INFLUENCE OF CROPPING SEQUENCE ON WHEAT PRODUCTION UNDER CONSERVATION AGRICULTURE IN THE EASTERN FREE STATE

by

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ABSTRACT

Crop rotation is one of the pillars of conservation agriculture (CA). It has been adopted moderately in the summer rainfall area of South Africa, but the adoption of conservation tillage has been very slow. It has been observed that research information on crop rotation helped with the adoption of the CA concept in the Western Cape.

Limited research has been done on crop rotation in the Eastern Free State. This study used the crop matrix trial design to evaluate the impact of different cropping sequences in a CA system on the growth, development, yield and quality of wheat as target crop. The profitability and production risk of the different crop rotations were also determined.

Only preceding summer crop sequences had a significant ($P \leq 0.1$) influence on the yield parameters of the final wheat crop. For the final wheat crop three preceding sequences, namely sorghum × soybean, maize × sunflower and soybean × maize, led to a lower ($P \leq 0.1$) number of plants and ears, with a lower biomass and residue yield unit area. Although the poorest response was always recorded on the preceding sorghum × soybean sequence plots, it did not differ significantly from those of the other two crop sequences. The final wheat crop also had a significantly higher TKM and harvest index on preceding sorghum × soybean sequence plots. It was concluded that the lower number of plants on these plots could be attributed to lesser in-row competition for water and nutrients, which resulted in bigger and heavier wheat kernels with a higher TKM.

The study confirmed previous research, namely that the final wheat crop planted on second season sunflower plots had a significantly ($P \leq 0.1$) higher number of ears m^{-2}, with a better $N_{(grain)}$ use efficiency. That resulted in a significantly higher grain protein content. However, the yield of the final wheat crop did not differ between plantings on second season summer crop plots.

Rotation with oats is often recommended to reduce Take-all, a soil-borne disease of wheat. It was found that the final wheat crop planted on second season oats plots had a significantly lower seedling number, with fewer ears and a lower grain yield per unit area. The wheat plants also had a lower ($P \leq 0.1$) precipitation use efficiency and grain nitrogen use efficiency, which led to a lower accumulation of grain protein. It was concluded that oats has a negative influence on wheat yield in a rotation system and that the crop should only be used as a break crop against Take-all.

Thirty two of the 50 crop rotations had a total profit margin above the chosen target income of R1,000 ha^{-1}. The soybean × maize × wheat rotation gave the highest total profit of R7,549.76 ha^{-1}, while the sorghum × dry bean × wheat rotation realised the highest total loss of R1,903.93. Maize had a stable yield over two seasons, while the yield of the other four preceding summer crops posed a higher production risk under rainy conditions (pod shattering in dry bean and soybean crops), or potential bird damage situations (sunflower and sorghum).

The crop matrix technique proved to be a reliable method to generate more information on cropping sequence in the same trial over a much shorter period. A multi-disciplinary approach in future cropping sequence research will help to provide producers with reliable information. If crop sequences can be proven to be effective at research level, clear guidelines and recommendations can be developed to help producers in implementing conservation tillage more successfully in the Eastern Free State.

Keywords: Conservation tillage, crop rotation, dryland wheat production, production cost, production risk

UITTREKSEL

Wisselbou is een van die drie pilare waarop die konsep van bewaringslandbou steun. Hoewel produsente in die Somerreënvalstreek van Suid-Afrika wisselbou geredelik toepas, is die aanvaarding van bewaringsbewerking maar stadig. Bewarings-bewerking is in die Wes-Kaap grootliks bevorder deur toepaslike navorsingsinligting oor verskillende wisselboustelsels.

Navorsingsinligting rakende wisselboustelsels in die Oos-Vrystaat is beperk. Hierdie studie het 'n gewasmatriksproefontwerp gebruik om die impak van verskillende gewasopeenvolgings binne 'n bewaringsbewerkingstelsel te evalueer. Die winsgewendheid en produksierisiko verbonde aan die verskillende wisselboustelsels is terselftertyd bepaal.

Slegs die voorafgaande somergewasse het 'n betekenisvolle ($P \leq 0.1$) invloed op die opbrengsparameters van die finale koringgewas gehad. Aanplantings van koring op voorafgaande sorghum × sojaboon, mielies × sonneblom en sojaboon × mielies persele het minder plante en are, met 'n laer biomassa en residu opbrengs per eenheidsoppervlakte tot gevolg gehad. Alhoewel die voorafgaande sorghum × sojaboon persele elke keer die swakste reaksie getoon het, het dit nie betekeninsvol verskil van die ander twee gewasopeenvolgings nie. Die finale koringaanplanting op die sorghum × sojaboon persele het ook 'n hoër ($P \leq 0.1$) duisendkorrelmassa en oes-indeks gehad. Die hoër hektolitermassa kan daaraan toegeskryf word dat mededinging vir water en voedingstowwe binne die plantrye heelwat minder was.

Desondanks het die opbrengs van die finale koringgewas wat op sonneblompersele van die tweede seisoen geplant is, nie betekenisvol van dié op ander persele verskil nie. In ooreenstemming met vorige navorsing is gevind dat koring op die tweede seisoen sonneblompersele meer ($P \leq 0.1$) are m^{-2} gevorm het, met 'n beter $N_{(graan)}$ verbruiksdoeltreffendheid. Dit het tot 'n hoër proteïeninhoud van die graan gelei.

Hawer word dikwels as 'n wisselbougewas gebruik om vrotpootjie, 'n grondgedraagde siekte van koring, te verminder. In die huidige studie is bevind dat die finale koringgewas op hawerpersele van die tweede seisoen 'n betekenisvol laer aantal saailinge met minder are en ‘n laer graanopbrengs per eenheidsoppervlakte gehad het. Die koringplante het ook ‘n laer ($P \leq 0.1$) reëngebruiksdoeltreffendheid en graanstikstofgebruiksdoeltreffendheid gehad, wat tot ‘n laer akkumulasie van graanproteïen gelei het. Die resultate van die studie het getoon dat hawer die potensiaal het om koringopbrengste in ‘n wisselboustelsel te verlaag en dus slegs vir vrotpootjiebeheer gebruik moet word.

Twee-en-dertig van die 50 gewasrotasies het ‘n groter totale winsgrens as die gekose mikpuntbedrag van ‘n R1,000 ha^{-1}getoon. Die sojaboon × mielie × koring rotasie het die hoogste wins van R7,549.79 ha^{-1} gelewer, terwyl die sorghum × droëboon × koring rotasie die grootste verlies van –R1,903.39 gerealiseer het. Mielies het ‘n bestendige opbrengs oor twee seisoene getoon. Die opbrengste van soja- en droëbone was egter laer na reën in die oestyd van die tweede seisoen en die opbrengste van sonneblomme en sorghum moes as gevolg van voëlskade afgeskryf word.

Die gewasmatriks-proefontwerp is suksesvol gebruik om meer inligting rakende gewasopvolging oor ‘n korter tydperk in te samel. Hierdie navorsingsveld is ‘n braakland vir samewerking tussen verskillende navorsingsdissiplines om betroubare riglyne aan produsente te verskaf waarmee hulle risiko meer effektief kan bestuur. Indien navorsinginligting rakende die riskoverlagende effek van gewasopeenvolgings aan produsente verskaf kan word, kan dit die aanvaarding van bewaringsbewerking-praktyke in die Oos-Vrystaat bevorder.

Sleutelwoorde: Bewaringsbewerking, droëland koringproduksie, gewasrotasie, produksiekoste, produksierisisko.

Declaration

I, hereby declare that this dissertation, prepared for the degree Magister Scientiae Agriculturae which was submitted by me to the University of the Free State, is my own original work and has not previously in its entirety or in part been submitted to any other University. I also agree that the University of the Free State has the right to the publication of this dissertation.

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MH Visser	Date

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List of abbreviations

Abbreviation	Meaning
CA	Conservation agriculture
cv	Coefficient of variation
DB	Dry bean
F	Fallow
FO	Fodder oats
HI	Harvest index
LSD	Least significant difference
M	Maize
$N_{(biomass)}$	Total nitrogen in biomass
$N_{(grain)}$	Total nitrogen in grain
$N_{(residue)}$	Total nitrogen in residue
NHI	Nitrogen harvest index
$NUE_{(grain)}$	Nitrogen use efficiency of grain
ns	Not significant
O	Oats
P	Probability
PUE	Precipitation use efficiency
r	Correlation coefficient
SB	Soybean
SF	Sunflower
SH	Sorghum
SOM	Soil organic matter
SWD	Soil water depletion
TKM	Thousand kernel mass
V	Vetch
W	Wheat
WUE	Water use efficiency

Abbreviations of common SI units and element names are not listed.

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CHAPTER 1

INTRODUCTION

Crop rotation is one of the pillars of conservation agriculture. Specific information on beneficial crop sequences to use in rotation systems has been instrumental in the successful adoption of no-till systems in Australia and the United States of America. Although adoption of crop rotation by wheat producers in the summer rainfall area of South Africa has been moderate, that of no-till has been minimal. A lack of observed benefits and an uncertainty about the most beneficial place for wheat in a rotational system have often been cited as reasons for non-adoption.

Cropping sequences of most rotation systems in the Eastern Free State are fixed and include summer crops like maize (*Zea mays*), soybean (*Glycine max*), dry bean (*Phaseolus vulgaris*) or sunflower (*Heliathus annuus*) and a fallow period prior to wheat. Limited research has been done on these systems and previous projects focused mainly on the benefits of fixed crop rotations in comparison to monoculture crops.

Most of the crop rotation research in South Africa was done with a limited number of crops which were planted for several years on the same field with conventional methods. Interpretation of results was often complicated by a huge variation in climatic conditions during the research. The crop matrix trial design is a new research tool that offers the opportunity to evaluate the rotational effect of several crops in the same experiment under similar weather and soil conditions. The technique is used successfully in other countries and was recommended for this study.

The hypothesis tested was that different cropping sequences would influence the growth and profitability of wheat as the final crop in a conservation tillage system. The main objective of the study was to evaluate the impact of different cropping sequences on the growth, development, grain yield and grain quality of wheat in a conservation tillage system. The secondary objective was to evaluate the profitability and production risk of cropping sequences in the trial.

If crop sequences can be proven effective at research level, clear guidelines and recommendations can be developed to help wheat producers in implementing conservation tillage more successfully in the Eastern Free State.

CHAPTER 2

GENERAL LITERATURE OVERVIEW

2.1 Introduction

Tillage has for centuries been fundamental to crop production (Baker and Saxton 2007). Although tillage had some benefits, it came at a cost to the environment and the natural resource base on which farming depended (Hobbs et al. 2008). Tillage destroys the natural soil structure and soil organic matter (SOM), together with the associated soil life and biodiversity, as well as many of the soil mediated ecosystem functions that provide, regulate and protect environmental services (Kassam et al. 2012). The tragic dust storms in the mid-western United States of America during the 1930's was the result of over ploughed and over grazed fields. It served as a wake-up call to how human interventions in soil management and tillage can cause unsustainability in agricultural systems (Hobbs et al. 2008).

Since the early 1960's farmers have been urged to adopt some form of conservation tillage that would save the planet's soil, cut back on the use of fossil fuels in food production, reduce runoff pollution of waterways and reduce wind erosion and air quality degradation (Baker and Saxton 2007). The Food and Agriculture Organisation of the United Nations (FAO 2012) has, in the light of growing concerns over the implication of many conventional agricultural practices, and especially deep tilling of soils, begun to promote a package of soil conserving practices under the banner of "conservation agriculture" (Knowler and Bradshaw 2007). Conservation agriculture (CA) is defined as an approach to manage ecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (FAO 2012). Conservation agriculture is seen as a concept that can enable farmers in many parts of the world to achieve the goal of sustainable agricultural production (Hobbs et al. 2008).

2.2 Conservation agriculture

Conservation agriculture is based on three linked principles, which aim to contribute and interact with soil carbon to improve sustainable soil quality and crop production (Baker and Saxton 2007). These principles include:

1. *Continuous minimum mechanical soil disturbance:*
   It includes no-till practices and direct seeding with low disturbance. Disturbance of the soil surface should not be more than 25% and disturbance in bands should not be wider than 15 cm.
2. *Permanent organic soil cover:*
   This refers to mulch from crop residues, other organic mulch materials or living crops (including cover crops). The level of soil cover should ideally be 100% of the soil surface, but never less than 30% and should always supply sufficient organic carbon to maintain and enhance soil organic matter levels.
3. *Diversification of crop species grown in sequence and/or associations:*
   This principle refers to rotation and sequences of annual crops, mixed, inter-, or relay cropping and cover crops in perennial orchard or plantations. It includes legumes which can be used for their nitrogen effect (FAO 2012, Kassam et al. 2012).

The principles have to coincide in time and space and have to be applied permanently to develop synergies (Kassam et al. 2012).

2.3 Benefits of conservation agriculture

The strength and longlivity of any civilisation depend on the ability to sustain and/or increase the productive capacity of its agriculture (Tisdale et al. 1993). Agricultural sustainability depends on many agronomic, environmental and social factors and it is more difficult to achieve in semi-arid and arid areas (Tisdale et al. 1993). To be widely adopted, all new technology needs to have benefits and advantages that attract a broad group of producers who understand the differences between what they are doing and what they need (FAO 2012).

2.3.1 Economic benefits

Economic benefits improve production efficiency.

2.3.1.1 Fuel, time and labour conservation

Derpsch et al. (2010) stated that the driving forces for adoption of no-till are the farmer's need to make time, labour and fuel savings and the higher economic returns that are offered by the technology. Llewellyn et al. (2012) examined the enabling factors for the adoption of no-till cropping systems in Australia. The main reasons for adoption by producers who used no-till were listed as reduced fuel and labour cost at planting, soil conservation and soil water management. Up to 80% less fuel is used to establish a crop and up to 60% person hours ha^{-1} is conserved by converting from tillage to no-till (Baker and Saxton 2007).

2.3.1.2 Higher productivity with lower input costs

Crop sequencing within crop rotations can have a significant impact on the productivity of succeeding crops and thus on the productivity of the crop rotation system as a whole (Cutforth et al. 2007). Sustainable cropping systems, where producers know how to sequence crops, will be able to take advantage of inherent internal resources such as synergisms, nutrient cycling and soil water to capitalise on external resources such as weather and markets (Tanaka et al. 2007). Proper sequencing of crops within rotations can have a long term positive yield and economic benefit for producers if good crop management practices are followed. Management should include control of weeds, diseases and other pests and timely seeding to better match crop phenology with seasonal water availability patterns (Cutforth et al. 2007).

