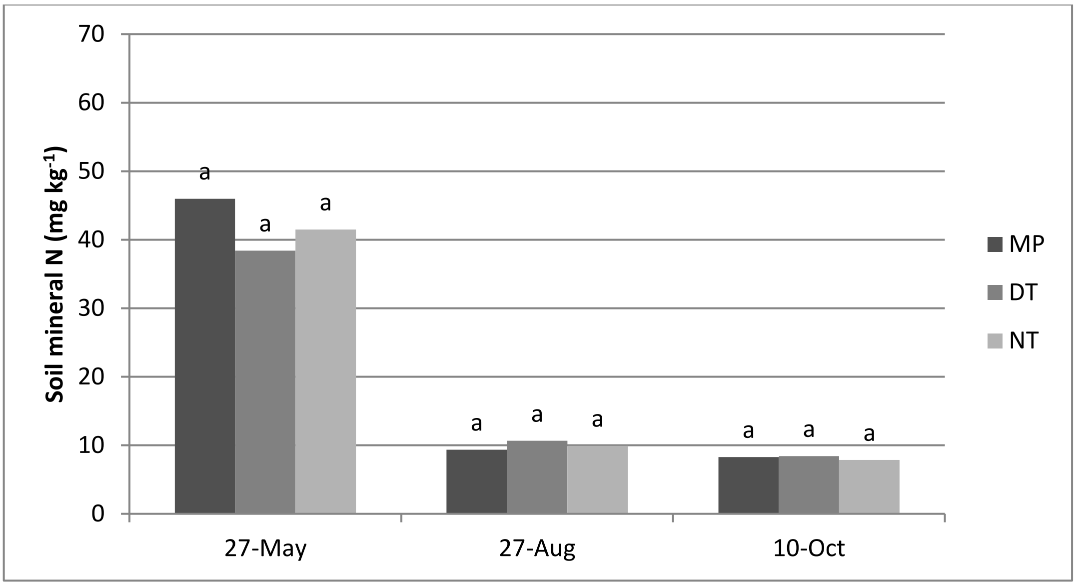
	19-May	23-Jun	14-Jul	20-Aug	21-Sep
CV %	34.0349	39.4787	19.5254	29.1575	10.5514
LSD	15.3090	21.1930	7.0143	5.3285	2.6855

Figure 3.1.9: Soil mineral nitrogen content (mg kg^{-1}) in a lupin-wheat-canola-wheat (LWCW) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Canola sequences

The WLWC plots showed no significant differences (P=0.05) in the amount of mineral nitrogen before tillage was applied (Figure 3.1.10). These initial values varied between 41 and 46 mg kg^{-1} and decreased as the season progressed.

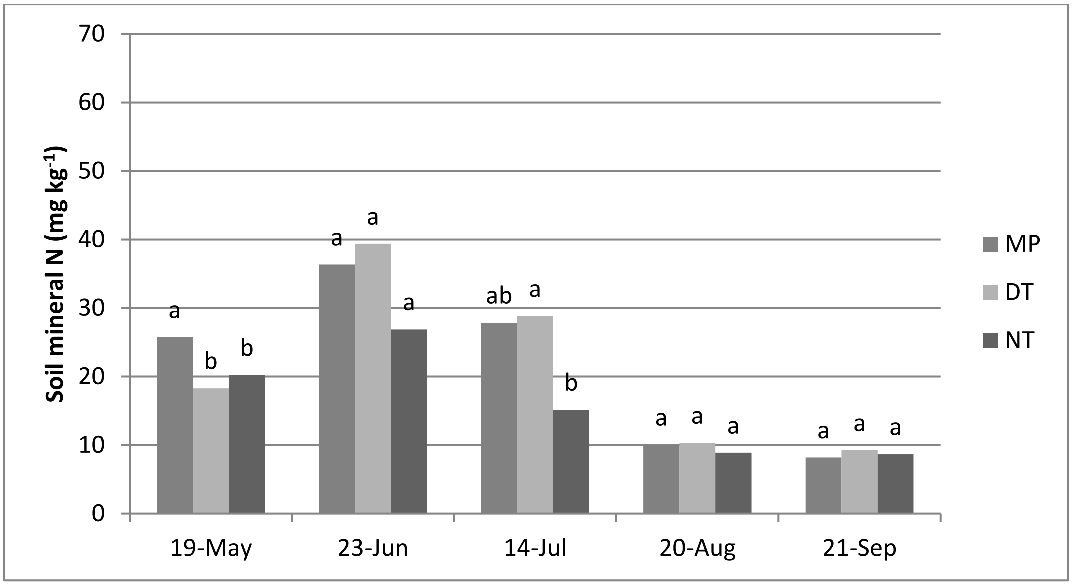


	27-May	27-Aug	10-Oct
CV %	25.9792	18.9868	15.6382
LSD	18.8610	3.2745	2.2587

Figure 3.1.10: Soil mineral nitrogen content (mg kg^{-1}) in a wheat-lupin-wheat-canola (WLWC) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 1 growing season at Langgewens Reseach Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

During year 2 in WLWC (Figure 3.1.11) significantly higher mineral nitrogen was recorded before planting for MP compared to DT and NT. These differences could have been the effect of MP tillage in the previous season. There were also significant differences recorded 60 days (14 July - Stem Elongation) after planting, with DT showing an increase in mineral nitrogen compared to NT. At 90 days (Heading) and 120 days (Physiological Maturity) after planting no significant differences were recorded between tillage treatments. The amount of mineral nitrogen was higher at 30 days after planting (Tillering), probably because of the nitrogen applied during planting. As the season progressed the amount of mineral nitrogen decreased as can be seen in Figures 3.1.10 and 3.1.11



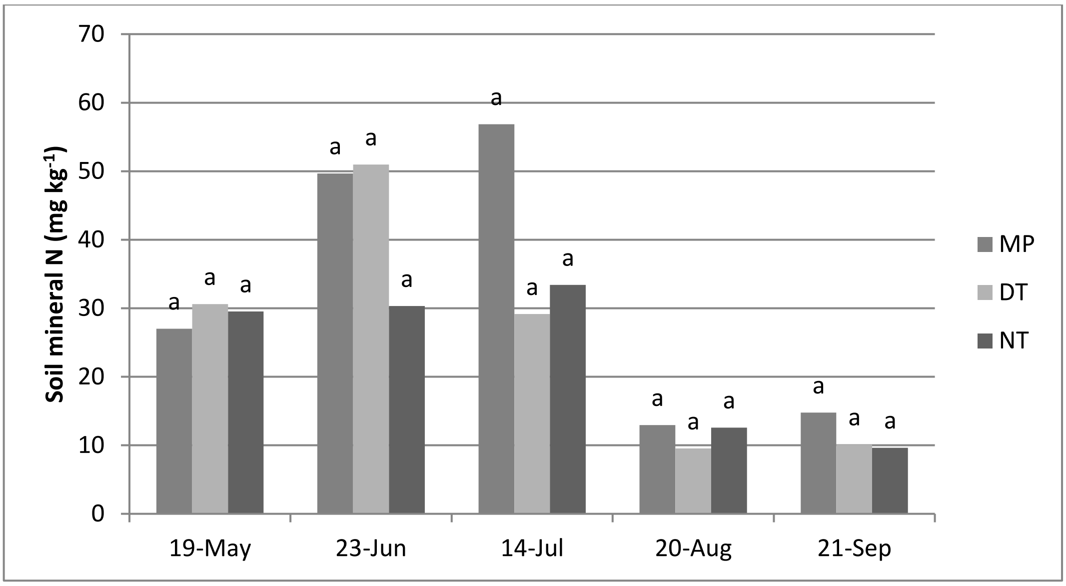
	19-May	23-Jun	14-Jul	20-Aug	21-Sep
CV %	14.1330	24.5616	31.4746	15.4851	8.1917
LSD	5.2373	14.5310	13.0380	2.6125	1.6158

Figure 3.1.11: Soil mineral nitrogen content (mg kg^{-1}) in a wheat-lupin-wheat-canola (WLWC) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Medic sequences

No significant differences were recorded between tillage treatments throughout the growing season in WMcWMc (Figure 3.1.12). The amount of mineral nitrogen increased slightly 60 and 90 days after planting in DT and MP although no fertiliser was applied to medic during year 2. Before planting, soil mineral nitrogen was the highest in plots that had WMcWMc (31.0 mg kg^{-1}) compared to WLWC (22.3 mg kg^{-1}) and LWCW (18.5 mg kg^{-1}).



	19-May	23-Jun	14-Jul	20-Aug	21-Sep
CV %	41.2098	31.7954	58.9794	37.4074	21.0598
LSD	20.7140	24.0170	40.1600	7.5636	5.4964

Figure 3.1.12: Soil mineral nitrogen content (mg kg^{-1}) in a wheat-medic/clover-wheat-medic/clover (WMcWMc) system as influenced by mouldboard (MP), deep tine (DT) and no-till (NT) during year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Mineral nitrogen content (mg kg^{-1}) before planting tended to be higher than mineral nitrogen recorded 90 and 120 days after planting. Blaise *et al.,* (2009) found that different tillage systems applied in autumn showed no significant differences in the amount of soil mineral nitrogen available to plants, although higher mineralisation rates were reported by Sprague & Triplett (1986) in plots that received tillage treatment.

3.1.3. Glomalin content

Year 1

The mean effect of cropping sequences on glomalin content for the year 1 season showed no significant differences (Table 3.1.1). The mean tillage effect however resulted in significant differences (P=0.05). DT increased the amount of glomalin (mg g^{-1}) recorded compared to NT. Zhang *et al.,* (2014) reported similar results and stated that tillage increased the amount of oxygen in the soil. This increase the amount of Arbuscular Mycorrhizal Fungal that is responsible for the increase in glomalin content. In contrast to these findings, Borie *et al.,*

(2000) reported that tillage reduced the amount of glomalin in soils by reducing the amount of soil carbon.

Table 3.1.1: Glomalin content (mg g^{-1}) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) and wheat in a lupin-wheat-canola-wheat (LWCW), medic/clover-wheat-medic/clover-wheat (McWMcW) and canola in a wheat-lupin-wheat-canola (WLWC) for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences			
	McWMcW (mg g^{-1})	LWCW (mg g^{-1})	WLWC (mg g^{-1})	Mean (Tillage) (mg g^{-1})
MP	0.99	1.08	0.96	**1.01 ab**
DT	1.07	1.10	1.03	**1.06 a**
NT	0.89	1.03	0.89	**0.93 b**
Mean (System)	**0.98 a**	**1.06 a**	**0.96 a**	
CV %	12.0261			
LSD (System)	0.2032			
LSD (Tillage)	0.12141			
LSD (System x Tillage)	0.2149			

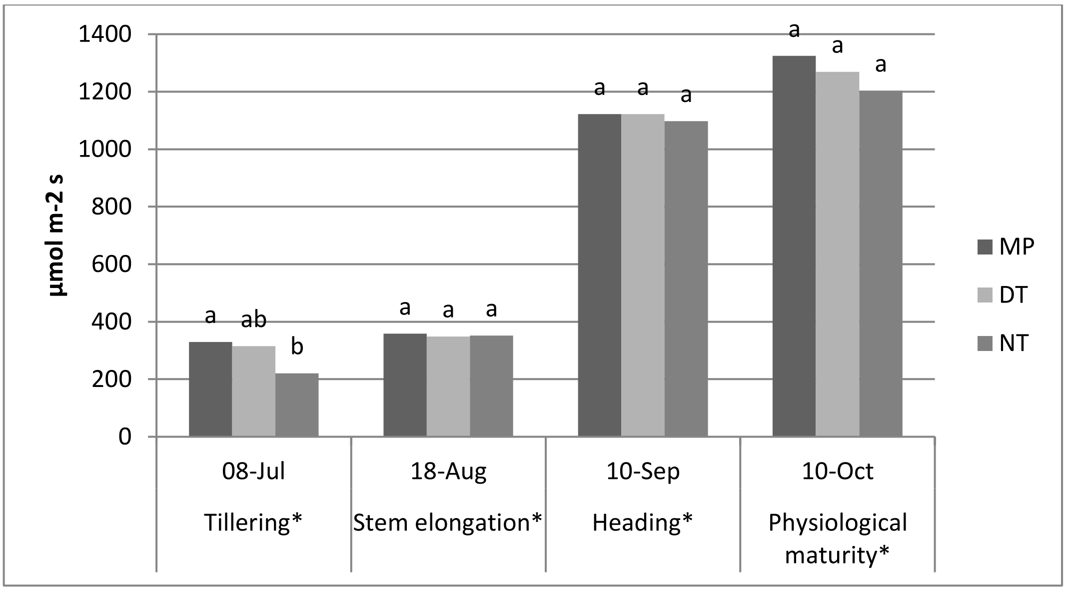
Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

3.2. Vegetative development

3.2.1. Light interception (LI)

Wheat phases

Figure 3.2.1 summarises the effect of tillage in McWMcW on mean LI during year 1. Except for 30 days (Tillering) after planting, the tillage treatments tested did not influence LI in McWMcW during year 1. At 30 days (Tillering) LI was significantly (P=0.05) lower at NT compared to MP. Aubertot *et al.* (1999) reported the reason for these significant differences found in their study could have been because of better seed soil contact associated with tilled soil which improved germination of seeds and plant density. An increase in LI was recorded between 60 (Stem elongation) and 90 (Heading) days after planting, reflecting an expansion of leaf area. Although no significant differences were recorded in this study 60 (Stem elongation) to 120 (Physiological maturity) days after planting, Uppal and Gooding (2013) found that LI decreased in smaller plant populations.