Crop diversity is a key concept in managing the risk of unpredictable rainfall and market patterns and is essential to the successful management of no-till systems (Peterson et al. 1996, Zentner et al. 2002). It may also add value to cropping systems by increasing the efficiency of cereal crop production (Miller et al. 2002b, Miller and Holmes 2005, Tanaka et al. 2005, Liebig et al. 2007, Tanaka et al. 2007).

Krupinsky et al. (2006) evaluated some of the soil and crop ecological interactions that influence crop production of ten crops grown under similar soil and environmental conditions in the Northern Great Plains. It was found that the crop sequencing influenced crop production, water depletion and plant diseases. Similarly, Miller and Holmes (2005) reported that relative yield of crops depended on amongst others previous crop residues, confirming that crop sequencing influences yield and that crop diversity in agricultural systems mitigates production risks.

2.3.2 Agronomic benefits

Soil quality is the fundamental foundation of environmental quality. It is largely governed by SOM content, which is dynamic and responds effectively to changes in soil management, tillage and plant production. Maintaining soil quality can reduce problems of land degradation, decreasing soil fertility, and rapidly declining production levels that occur in large parts of the world (Baker and Saxton 2007, Reicosky 2008). Organic matter provides much of a soil's capacity to store nutrients and water and it plays a critical role in the formation and stabilisation of soil structure (Weil and Magdoff 2004). Conservation agriculture leads to improvement of soil productivity, which is a combined result of the factors discussed below.

2.3.2.1 Increased organic matter and soil structure

The organic matter content of the top soil layer has been described as a property that is related to yield of principal crops. Diaz-Zorita and Grove (1999) reported that this property plays a role in water regulation, nutrient supply and maintenance of soil structure. The total amount of residue deposited, its composition and its resistance to complete mineralisation varies among plant species and this can interact in a complex way with cropping sequence and no-till. It was further suggested that crop sequences comprising of wheat and maize are beneficial for rapid soil organic matter accumulation.

Cover crops grown in the winter off-season in temperate regions are well known to improve soil aggregation (Murungu et al. 2010). The improvement in aggregation is often related to an increase in SOM, but differs among cover crop species grown, regardless of the effect on total SOM. Soil aggregation varies seasonally, but cover crops or mulches can prevent most of the decreased aggregate stability observed on bare soils from fall to spring (Hermawan and Bomke 1997).

2.3.2.2 Improved water infiltration and conservation

Soil conservation promotes practices that stop the decline in soil quality and over time it improves the soil quality significantly, particularly under diversified cropping systems (Lupwayi et al. 2004; Krupinsky et al. 2007b). Crop residues improve several soil properties such as soil aggregation, water infiltration, water storage, particle aggregation, microbial activity and biomass (Peterson et al. 1996, Merrill et al. 2006, Krupinsky et al. 2007b). Collectively, improvements in soil condition through retention of crop residues on the soil surface increase the resilience of cropping systems to drought, wet periods, intense precipitation events and extreme temperatures, all which are common in crop production (Peterson et al. 1996, Tanaka et al. 2005, Merrill et al. 2006).

About 60% of precipitation received during the fallow period is lost to evaporation under conventional practices (Greb 1983, Dao 1993). Stubble left on the surface will reduce evaporation, insulate the soil surface and reduce surface runoff due to better water infiltration (Peterson et al. 1996, Tanaka et al. 2005). The micro-environment is therefore modified, which then ultimately influences the growth and development of subsequent crops. Water conservation is important to soil conservation, because the additional water will improve crop growth and thus residue production in the following year (Merrill et al. 2007). Broadleaf crops such as dry bean, peas (*Pisum sativum*), and lentil (*Lens culinaris*) generally extract water from shallower depth than cereals (Tanaka et al. 2005). Shallow rooted crops appear to be best adapted to follow deep rooted crops because water recharge is likely to occur near the soil surface and a shallow rooted crop will not spend energy rooting deeper in search of water (Farahani et al. 1998).

Soil water use by one crop effects the following crop in a crop sequence and producers should take that into account in their annual planning, especially in water limited regions (Merrill et al. 2007). Nielsen et al. (1999) reported that the relatively high water use by sunflower decreased the yield of subsequent crops [winter wheat (*Triticum aestivum*) and proso millet (*Pennisetum glaucum*)] in eastern Colorado. Copeland et al. (1993) found that compared to monoculture, yield was increased by up to 30% when maize followed soybean and up to 11% when soybean followed maize. Miller et al. (2002b) evaluated the influence of soil water depletion by broadleaf crops and wheat on the productivity of spring wheat as the dominant crop in a system. It was found that wheat residue stored more soil water in the 0-60 cm layer than chickpea, lentil and sunflower residue, the same amount as dry pea and mustard residue and less soil water than dry bean residue. Merril et al. (2007) determined variation in seasonal soil water depletion (SWD) and recharge amongst ten crops over three years. Crops were ranked in descending order of their mean SWD as follow: sunflower, maize, sorghum (*Sorgum bicolor*), wheat, canola (*Brassica napus*), millet, buckwheat (*Fagopyrum esculentum*), chickpea (*Cicer arietinum*), lentil and dry pea. A ranking of crops by the least amount of soil water stored, roughly followed the ranking of these crops by average SWD. The results were influenced by variation in weather conditions over the three seasons, as well as difference of length in active growing seasons amongst crops.

Anderson (2011) was involved in a long-term rotational study in the Great Plains and observed from five year data that the presence of maize or dry beans in rotations improved the water use efficiency of wheat in comparison with the rotations without these two crops. It was also noted that the water use efficiency (WUE) of proso millet differed between maize and wheat as preceding crops. Total water use by proso millet was the same for both sequences, but proso millet was 24% more efficient in converting water to grain if maize was the preceding crop. The results proved that crop response to the rotation effect can be categorised as either:

- improved resource use efficiency, where the subsequent crop produces more grain with the same water use (synergistic sequences); or
- increased plant size and yield capacity, which means that the follow-on crop consumes more water to produce more grain.

2.3.2.3 *Improved nutrient cycling and nitrogen availability*

Crop residue serves as an important source of plant nutrients released through mineralisation (Weil and Magdoff 2004). A diverse cropping system, in addition to many other benefits, can help with nutrient availability because different crops have different demands for and ability to remove particular nutrients in the soil (Peterson et al. 1996, Miller et al. 2002b, Tanaka et al. 2002, Miller and Holmes 2005, Krupinsky et al. 2007b). Crop residues also contain plant nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulphur (S) and micronutrients, which promote nutrient cycling. The quantity of nutrients returned into the soil is therefore considerable (Krupinsky et al. 2007b).

Management practices that accumulate or maintain SOM usually tend to have a high capacity to supply nutrients. Wilson et al. (2001) found that N mineralisation potential (defined as the intrinsic ability of the soil to supply inorganic N through mineralisation over time):

- was higher in untilled perennial systems than in tilled annual systems;
- increased with the addition of compost; and
- was higher in rotation systems, including wheat and legume cover crops, than in maize-soybean rotations without cover crops.

Nitrogen is often the nutrient which limits crop production and therefore much attention has been given to N cycling in residue decomposition - especially of legume crops. It was shown in a study that cereals have the potential to recover between 11 and 28% of the ^{15}N-labeled N in legume residues that were added to the soil (Bremer and Van Kessel 1992).

Including legumes in crop rotation affects wheat yield through a series of complex interactions on soil water, soil nutrient supply and interruption of pest cycles (Miller et al. 2002a). Wheat yield responses can vary considerably depending on previous legumes, years and location. Miller et al. (2002a) observed that the extra N from the previous legumes is only beneficial for the subsequent crop when water is sufficient to utilise the increased N.

Miller et al. (2002b) found that the grain yield for wheat was the highest (21% more) when grown on legume (pulse) crop stubble, while grain yield for wheat grown on oilseed stubble did not differ from the grain yield of wheat grown on wheat stubble. Grain protein of wheat grown on both legume and oilseed crop stubble was higher (8% and 5% more respectively) than when grown on wheat stubble. Gan et al. (2003) found similar results for durum wheat grown on legume and oilseed stubble. The legume crop stubble contributed to soil N in such a way that the fertiliser N requirements for canola, mustard (*Brassica juncea*) and spring wheat, which were grown on legume stubble, could be reduced by an average of about 15 kg N ha^{-1}. Miller et al. (2003) also reduced the required N fertiliser amounts for crops grown after three legumes in order to account for the greater predicted soil N mineralisation.

2.3.3 Environmental benefits

Conservation agriculture includes benefits that protect the soil and make production more sustainable.

2.3.3.1 Reduction of soil erosion

Water erosion is a process by which soil aggregates and primary particles are detached form the soil matrix, transported down-slope by raindrops and flowing water, and deposited under certain energy limited conditions (Unger 1994).

The erosion of soil affects the productivity of soil significantly. Erosion alters the inherent physical and chemical properties of soil through soil removal, or sediment deposition. These alterations affect the processes that regulate the productivity of an ecosystem (Pierce 1991).

Soil erosion represents the greatest threat to sustained soil productivity and is a symptom of poor soil management (Tisdale et al. 1993). The major concerns about erosion are:

- rate and extent to which erosion is degrading soils worldwide and the extent to which this degradation will limit food and fibre production for a growing world population; and
- off-farm impacts of soil erosion, for example, non-point-source pollution of surface water resources (Pierce 1991).

Residue affects erosion in a number of ways:

1. *Interception:*
   Crop residues intercept and retain a certain fraction of rainfall. Residues can absorb rainfall from two to four times their mass when at, or near dryness (Unger 1994).
2. *Infiltration:*
   The presence of surface cover can greatly reduce the development of a surface seal (crust) on soils prone to seal formation, with the beneficial effect relating to the percentage of residue cover (Unger 1994).
3. *Runoff rate:*
   Residues reduce runoff velocity by causing ponding, which delays runoff. Gilley et al. (1986) quantified the effect of different amounts of maize residue on runoff rates. The average runoff rates for soil cover percentages of 0, 10, 31, 51 and 83% were 15.6, 10.7, 6.0, 1.8 and 0 mm h^{-1} respectively.
4. *Runoff volume:*
   Laflen et al. (1978) evaluated runoff and soil loss from six tillage systems with residues of 2% to 63% under simulated rainfall conditions for three soils. Soil losses from the no-till system were reduced by at least 80% on all soils compared to the conventional system.

Baker and Saxton (2007) concluded that no-till is the best farming technique developed yet by humankind to reduce wind and water erosion.

2.3.3.2 Increase in biodiversity

No-till practices transformed crop production in the Great Plains by improving precipitation use, increasing crop yields and restoring soil health. Crop systems that specialise in one or two crops provide minimal or no plant diversity to a system and ultimately will become unsustainable (Liebig et al. 2007). No-till stimulated an interest in crop diversity and rotation design (Anderson 2011). The dynamic systems approach, which was defined as: "*a long term strategy of annual crop sequencing that optimises the cropping options and the outcome of crop production, economics and resource conservation goals by using sound ecological management principles*", was proposed to accomplish that (Tanaka et al. 2007). Diversifying crops in cropping systems favours synergism, or the "rotation effect", where rotating crops generally increase yield compared with monoculture (Porter et al. 1997). Cropping systems that exploit the internal resource of a system take advantage of crop sequences through synergism (Tanaka et al. 2005). Yield improvement due to the crop rotation effect is still not fully understood, but some of the beneficial effects on following crops can be useful.

Understanding how crops and management practices interact is essential in the development of practical, efficient, and cost effective cropping systems capable of stabilising crop production while minimising the deleterious effects on the environment (Krupinsky et al. 2007b).

2.4 Limitations of conservation agriculture

The most important limitation in all areas where CA is practised is the initial lack of knowledge regarding no-till, adapted crops and the effect of crop sequencing in rotations, as well as weed and pest control measures (FAO 2012, Baker and Saxton 2007).

2.4.1 Diseases and pests

Reduced tillage changes the soil environment and these changes can result in an increase (Bockus and Shroyer 1998), a decrease, or no change in disease intensity or severity, depending on the cropping system and the disease (Johnson et al. 2001). No-till leaves residues on the surface of the soil, which favours pathogens that can survive and grow on surface crop residues. Crop rotation is a key factor in residue management for disease control (Bailey and Lazarovits 2003). The term "break crop" refers to breaking the life cycle of crop specific pathogens by growing a non-host crop in sequence (Kirkegaard et al. 2008). Proper crop sequencing can accentuate positive synergistic interactions among crops, reduce potential pest problems and is an important component of sustainable cropping systems (Tanaka et al. 2002, Krupinsky et al. 2004, Anderson 2005a, Krupinsky et al. 2006). Crop diversification can improve the management of plant diseases through crop selection and interruption of disease cycles (Krupinsky et al. 2004). Residue management practices can contribute to the suppression of some soil borne plant diseases, but knowledge on the mechanisms involved is limited (Bailey and Lazarovits 2003). Crop residues contribute to increasing soil microbial activity and thus increase the likelihood of competition among organisms in the soil (Bailey and Lazarovits 2003). Crop residues may further favour some soil pathogens by lowering soil temperature and increasing soil water. Crop sequence, in combination with management practices, can be one of the most inexpensive methods to manage a number of plant diseases (Krupinsky et al. 2002, Krupinsky et al. 2007a).

2.4.2 Weed control

Weeds have been highlighted as one of most difficult management issues within CA systems in a number of regions, particularly where weed resistance to herbicides has become widespread (Farooq et al. 2011). Weed control in CA is a greater challenge than in conventional agriculture because a large portion of the weed seed bank remains on, or close to the soil surface after planting (Chauhan et al. 2012). Pareja et al. (1985) found that 85% of all weed seeds were in the upper 5 cm of soil in a reduced tillage system, but only 28% seeds were found in the same region in a conventional system.

Crop residues, when uniformly and densely present, could suppress weed seedling emergence, delay the time of emergence and allow the crop to gain an initial advantage in terms of early vigour over weeds (Chauhan et al. 2012). Wicks et al. (1994), found that 1 ton ha^{-1} of wheat residues reduced weed seedling establishment by 14%. However, weed response to residue depends on the quantity, position and allelopathic potential of the residue and the biology of the weed species (Chauhan et al. 2012). Integrating crop diversity with other cultural tactics enabled producers to effectively control weeds with 50% less herbicide inputs compared with their initial experiences with no-till (Anderson 2003).

Rotating cool and warm season crops can reduce weed community density. Anderson (2005b) also found that different planting and harvesting dates among these crops provide opportunities for producers to prevent either weed plant establishment, or seed production by weeds. The benefit of this strategy is related to weed seed survival in soil, as seeds in the soil are the main source of weed infestations in future crops (Derksen et al. 2002).

Weed communities become more diverse under diverse crop systems, thus minimising the predominance of any single weed. Residues suppress weeds by reducing light penetration and soil temperature fluctuation (Wicks et al. 1994, Derksen et al. 2002).

Crop species vary naturally in their ability to compete with weeds. A general ranking (more competitive–less competitive) of crop competitiveness is rye (*Secale cereale*) > oats (*Avena sativa*)> barley (*Hordeum vulgare*)> wheat > canola > field pea > soybean > flax (*Linum usitatissimum*) > lentil. Producers should consider growing a competitive crop before growing a poorly competitive crop such as flax or lentil (Blackshaw et al. 2002).

Approaches such as uniform and dense crop establishment, use of cover crops and crop residues as mulch, crop rotation and practices for enhanced crop competiveness with a combination of pre- and post-emergence herbicides, should be integrated to develop sustainable and effective weed management strategies under CA systems (Chauhan et al. 2012).

A diverse cropping system inherently includes varying seeding rates, crop life cycle, herbicide modes of action, herbicide timing (pre-seeding, in-crop, pre-harvest, or post-harvest), crop residue layers and soil disturbance and provides an economical means of managing weeds by reducing weed densities and reliance on herbicides (Derksen et al. 2002).

2.5 Conclusion

Crop production in the next decade will have to produce more food from less land. This can only be achieved by making more efficient use of natural resources, managed in such a way that there is minimal impact on the environment. It is a significant challenge for agricultural scientists and producers to keep pace with food production demands, while preserving the land's productivity for future generations (Hobbs 2007). Crops and soil management systems that help improve soil health parameters (physical, biological and chemical) and reduce production costs are essential (Hobbs et al. 2008).

Conservation agriculture has received increasing attention by the commercial producer sector as it drastically reduces fuel and labour costs and minimises machinery wear and tear (Johansen et al. 2012). Derpsch et al. (2010) estimated that 111 million hectares would be cropped using the principles of CA, but this was mainly under commercial farming systems in the United States of America and Australia. Conservation agriculture principles are universally applicable to all agricultural landscapes and land uses with locally adapted practices. The initial lack of information is, however, a limitation in the adoption of these principles (FAO 2012). The components for crop and agro-ecological resource management in CA systems are complex and location specific. These components include crop residue management, cultivar selection and crop choice for rotation, strategies for nutrient management, tactics for weed management, disease and pest management, and soil water management practices. Research and development should focus on better understanding the effects and interaction among all these system components to develop site-specific CA options (Serraj and Siddique 2012).

The success or failure of CA depends greatly on the flexibility and creativity of the producers and researchers in a region. Trial and error, both by researchers and producers, is often the only reliable source of information (FAO 2012). There is only limited information available on the actual extent of CA adoption in South Africa, but it is estimated is that the area under CA has increased from 300 000 ha in 2005 to 368 000 ha in 2009 (Kassam et al. 2012). The Western Cape is one of the regions in South Africa where the adoption of conservation tillage practices and crop rotation, especially for wheat production, has escalated since 2000. Most crops are currently established with the no-till planting method (Tolmay et al. 2010).

Derpsch (2008) concluded that when mind-set, which is the main obstacle to adoption of the practice, can be overcome, the country can be a sleeping giant in terms of quick CA adoption in coming years. Research information, especially on crop rotation, played a vital role in the adoption of CA in the Western Cape and KwaZulu-Natal. This gave rise to the main purpose of this study, to generate crop rotation information and to assist producers in the Eastern Free State to adopt CA practices in future.

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CHAPTER 3

DESCRIPTION OF TRIAL SITE AND EXPERIMENTAL METHODOLOGY EMPLOYED

3.1 Introduction

Producers need information on the effect of different cropping sequences in their specific areas. The crop matrix (criss-cross) trial design offers the opportunity to evaluate multiple cropping sequences in the same field under similar climate and soil conditions. In this chapter the trial site, climatic conditions during study, planting equipment used, trial layout, treatments and agronomic practices, as well as measurements and analyses that were done in the 3rd year of study, will be discussed.

3.2 Trial site

The trial was planted on the premises of the ARC-Small Grain Institute (ARC-SGI) near Bethlehem (Latitude: -28.16279, Longitude: 28.29729, Altitude: 1.696 m). Based on the South African Soil Surveyors Organisation's field book for the classification of South African soils (Le Roux et al. 2013) the soil is a Westleigh form with an orthic A-horison of 40 cm and a plinthic B-horison of 70 cm (Figure 3.1).

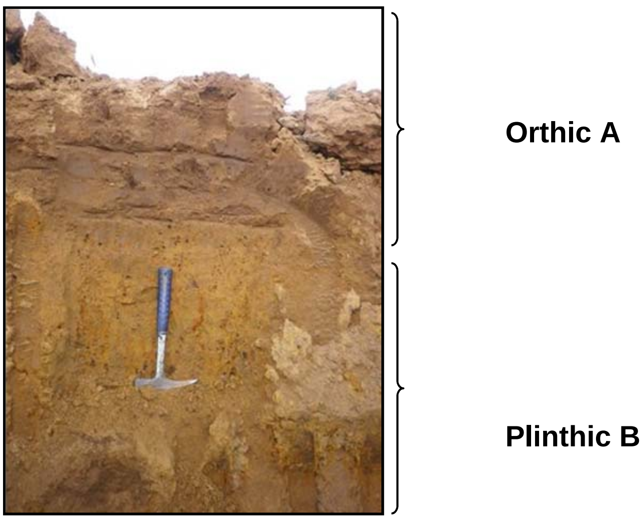

Figure 3.1 : The trial was planted on a soil of the Westleigh form with an orthic A horison and a plinthic B horison

An oats × fallow × wheat × fallow rotation preceded initiation of this research. The soil was cultivated with a tine implement to a depth of 45-50 cm during that time and fertilised with 8:2:1(31) N:P:K compound fertiliser applied at a rate of 218 kg ha^{-1}.

3.3 Climatic conditions

The ARC-SGI weather station is a few meters from the trial site. Climatic data is captured daily in a weather database of the ARC-Institute for Soil, Climate and Water in Pretoria. Weather data were obtained from this database (ARC-ISCW 2014). Average monthly rainfall data (2008 to 2011), as well as average monthly minimum and maximum temperature data were summarised in tables with long-term data of 60 years (1951 to 2012) and is presented in Chapter 4.

3.4 Planting equipment

A Gaspardo SP510 precision vacuum seed planter was used for planting. The planter had separate fertiliser (Figure 3.2a) and seed openers (Figure 3.2b), which placed fertiliser and seed at depths of 15 cm and 6 cm respectively in the same row/slot.

(a) (b) (c)

Figure 3.2 : Fertiliser (a) and seed (b) were placed in the same slot with separate openers at depths of 15 cm and 6 cm and was lightly compacted with two press wheels (c)

Source for (b): Gaspardo (2013)

The cast shoe (Figure 3.2b) had a u-shape seed opener, with a width of 3 cm. The slots were lightly compacted with two press wheels (Figure 3.2c) and the final disturbance within bands was less than 15 cm wide (Figure 3.3).

Figure 3.3 : Row widths were 45 cm and disturbance within band was less than 15 cm wide

3.5 Experimental layout and treatments

The trial included four treatment blocks (replicates) for summer crops and four treatment blocks (replicates) for winter crops (Figure 3.4). Research started in November 2008 with the planting of five summer crops, namely sunflower (SF), maize (M), sorghum (SH), dry bean (DB) and soybean (SB) (Figure 3.5). The crops were planted in strips of 11 m × 55 m, which was randomly allocated within each of the four blocks (Figure 3.6). Likewise, four winter crops, wheat (W), oats (O), fodder oats (FO) and vetch(V) (*Vica sativa*), a legume cover crop were planted in June 2009 with fallow (F) as the fifth treatment.

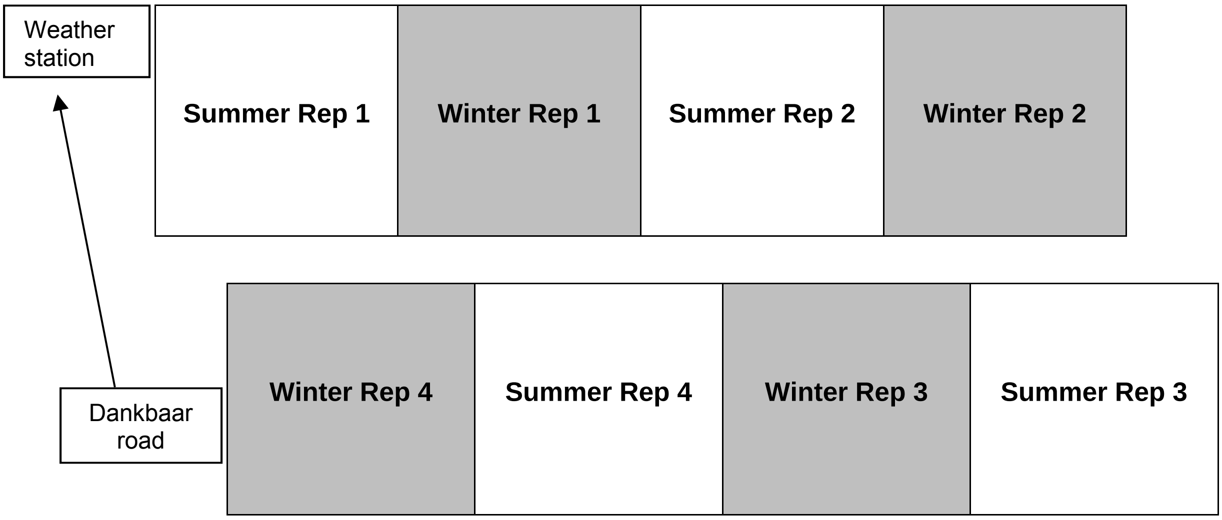

Figure 3.4 : Layout of summer and winter block replicates in the crop sequence trial at ARC-Small Grain Institute

Figure 3.5 : A summer block replicate with dry bean, sorghum and maize

The planting direction for crops (summer and winter) during the first season was from top to bottom in the different blocks (Figure 3.6).

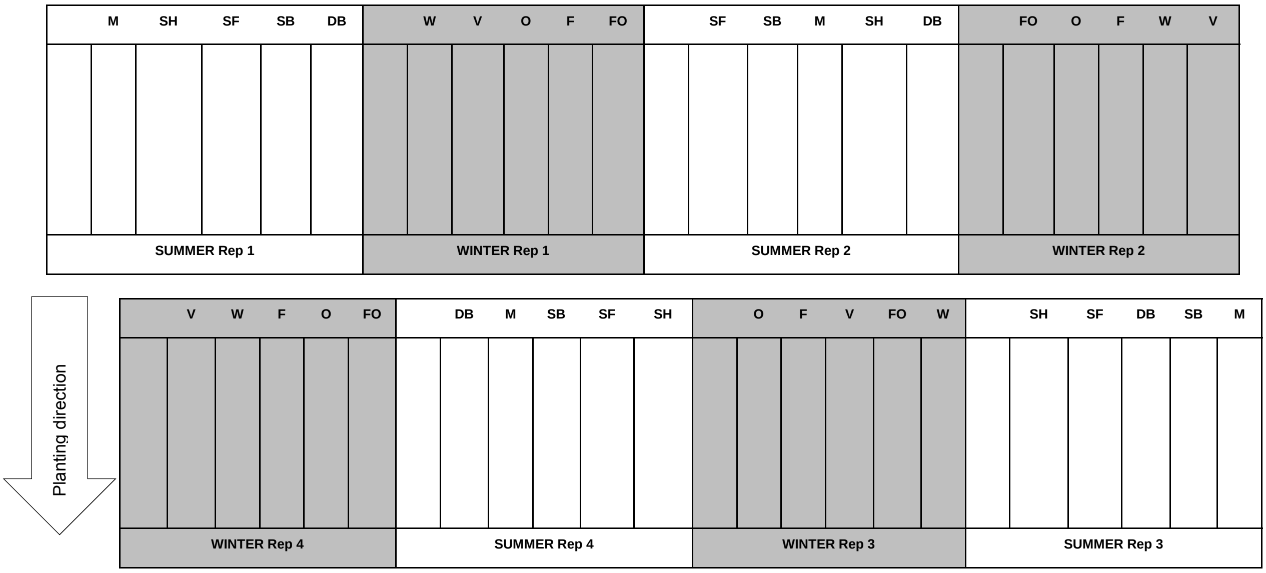

Figure 3.6 : Crop allocation and planting direction in the first season

The same treatments were applied in the second season from left to right in the blocks on the different crop residues that remained from the first season (Figure 3.7). During establishing this 5 × 5 crop-by-crop residue matrix with 25 cropping sequences for summer and winter crops respectively, the mentioned crops were planted over a two year period (Figure 3.8). The wheat cultivar Matlabas was planted on 23 June 2011 on the residue of all the preceding cropping sequences, at a planting density of 25 kg ha^{-1} and an inter-row spacing of 45 cm. The trial was fertilised with a 3:1:0(28) N:P:K mixture, applied at a rate of 200 kg ha^{-1}.