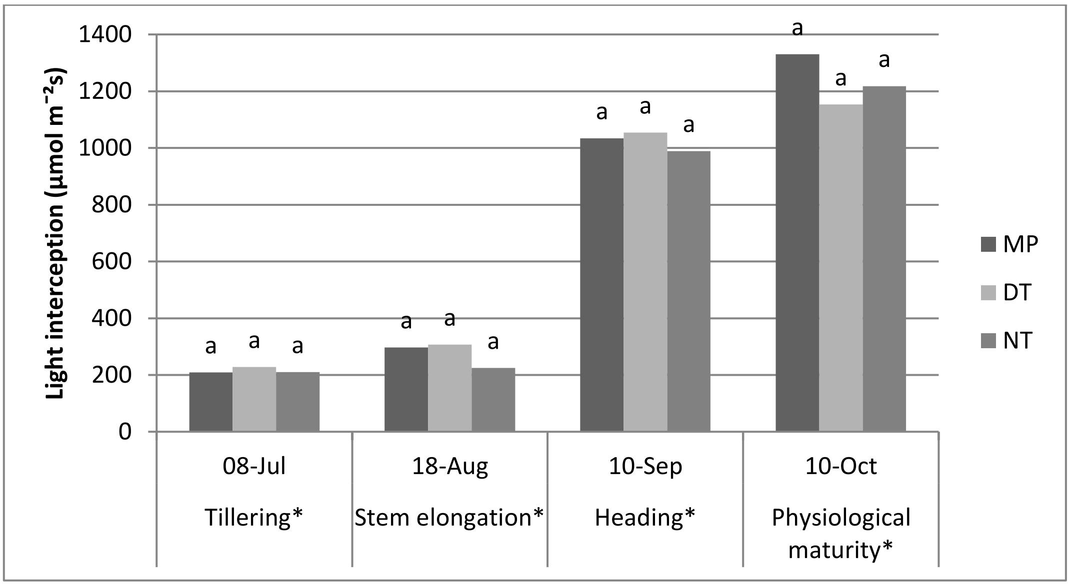


	08-Jul	18-Aug	10-Sep	10-Oct
CV %	19.9253	2.5356	2.6976	5.5648
LSD	99.4610	15.4970	52.0120	121.8500

Figure 3.2.1: Light interception (µmol m^{-2}s) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Mean LI was not influenced (P=0.05) by the tillage treatments in LWCW during year 1 (Figure 3.2.2). Similarly to McWMcW an increase in light interception was recorded for LWCW as the season progressed. LI of McWMcW tended to be higher compared to LWCW at heading (90 days). Similar results were reported by Gelantini *et al.* (2000) who found that crop rotations with N-binding legumes resulted in higher growth compared to either wheat rotated with natural grass pastures or continuous wheat. Crop rotations that included legume species may have a direct effect on the amount of nitrogen available to the succeeding crop due to N-binding legumes, or have an indirect effect due to the improvement of the soil physical, chemical and biological conditions (Soon *et al.,* 2001). The results described in chapter 3 show that a higher amount of mineral nitrogen was found in rotations with a legume (medic) every second year compared to a legume (lupin) every fourth year.

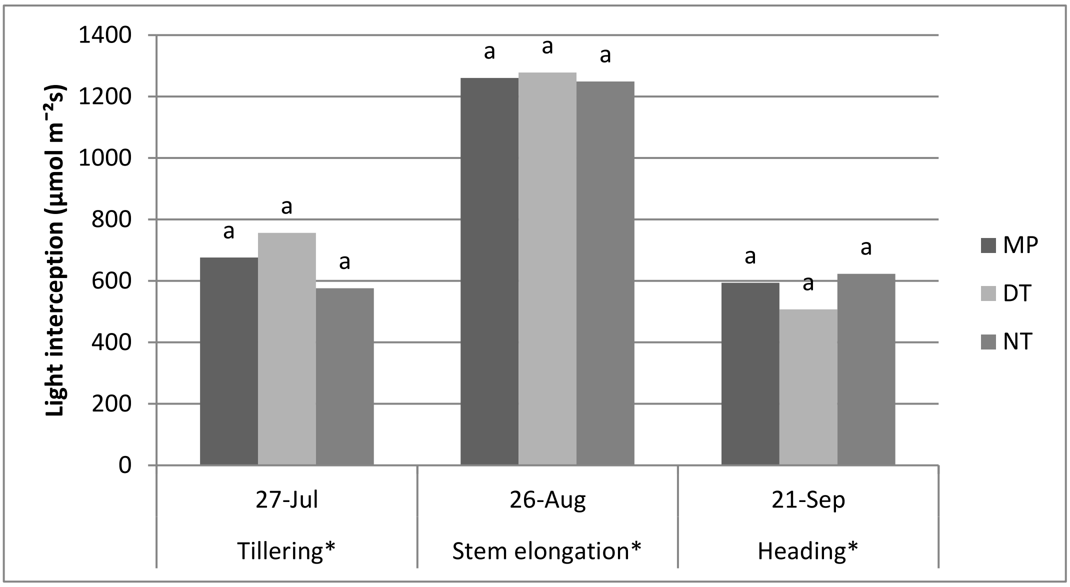


	08-Jul	18-Aug	10-Sep	10-Oct
CV %	38.9823	17.5712	5.2793	12.3932
LSD	145.3200	83.935	93.6810	264.5700

Figure 3.2.2: Light interception (µmol $m^{-2}s$) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

The mean amount of LI during year 2 for different tillage treatments in LWCW is illustrated in Figure 3.2.3. No significant differences (P=0.05) were recorded 60, 90 or 120 days after seedling emergence between tillage treatments. The amount of LI during September 2015 was higher compared to year 1 and lower during October 2015 compared to year 1. The dramatic lower LI recorded during year 2 can be ascribed to the severe in season drought and could have reduced yield potential. Milthorpe and Moorby (1974) reported that photosynthetic potential and yield was amongst other factors a function of the amount of light intercepted during the growing season.



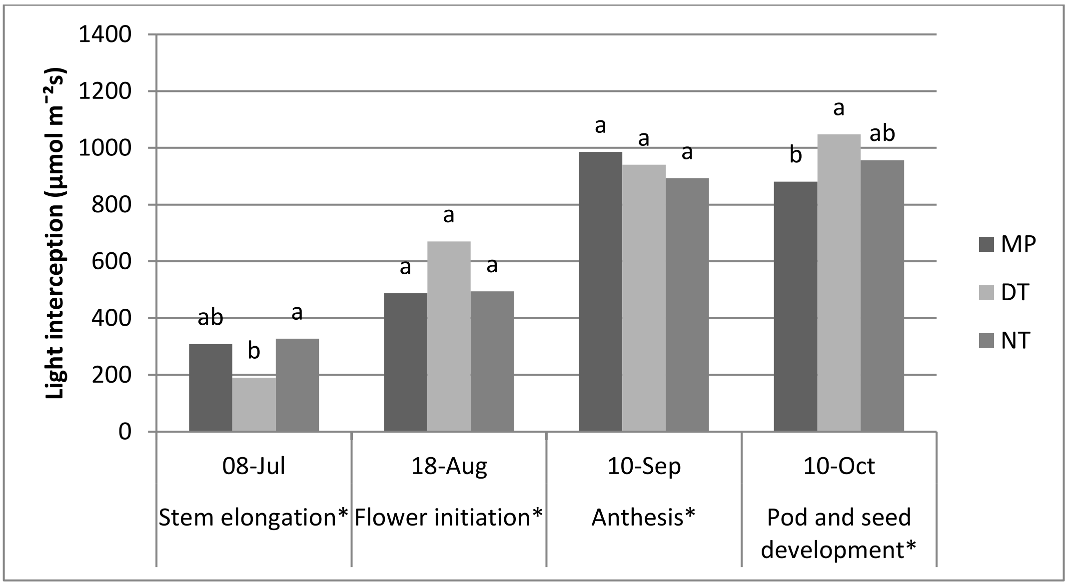
	27-Jul	26-Aug	21-Sep
CV %	18.2030	3.7704	20.1522
LSD	210.9700	82.3790	200.48

Figure 3.2.3: Light interception (µmol $m^{-2}s$) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Canola phases

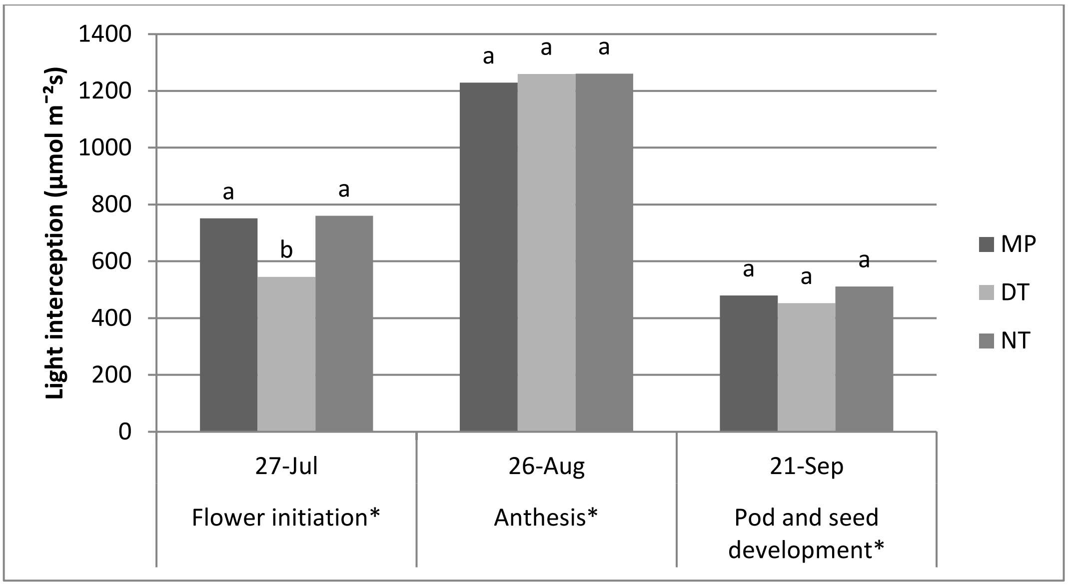
Tillage influenced (P=0.05) mean LI in canola 30 (Stem elongation) and 120 (Pod and seed development) days after planting during year 1 in the WLWC system (Figure 3.2.4). The response is however inconsistent as NT resulted in higher LI compared to DT at 30 days after planting whilst at 120 days DT resulted in higher LI than MP. Significant differences recorded at 120 days may have been because differences in leaf senescence for different tillage treatments. DT had a significantly higher LI compared to MP which could indicate that plants had more water available at the end of the season causing leaves to last longer, although not recorded in this study (Chapter 3.1). Rabiee *et al.* (2004) reported that during grain filling, leaves of canola die off, photosynthesis therefore took place in stems and pods and no longer by leaves. During year 2 (Figure 3.2.5) significant differences (P=0.05) were recorded 60 days (Flower initiation) after plant. DT was significant lower than MP and NT at 60 days. Fooladivand *et al.* (2009) however reported that canola was sensitive to poor seedbed preparation and that no-till resulted in lower values compared to conventional tillage because soil tillage enhanced the development of roots, resulting in increased uptake of nutrients and above ground plant growth (Hulugalle *et al.,* 2005).



	08-Jul	18-Aug	10-Sep	10-Oct
CV %	22.8171	22.2892	10.3980	7.3093
LSD	108.9000	212.5900	169.1000	121.6800

Figure 3.2.4: Light interception (µmol $m^{-2}s$) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level



	27-Jul	26-Aug	21-Sep
CV %	12.4978	2.1345	5.5139
LSD	148.2600	46.1600	45.9270

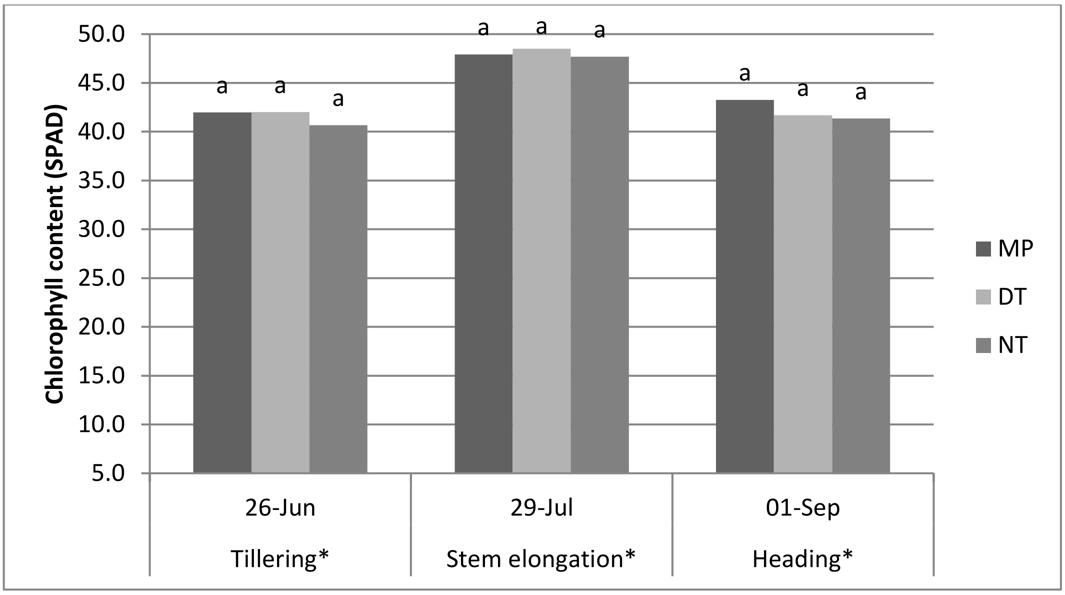
Figure 3.2.5: Light interception (µmol m^{-2}s) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