Figure 3.7 : Wheat planted in second season across wheat, fallow and oats strips of first season

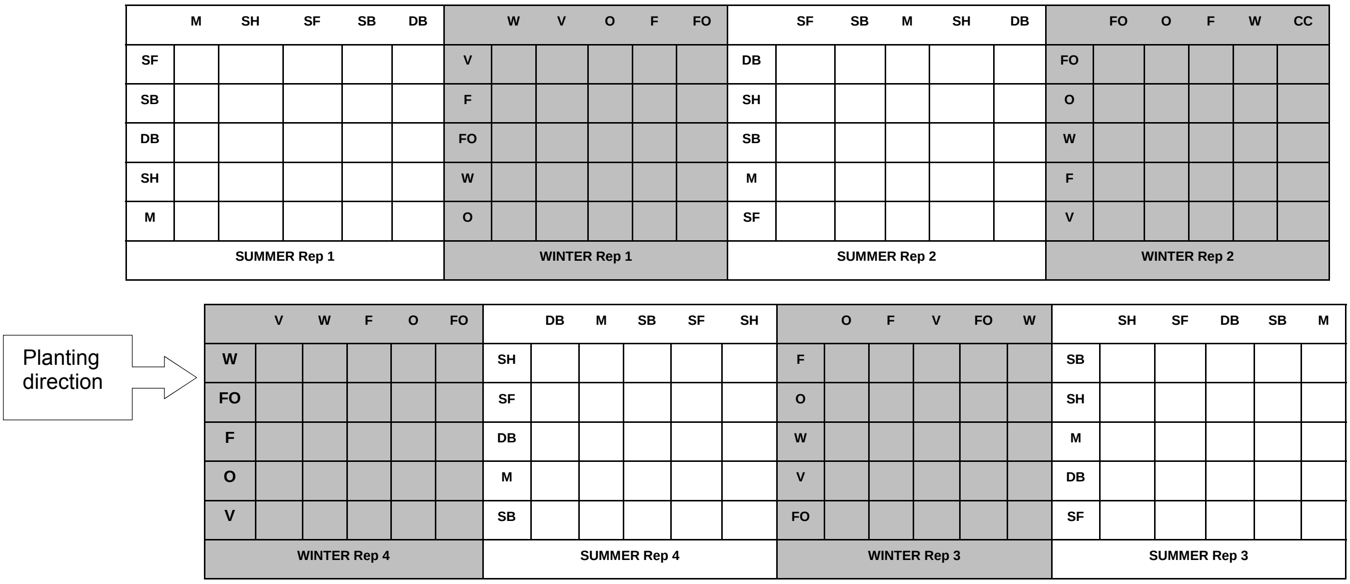

Figure 3.8 : Crop allocation and planting direction in the second season

3.6 Agronomic practices

The experiment was executed under normal rain fed conditions (dryland) and all the crops were planted according to farmer based recommended agronomic practices. Cultivars used, as well as planting and harvesting dates are listed in Table 3.1. The vetch and fodder oats were terminated with Glyphosate (Round-up™) at a rate of 2.5 l ha $^{-1}$ before seed set to mimic the on-farm situation were these crops would have been used for animal grazing.

Table 3.1 : Crop cultivars planted during the first two seasons

Crops		First season		Second season	
Summer	**Cultivar**	**Planting date**	**Harvesting date**	**Planting date**	**Harvesting date**
Dry bean	PAN 148	08/12/2008	14/4/2009	12/11/2009	31/05/2010
Maize	DKC 66-2B	08/12/2008	19/08/2009	11/11/2009	23/07/2010
Sorghum	PAN 8609	09/12/2008	27/05/2009	12/11/2009	24/05/2010
Soybean	PAN 535R	09/12/2008	15/05/2009	06/11/2009	25/05/2010
Sunflower	PAN 7049	08/12/2008	21/4/2009	12/11/2009	24/05/2010
Winter	**Cultivar**	**Planting date**	**Harvesting date**	**Planting date**	**Harvesting date**
Vetch	Max	06/08/2009	*	08/09/2010	*
Fodder oats	Pallinup	17/07/2009	*	07/07/2010	*
Oats	Overberg	17/07/2009	30/12/2009	07/07/2010	30/12/2010
Wheat	Elands	17/07/2009	30/12/2009	07/07/2010	30/12/2010

* The vetch and fodder oats were terminated with Round-up before seed set

Dry bean, maize, sorghum and sunflower were fertilised with a 3:1:0(28) mixture at a rate of 286 kg ha^{-1} and sorghum with a 2:3:4(30) mixture at a rate of 150 kg ha^{-1}. Solubor (5 kg ha^{-1}) was applied for additional boron on sunflower. All the winter crops were fertilised with 2:1:0(30) and LAN(28) at rates of 150 kg ha^{-1} and 50 kg ha^{-1}, respectively.

Wheat seed was treated before planting with Vitavax® 200FF (active ingredients: Carboxin and Thiram) and Gaucho® 350FS (active ingredient Imidacloprid) to protect emerging seedlings against potential soil fungal diseases. The herbicides Glyphosate (Round-up™) and Atrazine (Robyn) that control broad leaf weeds and grasses, were used before planting to ensure a head start for emerging crops. Field inspections were done weekly. Standard procedures and application rates were applied to address disease, insect and weed problems that occurred (Table 3.2, Figure 3.9). The adjuvants Qwemiwet and Comiblem were used with some of the herbicides to improve their effectiveness.

Table 3.2 : Products used for weed, insect and disease control

Crop	Problem	Active ingredients	Application rate	Product trade name
Wheat	Broad leaf weeds	Bromoxynil as the octanoate (nitrile)	700 ml ha^{-1}	Bromoxinil (H)
Oats, wheat	Broad leaf weeds	Metsulfuron methyl (sulfonyl urea)	12.5 g ha-1	Brush off® (H)
Wheat	Yellow rust	Propiconazole	400 ml ha^{-1}	Bumper 418 EC (F)
Sunflower, dry bean, soybean	Grass weeds	Dimethenamid-P	750 ml ha^{-1}	Frontier®-P (H)
Oats, wheat	Grass weeds	Chlorsulfuron	12.5 g ha^{-1}	Glean (H)
Maize, soybean	Grass weeds	Guardian® Plus is a combination of 3 products: Classic® Grande: Chlorimuron ethyl Polaris™: Glyphosate Valtera*: Flumioxazin	800 ml ha^{-1}	Guardian® Plus (H)
Dry bean, soybean	Broad leaf weeds	Carfentrazone-ethyl	350 ml ha^{-1}	Hammer (H)
Wheat	Aphids	Parathion	1 l ha^{-1}	Parathion 500 EC (I)
Maize	Pre-emergence broad leaf and grass weeds Cut worms	Atrazine Esfenvalerate as an EC formulation	2.5 l ha^{-1} 250 ml ha^{-1}	Robyn (H) Sumi-Alpha (I)
All the crops except for maize	Pre-emergence broad leaf and grass weeds	Glyphosate	2.5 l ha^{-1}	Round up (H)
Dry bean, soybean, sunflower, maize, wheat	Cut worms	Esfenvalerate as an EC formulation	250 ml ha^{-1}	Sumi-Alpha (I)
Oats, wheat	Wild oats	Clodinafop-propargyl and cloquintocetmexyl	350 ml ha^{-1}	Topik (H)

(H) = Herbicide (F) = Fungicide (I) = Insecticide

Figure 3.9 : Weed control was applied when needed

3.7 Analyses, measurements and calculations

The study focused on the influence of different preceding crop treatments on wheat as the target crop. Therefore the most important measurements and analyses were done in the final growing season (2011) when wheat was planted on the residue of the preceding cropping sequences. The different measurement, analyses and calculations will be discussed in sections 3.7.1 to 3.7.8.

3.7.1 Soil parameters

Soil samples were collected in duplicate prior to the first planting in 2008. The samples were collected from the strips within the replicated blocks. These representative samples from both the 0-20 cm and 20-40 cm soil layers, were analysed according to standard procedures (Non-Affiliated Soil Analysis Work Committee, 1990) at the ARC-Small Grain Institute Soil Laboratory. Analyses included pH (KCl method; Crison micro pH 2000 meter), extractable P (Bray 1 method; Seal P Auto analyser), exchangeable K, Ca, Mg and Na (Ammonium acetate method; ICP – Optima 5300V Perkin Elmer), acid saturation (K_2SO_4 titration method) and total N (Leco combustion method; Leco FP-2000, Nitrogen/Protein Analyser). The fertility status of the soil will be given in Chapter 4.

The same sampling procedures were followed in 2011, when soil was sampled per plot before the final wheat crop was planted. Similar analyses were done on these samples to monitor if the different preceding crop treatments had an influence on the soil nutrient status.

One week before the final wheat crop was planted in 2011, two soil samples per plot were also taken to 40 cm depth for water content determinations. The moist samples were bagged and taken to the laboratory, where it was weighed immediately. The samples were then dried for 24 hours at 105°C in an oven to a constant weight. Both gravimetric ($\theta_{\mathbf{m}}$) and volumetric (θ_v) water content were calculated on a percentage basis using equations 3.1 and 3.2 (Miller and Donahue 1990), respectively:

$$(\theta_m) = \left[\frac{\text{moist soil weight} - \text{oven dry soil weight}}{\text{oven dry soil weight}}\right] \times 100 \qquad (3.1)$$

$$(\theta_v) = \left[\frac{\text{weight of water}}{\text{weight of dry soil}}\right] \times \left[\frac{\text{bulk density of soil}}{\text{density of water}}\right] \times 100 \qquad (3.2)$$

3.7.2 Plant parameters

Seedling survival rate was calculated from seedling counts done eight weeks after planting. Three strips of 0.5 m each (Figure 3.10) were randomly identified per plot and permanent plant pegs were placed on both sides of a strip to enable identification on later stages in the trial. The number of seedlings was recorded per strip. The sample area was calculated as 1.5 m multiplied by the used row width of 45 cm. Seedling number m^{-2} was used to calculate seedling survival percentage per plot with equations 3.3^a and 3.3^b:

$$\text{Seedling survival (\%)} = \frac{\text{Seedling numbers m}^{-2}}{{}^{*}\text{Number of seeds placed m}^{-2}} \times 100 \qquad (3.3^{a})$$

$$\text{*The number of seeds placed m}^{-2} = \frac{\text{kg seed ha}^{-1}}{\text{Thousand kernel mass}} \qquad (3.3^{b)})$$

Figure 3.10 : Plant counts were done in 3 replicate strips of 0.5 m each per plot

3.7.3 Yield parameters

3.7.3.1 Number of plants, tillers and ears, biomass yield and residue yield

All the plants in the three identified strips per plot were pulled from the soil and bagged before harvest. Plot sampling area was calculated as 0.675 m^{-2} (3 × 0.5 m strips × 0.45 m row width). In the laboratory, the number of plants, tillers and ears were recorded per plot. Plant roots were cut off before the plants were over dried at 60°C for 48 hours. The dry plant material was weighed and the above ground biomass calculated (g m^{-2}). Residue (straw) yield was calculated by subtracting the grain yield (g m^{-2}) obtained in section 3.7.3.3 from the biomass yield.

3.7.3.2 Thousand kernel mass

The thousand kernel mass (TKM) was determined for each sample by counting 500 kernels with a numerical seed counter and multiplying the weight (g) by two.

3.7.3.3 Grain yield

A Wintersteiger plot harvester was used to harvest three rows of 10 m each per plot. After harvest, samples were cleaned by removing all the chaff that remained in the sample. The samples were weighed to determine the plot weight, from which grain yield (kg ha^{-1}) was calculated.

3.7.3.4 Harvest index

Harvest index (HI) was calculated as the ratio between the grain yield and the total above-ground biomass at harvest.

3.7.4 Quality grading parameters

Representative subsamples of the cleaned grain in section 3.7.3.3 were collected and sent to the Grain Quality Laboratory at ARC-Small Grain Institute for determination of the following three quality grading parameters:

3.7.4.1 Protein

Grain protein (%) was determined with a Technicon Infra-Alyzer-400 (calculated as % N × 5.7) and corrected to 12% water content. The Near–Infrared Reflectance method for protein determination in wheat flour AACC Method 39-11 (American Association of Cereal Chemists, 2000b) was used.

3.7.4.2 Hectolitre mass

Hectolitre mass (kg hl^{-1}), was determined according to AACC Method 55-10 (American Association of Cereal Chemists, 2000c). A Dickey John automated apparatus was used for determinations.

3.7.4.3 Falling number

Falling number in seconds (s), was measured according to the AACC Method 56-81B (American Association of Cereal Chemists, 2000a) with a Falling Number instrument (FN 1800 model).

3.7.5 Nitrogen use parameters

3.7.5.1 Potential available nitrogen supply

Soil was sampled one week before planting of the final wheat crop. The samples were analysed for total nitrogen (method described in 3.7.1). A total of 42 kg N ha^{-1} was added to the soil when the trial was fertilised with a 3:1:0(28) mixture at an application rate of 200 kg ha^{-1}. Potential available nitrogen (PAN) for crop use was calculated with equation 3.4:

$$\text{PAN (kg N ha}^{-1}\text{)} = \text{Total soil N at planting + fertiliser N} \qquad (3.4)$$

3.7.5.2 Nitrogen uptake

The Leco combustion method was used to analyse the grain (seed) and residue (straw) samples for total nitrogen % (Leco FP-2000, Nitrogen/Protein Analyser). Equations 3.5 to 3.8 were used to calculate nitrogen uptake in the grain ($N_{(grain)}$), in the residue ($N_{(residue)}$), in the biomass ($N_{(biomass)}$) as well as the N harvest index (NHI) :

$$N_{(grain)} \text{ (kg N ha}^{-1}\text{)} = \frac{\text{grain yield (kg ha}^{-1}\text{)} \times N_{(grain)} (\%)}{100} \qquad (3.5)$$

$$N_{(residue)} \text{ (kg N ha}^{-1}\text{)} = \frac{\text{residue yield (kg ha}^{-1}\text{)} \times N_{(residue)} (\%)}{100} \qquad (3.6)$$

$$N_{(biomass)} \text{ (kg N ha}^{-1}\text{)} = N_{(grain)} + N_{(residue)} \qquad (3.7)$$

$$\text{NHI (\%)} = \frac{N_{(grain)}}{N_{(biomass)}} \times 100 \qquad (3.8)$$

3.7.5.3 Nitrogen use efficiency

The % nitrogen use efficiency ($NUE_{(grain)}$) of the final wheat grain was calculated with equation 3.9:

$$NUE_{(grain)}\ (\%) = \frac{N_{(grain)}\ (kg\ N\ ha^{-1})}{Nsupply_{\ (soil\ +\ fertiliser\ )}\ (kg\ N\ ha^{-1})} \times 100 \qquad (3.9)$$

3.7.6 Precipitation use efficiency

Precipitation use efficiency (PUE) gives an indication of the effectiveness with which crop sequences use precipitation.

$$PUE\ (kg\ ha^{-1}\ mm^{-1}) = \frac{\text{grain yield}\ (kg\ ha^{-1})}{\text{precipitation from harvest of one crop to harvest of following crop (mm)}} \qquad (3.10)$$

3.7.7 Profitability and production risk

Data on production costs and prices of crops were obtained from VKB Agriculture Pty. and measured yields, obtained in the trial, were used for calculation. Risk was calculated as the cumulative sum of shortfalls when annual net returns fall below a specified net target for a specified number of years (Nel and Loubser 2004).

3.7.8 Statistical analysis

The Biometry Unit at the ARC analysed the data with the statistical programme Genstat® (Payne et al. 2007). ANOVA for a strip-plot (or criss-cross) design was performed on all the measurements and analyses results. Three treatment factors described the effect of preceding summer and winter crop treatments on wheat as the target crop. The factor (season 1), as well as the factor (season 2), indicated the influence of crop treatments per season on the final wheat crop, while the factor (season 1 × season 2) indicated the effect of preceding crop sequences on the final wheat crop. The least significant differences (LSD) were calculated with the Fisher's protected LSD test at 95% and 90% confidence levels. Based on the outcome it was decided to report only the 90% confidence levels. Differences and significance levels of differences between treatment means and interactions are summarised in Table 4.6 to Table 4.33 (section 4.4 in Chapter 4). Means followed by the same letter did not differ significantly. A crop planted in its own residue was seen as monoculture and the specific results were underlined in all the tables to identify it as such.

Correlation matrices were calculated for identified parameters and the correlation coefficients were tested at a 95% probability level. The results are summarised in Tables 4.34 and 4.35 (section 4.4.7 in Chapter 4).

3.8 References

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CHAPTER 4

INFLUENCE OF CROPPING SEQUENCE ON WHEAT GROWTH IN A CONSERVATION AGRICULTURE SYSTEM

4.1 Introduction

South Africa is divided into nine provinces, of which the Free State Province is the third largest. The province is situated in the heart of South Africa with the Vaal River as the northern border and the Orange River as the southern border (GCIS 2013). It covers a total area of 12.9 million ha of which approximately 3.82 million ha is potentially arable. It is estimated that 8% of the province is of very low agricultural potential, while 49% and 43% of the area is of low and medium agricultural potential respectively. The climate is mostly semi-arid, except for the south-western area which is arid (Hensley et al. 2006).

The province is divided into four dryland crop production regions, namely the Central, Eastern, North Western and South Western Free State (ARC-SGI 2013). Crop production is mostly rain-fed, with less than 10% of the arable land being under irrigation (Moeletsi et al. 2011).

In 2012 the Free State Province produced 40% of the maize, 47% of the sunflower, 30% of the soybean, 45% of the sorghum, 37% of the dry bean and 20% of the wheat in South Africa (SAGIS 2013). However, this contribution to national crop production fluctuates often due to the variability in rainfall (Purchase et al. 2000).

Table 4.1 summarises the total area planted per crop in the Free State from 2009 to 2012 (SAGIS 2013). The area planted with soybean increased consistently over the four years in comparison with a variation in planted area of maize, sunflower and wheat, while the planted area of sorghum declined. Maize dominated in all four years which indicates that the benefits of crop rotation are to a large extent still unexploited by producers in the Free State.

Table 4.1 : Total area planted per crop in the Free State from 2009 to 2012

Crops	Area (ha) planted per crop per annum			
	2009	2010	2011	2012
Maize	955 000	1 156 000	990 000	1 160 000
Sunflower	280 000	175 000	300 000	190 000
Soybean	55 000	95 000	135 000	175 000
Sorghum	55 000	50 000	43 000	22 000
Dry bean	18 000	16 000	15 000	16 000
Wheat	235 000	204 000	225 000	130 000
Total area planted	1 598 000	1 696 000	1 708 000	1 693 000

Source: SAGIS (2013)

Research that has been done in the area to identify possible causes for the rotational effect, concentrated on the improvement of soil profile conditions by fallowing and nitrogen enrichment (Nel 2005). Nel et al. (2003) quantified the effect of dry bean, lupin, sunflower and fallow on a subsequent wheat crop in the Eastern Free State. Higher wheat yields were recorded after crop rotation. Wheat yielded 40% more after an 18 month fallow period, 31% more after lupin, 25% more after dry bean and 54% more after sunflower. Wheat yields were, with the exception of preceding dry bean, stabilised by crop rotation and the protein and hectolitre mass of wheat grain were also improved by crop rotation (Nel et al. 2003).

The main objective of this study was to evaluate the impact of different cropping sequences on the growth, development, yield and quality of wheat as target crop in a conservation tillage system in the Eastern Free State. Six parameters (soil, plant, yield, quality grading, nitrogen use and precipitation) were evaluated to test the hypothesis that wheat growth will be influenced by preceding cropping sequences in a CA system.

4.2 Procedure

The most relevant data for this study was collected in 2011 when wheat was planted as the target crop in the residue of 50 preceding cropping sequences. The trial site, planting equipment, experimental layout and treatments are discussed in sections 3.2, 3.4 and 3.5 of Chapter 3. Climatic conditions during the study period will be discussed in section 4.3. Significant treatment means and interactions ($P \leq 0.1$) is discussed and summarised in section 4.4.

4.3 Climate

The climate of a specific locality largely determines the suitability thereof for crop production. Hectolitre mass, protein content and falling number, the quality parameters of wheat, are largely determined by environmental conditions experienced from grain filling to. Wheat plants thrive in cool conditions, whereas high temperatures severely limit wheat yield. The grain filling period is critical for producing high yields because kernel size and weight are determined during this stage. The longer this filling period lasts, the greater the probability for higher yields is maturity (Otto 2007, ARC-SGI 2013). Climatic data played an important role in the interpretation of data recorded in the final study year and were obtained from the ARC – Institute for Soil, Climate and Water.

4.3.1 Rainfall

The Free State Province forms part of the summer rainfall region of South Africa and receives insignificant precipitation during the winter months. Average annual rainfall ranges from 300 mm to over 900 mm with more than 70% of the rainfall occurring from September/October to April/May. The duration of the rainy season in most parts of the Northern and Eastern Free State is between 181 and 200 days (Moeletsi et al. 2011).

Summer crops are planted from October to December depending on the time of onset of the rainy season. The earliest onsets of rain in the province usually occurs between 20 September and 10 October in the north eastern and eastern parts which include the districts of Bethlehem, Frankfort, Ficksburg, Harrismith, Warden and Vrede

(Moeletsi et al. 2011). Winter crops are planted from April to July on residual water in the soil profile conserved during the summer rainfall months. The crops are dependent on highly variable spring rainfall from September to November to ensure economic yields.

The average monthly rainfall of the study period is listed including long term data in Table 4.2. The total amount of rainfall in 2008, 2009 and 2011 was less than the annual long term average (22%, 14% and 20% less respectively), while the annual rainfall in 2010 was 23% higher. Recorded rainfall for the first six months (January to June) was 375 mm, 535 mm and 419 mm respectively for 2009, 2010 and 2011, while the long term average for the same period is 458 mm. The greatest deviation from total monthly long-term rainfall was observed in January 2010 when 296 mm was recorded compared to the long term rainfall of 120 mm (Table 4.2).

Table 4.2 : Monthly rainfall (mm) at the trial site for 2008-2011, as well as the average rainfall for 60 years ending 2012

Month	Average monthly rainfall* (mm)				
	2008	2009	2010	2011	60 years
January	90	83	296	172	120
February	72	172	101	102	97
March	78	39	89	24	79
April	8	5	43	67	48
May	41	17	5	30	23
June	25	59	1	24	12
July	1	0	0	14	8
August	0	20	1	4	17
September	0	8	0	6	30
October	15	42	42	33	76
November	150	75	91	29	95
December	70	87	200	61	104
Total	**550**	**607**	**869**	**566**	**709**

* Highlighted values exceeded the 60 year average monthly rainfall

It is well known that grain yield of crops are reduced when water stress is experienced from anthesis to grain fill (Mengel and Kirkby 2001, Otto 2007). Potential water stress periods during the study were identified by comparing agronomic characteristics of planted crops with measured rainfall (Table 4.2 and Table 4.3).

Table 4.3 : Agronomic characteristics of crops

Crop	Relative days to 50% flower	Relative days to physiological ripe	Crop sensitive to water stress (months)	Days to harvest
Dry bean	50 - 60	100 - 120	Feb - Mar/Apr	100 - 120
Maize (Yellow)	76 - 82	140 - 162	Mar - Jun	175 - 240
Sorghum	79 - 85	135 - 145	Mar - May	135 - 145
Soybean	50 - 62	124 - 138	Feb - May	124 - 138
Sunflower	70 - 77	124 - 130	Mar - Apr/May	140 - 155
Oats	No information	No information	Oct - Nov	140 - 150
Wheat	109 - 138	157 - 176	Oct - Nov	169 - 186

Source: PANNAR (2013)

Rainfall recorded during October and November (2008 - 2011) was 23% to 64% less than the long term rainfall of 171 mm for these two months. Table 4.3 indicates that winter crops such as wheat and oats would suffered water stress because of the low rainfall.

4.3.2 Temperature

The trial started in December 2008 with the planting of the first summer crops. Both the average minimum and maximum temperatures for December were 2°C higher during 2008 than the long term temperatures. The minimum average temperatures of the first three months in 2009 and 2010 were 1°C and 2°C higher than long-term minimum temperatures. However, the differences were probably too small to have an influence on the growth of preceding summer crops in the trial. The most significant deviation from the long-term maximum temperatures occurred in September 2010, when 26°C was measured compared to the long term average of 22°C.

Table 4.4 : Minimum and maximum monthly temperatures (°C) during the research period as well as average long-term data (60 years)

Monthly minimum and maximum temperatures* (°C)										
Month	2008		2009		2010		2011		60 year	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Jan	13.0	26.0	15.0	27.0	15.0	25.0	14.0	24.0	**14.0**	**27.0**
Feb	13.0	26.0	14.0	25.0	14.0	26.0	14.0	25.0	**13.0**	**26.0**
Mar	11.0	23.0	12.0	25.0	13.0	25.0	13.0	26.0	**11.0**	**25.0**
Apr	5.0	21.0	6.0	23.0	9.0	22.0	8.0	20.0	**7.0**	**22.0**
May	4.0	20.0	3.0	19.0	4.0	20.0	4.0	18.0	**2.0**	**19.0**
Jun	0.0	17.0	1.0	15.0	-2.0	17.0	-1.0	16.0	**-2.0**	**16.0**
Jul	-2.0	17.0	-3.0	15.0	-1.0	17.0	-3.0	14.0	**-2.0**	**16.0**
Aug	1.0	21.0	1.0	19.0	0.0	21.0	0.0	19.0	**0.0**	**19.0**
Sep	2.0	24.0	5.0	24.0	5.0	26.0	5.0	24.0	**5.0**	**22.0**
Oct	9.0	27.0	9.0	24.0	8.0	25.0	8.0	25.0	**8.0**	**24.0**
Nov	12.0	26.0	10.0	24.0	11.0	25.0	10.0	26.0	**11.0**	**25.0**
Dec	14.0	28.0	13.0	28.0	13.0	25.0	13.0	26.0	**12.0**	**26.0**
Annual average	6.8	23.0	7.2	22.3	7.4	22.8	7.1	21.9	**6.6**	**22.3**

*Highlighted values exceeded the 60 year average monthly temperature
Underlined values were lower than the 60 year average monthly temperature

4.4 Results and Discussion

4.4.1 Soil parameters

4.4.1.1 Fertility status of soil

Top and sub soil samples (sampling depths of 0 to 20 cm and 20 to 40 cm each) were collected and analysed in November 2008 to establish the different baseline values listed under 2008 in Table 4.5. The analyses results were within acceptable norms for general crop production (ARC-SGI Soil Analyses Laboratory).

Plots were sampled for a second time in July 2011 prior to final wheat crop planting, to monitor if the different cropping sequences and applied fertiliser had an effect on the soil fertility status of the no-till system. The average $pH_{(KCl)}$ of sub-soils in the winter blocks improved from 4.65 in 2008 to 4.84 in 2011, while the phosphorus (P) decreased from a medium 18.8 mg kg^{-1} to a low 12.5 mg kg^{-1}. Fertiliser applications ensured, however, that medium to high P values (24.5 to 25.5 mg kg^{-1}) were maintained in the top-soils of the trial (summer and winter blocks). Although the potassium (K) values of sub-soils decreased from 203 mg kg^{-1} to 167 mg kg^{-1} in the summer blocks and from 196 mg kg^{-1} to 159 mg kg^{-1} in the winter blocks, it was still acceptable for general wheat production (ARC-SGI 2013).

Table 4.5 : Soil analyses of the experimental site in 2008 and prior to planting of the final wheat crop in 2011

Soil analyses	Summer blocks				Winter blocks			
	2008		2011		2008		2011	
	Top	Sub	Top	Sub	Top	Sub	Top	Sub
pH (KCl)	5.00	4.87	4.95	4.88	4.78	4.65	4.85	4.84
P (Bray1) (mg kg^{-1})	25.4	19.2	25.5	12.5	24.5	18.8	25.4	12.5
K (Am. acetate) (mg kg^{-1})	252	203	242	167	228	196	226	159
Ca (Am. acetate) (mg kg^{-1})	531	528	517	528	493	483	494	515
Mg (Am. acetate) (mg kg^{-1})	106	111	104	117	104	109	101	115
Na (Am. acetate) (mg kg^{-1})	2.0	3.9	2.0	3.3	1.8	2.5	2.3	3.7
% Acid saturation	3.10	3.71	4.80	3.50	4.47	5.26	4.80	3.43

4.4.1.2 Soil water content at planting

The final wheat crop was planted on residual soil water conserved during the summer months. A total of 433 mm rain was measured from January to July 2011 and the maximum temperatures exceeded the long-term records only in March. The residual water was stored in a soil profile of 110 cm, with a storage capacity of about 125 mm per 600 mm depth (Engelbrecht et al. 1986). Volumetric water content was measured per plot at planting in July 2011 to monitor if the preceding crop sequences had an effect on the plant available water. Table 4.6 indicates that summer blocks had an average volumetric water content of 21.8% which is similar to the average 22% of the winter blocks. Differences between the volumetric water contents of the different plots were also not significant. The lowest value of 19.7% was measured on the preceding fallow × fodder oats plot and the highest value of 24.4% on the preceding fodder oats × oats plot (values highlighted in the winter plantings of Table 4.6).