3.2.2. Chlorophyll content (CC)

Wheat phases

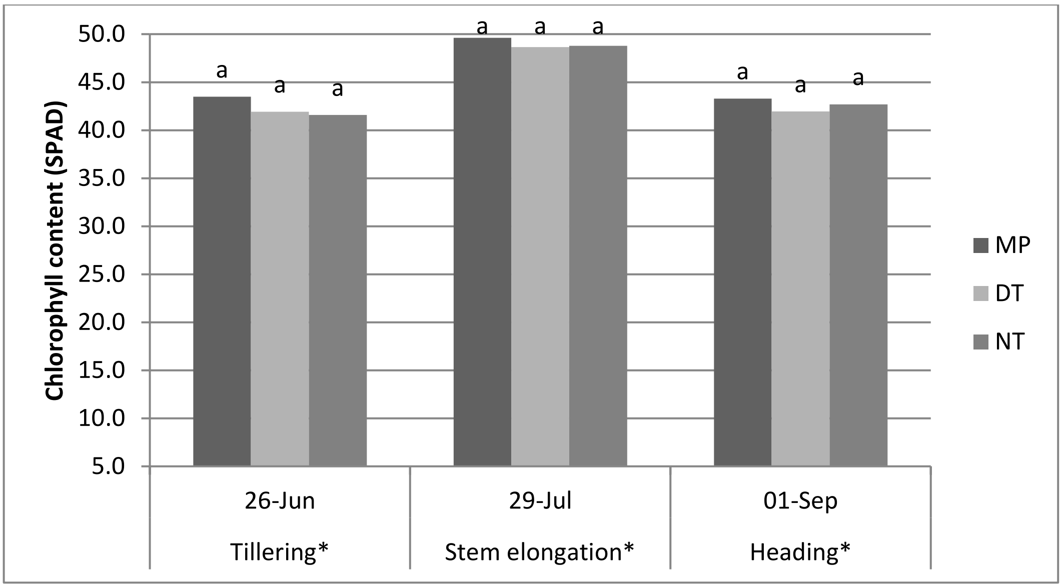
Mean chlorophyll content was not influenced (P=0.05) by tillage treatments in McWMcW (Figure 3.2.6) or LWCW (Figure 3.2.7) during year 1 production season. CC increased to a maximum 60 days after planting in both wheat sequences studied. The expected higher mean CC of the wheat in the McWMcW (after N-fixing legume) compared to LWCW in the LWCW did not realise. Ziadi *et al.* (2010) reported that the amount of CC of the flag leaf during anthesis is a reliable indicator of the status of nitrogen within the crop. The chlorofil content of the flag leaf during heading stage can also be related to the translocation potential of tissue N to wheat kernels (López-Bellido *et al.*, 2004).



	26-Jun	29-Jul	01-Sep
CV %	8.4189	2.7270	4.1912
LSD	6.0524	2.2668	3.0536

Figure 3.2.6: Chlorophyll content (SPAD) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

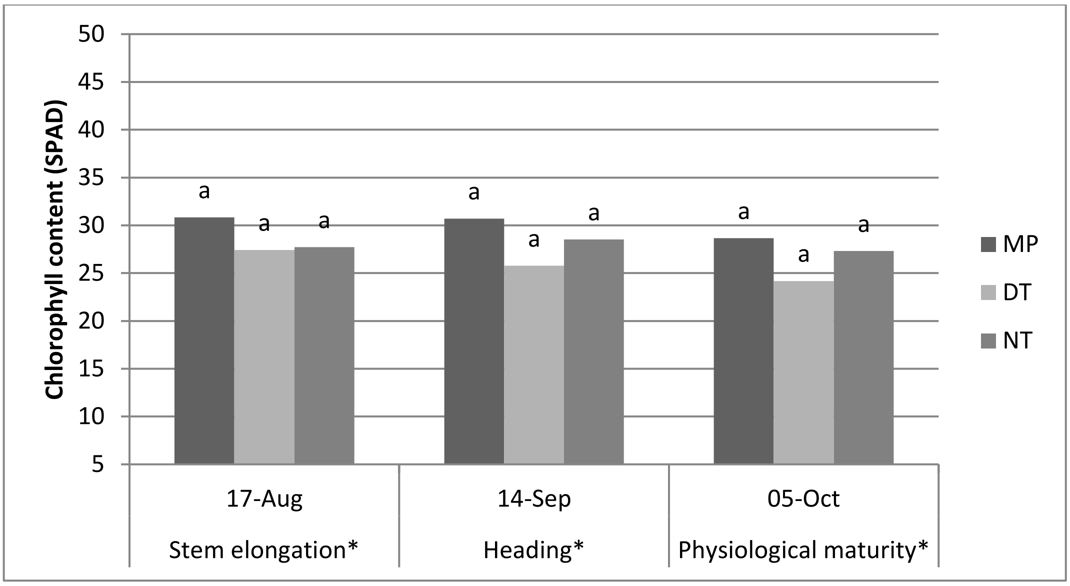


	26-Jun	29-Jul	01-Sep
CV %	4.7135	2.6611	2.6538
LSD	3.4518	2.2569	1.9584

Figure 3.2.7: Chlorophyll content (SPAD) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Figure 3.2.8 shows the effect of strategic tillage throughout year 2 in LWCW. No significant differences (P=0.05) were recorded between tillage treatments. The increase in nitrogen fertiliser application should also increase the CC (Ziadi *et al.,* 2010). There was however no significant increase reported in this study (Chapter 3.1) and the assumption can be made that tillage did not increase the amount of plant available N and thus CC of leaves. The CC in year 1 (first year after tillage) was slightly higher (40-45 SPAD) compared to year 2 (25-35 SPAD).



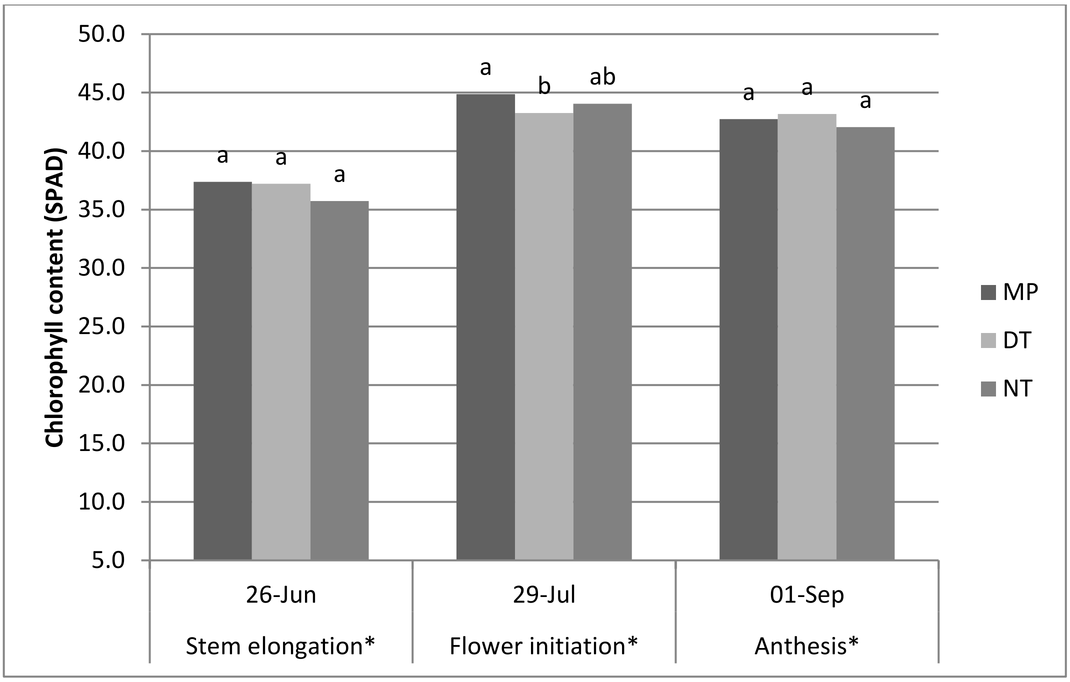
	17-Aug	14-Sep	05-Oct
CV %	8.9270	11.4050	12.5231
LSD	4.4257	5.5907	5.7885

Figure 3.2.8: Chlorophyll content (SPAD) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

Canola phases

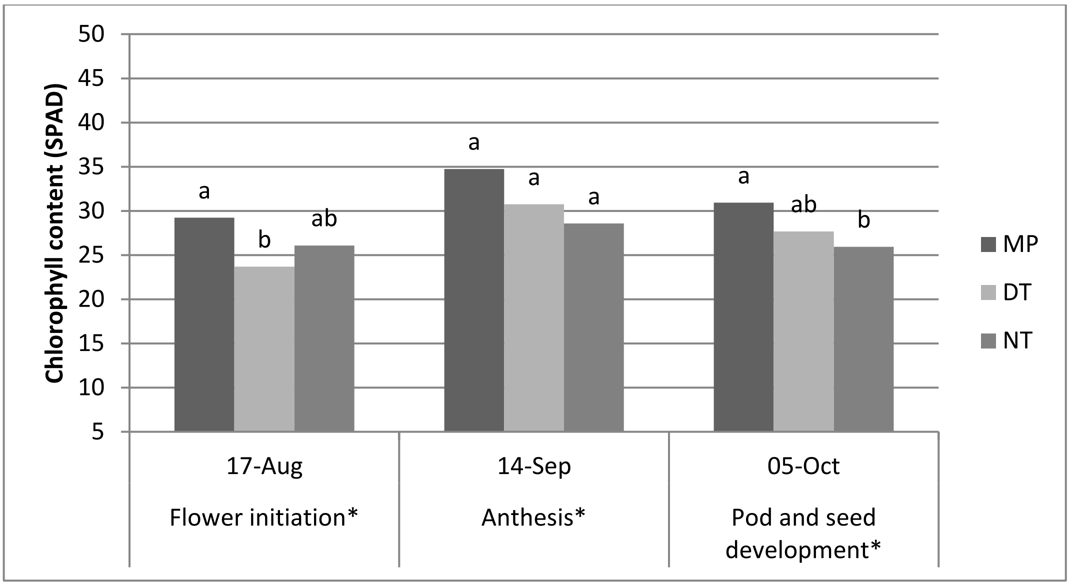
Tillage treatments applied in year 1 only resulted in differences in CC at flower initiation (60 days after planting) WLWC (Figure 3.2.9). DT resulted in lower (P=0.05) CC compared to MP. During year 2, DT resulted in significantly lower SPAD values 60 days after planting compared to MP treatments (Figure 3.2.10). MP caused significantly higher SPAD values during pod and seed development (120 days) compared to NT (Figure 3.2.10). Kesi and Pawel (2012) reported that tillage systems had no significant effect on chlorophyll (SPAD) values in corn.



	26-Jun	29-Jul	01-Sep
CV %	4.6222	1.4724	4.6080
LSD	2.9404	1.1224	3.4005

Figure 3.2.9: Chlorophyll content (SPAD) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level



	17-Aug	14-Sep	05-Oct
CV %	**9.0610**	**12.8069**	**10.2092**
LSD	**4.1287**	**6.9477**	**4.9782**

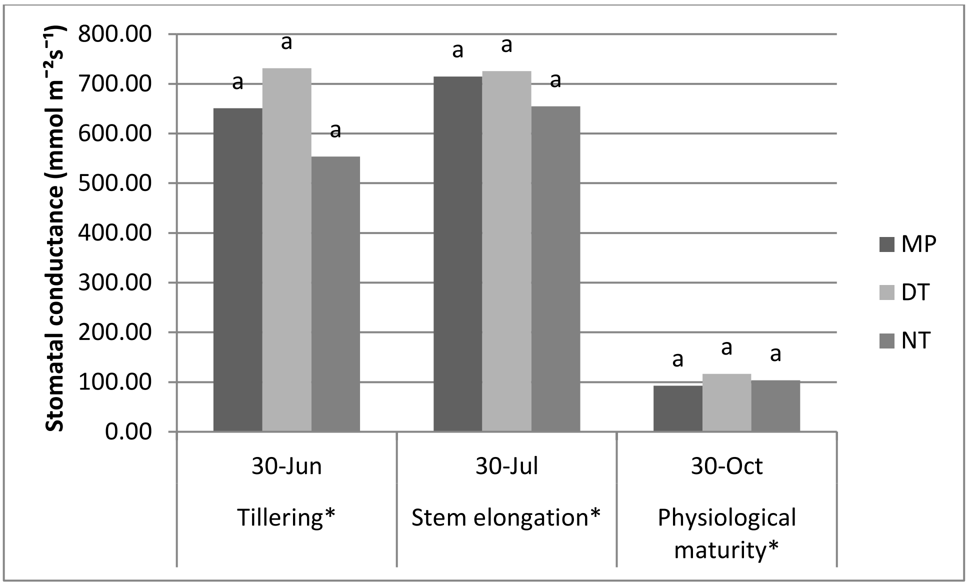
Figure 3.2.10: Chlorophyll content (SPAD) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

3.2.3. Stomatal conductance (SC)

Wheat and canola phases

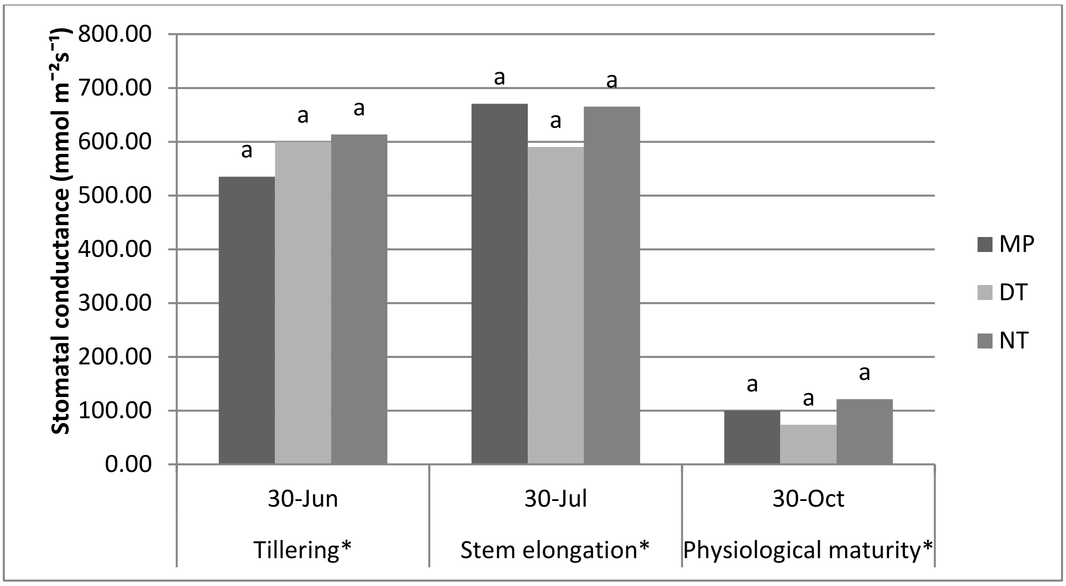
Mean stomatal conductance was not influenced (P=0.05) by tillage treatments in McWMcW, LWCW (Figures 3.2.11 and 3.2.12) and WLWC (Figure 3.2.13) for year 1. SC decreased during the last growth stages and Koc *et al*. (2004) reported that these effects can be related to the amount of nitrogen and water available to plants. As discussed in chapter 3.1, soil water and mineral nitrogen decreased as the season progressed and plants reach maturity. Fisher *et al.* (1998) found that higher grain yields were obtained with increase in SC because of an increase in the maximum photosynthetic rate. Prior *et al.* (2005) found that the amount of SC decreased in cotton plants with conventional tillage compared to no-till. Measurements on canola plants 120 days after planting (Figure 3.2.13) were not possible as leaves had already died off. Rabiee *et al.* (2004) found that during grain filling, leaves of canola die off and therefore photosynthesis took place in stems and pods and no longer by leaves.