It is well known that diverse crop rotations utilise water from different soil profile depths and that plant available water to a following wheat crop can be 19.9% and 9.3% lower after sunflower and soybean respectively, than after maize and sorghum (Norwood 2000, Merril et al. 2002). The effect is however more important in years with lower than average rainfall (Nel 2005), which explains the non-significant differences

Table 4.6 : Average volumetric soil water content (%) at planting of final wheat crop in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	Crops	Dry bean	Maize	Sorghum	Soybean	Sun-flower	Avg.	Crops	Vetch	Fallow	Fodder oats	Oats	Wheat	Avg.
	Dry bean	22.3	21.3	20.8	20.6	21.7	21.3	Vetch	21.6	21.7	20.7	22.1	21.7	21.6
	Maize	21.7	22.6	21.9	22.0	21.6	21.9	Fallow	21.3	23.5	19.7	22.7	22.3	21.9
	Sorghum	22.5	23.0	23.1	21.0	22.9	22.5	Fodder oats	22.6	22.5	22.6	24.4	22.6	22.9
	Soybean	22.0	22.9	21.8	21.4	21.4	21.9	Oats	21.2	21.8	21.7	22.7	22.6	22.0
	Sunflower	20.8	21.6	22.9	20.6	22.1	21.6	Wheat	21.6	21.4	21.7	22.3	22.0	21.8
	Avg.	21.8	22.3	22.1	21.1	21.9	21.8	Avg.	21.7	22.2	21.3	22.8	22.2	22.0
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant

between the volumetric water contents from different crop sequence treatment plots in the study.

4.4.2 Plant parameters

4.4.2.1 Seedling survival rate

Table 4.7 indicates that the average seedling survival rate of the final wheat planting was 72% in the summer blocks, while that of final wheat seedlings in the winter blocks was 64%. The soil fertility status and residual water content of plots can influence seedling survival rate, but Tables 4.5 and 4.6 showed that differences due to different crop treatments were not significant in both the plant available nutrient and water results. The 8% higher seedling survival rate on summer blocks could be ascribed to a longer fallow period (10 to 12 months) between the harvest of second season summer crops, compared to a 6 month fallow period of second season winter crops before the final wheat crop planting.

Differences in final wheat seedling survival rate due to crop treatments were not significant in the summer blocks (Table 4.7). However, average seedling survival rate of the final wheat crop was significantly lower on second season oats treatment plots (58%), than on second season fallow (66%), wheat (66%), and fodder oats (65%) treatment plots. Wheat seedling survival on second season vetch plots did not differ significantly from that of second season oats plots.

Table 4.7 : Average seedling survival rate (%) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	82	77	74	70	75	76	**Vetch**	55	68	66	47	67	61
	Maize	72	75	73	75	63	71	**Fallow**	67	73	63	61	64	65
	Sorghum	65	81	74	53	71	69	**Fodder oats**	72	69	73	64	72	70
	Soybean	73	62	69	73	78	71	**Oats**	56	62	66	56	66	61
	Sunflower	80	64	79	70	62	71	**Wheat**	64	61	60	60	63	61
	Avg.	74	72	74	68	70	72	**Avg.**	63^{ab}	66^{a}	65^{a}	58^{b}	66^{a}	64
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 5 cv = 6.3%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

4.4.3 Yield parameters

Yield parameters (number of plants m^{-2}, tillers m^{-2}, ears m^{-2}, biomass and residue yield, TKM, grain yield and harvest index) were determined on the final wheat crop which was planted on all the plots. Analyses of variance were performed on these yield parameters and indicated that preceding summer crop sequences (season 1 × season 2) impacted significantly on the number of plants m^{-2}, ears m^{-2} and TKM, as well as on the biomass and residue yield, and the harvest index of the final wheat crop (Table 4.8). The influence of second season summer crop treatments (season 2) were not significant on final wheat yield parameters, while first season summer crop treatments (season 1) caused significant differences ($P \leq 0.1$) in the number of tillers and ears m^{-2}, as well as the TKM of final wheat. First season winter crop treatments (season 1) resulted in significant differences ($P \leq 0.1$) in the biomass and grain yield of the final wheat crop, while the number of plants m^{-2} and number of ears m^{-2}, as well as the grain yield and harvest index of the final wheat crop was influenced ($P \leq 0.1$) by the second season winter crop treatments (season 2). The influence of preceding winter crop sequences was not significant on the measured yield parameters of the final wheat crop. The detailed results are given in Tables 4.9 to 4.20.

4.4.3.1 Plants, tillers and ears

Summer blocks showed an average of five more wheat plants per m^{-2} (49) in the final planting of 2011, than winter blocks (44 wheat plants) (Table 4.9). The average number of wheat plants on winter blocks, where oats was planted as second season treatment, was significant lower (40) than plots where the second season plantings were wheat (46), fallow (46) or fodder oats (45) (Table 4.9). No significant differences were observed between the average number of wheat plants in the preceding oats, or the vetch planting of the second season.

Table 4.10 gives an indication of the effect of summer cropping sequences (season 1 × season 2) on the number of wheat plants in the final planting (2011). Significant more wheat plants were recorded in the final planting on preceding sequences of dry bean × dry bean (59) and sorghum × maize (56), than on the last six sequences (sorghum × dry bean (45) to sorghum × soybean (33)) listed in Table 4.10.

Table 4.8 : Summary of analyses of variance indicating the effect of treatment factors on selected yield parameters of final wheat crop

Factors summer crops	Number of plants m^{-2}	Number of tillers m^{-2}	Number of ears m^{-2}	Biomass yield	Residue yield	TKM	Grain yield (ton ha^{-1})	Harvest Index
season 1	ns	*	*	ns	ns	*	ns	ns
season 2	ns	ns	ns	ns	ns	ns	ns	ns
season 1 × season 2	*	ns	*	*	*	*	ns	*
Factors winter crops	**Number of plants m^{-2}**	**Number of tillers m^{-2}**	**Number of ears m^{-2}**	**Biomass yield**	**Residue yield**	**TKM**	**Grain yield (ton ha^{-1})**	**Harvest Index**
season 1	ns	ns	ns	*	ns	ns	*	ns
season 2	*	ns	*	ns	ns	ns	*	*
season 1 × season 2	ns	ns	ns	ns	ns	ns	ns	ns

* ≤ P 0.10
ns = not significant

Table 4.9 : Average number of plants (m^{-2}) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	59	53	51	49	52	53	**Vetch**	38	47	46	32	46	42
	Maize	49	53	51	52	43	50	**Fallow**	46	50	44	42	44	45
	Sorghum	45	56	51	33	49	47	**Fodder oats**	50	47	50	44	50	48
	Soybean	51	43	48	51	54	49	**Oats**	38	43	46	39	45	42
	Sunflower	55	44	55	48	43	49	**Wheat**	44	42	41	41	43	42
	Avg.	52	50	51	46	48	49	**Avg.**	43^{ab}	46^{a}	45^{a}	40^{b}	46^{a}	44
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 4 cv = 6%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.10 : Average number of plants of final wheat crop planted in residues of preceding summer cropping sequences

Cropping sequence two seasons before final wheat planting in 2011	Plants m^{-2}
Dry bean × Dry bean	59^{a}
Sorghum × Maize	56^{a}
Sunflower × Dry bean	55^{ab}
Sunflower × Sorghum	55^{abc}
Soybean × Sunflower	54^{abcd}
Dry bean × Maize	53^{abcde}
Maize × Maize	53^{abcde}
Dry bean × Sunflower	52^{abcde}
Maize × Soybean	52^{abcde}
Dry bean × Sorghum	51^{abcde}
Soybean × Dry bean	51^{abcde}
Sorghum × Sorghum	51^{abcde}
Soybean × Soybean	51^{abcde}
Maize × Sorghum	51^{abcde}
Maize × Dry bean	49^{abcde}
Sorghum × Sunflower	49^{abcde}
Dry bean × Soybean	49^{abcde}
Sunflower × Soybean	48^{abcde}
Soybean × Sorghum	48^{abcdef}
Sorghum × Dry bean	45^{bcdef}
Sunflower × Maize	44^{def}
Maize × Sunflower	43^{bcdef}
Soybean × Maize	43^{cef}
Sunflower × Sunflower	43^{def}
Sorghum × Soybean	33^{f}
$LSD_{(season1 \times season2)(0.10)} = 12$ cv = 17%	

Underlined values = final wheat planted on monoculture crops
Averages followed by the same letter did not differ significantly

The average number of wheat plants on these two sequences (dry bean × dry bean and sorghum × maize) did however not differ significantly from that of the following 17 sequences listed in Table 4.10. Four monoculture sequences were included in these 19 sequences and the highest number of wheat plants (59) was recorded on the dry bean × dry bean preceding sequence. The lowest average number of wheat plants (33) in the final planting occurred on preceding sorghum × soybean sequence plots.

The number of tillers m^{-2} in the final planting was determined for each plot and the results are shown in Table 4.11. Summer blocks showed an average of 354 tillers m^{-2} comparing to the average of 315 tillers m^{-2} produced in the winter blocks. The results in Table 4.11 indicate that the final wheat crop planted on plots where sunflower was planted in the first season, had a significantly higher number of tillers m^{-2} (380) than plots planted with maize, sorghum or soybean in the same season (336, 337 and 344 tillers m^{-2} respectively).

An average of 334 filled ears m^{-2} was recorded on summer blocks compared to the 281 m^{-2} filled ears on winter blocks (Table 4.12). Summer blocks had on average five more wheat plants m^{-2} (Table 4.9), with 39 more tillers m^{-2} (Table 4.11) and 53 more filled ears m^{-2} (Table 4.12) than winter blocks.

The average number of ears m^{-2} of the final wheat crop differed significantly between first season crop treatments and second season crop treatments in the winter blocks (Table 4.12). Significant more final wheat ears were counted on first season fallow treatment plots (310), than on first season oats (271), vetch (270) and wheat (258) treatment plots. The number of wheat ears that was recorded on plots where oats was planted as second season treatment, was significantly lower than those plots that were planted with wheat, fallow and vetch as second season treatments.

Table 4.13 gives the number of filled ears m^{-2} in the final planting of wheat on preceding summer crop sequences. The highest number of filled wheat ears was recorded on the preceding sunflower × dry bean sequence. Although this did not differ significantly from the number of wheat ears m^{-2} recorded for the following seven sequences listed in Table 4.13, it was significantly higher than the number of filled ears m^{-2} of the last 17 sequences listed in Table 4.13. The sorghum × soybean sequence plots, which showed the lowest, although not significant, average number of wheat plants m^{-2} in Table 4.10, also showed the lowest number of filled ears m^{-2} in Table 4.13.

Table 4.11 : Average number of tillers (m^{-2}) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	379	387	367	342	382	372^{ab}	**Vetch**	251	317	345	246	325	297
	Maize	358	357	337	338	287	336^{c}	**Fallow**	348	347	313	334	350	338
	Sorghum	331	407	333	279	334	337^{c}	**Fodder oats**	361	316	316	292	347	326
	Soybean	323	318	335	386	360	344^{bc}	**Oats**	305	321	290	324	325	313
	Sunflower	430	370	359	365	375	380^{a}	**Wheat**	302	311	274	308	305	300
	Avg.	364	368	346	342	348	354	**Avg.**	314	322	307	301	330	315
	$LSD_{(season1)(0.10)}$ = 32 cv = 7% $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.12 : Average number of filled ears (m^{-2}) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	Crops	Dry bean	Maize	Sorghum	Soybean	Sun-flower	Avg.	Crops	Vetch	Fallow	Fodder oats	Oats	Wheat	Avg.
	Dry bean	343	377	351	324	349	349	Vetch	233	296	312	208	299	270^{bc}
	Maize	323	342	313	321	271	314	Fallow	332	317	271	286	343	310^{a}
	Sorghum	323	387	317	262	313	320	Fodder oats	327	294	286	247	320	295^{ab}
	Soybean	313	306	318	369	343	330	Oats	247	291	252	275	289	271^{bc}
	Sunflower	410	353	344	342	352	360	Wheat	278	270	243	237	262	258^{c}
	Avg.	342	353	328	323	325	334	Avg.	283^{ab}	293^{ab}	273^{bc}	251^{c}	303^{a}	281
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = 32 cv = 9% $LSD_{(season2)(0.10)}$ = 25 cv = 7%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.13 : Average number of filled ears of final wheat crop planted in residues of preceding summer cropping sequences

Cropping sequence two seasons before final wheat planting in 2011	Ears m^{-2}
Sunflower × Dry bean	410^{a}
Sorghum × Maize	387^{ab}
Dry bean × Maize	377^{abc}
Soybean × Soybean	369^{abc}
Sunflower × Maize	353^{abcd}
Sunflower × Sunflower	352^{abcd}
Dry bean × Sorghum	351^{abcd}
Dry bean × Sunflower	349^{abcd}
Sunflower × Sorghum	344^{bcd}
Soybean × Sunflower	343^{bcd}
Dry bean × Dry bean	343^{bcd}
Maize × Maize	342^{bcd}
Sunflower × Soybean	342^{bcd}
Dry bean × Soybean	324^{bcde}
Maize × Dry bean	323^{cdef}
Sorghum × Dry bean	323^{cdef}
Maize × Soybean	321^{cdefg}
Soybean × Sorghum	318^{cdefgh}
Sorghum × Sorghum	317^{cdefgh}
Maize × Sorghum	313^{cdefgh}
Sorghum × Sunflower	313^{cdefgh}
Soybean × Dry bean	313^{cdefgh}
Soybean × Maize	306^{defgh}
Maize × Sunflower	271^{efgh}
Sorghum × Soybean	262^{fh}
LSD$_{(season1 \times season2)\ (0.10)}$ = 64 cv = 14%	

Underlined values = final wheat planted on monoculture crops
Averages followed by the same letter did not differ significantly

4.4.3.2 Biomass yield and residue yield

The biomass yield and residue yield of the final wheat crop were obtained with the method described in Chapter 3 (section 3.7.3.1). Results are shown in Tables 4.14 and 4.15.

The recorded biomass and residue yields of the final wheat crop were significantly higher on the sorghum × maize plots than on the last 13 biomass yields and the last 11 residue yields listed in Table 4.14 (indicated with *). The biomass and residue yields of final wheat plantings on sorghum × soybean sequence plots were the lowest in the summer blocks. The biomass wheat yields obtained on this sequence were however not significantly different from those obtained on maize × sunflower and soybean × maize plots. The residue wheat yield did also not differ significantly from those recorded on final wheat plantings in soybean × maize plots.

Table 4.15 indicates that the biomass yield of the final wheat crop planted on first season fallow treatment plots was significantly higher (664.4 gm^{-2}) than the biomass of the final wheat planting on the other four winter crop treatments plots.

4.4.3.3 Thousand kernel mass

The average thousand kernel mass (TKM) of the final wheat crop planting on the first season dry bean, soybean and sunflower treatment plots was significantly lower than the TKM of wheat planted on first season sorghum treatment plots (Table 4.16). Final wheat on second season soybean plots had however a significantly higher TKM than wheat on second season dry bean, sorghum and sunflower plots (Table 4.16).

Table 4.17 indicates that TKM of the final wheat crop on a preceding sorghum × soybean sequence was significantly higher than any other sequences in the summer block. A significant lower TKM was also recorded for final wheat on preceding soybean × sunflower and sunflower × soybean sequences, than for final wheat on preceding sorghum × soybean, maize × maize and sorghum × maize sequences (Table 4.17). This is however not of economic importance since the TKM of all treatments was acceptable.

Table 4.14 : Average biomass yield and residue yield of final wheat crop planted in residues of preceding summer cropping sequences

Cropping sequence two seasons before final wheat planting in 2011	Biomass yield (g m^{-2})	Residue yield (g m^{-2})
Sorghum × Maize	776.5[a]	584.4[a]
Sunflower × Dry bean	761.9[ab]	574[ab]
Sunflower × Maize	722.0[abc]	537[abc]
Soybean × Soybean	712.3[abc]	525.7[abc]
Maize × Maize	707.1[abc]	517.5[abc]
Dry bean × Maize	704.4[abc]	511.1[abc]
Sunflower × Soybean	695.8[abcd]	508.9[abcd]
Sunflower × Sorghum	682.8[abcd]	494.3[abcd]
Dry bean × Dry bean	674.3[abcd]	486.3[abcd]
Maize × Sorghum	672.8[abcd]	485.9[abcd]
Dry bean × Sorghum	667.9[abcd]	485.4[abcd]
Sunflower × Sunflower	664.7[abcd]	482[abcd]
Sorghum × Dry bean	*657.3[cd]	476.6[abcd]
Soybean × Sorghum	*650.8[bcd]	476.2[abcd]
Maize × Dry bean	*646.9[cd]	*473.8[bcd]
Sorghum × Sunflower	*646.8[bcd]	*470.4[bcd]
Soybean × Dry bean	*646.0[cd]	*469.7[cd]
Soybean × Sunflower	*644.7[cd]	*468.9[bcd]
Dry bean × Soybean	*641.1[cd]	*456.9[cd]
Dry bean × Sunflower	*637.1[cd]	*455.6[cd]
Sorghum × Sorghum	*635.0[cd]	*455.2[cd]
Maize × Soybean	*620.6[cd]	*448.5[cd]
Maize × Sunflower	*613.0[cde]	*427.3[cd]
Soybean × Maize	*597.9[de]	*404.9[de]
Sorghum × Soybean	*523.9[e]	*342.3[e]
Total biomass yield: $LSD_{(season1 \times season2)(0.10)}$ = 111.8 cv = 12 % Residue yield: $LSD_{(season1 \times season2)(0.10)}$ = 110.0 cv = 16%		

Underlined values = final wheat planted on monoculture crops
Averages followed by the same letter did not differ significantly

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Table 4.15 : Average biomass yield (g m^{-2}) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							**Winter block plantings**						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	674.3	704.4	667.9	641.1	637.1	665.0	**Vetch**	474.9	596.6	664.9	515.9	611.4	572.7^{b}
	Maize	646.9	707.1	672.8	620.6	613.0	652.1	**Fallow**	735.8	672.5	616.1	592.8	704.6	664.4^{a}
	Sorghum	657.3	776.5	635.0	523.9	646.8	647.9	**Fodder oats**	637.1	588.3	623.4	577.8	629.9	611.3^{b}
	Soybean	646.0	597.9	650.8	712.3	644.7	650.3	**Oats**	593.1	594.5	585.6	635.4	556.0	592.9^{b}
	Sunflower	761.9	722.0	682.8	695.8	664.7	705.4	**Wheat**	581.6	590.4	530.4	648.0	611.5	592.4^{b}
	Avg.	677.3	701.6	661.9	638.7	641.3	664.2	**Avg.**	604.5	608.5	604.1	594.0	622.7	606.8
	$LSD_{(season1)(0.10)}$ = 32 cv = 7% $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = 51,0 cv = 6.7% $LSD_{(season2)(0.10)}$ = ns						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.16 : Average thousand kernel mass (g) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	Crops	Dry bean	Maize	Sorghum	Soybean	Sun-flower	Avg.	Crops	Vetch	Fallow	Fodder oats	Oats	Wheat	Avg.
	Dry bean	38.0	38.3	37.6	37.7	37.7	37.8^{bc}	Vetch	35.1	35.1	35.8	35.6	36.2	35.5
	Maize	38.2	39.0	37.3	38.5	38.4	38.3^{ab}	Fallow	36.2	35.0	35.1	35.7	37.1	35.8
	Sorghum	37.0	38.8	37.8	43.3	37.2	38.8^{a}	Fodder oats	35.7	36.3	33.8	34.8	36.3	35.4
	Soybean	37.9	38.0	37.0	37.3	36.4	37.3^{c}	Oats	34.8	35.3	35.7	35.3	36.5	35.5
	Sunflower	36.9	37.3	37.5	36.5	37.3	37.1^{c}	Wheat	36.5	35.1	35.4	34.4	35.6	35.4
	Avg.	37.6^{bc}	38.2^{ab}	37.4^{bc}	38.6^{a}	37.4^{c}	*	Avg.	35.6	35.3	35.1	35.1	36.3	*
	LSD$_{(season1)(0.10)}$ = 0.97 cv = 2.o% LSD$_{(season2)(0.10)}$ = 0.83 cv = 1.7%							LSD$_{(season1)(0.10)}$ = 51,0 cv = 6.7% LSD$_{(season2)(0.10)}$ = ns						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4. 17 : Average thousand kernel mass (TKM) of final wheat crop planted in residues of summer cropping sequences

Cropping sequence two seasons before final wheat planting in 2011	TKM
Sorghum × Soybean	43.3^{a}
Maize × Maize	39.0^{b}
Sorghum × Maize	38.8^{b}
Maize × Soybean	38.5^{bc}
Maize × Sunflower	38.4^{bc}
Dry bean × Maize	38.35^{bc}
Maize × Dry bean	38.2^{bc}
Dry bean × Dry bean	39.0^{bc}
Soybean × Maize	38.0^{bc}
Soybean × Dry bean	37.9^{bc}
Sorghum × Sorghum	37.8^{bc}
Dry bean × Sunflower	37.7^{bc}
Dry bean × Soybean	37.7^{bc}
Dry bean × Sorghum	37.55^{bc}
Sunflower × Sorghum	37.5^{bc}
Maize × Sorghum	37.3^{bc}
Sunflower × Sunflower	37.3^{bc}
Soybean × Soybean	37.3^{bc}
Sunflower × Maize	37.3^{bc}
Sorghum × Sunflower	37.2^{bc}
Soybean × Sorghum	37.0^{bc}
Sorghum × Dry bean	37.0^{bc}
Sunflower × Dry bean	36.9^{bc}
Sunflower × Soybean	36.5^{c}
Soybean × Sunflower	36.4^{c}
$LSD_{(season1 \times season2)(0.10)}$ = 2.1, cv = 5 %	

Underlined values = final wheat planted on monoculture crops
Averages followed by the same letter did not differ significantly

4.4.3.4 Grain yield

Grain yield is known to be influenced by crop sequencing in rotation systems (Nel et al. 2003, Nel 2005, Krupinsky et al. 2006). Grain yield was determined for the final wheat crop that was planted on the preceding summer and winter crops. Results are given in Table 4.18. The final wheat grain yield of the fifty cropping sequences included in the study did not differ significantly from each other. Significant differences in final wheat yield only occurred when the grain yield was grouped in first and second season winter crop treatments. The average grain yield of final wheat on first season fallow treatments plots were significantly higher (2.13 ton ha^{-1}) than the yield obtained in the rest of the winter blocks. Final wheat on first season fallow and fodder oats plots yielded significantly higher than wheat on the oats treatment plots, while final wheat on the second season oats plots yielded significantly lower than the rest of all the second season winter crop treatment plots (Table 4.18).

4.4.4.5 Harvest index

The harvest index (HI) is the ratio between the grain yield and the biomass yield at harvest. Harvest index results in Table 4.19 indicated that the final wheat crop planted on second season oats plots had a significantly lower harvest index than wheat planted on the other winter crop treatment plots. The harvest index of the final wheat crop planted on the preceding sorghum × soybean sequences was significantly higher than the harvest index of final wheat on the last 19 sequences listed in Table 4.20. The difference in the harvest index of the final wheat crop planted on the first five preceding sequences listed in Table 4.20 was not significant.

Table 4.18 : Average grain yield (ton ha^{-1}) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2^{nd} season plantings													
	Summer block plantings							**Winter block plantings**						
Final wheat crop on 1^{st} season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	2.46	2.65	2.61	2.57	2.33	2.52	**Vetch**	1.89	1.99	1.93	1.46	2.07	1.87^{bc}
	Maize	2.61	2.59	2.55	2.26	2.59	2.52	**Fallow**	2.21	2.40	2.15	1.72	2.17	2.13^{a}
	Sorghum	2.39	2.63	2.55	2.51	2.42	2.50	**Fodder oats**	1.94	2.42	1.91	1.52	2.06	1.97^{b}
	Soybean	2.41	2.64	2.38	2.43	2.46	2.46	**Oats**	1.88	2.09	1.86	1.52	1.71	1.81^{c}
	Sunflower	2.57	2.69	2.70	2.58	2.50	2.61	**Wheat**	2.25	1.90	2.03	1.44	1.90	1.90^{bc}
	Avg.	2.49	2.64	2.56	2.47	2.46	2.52	**Avg.**	2.03^{a}	2.16^{a}	1.98^{a}	1.53^{b}	1.98^{a}	1.93
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = 0.14 cv = 5.8% $LSD_{(season2)(0.10)}$ = 0.27 cv = 11.0%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.19 : Average harvest index (%) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							**Winter block plantings**						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	37.7	38.5	39.2	40.8	37.1	38.6	**Vetch**	41.1	34.1	29.6	29.1	33.9	33.5
	Maize	40.9	37.1	39.6	36.6	42.2	39.3	**Fallow**	30.3	36.0	34.9	29.7	31.3	32.4
	Sorghum	37.9	33.8	40.6	47.8	37.9	39.6	**Fodder oats**	30.6	40.9	30.8	27.3	32.9	32.5
	Soybean	38.7	45.8	37.3	34.2	38.2	38.8	**Oats**	32.3	35.4	32.3	23.9	31.7	31.1
	Sunflower	34.1	37.2	39.9	37.5	38.1	37.4	**Wheat**	38.3	33.7	38.4	22.8	32.1	33.0
	Avg.	37.9	38.5	39.3	39.4	38.7	38.8	**Avg.**	34.5^{a}	36.0^{a}	33.2^{a}	26.5^{b}	32.4^{a}	32.5
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 5.0 cv = 12.1%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.20 : Average harvest index of final wheat crop planted in residues of preceding summer cropping sequences

Cropping sequence two seasons before final wheat planting in 2011	Harvest Index (%)
Sorghum × Soybean	47.8[a]
Soybean × Maize	45.8[ab]
Maize × Sunflower	42.2[abc]
Maize × Dry bean	40.9[abcd]
Dry bean × Soybean	40.8[abcd]
Sorghum × Sorghum	40.6[abcd]
Sunflower × Sorghum	*40.0[bcd]
Maize × Sorghum	*40.0[bcd]
Dry bean × Sorghum	*39.2[bcd]
Soybean × Dry bean	*38.7[bcd]
Dry bean × Maize	*38.5[cd]
Soybean × Sunflower	*38.2[cd]
Sunflower × Sunflower	*38.1[cd]
Sorghum × Sunflower	*37.9[cd]
Sorghum × Dry bean	*37.9[cd]
Dry bean × Dry bean	*37.7[cd]
Sunflower × Soybean	*37.5[cd]
Soybean × Sorghum	*37.3[cd]
Sunflower × Maize	*37.2[cd]
Maize × Maize	*37.1[cd]
Dry bean × Sunflower	*37.1[cd]
Maize × Soybean	*36.6[cd]
Soybean × Soybean	*34.2[d]
Sunflower × Dry bean	*34.1[d]
Sorghum × Maize	*33.8[d]
$LSD_{(0.10)}$ = 7.5 cv = 14.5%	

Underlined values = final wheat planted on monoculture crops
Averages followed by the same letter did not differ significantly

4.4.4 Quality grading parameters

Improvement of grain quality is an important benefit of crop rotation because grain prices are determined partially by the quality of the crop (Nel et al. 2003). The grading system in South Africa has one bread wheat class with six grades namely B1, B2, B3, B4, utility and class other. These classes are determined by the protein content, as well as the hectolitre mass and falling number (Table 4.21). Hectolitre mass and protein content are largely influenced by environmental conditions from grain fill to maturity of the wheat crop. Availability of soil water and nitrogen, as influenced by management practices, also play an important role in these two quality parameters (Otto 2007, ARC-SGI 2013).

Table 4.21 : Classes and grades of bread wheat

Grading regulations			
Bread wheat – Class B			
Grade	**Minimum protein (12 % water basis)**	**Minimum hectolitre mass (kg/hl)**	**Minimum falling number (seconds)**
B1	12	77	220
B2	11	76	220
B3	10	74	220
B4	9	72	200
Utility	8	70	150
Class other	Do not comply to abovementioned or any other grading regulations		

Source: ARC-Small Grain Institute (2013)

The analyses of variance indicated the effect of treatment factors on the different components of quality and the results are summarised in Table 4.22. The effect of both first season summer crop treatments (season 1) and preceding summer crop sequences (season 1 × season 2) on the quality components of the final wheat crop was not significant. The second season summer crop treatments (season 2), however, had a significant ($P \leq 0.1$) influence on the protein and falling number results of the final wheat crop. The protein content of the final wheat crop was significantly ($P \leq 0.1$) affected by all the treatment factors of the winter crop treatments, while hectolitre mass was only influenced significantly (P≤0.1) by the second season winter crop treatment. The detailed results are given in Tables 4.23 to 4.26.