	30-Jun	30-Jul	30-Oct
CV %	19.6957	12.7073	28.4168
LSD	219.9400	153.5500	51.3510

Figure 3.2.11: Stomatal conductance (mmol $m^{-2}s^{-1}$) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

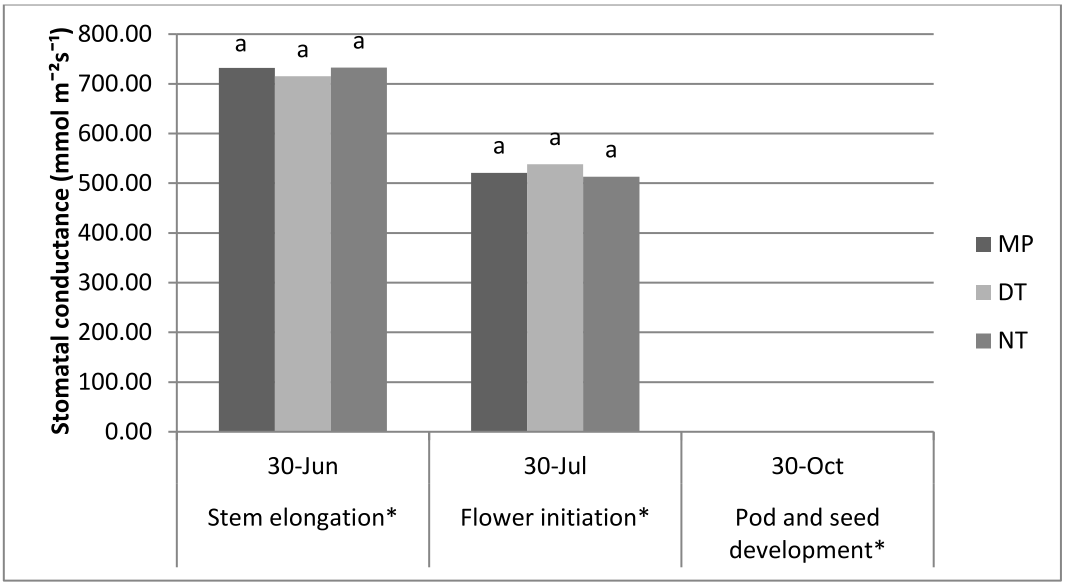
Bars with the same letter at the same date are not significantly different at 0.05 probability level



	30-Jun	30-Jul	30-Oct
CV %	13.6192	12.9280	28.5032
LSD	137.2500	143.5900	49.3170

Figure 3.2.12: Stomatal conductance (mmol $m^{-2}s^{-1}$) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level



	30-Jun	30-Jul	30-Oct
CV %	4.6629	18.5281	.
LSD	58.6160	168.09	.

Figure 3.2.13: Stomatal conductance (mmol $m^{-2}s^{-1}$) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm. (*Growth stage Anon. 2009).

Bars with the same letter at the same date are not significantly different at 0.05 probability level

3.2.4. Biomass production (BMP)

Wheat

Biomass production (BMP) data for year 1 is not available. The year 2 season however showed no significant differences (P=0.05) between tillage treatments in LWCW (Table 3.2.1). Wheat mean biomass production data is supported by the LI results of year 2 showing no differences between the tillage treatments tested. BMP varied between 8100 kg ha^{-1} to 8547 kg ha^{-1}. Kumudini *et al.* (2008) found similar results and also reported that no significant differences were recorded between tillage treatments. These results however contradict results found by Hemmat and Eskandari (2006) and Rieger *et al.* (2008) who reported that NT treatments tended to produce more biomass compared to CT treatments.

Table 3.2.1: Biomass production (kg ha^{-1}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(kg ha^{-1})
MP	8547 **a**
DT	8100 **a**
NT	8530 **a**
CV %	7.8652
LSD (Tillage)	1142.1000

Values followed by the same letter in column are not significantly different at the 0.05 probability level

Canola

Table 3.2.2 summarises mean biomass production of WLWC for year 1. The BMP for canola was taken at the end of pod and seed development (30 Oct). MP (6038 kg ha^{-1}) resulted in higher (P=0.05) biomass production than NT (4727 kg ha^{-1}) during year 2 (Table 3.2.3). Although the total BMP for the year 2 season was lower, MP had a significantly higher value compared to NT and DT (Table 3.2.3). Alizadeh and Allameh (2015) reported that tillage method had a significant effect on plant height and the maximum height was recorded with MP. Rabiee *et al.* (2004) also reported that because of the loss of leaves during grain filling stage the amount of BMP of plant will play a contributing role to the amount of photosynthetic potential. Photosynthetic potential of canola plants is thus dependent on the amount of shoots and pods during this stage (Chapter 3.3). Parameters that will influence BMP, among other are the relationship between growth and root penetration (Heikkinen & Auld, 1991). Jamshidian and Khajehpour (1999) reported that when roots penetrated deeper into soil because of tillage practice, these plants will produce considerably more vegetative growth.

Table 3.2.2: Biomass production (kg ha^{-1}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(kg ha^{-1})
MP	6038 **a**
DT	5549 **ab**
NT	4727 **b**
CV %	12.1945
LSD (Tillage)	114.7540

Values followed by the same letter in column arenot significantly different at the 0.05 probability level

Table 3.2.3: Biomass production (kg ha^{-1}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(kg ha^{-1})
MP	1716 **a**
DT	1402 **b**
NT	1476 **b**
CV %	9.5915
LSD (Tillage)	254.2100

Values followed by the same letter in column are not significantly different at the 0.05 probability level

Medic

Medic mean BMP for year 2 is illustrated in Table 3.2.4. No significant differences (P=0.05) were recorded between tillage treatments. Since medic have to regenerate every second year Kotzé *et al.* (1997) reported that MP could displace some medic seeds to deeper soil layers which could result in seedling emergence delays or unsuccessful seedling establishment and reduce the amount of BMP of the medic crop. This was however not recorded in this study when comparing the biomass production of different tillage practices.

Table 3.2.4: Biomass production (kg ha^{-1}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-medic/clover-wheat-medic/clover (WMcWMc) for year 2 growing season at Langgewens Research Farm.

Tillage practice	WMcWMc
	(kg ha^{-1})
MP	1609 **a**
DT	2255 **a**
NT	1946 **a**
CV %	51.9827
LSD (Tillage)	1742.4000

Values followed by the same letter in column are not significantly different at the 0.05 probability level

3.2.5. Initial root mass (IRM)

Wheat

The effect of tillage on mean initial root mass in wheat for year 1 is illustrated in table 3.2.5 and 3.2.6. No significant differences (P=0.05) were recorded between tillage treatments in McWMcW and LWCW. These results are in accordance with Wulfsohn *et al.* (1996) who reported that tillage did not increase root biomass.

Table 3.2.5: Initial root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	McWMcW
	(g m^{-3})
MP	158.36 **a**
DT	157.47 **a**
NT	141.58 **a**
CV %	17.5341
LSD (Tillage)	0.1318

Values followed by the same letter in column are not significantly different at the 0.05 probability level

Table 3.2.6: Initial root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(g m^{-3})
MP	141.00 **a**
DT	126.44 **a**
NT	158.37 **a**
CV %	23.0904
LSD (Tillage)	0.1616

Values followed by the same letter in column are not significantly different at the 0.05 probability level

Table 3.2.7 summarises mean initial root mass for year 2 in LWCW. DT increased IRM significantly (P=0.05) compared to MP. These increases could be because of roots penetrating easier into soil that was loosened the previous year. Benítez-Malvido *et al.* (2006) reported similar results and found an increase in penetration resistance in the topmost 10 cm layer under MP compared to DT. Qin *et al.* (2010) in contrast found that in sandy loam soils, MP could be associated with an increase in root mass in rice but only in the 0-5 cm layer.

Table 3.2.7: Initial root mass (g m^{-3}) as influenced by tillage namely mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(g m^{-3})
MP	258.15 **b**
DT	392.51 **a**
NT	333.30 **ab**
CV %	20.0157
LSD (Tillage)	0.3237

Values followed by the same letter in column are not significantly different at the 0.05 probability level

Canola

Tables 3.2.8 and 3.2.9 illustrate the effect of tillage on mean IRM in WLWC for year 1 and year 2 season. During both seasons, DT caused a significantly higher (P=0.05) mean initial root mass compared to NT. Although soil compacting was not tested in this study, Sarkees (2013) noted that by reducing soil compaction with tillage the development and growth of roots inside the soil profile increased. Bonari *et al.* (1995) reported similar results after comparing minimum-tillage with conventional tillage. Initial canola root growth is sensitive to poor seedbed establishment, this could decrease the biomass of roots effecting yield (Fooladivand *et al.,* 2009). Seedling emergence may be slows due to greater root penetration resistance of drier soil (Jamshidian & Khajehpour 1999).

Table 3.2.8: Initial root mass (g m^{-3}) as influenced by tillage namely mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(g m^{-3})
MP	44.37 **b**
DT	70.19 **a**
NT	35.01 **b**
CV % LSD (Tillage)	29.1826 0.0717

Values followed by the same letter in column are not significantly different at the 0.05 probability level

Table 3.2.9: Initial root mass (g m^{-3}) as influenced by tillage namely mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(g m^{-3})
MP	114.09 **ab**
DT	121.43 **a**
NT	99.57 **b**
CV % LSD (Tillage)	14.4631 0.0869

Values followed by the same letter in column are not significantly different at the 0.05 probability level

Medic

The effect of tillage on mean IRM in WMcWMc in year 2 is illustrated in Table 3.2.10. NT had a significantly higher (P=0.05) mean initial root mass compared to MP but did not differ significantly compared to DT. By comparing the biomass production in Table 3.2.4 with the IRM, it is not clear what the reason could be for the difference recorded in Table 3.2.10. It is suspected that MP tillage reduced the amount of seedlings on the soil surface causing seedling emergence delays. These delays could have reduced the amount of initial roots produced when samples was collected (Wiese 2013).

Table 3.2.10: Initial root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-medic/clover-wheat-medic/clover (WMcWMc) for year 2 growing season at Langgewens Research Farm.

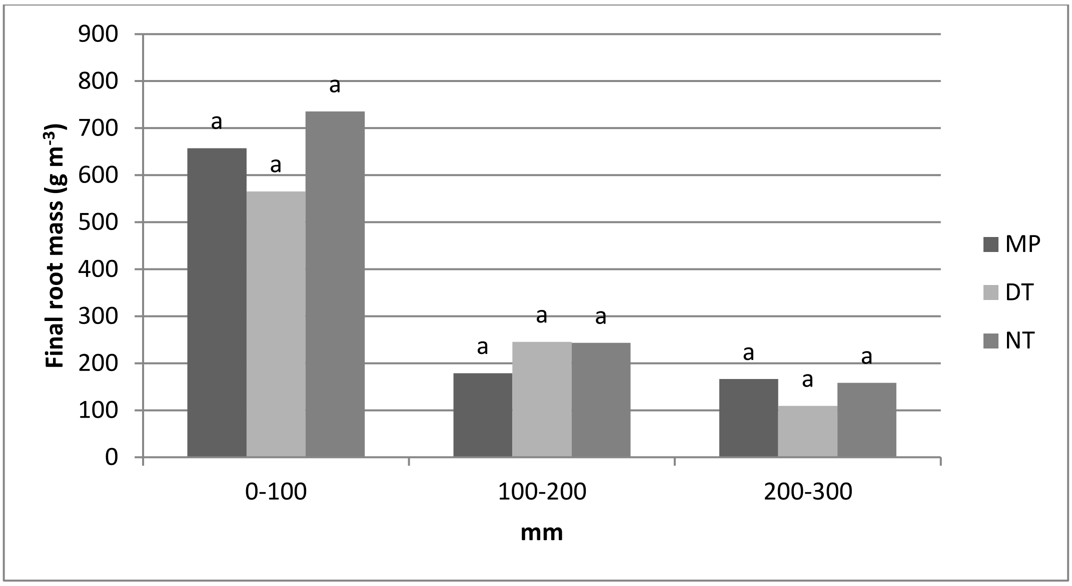
Tillage practice	WMcWMc
	(g m^{-3})
MP	97.12 **b**
DT	170.16 **ab**
NT	224.63 **a**
CV %	30.0770
LSD (Tillage)	0.2432

Values followed by the same letter in column are not significantly different at the 0.05 probability level

3.2.6. Final root mass (FRM)

Wheat

No significant differences (P=0.05) in final root mass in McWMcW rotation (Figure 3.2.14) were recorded between tillage treatments. In contrasts to these Barraclough and Weir (1988) found that root growth increased to the end of the season in ploughed treatments. The amount of roots (g m^{-3}) decreased with depth in all the tillage treatments although not statistically tested. This statement is similar to results reported by Vos & van der Putten (1998).

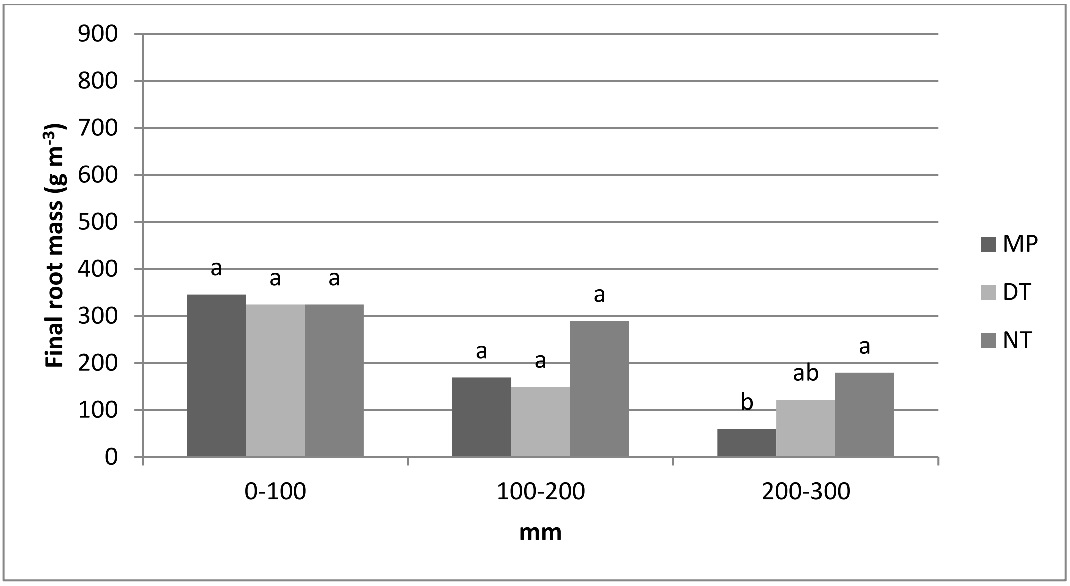


	0-100	100-200	200-300
CV %	81.2189	55.7417	88.5213
LSD	180.2015	42.2652	43.4563

Figure 3.2.14: Final root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Bars with the same letter at the same depth are not significantly different at 0.05 probability level

The mean FRM of LWCW for year 1 is illustrated in Figure 3.2.15. No significant differences (P=0.05) were recorded between 0 and 200 mm for MP, DT and NT. There were however significant differences for the 200 to 300 mm depth with NT having a significantly higher mean mass of roots (g m^{-3}) compared to MP. These results are similar to those reported by Barraclough and Weir (1988) who found that root lengths increased with incorporation of NT. As seen in Figure 3.2.14 the mass of roots decreased with depth. An observation was made that there was an increase in root biomass in the 0-100 mm depth in the McWMcW rotation compared to LWCW.

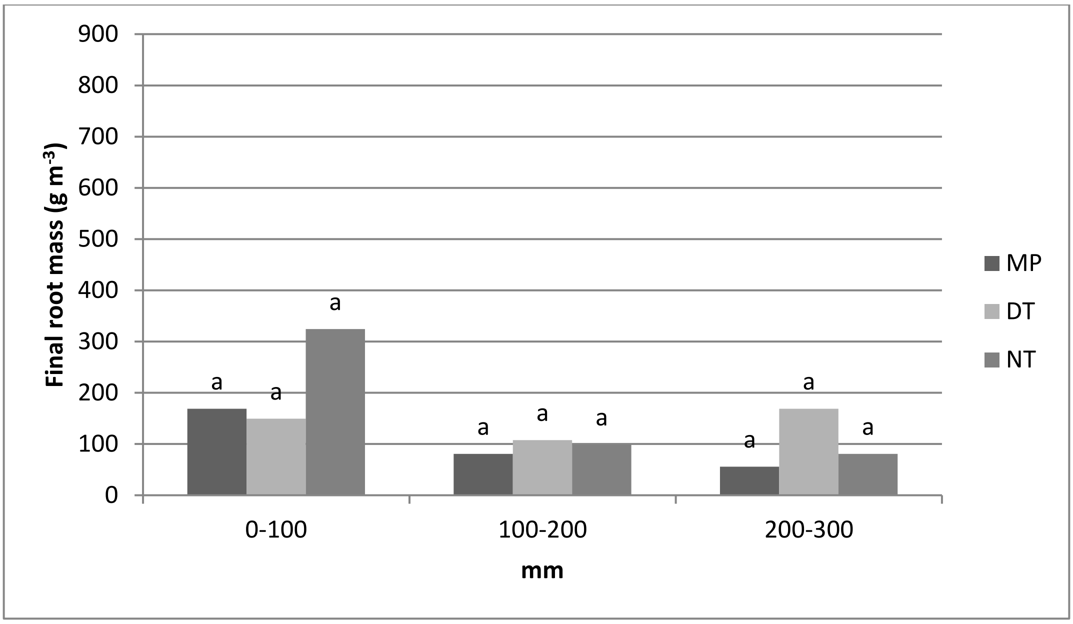


	0-100	100-200	200-300
CV %	56.0422	42.7789	36.5446
LSD	58.6160	29.4256	14.9255

Figure 3.2.15: Final root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 1 growing season at Langgewens Research Farm.

Bars with the same letter at the same depth are not significantly different at 0.05 probability level

The effect of tillage on mean FRM in LWCW during year 2 is represented in Figure 3.2.16. No significant differences (P=0.05) were recorded between tillage treatments and the mean mass of roots in the soil profile. A decrease of root mass with depth was recorded for year 2. These results was also recorded by Vos & van der Putten (1998).



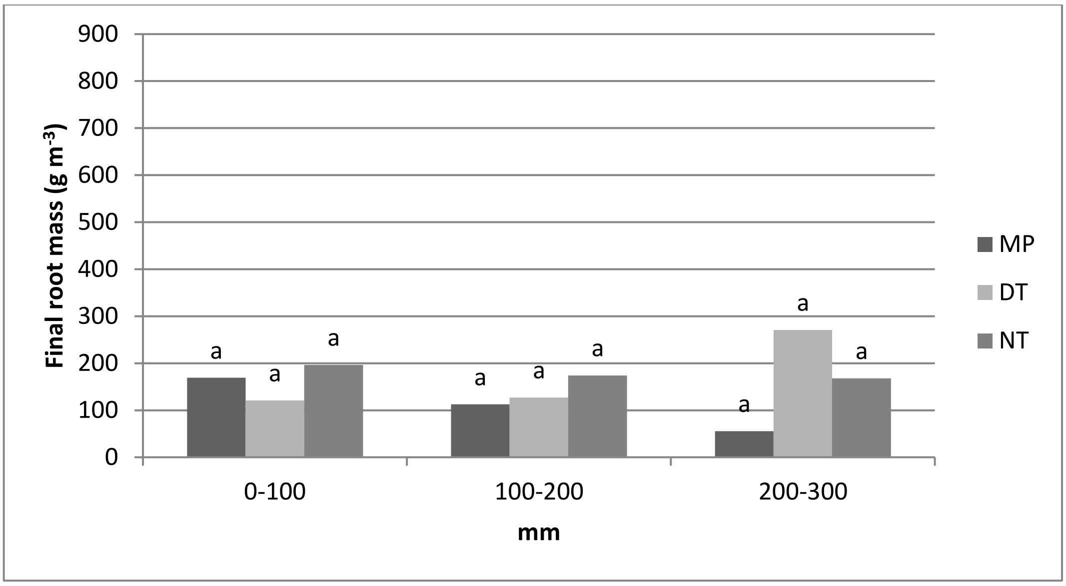
	0-100	100-200	200-300
CV %	**68.7758**	**25.9149**	**42.0307**
LSD	**49.9785**	**8.4225**	**9.1124**

Figure 3.2.16: Final root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same depth are not significantly different at 0.05 probability level

Canola

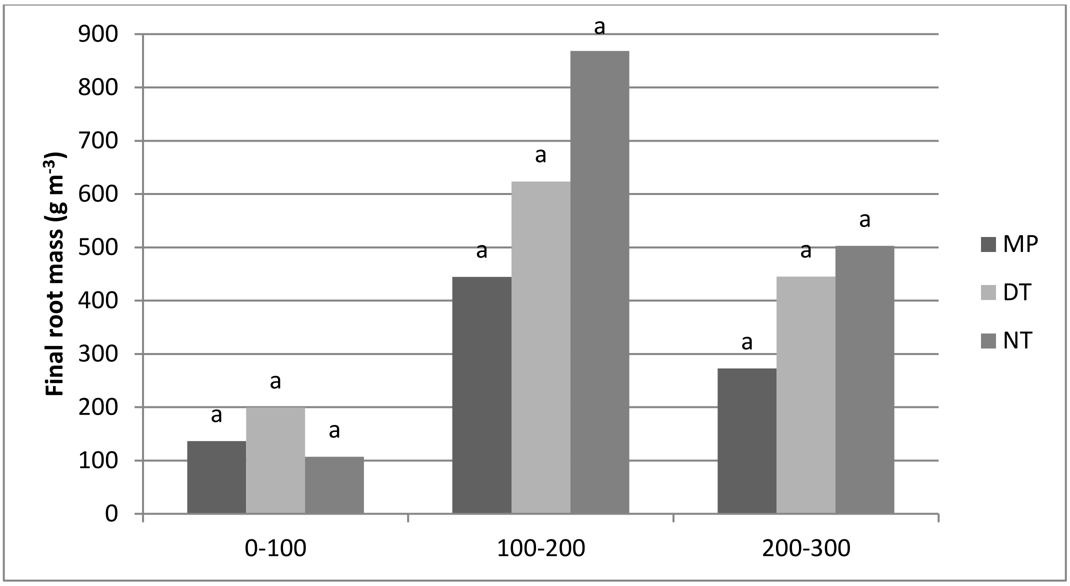
The mean FRM for WLWC during year 1 and year 2 seasons are illustrated in Figures 3.2.17 and 3.2.18. No significant differences (P=0.05) were recorded between tillage treatments for both seasons. The mean root mass was higher in year 2 compared to year 1. A possible reason for this observation is the severe drought of 2015 (year 2). The drier season increased root growth, development and root soil exploration as plants searched for water (Bescansa *et al.* 2006).



	0-100	100-200	200-300
CV %	103.4954	104.4003	197.7950
LSD	5.2452	4.0897	43.3029

Figure 3.2.17: Final root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Bars with the same letter at the same depth are not significantly different at 0.05 probability level



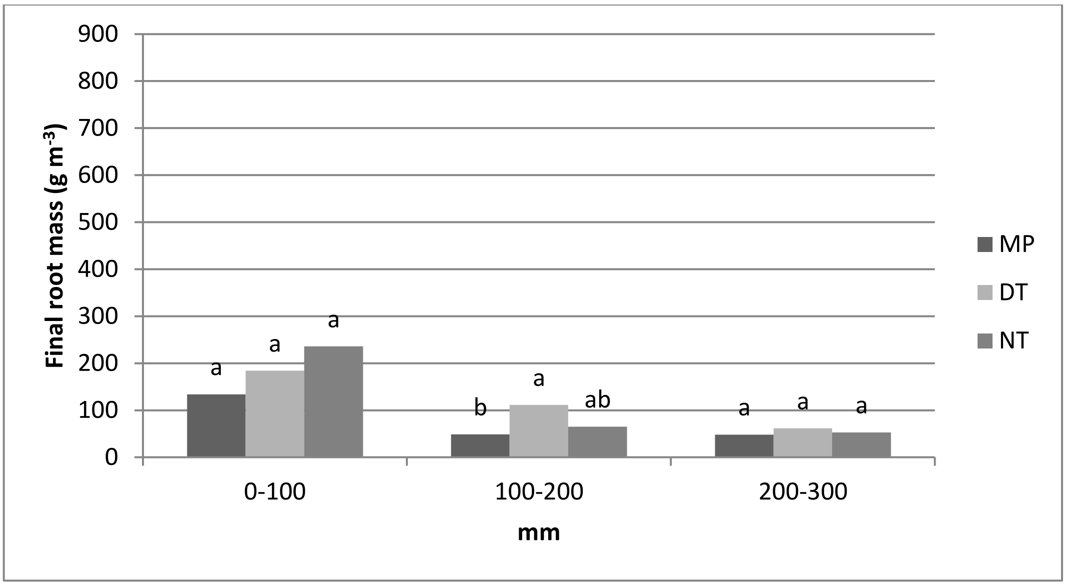
	0-100	100-200	200-300
CV %	38.8509	58.6546	49.9321
LSD	17.2121	120.6558	69.1592

Figure 3.2.18: Final root mass (g m^{-3}) as influenced by tillage namely mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same depth are not significantly different at 0.05 probability level

Medic

Figure 3.2.19 illustrates the effect of tillage on mean FRM of WMcWMc for year 2. No significant differences (P=0.05) were recorded between mean root mass for 0-100 mm and 200-300 mm layers. There was however a significant difference in the 100 to 200 mm ranges. MP resulted in significantly lower root mass compared to DT (Figure 3.2.19). Kotzé *et al.* (1997) reported similar results and found that MP could transport some medic seeds to deeper soil layers, which could have an effect on the amount of medic that establish and could reduce the amount of roots in the soil.



	0-100	100-200	200-300
CV %	50.3378	40.6497	68.5200
LSD	31.5368	40.5923	12.6489

Figure 3.2.19: Final root mass (g m^{-3}) as influenced by tillage namely: mouldboard plough (MP), deep tine (DT) and no-till (NT) in a wheat-medic/clover-wheat-medic/clover (WMcWMc) for year 2 growing season at Langgewens Research Farm.

Bars with the same letter at the same depth are not significantly different at 0.05 probability level

3.3. Wheat growth, development, yield and quality.

3.3.1. Seedling emergence and survival

According to the Langgewens Technical Committee Protocol (2014) the optimum number of wheat seedlings should vary between 120 and 175 per m^2 depending on crop rotation system. The number of seedlings in year 1 (Table 3.3.1) and year 2 (Table 3.3.2) was lower than the average recommended.

The number of seedlings recorded for year 1 varied between 92 and 111 per m^2 (Table 3.3.1) in LWCW and McWMcW respectively. Seedling emergence and survival were not significantly influenced by the treatments tested. Although not significant, NT resulted in a slightly higher number of seedling per m^2 compared to the other tillage treatments included in the study. The number of seedlings recorded for year 2 varied between 123 and 135 m^2 (Table 3.3.2). NT resulted in higher (P=0.05) seedling survival rates compared to MP, but did not differ from DT. Hemmat and Eskandari (2005) recorded significantly higher seedling survival rates with no-till treatments. In contrast to these findings, Rieger *et al.,* (2008) reported lower number of seedlings in no-till treatments compared to conventional treatments. Braunack & Dexter (1989) ascribed a lower seedling survival rate, under reduced tillage, to weak seed-soil contact resulting in lower germination percentage.

Table 3.3.1: Seedling emergence and survival per m² as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (per m²)	**LWCW (per m²)**	**Mean (Tillage) (per m²)**
MP	92.3	92.3	**92.3 a**
DT	107.5	101.3	**104.4 a**
NT	106.8	111.8	**109.3 a**
Mean (System)	**101.75 a**	**102.17 a**	
CV %	16.0683		
LSD (System)	22.2410		
LSD (Tillage)	17.8480		
LSD (System x Tillage)	25.2410		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.2: Seedling emergence and survival per m² as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(per m²)
MP	123.4 **b**
DT	130.5 **ab**
NT	135.0 **a**
CV %	12.3210
LSD (Tillage)	28.4420

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

3.3.2. Ear-bearing tillers per m²

The final number of wheat ears per m² is a good indicator of grain yield potential (Norwood, 2000). The number of ear-bearing tillers for year 1 varied between 198 per m² and 239 per m² (Table 3.3.3). MP and DT resulted in higher (P=0.05) mean ear-bearing tillers compared to NT. Research reported by Rieger *et al.,* (2008) is similar to this finding. According to Rieger *et al.,* (2008) a positive correlation exists between the amount of nitrogen supplied to the wheat crop and tiller formation and survival. Tillage practices, such as DT and MP, can potentially improve plant available nitrogen in soils and therefore can contribute to an increase in tiller formation and survival although it was not found in this study (see Chapter 3). However, during year 2 (Table 3.3.4) the number of ear-bearing tillers in NT was significantly higher compared to MP and DT. The higher amount of wheat ears in NT could be because of the higher seedling survival rate recorded in the beginning of year 2. Norwood (2000) also found that a higher number of seedlings per square metre increased the number of ear-bearing tillers.

In contrast, Hemmat and Eskandari (2005) reported that tillage compared to NT, reduced the number of ears per square metre significantly. Rieger *et al.,* (2008) however, reported that the average number of ears was slightly but not significantly lower in no-till systems.

Table 3.3.3: The number of ear-bearing tillers per m^2 as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (per m^2)	LWCW (per m^2)	Mean (Tillage) (per m^2)
MP	225.3	228.7	**227.0 a**
DT	234.0	239.1	**235.6 a**
NT	203.0	198.3	**200.6 b**
Mean (System)	**220.0 a**	**222.0 a**	
CV %	10.0087		
LSD (System)	60.427		
LSD (Tillage)	24.101		
LSD (System x Tillage)	34.084		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.4: The number of ear-bearing tillers per m² that reached maturity as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(per m^2)
MP	238.3 **b**
DT	241.8 **b**
NT	254.4 **a**
CV %	2.4257
LSD (Tillage)	11.3400

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.3.3. Spikelets per ear

Assimilate partitioning related to formation of spikelets takes place during tillering (Satorre & Slafer, 1999). The number of spikelets per ear can therefore be influenced by environmental conditions during spikelet initiation (van Biljon, 1987). Tillage treatments did not influence the number of spikelets per ear in year 1 (Table 3.3.5).

The expected positive effect of N-fixing legumes on spikelet initiation and survival did not materialise in year 2 (Table 3.3.6). The mean numbers of spikelets in McWMcW was non-significantly higher (P=0.05). In contrast, López-Bellido *et al.,* (2000) and Alijani *et al.,* (2012) recorded an increase in yield components and spikelets respectively when a N-fixing legume crop was included in the rotation.

Table 3.3.5: Number of spikelets per ear as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (per ear)	**LWCW (per ear)**	**Mean (Tillage) (per ear)**
MP	19.6	18.9	**19.3 a**
DT	19.2	18.8	**19 a**
NT	19.2	18.4	**18.8 a**
Mean (System)	**19.3 a**	**18.7 a**	
CV %	3.6727		
LSD (System)	0.8218		
LSD (Tillage)	0.7612		
LSD (System x Tillage)	1.0765		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.6: Number of spikelets per ear as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(per ear)
MP	18.1 **a**
DT	17.8 **a**
NT	17.3 **a**
CV %	4.1660
LSD (Tillage)	1.2777

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.3.4. Mean number of kernels per ear

The mean number of kernels per ear for year 1 varied between 58 and 67 per ear (Table 3.3.7). NT resulted in significantly higher (P=0.05) mean number of kernels per ear compared to DT. These results are in accordance with results found by Hemmat and Eskandari (2005) who reported a significant increase in number of kernels per ear with NT. There were no significant differences between rotation systems and the mean number of kernels per ear for year 1. Tillage did not influence the number of kernels per ear in year 2 (Table 3.3.8), similar to findings by Rieger *et al.,* (2008) who found that tillage had no significant effect on the number of kernels per ear. Alijani *et al.,* (2012) reported that nitrogen rates applied were the only factor which significantly increased the number of kernels per ear and not tillage.

Table 3.3.7: The number of grains per ear as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (per ear)	**LWCW (per ear)**	**Mean (Tillage) (per ear)**
MP	63.9	62.9	**63.4 ab**
DT	58.4	64.7	**62 b**
NT	67.2	66.3	**66 a**
Mean (System)	**63.6 a**	**64.6 a**	
CV %	5.3584		
LSD (System)	1.9628		
LSD (Tillage)	3.8697		
LSD (System x Tillage)	5.4932		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.8: The number of grains per ear as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(per ear)
MP	42.7 **a**
DT	43.1 **a**
NT	42.4 **a**
CV %	9.6053
LSD (Tillage)	7.1071

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.3.5. Thousand Kernel Mass (TKM)

Thousand kernel mass is a good indicator of environmental and soil factors influencing crop growth after anthesis (Wiatrak *et al.,* 2006). Tillage and rotation had no significant effect (P=0.05) on mean TKM in year 1 (Table 3.3.9). These findings are in accordance with results reported by Wiatrak *et al.,* (2006) who found no significant changes in the TKM due to different tillage practices. During year 2 significant differences were however recorded (Table 3.3.10). NT had a significantly higher TKM compared to MP. In contrast to these findings, Rieger *et* *al.,* (2008) found the TKM decreased in treatments receiving no-till compared to conventional and minimum-tillage. A reduction in mass per grain may also be a result of infestation by *Fusarium*, (Parry *et al.,* 1995), but no symptoms were observed during the current study.

Table 3.3.9: TKM (g) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (g)	LWCW (g)	Mean (Tillage) (g)
MP	40.2	43.3	**41.8 a**
DT	41.3	41.8	**41.6 a**
NT	41.3	41.9	**41.6 a**
Mean (System)	**40.9 a**	**42.4 a**	
CV %	4.6152		
LSD (System)	2.3014		
LSD (Tillage)	2.1652		
LSD (System x Tillage)	3.0737		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.10: TKM (g) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(g)
MP	27.2 **b**
DT	27.3 **ab**
NT	29.1 **a**
CV %	3.2329
LSD (Tillage)	1.7298

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.3.6. Grain yield

Grain yield was not influenced by the treatment combinations in year 1 (Table 3.3.11). Although not significant, grain yield for MP was the highest followed by DT compared to NT. *Rieger et al.,* (2008) found that no-till resulted in significantly lower grain yields than conventional and minimum-tillage. During year 2 NT had a significantly higher (P=0.05) mean yield compared to DT and MP (Table 3.3.12). The current findings are similar to results reported by Mrabet (2000) who found that NT resulted in increased yield compared to DT and MP. In the current study it was expected that higher crop residue cover in NT would result in better water infiltration and less evaporation, very important factors during year 2. The results show that water content in year 2 was significantly higher on the 20 August in NT (Chapter 3.1).

Table 3.3.11: The grain yield (kg ha^{-1}) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (kg ha^{-1})	LWCW (kg ha^{-1})	Mean (Tillage) (kg ha^{-1})
MP	4066	3800	**3932.9 a**
DT	3925.4	3802	**3863.7 a**
NT	3888	3656	**3772 a**
Mean (System)	**3956.8 a**	**3752.6 a**	
CV %	6.5563		
LSD (System)	709.8600		
LSD (Tillage)	275.4300		
LSD (System x Tillage)	389.5200		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.12: The grain yield (kg ha^{-1}) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(kg ha^{-1})
MP	2004.7 **b**
DT	2108.3 **b**
NT	2378.1 **a**
CV %	5.5392
LSD (Tillage)	207.37

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.3.7. Grain protein

Wheat protein is an important wheat quality parameter. Grain protein content was higher than the minimum content required by the South African baking industry for both years covered by the study (Tables 3.3.13 and 3.3.14) (Anon. 2012b). Mean grain protein content was not influenced by tillage in year 1 (Table 3.3.13). There was however significant influences on crop rotations and mean grain protein for year 1. McWMcW resulted in higher (P=0.05) mean protein content compared to LWCW. The higher protein content reported in McWMcW can be ascribed to the expected higher soil nitrogen content as a result of the legume (medic) every alternate year compared to lupin every fourth year in LWCW (Chapter 3.1). Year 2 however showed significant increases in protein contents with DT and MP (Chapter 3.1). During year 2 mineral nitrogen content was higher at two sampling dates (14 July and 21 September) in MP and the 21 September for DT (Figure 3.1.9). throughout the growing season. Rieger *et al.,* (2008) reported similar findings and found a slight increase in grain protein with conventional tillage although not significantly so. Rharrabti *et al.,* (2001) reported that wheat protein is negatively correlated with yield.

Table 3.3.13: Grain protein (%) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (%)	**LWCW (%)**	**Mean (Tillage) (%)**
MP	11.5	10.9	**11.2 a**
DT	12.4	10.5	**11.5 a**
NT	11.8	10.6	**11.2 a**
Mean (System)	**11.92 a**	**10.66 b**	
CV %	4.5061		
LSD (System)	0.8061		
LSD (Tillage)	0.5543		
LSD (System x Tillage)	0.7839		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.14: Grain protein (%) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(%)
MP	15.1 **a**
DT	15.0 **a**
NT	12.8 **b**
CV % LSD (Tillage)	3.8695 0.9569

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.3.8. Hectolitre mass

Hectolitre mass was not influenced by the treatments in year 1 (Table 3.3.15) as was also reported by Hemmat & Eskandari (2005). During year 2 NT resulted in significantly higher (P=0.05) mean hectolitre mass compared to MP (Table 3.3.16). This however could have been the effect of the drought during year 2 where NT preserved more water efficiently in the profile (Chapter 3.1). Lampurlanés & Cantero-Martínez (2003) found similar results and reported that NT increased water preservation in soil compared to DT and MP.

Table 3.3.15: Hectolitre mass (kg hl^{-1}) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) and medic/clover-wheat-medic/clover-wheat (McWMcW) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequences		
	McWMcW (kg hl^{-1})	LWCW (kg hl^{-1})	Mean (Tillage) (kg hl^{-1})
MP	79.6	79.7	**79.7 a**
DT	78.9	79.9	**79.4 a**
NT	79.6	79.6	**79.6 a**
Mean (System)	**79.3 a**	**79.7 a**	
CV %	0.9473		
LSD (System)	1.7352		
LSD (Tillage)	0.8207		
LSD (System x Tillage)	1.1606		

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.3.16: Hectolitre mass (kg hl^{-1}) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a lupin-wheat-canola-wheat (LWCW) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	LWCW
	(kg hl^{-1})
MP	73.2 **b**
DT	73.6 **ab**
NT	75.4 **a**
CV %	1.3608
LSD (Tillage)	1.7434

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.4. Canola growth, development, yield and quality.

3.4.1. Seedling emergence and survival per m^2

According to the Langgewens Technical Committee Protocol (2014) the optimum number of canola seedlings should vary between 38 and 70 per m^2 depending on crop rotation system. Although the number of seedlings per m^2 in year 1 (39 per m^2) and year 2 (50 per m^2) was lower than the average recommended by the Langgewens Technical Committee Protocol (2014) it was still within the acceptable range. The seedling survival rate 3 weeks after germination for year 1 and year 2 are summarised in Tables 3.4.1 and 3.4.2 Seedling emergence and survival rate was not influenced by the tillage treatments tested. In contrast, Alizadeh and Allameh (2015) reported that seedling emergence and survival was positively influenced by an increase in seed soil contact found in tilled treatments.

Table 3.4.1: Seedling emergence and survival per m^2 as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	**WLWC**
	(per m^2)
MP	40.3 **a**
DT	36.3 **a**
NT	42.5 **a**
CV % LSD (Tillage)	26.8056 18.3590

Values followed by the same letter in column are not significantly different at 0.05 probability level

Table 3.4.2: Seedling emergence and survival per m^2 as influenced by tillage namely mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	**WLWC**
	(per m^2)
MP	47.6 **a**
DT	52.0 **a**
NT	51.6 **a**
CV % LSD (Tillage)	10.6931 9.3236

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.4.2. Number of pods

Chay and Thurling (1989) reported that the number of pods per canola plant was of most importance in yield production because of their effect on photosynthesis and seed storage, thus the assumption can be made that the higher the number of pods, the more photosynthetic potential the plant developed. Ilkaee and Imam (2003) found that an increase in the number of pods indicated increases in the number of branches per plant, improving biomass production.

The mean number of pods per m^2 recorded for year 1 growing season did not differ significantly (P=0.05) between tillage treatments (Table 3.4.3). Treatments that received tillage showed a slight, not significant, increase in pod numbers per m^2 compared to NT. During year 2 MP and DT resulted in significantly higher (P=0.05) mean pod numbers per m^2 compared to NT (Table 3.4.4). Alizadeh and Allameh (2015) reported an increase in the number of pods with MP and a decrease in the number of pods with NT.

Table 3.4.3: Number of pods per m^2 as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(per m^2)
MP	7852.0 **a**
DT	9217.0 **a**
NT	6723.0 **a**
CV %	30.9582
LSD (Tillage)	4248.2000

Values followed by the same letter in row are not significantly different at 0.05 probability level

Table 3.4.4: Number of pods per m^2 as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(per m^2)
MP	6733.0 **a**
DT	7030.4 **a**
NT	6305.5 **b**
CV % LSD (Tillage)	20.2592 401.0180

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.4.3. Seeds per pod

The mean number of seeds per pod for year 1 growing season is summarised in Table 3.4.5. The number of seeds per pod varied between 18 per pod and 19 per pod. Tillage did not influence (P=0.05) the number of seeds per pod. Similar results were obtained for year 2 with no significant differences between tillage treatments (Table 3.4.6). Alizadeh and Allameh (2015) also reported no significant difference in the number of seeds per canola pod recorded between tillage treatments.

Table 3.4.5: Number of seeds per pod as influenced by tillage namely mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(per pod)
MP	19.1 **a**
DT	18.0 **a**
NT	18.0 **a**
CV % LSD (Tillage)	13.9722 4.4446

Values followed by the same letter in column are not significantly different at 0.05 probability level

Table 3.4.6: Number of seeds per pod as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(per pod)
MP	17.5 **a**
DT	19.2 **a**
NT	17.6 **a**
CV % LSD (Tillage)	9.4729 2.9701

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.4.4. Seed yield

The effect of tillage treatments on mean canola seed yield (kg ha^{-1}) is summarised in Table 3.4.7. Since Alizadeh and Allameh (2015) reported a significant canola yield increase with additional tillage, the results of this study were expected, even though it was not significantly (P=0.05). Hosseini *et al.,* (2006) suggested that yield increases were the result of enhanced plant establishment in tilled fields, although results recorded in this study showed no significant differences in plant establishment (Table 3.4.1 and Table 3.4.2). During year 2 MP increased yield slightly although not significantly so (Table 3.4.8). Sarkees (2013) reported that yield increased with tillage because of an increase in root penetration, development and exposure to more nutrients and water as compaction was reduced, which could have been the contributing factor for slight yield increases in the current study, although these increases were not significant.

Table 3.4.7: The seed yield (kg ha^{-1}) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(kg ha^{-1})
MP	2131.3 **a**
DT	2043.8 **a**
NT	1913.0 **a**
CV % LSD (Tillage)	10.5478 370.3500

Values followed by the same letter in column are not significantly different at 0.05 probability level

Table 3.4.8: The seed yield (kg ha^{-1}) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(kg ha^{-1})
MP	1529.4 **a**
DT	1409.9 **a**
NT	1415.9 **a**
CV %	18.1279
LSD (Tillage)	455.3500

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.4.5. Thousand Seed Mass (TSM)

The tillage treatments tested did not influence (P=0.05) mean TSM in both years of the study (Tables 3.4.9 and 3.4.10). Alizadeh and Allameh (2015) in contrast found significant differences between tillage treatments with NT resulting in the lowest TSM compared to MP in canola.

Table 3.4.9: Thousand seed mass (g) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(g)
MP	2.99 **a**
DT	2.86 **a**
NT	2.84 **a**
CV %	8.7729
LSD (Tillage)	0.4397

Values followed by the same letter in column are not significantly different at 0.05 probability level

Table 3.4.10: Thousand seed mass (g) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(g)
MP	2.94 **a**
DT	2.86 **a**
NT	2.87 **a**
CV % LSD (Tillage)	3.9101 0.1955

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.4.6. Oil content

The oil content of canola (%) is summarised in Tables 3.4.11 and 3.4.12 for year 1 and year 2. During the year 1 season significant differences (P=0.05) were recorded. NT resulted in significantly higher mean oil content compared to MP but did not differ significantly from DT. Hosseini *et al.,* (2006) in contrast reported that the degree of tillage significantly increased the percentage oil compared to NT. These authors reasoned that NT increased the rate of N immobilisation as well as a higher amount of soluble C and N, causing microorganisms to have a higher amount of C and N available, a situation resulting in lower oil content. During year 2 no significant differences were recorded between tillage treatments.

Table 3.4.11: Percentage oil (%) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 1 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(%)
MP	39.6 **b**
DT	40.1 **ab**
NT	40.5 **a**
CV % LSD (Tillage)	1.2963 0.8989

Values followed by the same letter in column are not significantly different at 0.05 probability level

Table 3.4.12: Percentage oil (%) as influenced by tillage namely: mouldboard (MP), deep tine (DT) and no-till (NT) in a wheat-lupin-wheat-canola (WLWC) system for year 2 growing season at Langgewens Research Farm.

Tillage practice	WLWC
	(%)
MP	37.0 **a**
DT	36.1 **a**
NT	37.2 **a**
CV %	2.7079
LSD (Tillage)	1.7230

Values followed by the same letter in column are not significantly different at 0.05 probability level

3.5. Weed populations

3.5.1. Seed bank study

Year 1

Table 3.5.1 illustrates the number of *Lolium multiflorum* for subplots before a once-off strategic tillage. No significant differences (P=0.05) were recorded between subplots before tillage was aplied. This is a good indication that the number of *Lolium multiflorum* infestation was consequent for each crop rotation before tillage was applied to each plot. Plots that had a wheat crop in 2013 had significantly higher amounts of *Lolium multiflorum* compared to plots that had canola. O'Gara, (2010) found that *Lolium multiflorum* and other grass weed species are harder to control during wheat phases because of similarity in phenotypes.

Table 3.5.1: The number of *Lolium multiflorum* weeds per m^2 counted under shade from soil collected in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system before mouldboard (MP), deep tine (DT) and no-till (NT) tillage was applied to plots for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	WLWC	McWMcW	LWCW	
MP	30.3	14.4	11.4	**21.3 a**
DT	22.4	26	15.5	**21.3 a**
NT	19.9	17.5	13.6	**17.1 a**
Mean (System)	**24.4 a**	**19.3 ab**	**13.4 b**	
CV %	59.2922			
LSD (System)	12.242			
LSD (Tillage)	6.0170			
LSD (System x Tillage)	10.4420			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

The number of *Polygonum aviculare* and *Vicia sativa* before a once-off strategic tillage is illustrated in Table 3.5.2 and 3.5.3. No significant differences (P=0.05) were recorded between subplots before tillage was applied. This indicates that there was no differences between between sub-plots before treatments were applied. *Polygonum aviculare* and *Vicia sativa* are broadleaved species and can be easily controlled by incorporation of crop rotations with a grass species (Anon. 2012). The number of *Polygonum aviculare* recorded for LWCW was significantly higher than McWMcW and WLWC because of canola crop grown in 2013 (year before strategic tillage).

Table 3.5.2: The number of *Polygonum aviculare* weeds per m^2 counted under shade net from soil collected in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system before mouldboard (MP), deep tine (DT) and no-till (NT) tillage was applied to plots for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	WLWC	McWMcW	LWCW	
MP	7.3	0.5	29.0	**12.3 a**
DT	8.0	0.3	41.5	**16.6 a**
NT	6.5	0.8	45.3	**17.5 a**
Mean (System)	**7.3 a**	**0.5 a**	**38.4 a**	
CV %	32.0525			
LSD (System)	26.7380			
LSD (Tillage)	8.6984			
LSD (System x Tillage)	17.6940			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Table 3.5.3: The number of *Vicia sativa* weeds per m^2 counted under shade net from soil collected in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system before mouldboard (MP), deep tine (DT) and no-till (NT) tillage was applied to plots for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	WLWC	McWMcW	LWCW	
MP	1	0.8	0.3	**0.7 a**
DT	0.5	0.3	2	**0.9 a**
NT	0.8	0.3	1.8	**1.0 a**
Mean (System)	**0.8 a**	**0.5 a**	**1.4 a**	
CV %	79.4706			
LSD (System)	13.2545			
LSD (Tillage)	15.1060			
LSD (System x Tillage)	13.5839			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Year 2

During year 2 significant differences were recorded between tillage treatments and crop rotation under shade netting (Table 3.5.4). Wheat after medic in McWMcW showed a significant increase in the number of *Lolium multiflorum* seedlings compared to LWCW. The number of *Lolium multiflorum* seedlings also reduced with incorporation of a strategic tillage the previous year (year 1). MP had a significantly lower number of *Lolium multiflorum* seedlings compared to NT. The reduction could have been the effect of MP removing *Lolium multiflorum* seeds from the surface and thus reducing the seed population that could germinate.

Table 3.5.4: The number of *Lolium multiflorum* weeds per m^2 counted under shade net from soil collected in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system after mouldboard (MP), deep tine (DT) and no-till (NT) tillage was applied to plots for year 2 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	LWCW	WMcWMc	WLWC	
MP	14.5	3.5	17.8	**11.9 b**
DT	13.3	3.8	44.3	**20.5 ab**
NT	20.0	4.0	52.0	**25.3 a**
Mean (System)	**15.6 b**	**3.8 b**	**38.0 a**	
CV %	89.5426			
LSD (System)	16.5642			
LSD (Tillage)	9.6544			
LSD (System x Tillage)	13.3235			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

The effect of a once-off tillage on the number of *Polygonum aviculare* seedlings is illustrated in Table 3.5.5. MP had a significantly (P=0.05) lower number of *Polygonum aviculare* seedlings infestation compared to DT and NT. These reductions could be the result of the inversion effect of mouldboard that can bury seed to depths where germination is inhibited. Santín Montanyá & Catalán (2006) reported similar findings with a decrease in weed infestation with plots receiving MP.

Table 3.5.5: The number of *Polygonum aviculare* weeds per m^2 counted under shade net from soil collected in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system after mouldboard (MP), deep tine (DT) and no-till (NT) tillage was applied to plots for year 2 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	LWCW	WMcWMc	WLWC	
MP	35.3	36.0	24.0	**31.8 b**
DT	38.8	65.0	41.5	**48.4 a**
NT	60.0	48.3	54.3	**54.2 a**
Mean (System)	**44.7 a**	**49.8 a**	**39.9 a**	
CV %	21.2542			
LSD (System)	18.6582			
LSD (Tillage)	25.6777			
LSD (System x Tillage)	23.5648			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

The number of *Vicia sativa* weeds is illustrated in Table 3.5.6. No significant differences (P=0.05) were recorded between tillage treatment and crop rotations for year 2. Bàrberi *et al.,* (2001) reported that annual dycotyledonous plants could be easily controlled by herbicides compared to annual grasses and perennial weeds.

Table 3.5.6: The number of *Vicia sativa* weeds per m^2 counted under shade net from soil collected in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system after mouldboard (MP), deep tine (DT) and no-till (NT) tillage was applied to plots for year 2 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	LWCW	WMcWMc	WLWC	
MP	**0.3**	**0.0**	**0.0**	**0.1 a**
DT	**0.8**	**0.0**	**0.3**	**0.4 a**
NT	**0.0**	**0.0**	**0.0**	**0.0 a**
Mean (System)	**0.4 a**	**0.0 a**	**0.1 a**	
CV %	88.6546			
LSD (System)	1.2544			
LSD (Tillage)	0.1554			
LSD (System x Tillage)	0.8971			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

3.5.2. In field

Year 1

Table 3.5.7 shows results of a once-off strategic tillage on the number of *Lolium multiflorum* weeds in the first year after tillage. MP reduced *Lolium multiflorum* seedlings significantly compared to NT. DT did not have a significant effect on the amount of *Lolium multiflorum* compared to the control (NT). Similar results were also observed by Kettler *et al.,* (2000) and Kirkegaard *et al*., (2016) with results showing a 40% to 90% reduction in weed species with incorporation of strategic MP tillage. McLean *et al.,* (2012) also reported a reduction in the number of glyphosate-resistant weeds with incorporation of MP tillage. Crop rotation significantly reduced the number of *Lolium multiflorum* seedlings observed three weeks after planting. LWCW and McWMcW had the lowest number of *Lolium multiflorum* seedlings compared to WLWC. This sinificant reduction in *Lolium multiflorum* was a result of more effective control of grass weed species during broadleaf crop production (Llewellyn *et al.,* 2012).

Table 3.5.7: The number of *Lolium multiflorum* weeds per m² counted in field three weeks after planting in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system and tillage namely: Inversion tillage (MP), Non-inversion tillage (DT) and No-till (NT) for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	WLWC	McWMcW	LWCW	
MP	212.6	2.2	0.8	**71.87 b**
DT	433.4	6	11.8	**150.4 ab**
NT	555.8	20.4	10.2	**195.47 a**
Mean (System)	**400.6 a**	**9.53 b**	**7.6 b**	
CV %	75.8559			
LSD (System)	170.51			
LSD (Tillage)	90.5940			
LSD (System x Tillage)	156.9100			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

The number of broadleaved weed species that could be identified in field is illustrated in Table 3.5.8. No significant differences (P=0.05) were recorded between tillage treatments and crop rotations.

Table 3.5.8: The number of broadleaf weeds per m² counted in field three weeks after planting in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system and tillage namely: Inversion tillage(MP), Non-inversion tillage(DT) and No-till (NT) for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	WLWC	McWMcW	LWCW	
MP	0.0	0.0	0.0	**0.0 a**
DT	0.0	0.0	0.2	**0.1 a**
NT	0.0	0.0	10.2	**3.4 a**
Mean (System)	**0.0 a**	**0.0 a**	**3.5 a**	
CV %	20.2554			
LSD (System)	1.0256			
LSD (Tillage)	2.2545			
LSD (System x Tillage)	1.9585			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

The number of unidentified weeds species in Table 3.5.9. Significant differences (P=0.05) were recorded between tillage treatments. MP and NT had lower number of weed infestation compared to DT. Kettler *et al.,* (2000) reported that DT did not significantly reduce weed infestation compared to MP. By incorporating NT the number of weed seeds can easily be controlled because they are not removed from the soil surface. Llewellyn *et al.,* (2012) reported that if conditions are favourable these seeds will germinate quicker and be able to be controlled by pre - emergence herbicides. WLWC cropping sequence had significantly higher number of weeds compared to McWMcW and LWCW. Although there is not a clear explanation for this, these differences could be because of wheat planted the previous year.

Table 3.5.9: The number of unidentified weeds per m^2 counted in field three weeks after planting in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system and tillage namely: Inversion tillage (MP), Non-inversion tillage(DT) and No-till (NT) for year 1 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	WLWC	McWMcW	LWCW	
MP	32.0	16.6	20.6	**23.1 b**
DT	142.6	50.2	27.8	**73.5 a**
NT	46.4	66.8	4.2	**39.1 b**
Mean (System)	**73.7 a**	**44.5 b**	**17.3 b**	
CV %	67.8035			
LSD (System)	30.5640			
LSD (Tillage)	26.3120			
LSD (System x Tillage)	45.5730			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Year 2

Table 3.5.10 illustrate the effect of tillage on *Lolium multiflorum* seedlings the second year after tillage and cropping sequence were applied (year 2). A significant reduction in the number of *Lolium multiflorum* was observed during year 2, which indicates that the strategic tillage reduced the number of seeds that could germinate for two consecutive years. These results were also found by Kettler *et al.,* (2000) who indicated a positive reduction in weed seed banks with incorporation of tillage. In contrast to previous results, the number of *Lolium multiflorum* seedlings increased in LWCW and WMcWMc plots that had LWCW compared to McWMcW. The reason for this is not clear, but could be an indication that the McWMcW crop rotation generally had a lower number of *Lolium multiflorum* weeds compared to LWCW.

Table 3.5.10: The number of *Lolium multiflorum* weeds per m^2 counted in field three weeks after planting in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system and tillage namely: Inversion tillage (MP), Non-inversion tillage (DT) and No-till (NT) for year 2 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	LWCW	**WMcWMc**	**WLWC**	
MP	19.8	8.8	9.0	**12.5 b**
DT	24.0	5.3	13.3	**14.2 b**
NT	45.3	11.5	61.8	**39.4 a**
Mean (System)	**29.7 a**	**8.5 b**	**28.0 a**	
CV %	13.5478			
LSD (System)	7.0217			
LSD (Tillage)	18.2447			
LSD (System x Tillage)	15.3336			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

Tillage had no significant effect (P=0.05) on the mean number of broadleaf weed species (Table 3.5.11). There were however significant differences recorded between crop rotations. WLWC had the lowest number of broadleaf weed species compared to WMcWMc and LWCW. The reason could be that more effective broadleaf weed control was achieved in WLWC as previously reported by Anonymous, (2012).

Table 3.5.11: The number of broadleaf weeds per m^2 counted in field three weeks after planting in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system and tillage namely: Inversion tillage (MP), Non-inversion tillage (DT) and No-till (NT) for year 2 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	LWCW	WMcWMc	WLWC	
MP	9.5	8.3	0	**5.9 a**
DT	11.8	9	0.3	**7 a**
NT	1.5	17.3	0.3	**6.4 a**
Mean (System)	**7.6 a**	**11.5 a**	**0.2 b**	
CV %	23.5799			
LSD (System)	6.9023			
LSD (Tillage)	3.2547			
LSD (System x Tillage)	5.4578			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

The effect of tillage and crop rotation on the mean number of unidentifiable weed species (other) is illustrated in Table 3.5.12. Although this result cannot be explained, NT significantly (P=0.05) reduced the number of other weeds compared to MP. Bàrberi *et al.,* (2001) reported that with incorporation of NT tillage the number of weed seeds is allocated in the 0 – 5 cm layer, this causes uniform germination and control with herbicides is more effective. LWCW and WMcWMc cropping sequences significantly reduced the number of unidentifiable weed species during year 2.

Table 3.5.12: The number of unidentified weeds per m^2 counted in field three weeks after planting in a lupin-wheat canola (WLWC), medic/colver-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) system and tillage namely: Inversion tillage (MP), Non-inversion tillage (DT) and No-till (NT) for year 2 growing season at Langgewens Research Farm.

Tillage practice	Cropping sequence			Mean (Tillage)
	LWCW	WMcWMc	WLWC	
MP	4.8	25.0	52.5	**27.4 a**
DT	0.8	8.0	55.0	**21.3 ab**
NT	0.3	7.5	35.0	**14.3 b**
Mean (System)	**2.0 b**	**13.5 b**	**47.5 a**	
CV %	17.5968			
LSD (System)	12.5556			
LSD (Tillage)	8.8934			
LSD (System x Tillage)	32.5783			

Values (in bold) followed by the same letter in columns or rows are not significantly different at the 0.05 probability level

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Chapter 4

Summary and recommendation

The Western Cape is the most important wheat producing region in South Africa. The majority of the wheat, canola and medic farmers in the Western Cape are dry-land farmers. The Western Cape is the second driest region in South Africa and strategies need to be in place to ensure that farmers can utilise resources effectively. Due to an increasing human population, attention has been given to ensure a sustainable soil with high quality, as this is one of the important factors that ensure food security. No-till (NT) and crop rotation systems are strategies that can be used to maximise the rainwater usage efficiency in an effort to utilise and conserve more water. Management strategies and situations differ between farms. The principles of crop rotation systems and NT are well understood and can be applied to fit any farmer's circumstances with a great success. However no-till also has its unique challenges such as resistant weed species, stratification of certain elements in soil, higher soil bulk density, a high amount of straw on the surface (problematic for planters) and ineffective pest control. These problems started to become an important factor in crop production.

The effect of a once-off strategic tillage operation with a mouldboard plough (MP) and deep tine implement (DT) on crop response of wheat, canola and medic was compared to continuous NT in medic/clover-wheat-medic/clover-wheat (McWMcW) and lupin-wheat-canola-wheat (LWCW) crop rotations. This trial was done at the Langgewens Research Farm in the Western Cape during 2014 (year 1) and 2015 (year 2).

Soil water content (SWC), mineral nitrogen and glomalin content play an important role in sustainable agriculture. The effective management of SWC, mineral nitrogen and glomalin content can be cost saving for producers and is one of the factors that can increase yield. During this study results were obtained indicating that a once-off strategic tillage could influence SWC, mineral nitrogen and glomalin content, however no specific trends were found. Once-off tillage with MP and DT resulted in higher SWC in the LWCW system when compared to NT early in year 1. This is possibly because the ploughing increased the infiltration, although this was only found in the first year of the study. In the second year, NT had higher SWC in the middle of the season, after 90 days. It is possible that the stubble in the NT helped with the conservation of water in this, the driest year of the study. Tillage had no effect on SWC in wheat-lupin-wheat-canola (WLWC) compared to NT for either year 1 or year 2. The stronger root system of canola has the potential to create a tillage effect in soil, opening root pores and increasing water infiltration. During year 2 in wheat-medic/clover-wheat-medic/clover (WMcWMc) rotations also showed no significant differences between tillage operations with regard to SWC. Strategic tillage did not influence mineral nitrogen in the wheat phases (LWCW) and canola phases (WLWC) during year 1. Significant differences were however recorded the following year (year 2) 60 and 120 days after planting in LWCW and 60 days after planting in WLWC with NT showing a reduction in the amount of mineral nitrogen compared to DT an MP. The reason for these differences between year 1 and year 2 could be due to tillage that was applied during a time when soil temperature and microbial activity were low, compared to year 2 with higher soil temperature and microbial activity that causes more released mineral nitrogen.

The glomalin content of the soil during year 1 was significantly higher with DT than NT, and could be due to a higher amount of oxygen that was available in the soil after DT tillage.

Application of a once-off strategic tillage operation in the Swartland showed no significant increase or decrease in most vegetative parameters during year 1 (first year after tillage) in McWMcW and LWCW. NT resulted in an increase in the mass of roots produced in the deeper soil layers at the end of the season compared to MP in LWCW. The reason for the increase in root mass could be that roots had to grow deeper to find sufficient water because of the lower SWC found in NT plots during year 1. Mouldboard plough (MP) increased chlorophyll content and BMP compared to DT and NT in WLWC. The initial mineral nitrogen released with MP tillage (year 1) could be the reason for an increased chlorophyll content and BMP. Deep tine (DT) however increased IRM compared to both NT and MP in WLWC. The effect of DT on soil structure could have helped roots to grow easily in soil profile.

The year 2 results as obtained under low rainfall conditions after a strategic once-off tillage indicate that incorporation of a MP or DT will have no significant effect on LI, chlorophyll content, BMP and FRM compared to NT in LWCW. Deep tine (DT) cultivation increased wheat IRM compared to MP in LWCW rotation. Regeneration of medic in the system (WMcWMc) showed no negative effect due to MP tillage, and regenerated sufficiently compared to NT. Strategic tillage operation showed to have positive effects on root growth during year 1 (canola) and year 2 (wheat) and showed no negative effects in medic regeneration potential.

No significant differences between the three tillage strategies were found on seedling emergence and survival, spikelets per ear, grain mass (TKM), grain yield, grain protein and hectolitre mass during the year 1 (first year after tillage) in wheat trials (LWCW and McWMcW). However, MP and DT tillage increased the number of ear-bearing tillers per m^2 compared to NT, but continuous NT delivered the highest number of kernels per ear. The reason could be that the wheat planted in tilled soils had more uneven seedling emergence, thus creating more competition between plants, reducing ear length and kernels per ear during year 1. However no significant difference was recorded in yield between tillage treatments.

During year 2 NT showed an increase in the amount of ear-bearing tillers per m^2, yield and hectolitre mass compared to tilled treatments (MP and DT) in LWCW. The higher amount of residues on the soil surface in NT increased the SWC. This was a crucial factor during the drought in year 2 and could have contributed to the increase in yield, ear-bearing tillers per m^2 and hectolitre mass. Tillage treatments (MP and DT) in year 2 showed an increase in the protein content and TKM. The reason could be that a lower yield is associated with a higher protein content and TKM, because more resources (N, P and K) are available to a smaller number of ear bearing plants per m^2.

Canola planted the first year (2014) after tillage treatment was applied (MP and DT) only had a significant higher oil percentage per seed for WLWC. During year 2 NT also had a significantly higher number of pods per m^2 compared to tillage treatments. There was however no significant differences recorded in yield. Biomass production of medic was not influenced by tillage.

The once-off strategic MP tillage significantly reduced the amount of *Lolium multiflorum* and *Polygonum aviculare* weeds in field and under shade net compared to continuous NT. The reason could be that MP removed the seeds from the soil surface and placed them at a deeper depth in the soil profile, were germination and growth are not easily stimulated. These reductions were recorded for two consecutive years and showed that MP reduced the weed seedbank. Crop rotation also had an influence on the weed populations. The number of *Lolium multiflorum* weeds was effectively reduced in canola and medic phases (WLWC and WMcWMc). The control of grass weed I during a broadleaf crop is much more efficient.

The research done during 2014 (year 1) and 2015 (year 2) provided insight into the effect of a strategic once-off tillage operation in the Swartland, as well as the benefits, time and crop rotation systems best suited to improve yield and sustainable agriculture. Tillage showed an immediate effect on crop production after the first year. Although not all of these effects were significant the general trend was positive. The negative effects, if any, as a result of tillage recovered relatively quickly. Although both years of this study had below average rainfall no yield was lost except for LWCW in year 2. If a tillage operation is not repeated every year, the parameters tested in this study recovered relatively quickly. The statement can thus be made that most of the beneficial changes associated with NT will not be lost with incorporation of a once-off strategic tillage operation. Tillage practices tested in this study had a significant impact in controlling problem weed species. The weeds were significantly reduced by tillage which means the use of herbicides can be reduced, creating a healthier environment.

Incorporation of a once-off strategic tillage operation is feasible within a NT system and can be implemented to improve crop production. In some cases the negative effects (stratification of certain elements, weed resistance and a high amount of stubble on the surface) associated with NT can be reduced with incorporation of tillage. However, tillage cannot be incorporated without taking the following variables into account: weed seed bank, soil water status, rainfall predictions and subsoil constraints. If one of these variables is not favourable it is not recommended that a tillage operation is executed. Time of tillage and depth of tillage have to be considered next. For example in more clayish soils, tillage must be incorporated at the beginning of the season to prevent smearing and compaction. Sandy soils can however be tilled at a higher water content without these risks. Tillage in this study was however incorporated on soil with higher clay content and tillage had to take place in the beginning of the season. Both the tillage operations varied between a depth of 250 mm and 400 mm.

A strategic tillage operation can have positive effects on crop production. There is however a lot of variables that has to be taken into account before a decision can be made on the farm. The effect of a tillage operation has to be economically viable and improve yield without damaging the environment.

Further research needs to be focused on the effects of different tillage depths, timing and repeated tillage operations. The cost of a once-off tillage operation also has to be evaluated to determine if these practices are economically feasible.