Table 4.22 : Summary of analyses of variance indicating the effect of treatment factors on quality grading parameters of final wheat crop

Factors summer crops	Protein (%)	Hectolitre mass ($kg\ hl^{-1}$)	Falling number (s)
season 1	ns	ns	ns
season 2	*	ns	*
season 1 × season 2	ns	ns	ns
Factors winter crops	**Protein (%)**	**Hectolitre mass ($kg\ hl^{-1}$)**	**Falling number (s)**
season 1	*	ns	ns
season 2	*	*	ns
season 1 × season 2	*	ns	ns

* ≤ P 0.10
ns =not significant

4.4.4.1 Protein

The final wheat protein content varied from 13.3% to 15.6%, which is well above the threshold of 12% set for grade B1 bread wheat. Although the average protein content of the final wheat crop on the monoculture vetch sequence plots did not differ significantly from the first 11 sequence plots listed in Table 4.23, it was significantly higher than the protein content of final wheat planted on the last 14 preceding winter crop sequences in Table 4.23.

Differences in protein content of the final wheat crop occurred in both the summer and winter treatment blocks. Second season sunflower plots resulted in final wheat with significantly higher protein than second season maize, soybean, or sorghum plots (Table 4.24). The protein content of the final wheat planted on first season vetch, fallow, or fodder oats plots, was significantly higher than the protein % of final wheat on first season wheat plots. A significantly lower protein % was measured for final wheat planted on second season oats plots, than for wheat planted on other second

Table 4.23 : Average protein content of final wheat crop planted in residues of preceding winter cropping sequences

Cropping sequence two seasons before final wheat planting in 2011	Protein (%)
Vetch × Vetch	15.6^{a}
Fallow × Fallow	15.4^{ab}
Oats × Vetch	15.4^{ab}
Wheat × Fodder oats	15.3^{ab}
Vetch × Fallow	15.3^{ab}
Fodder oats × Vetch	15.3^{ab}
Fallow × Fodder oats	15.2^{abc}
Vetch × Fodder oats	15.1^{abcd}
Fallow × Vetch	15.1^{abcd}
Fodder oats × Fodder oats	15.0^{abcde}
Oats × Fodder oats	15.0^{abcde}
*Fodder oats × Fallow	14.9^{bcde}
*Wheat × Vetch	14.5^{cdef}
*Fodder oats × Wheat	14.5^{defg}
*Wheat × Fallow	14.5^{defgh}
*Oats × Fallow	14.4^{defghi}
*Fallow × Wheat	14.4^{defghi}
*Oats × Wheat	14.4^{defghi}
*Fallow × Oats	14.3^{efghij}
*Fodder oats × Oats	14.0^{fghijk}
*Oats × Oats	14.0^{fghijk}
*Wheat × Wheat	$13.9^{fghijkl}$
*Vetch × Wheat	13.9^{fhijkl}
*Vetch × Oats	13.7^{ikl}
*Wheat × Oats	13.3^{l}
$LSD_{(0.10)} = 0.7$ cv = 3.3%	

Underlined values = final wheat planted on monoculture crops
Averages followed by the same letter did not differ significantly

Table 4.24 : Average protein content (%) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2^{nd} season plantings													
	Summer block plantings							**Winter block plantings**						
Final wheat crop on 1^{st} season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	15.3	14.9	15.3	15.1	15.8	15.3	**Vetch**	15.6	15.3	15.1	13.7	13.8	14.7^{a}
	Maize	15.3	14.7	15.1	15.0	15.6	15.1	**Fallow**	15.1	15.4	15.2	14.3	14.4	14.9^{a}
	Sorghum	15.6	14.3	15.2	15.3	15.5	15.2	**Fodder oats**	15.4	14.9	15.0	14.0	14.5	14.8^{a}
	Soybean	15.6	15.2	15.5	15.3	15.8	15.4	**Oats**	15.4	14.4	15.0	14.0	14.4	14.6^{ab}
	Sunflower	15.5	14.8	15.0	15.3	15.6	15.3	**Wheat**	14.5	14.5	15.3	13.3	13.9	14.3^{b}
	Avg.	15.4^{ab}	14.8^{c}	15.2^{b}	15.2^{b}	15.6^{a}	15.2	**Avg.**	15.2^{a}	14.9^{a}	15.1^{a}	13.9^{b}	14.2^{a}	14.7
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 0.40 cv 2.1%							$LSD_{(season1)(0.10)}$ = 0.3 cv = 1.9% $LSD_{(season2)(0.10)}$ = 0.5 cv = 2.8%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

season winter crop treatment plots (Table 4.24). However, all these protein values were high and acceptable for grade 1 bread wheat.

4.4.4.2 Hectolitre mass

The average HLM of the final wheat crop planted on summer crop sequences was 76 kg hl^{-1} (Table 4.25), with a grading of B2 (Table 4.21), while final wheat on winter blocks had an average HLM of 74.5 kg hl^{-1}, with a B3 grading. During the 2011/12 season wheat prices were structured in such a way that producers were penalised with R115 ton^{-1} $grade^{-1}$ lower than B1 (SAFEX 2013). That implies that the income of the final wheat on preceding summer crop sequences would have been R115 ton^{-1} more than the income of final wheat on preceding winter crop sequences.

The results in Table 4.25 also indicates that the HLM, similar to the protein (Table 4.24) of final wheat on second season oats plots, was significantly lower than the HLM results of final wheat on the rest of the second season winter crop treatment plots. Final wheat on the second season oats treatment plot had a HLM of 73 kg hl^{-1}, with a B4 grading which gave a lower income ton^{-1} than the B3 grading of wheat plantings on the other four winter crop sequence plots.

4.4.4.3 Falling number

A minimum of 220 seconds is needed to qualify as grade B1 bread wheat. The falling number of final wheat planted on all the preceding crop sequences exceeded the set threshold (Table 4.26). Final wheat on second season soybean plots had significantly lower falling number results than final wheat planted on second season dry bean, maize, sorghum and sunflower plots (Table 4.26). However, these differences did not contribute to grade differences (Table 4.21).

Table 4.25 : Average hectolitre mass (kg hl^{-1}) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings														
	Summer block plantings							Winter block plantings							
Final wheat crop on 1st season plantings	Crops	Dry bean	Maize	Sorghum	Soybean	Sun-flower	Avg.	Crops	Vetch	Fallow	Fodder oats	Oats	Wheat	Avg.
	Dry bean	75.8	76.5	75.8	76.5	75.8	76.1	Vetch	74.3	75.0	74.3	74.3	75.0	74.6
	Maize	76.5	76.5	75.8	76.0	76.0	76.2	Fallow	75.0	75.3	74.8	73.3	74.8	74.6
	Sorghum	76.3	76.3	76.0	76.2	76.3	76.2	Fodder oats	74.1	75.3	74.3	73.8	75.5	74.6
	Soybean	76.0	76.0	75.5	76.0	75.8	75.9	Oats	73.8	74.5	74.5	73.3	74.3	74.1
	Sunflower	75.5	75.8	75.8	75.3	75.8	75.6	Wheat	75.3	75.8	75.0	72.8	74.8	74.7
	Avg.	76.0	76.2	75.8	76.0	75.9	76.0	Avg.	74.5[a]	75.2[a]	74.6[a]	73.5[b]	74.9[a]	74.5
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 0.7 cv = 0.8%							

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.26 : Average falling number (in sec) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2^{nd} season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1^{st} season plantings	Crops	Dry bean	Maize	Sorghum	Soybean	Sun-flower	Avg.	Crops	Vetch	Fallow	Fodder oats	Oats	Wheat	Avg.
	Dry bean	381	387	371	368	378	377	Vetch	388	386	381	379	392	385
	Maize	387	373	372	375	374	376	Fallow	380	378	380	368	389	379
	Sorghum	375	388	373	357	395	377	Fodder oats	383	375	357	387	385	377
	Soybean	391	369	377	369	382	377	Oats	388	372	363	382	356	372
	Sunflower	377	389	388	367	388	381	Wheat	355	381	363	402	384	377
	Avg.	382^a	381^a	376^a	367^b	383^a	378	Avg.	379	378	369	383	381	378
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 8.7 cv = 1.8%							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

4.4.5. Nitrogen use parameters

The profitability of wheat production in South Africa depends on grain yield and grain protein content of the crop and both are influenced by the availability of nitrogen (Otto 2007). A major benefit of crop rotation is the supply of nitrogen through the symbiotic fixation by legumes and the availability thereof to following grain crops, which minimise requirements for synthetic nitrogen fertiliser (Nel 2005). Legumes were included in some of the cropping sequences of the study. Nitrogen components were therefore measured to identify any possible effects of preceding crop sequences on the final wheat crop.

Table 4.27 summarises the effect of treatment factors on the different components of nitrogen. The grain nitrogen of the final wheat crop was the only nitrogen component that was affected significantly ($P \leq 0.1$) by summer crop treatments of the first two seasons. First season winter crop sequences influenced the grain nitrogen of final wheat significantly, while second season winter crop sequences had a significant effect on the grain and residue nitrogen, as well as the nitrogen harvest index and the nitrogen use efficiency of the final wheat crop.

4.4.5.1 Potential available nitrogen

Potential nitrogen supply to the final wheat crop included total soil nitrogen at planting and applied fertiliser nitrogen. Total soil nitrogen was analysed a week prior to planting and nitrogen fertiliser was applied at a rate of 42 kg N ha^{-1} with planting. Table 4.28 indicates that differences between the total soil nitrogen of the plots were not significant.

Table 4.27 : Summary of analyses of variance indicating the effect of treatment factors on selected nitrogen components

Factors summer crops	Total soil N (%)	$N_{(grain)}$ (%)	$N_{(residue)}$ (%)	NHI	$NUE_{(grain)}$
season 1	ns	*	ns	ns	ns
season 2	ns	*	ns	ns	ns
season 1 × season 2	ns	ns	ns	ns	ns
Factors winter crops	**Total soil N (%)**	**$N_{(grain)}$ (%)**	**$N_{(residue)}$ (%)**	**NHI**	**$NUE_{(grain)}$**
season 1	ns	*	ns	ns	ns
season 2	ns	*	*	*	*
season 1 × season 2	ns	ns	ns	ns	ns

* ≤ P 0.10
ns = not significant

Table 4.28 : Average total soil nitrogen content (%) before planting of final wheat crop in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	0.067	0.061	0.065	0.061	0.063	0.063	**Vetch**	0.068	0.072	0.074	0.071	0.070	0.071
	Maize	0.064	0.069	0.067	0.067	0.070	0.067	**Fallow**	0.061	0.064	0.061	0.059	0.057	0.060
	Sorghum	0.066	0.062	0.063	0.061	0.068	0.064	**Fodder oats**	0.065	0.065	0.067	0.071	0.067	0.067
	Soybean	0.069	0.068	0.064	0.066	0.068	0.067	**Oats**	0.064	0.069	0.062	0.066	0.066	0.065
	Sunflower	0.065	0.120	0.109	0.085	0.076	0.091	**Wheat**	0.064	0.064	0.076	0.074	0.071	0.070
	Avg.	0.066	0.076	0.074	0.068	0.069	0.070	**Avg.**	0.064	0.067	0.068	0.068	0.066	0.060
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant

4.4.5.2 Nitrogen uptake

Biomass nitrogen uptake of the final wheat crop was calculated as the total nitrogen in both the grain ($N_{(grain)}$) and the residue ($N_{(residue)}$) of the wheat crop (Equation 3.7). The effect of preceding sequences on biomass nitrogen uptake of the final wheat crop was not significant and will therefore not be discussed.

Significant differences did, however, occurred in the grain nitrogen of the final wheat crop on first and second season treatments of both the summer and winter blocks (Table 4.29). Final wheat on first season soybean plots accumulated on average significantly more grain nitrogen than wheat on first season sorghum and maize plots. Grain nitrogen of the final wheat crop on second season sunflower plots was also significantly higher than the grain nitrogen of wheat on second season maize, sorghum and soybean plots. The grain nitrogen of final wheat planted on first season fallow and fodder oats plots in the winter blocks was significantly higher than the grain nitrogen of wheat planted on first season wheat plots. Second season wheat and oats plots resulted in lower final wheat grain nitrogen content than the rest of the second season winter crop treatment plots.

The residue nitrogen of the final wheat crop planted on second season oats plots was significantly higher than the residue nitrogen of wheat planted on second season fodder oats, fallow and wheat treatment plots (Table 4.30).

The nitrogen harvest index (NHI) is the ratio of nitrogen in the grain to the total amount of nitrogen stored in the biomass at harvest. The NHI indicates how efficiently a plant utilised acquired nitrogen for the production of grain protein. Depending on climate, cereal species, cultivar and management practices, 40-90% of total biomass nitrogen is stored in the grain (Otto 2007). The results in Table 4.31 indicates that the NHI of final wheat planted on second season oats treatment plots, was significantly lower than the NHI of final wheat produced on the other four second season winter crop treatment plots.

Table 4.29 : Average grain nitrogen content (%) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	2.63	2.57	2.61	2.59	2.77	2.64^{ab}	**Vetch**	2.66	2.60	2.58	2.38	2.41	2.53^{ab}
	Maize	2.65	2.49	2.53	2.57	2.64	2.58^{c}	**Fallow**	2.66	2.72	2.66	2.41	2.44	2.58^{a}
	Sorghum	2.68	2.52	2.57	2.56	2.64	2.59^{bc}	**Fodder oats**	2.63	2.62	2.66	2.57	2.51	2.60^{a}
	Soybean	2.68	2.58	2.70	2.62	2.72	2.66^{a}	**Oats**	2.63	2.48	2.62	2.42	2.47	2.53^{ab}
	Sunflower	2.67	2.53	2.60	2.61	2.73	2.63^{ab}	**Wheat**	2.51	2.51	2.54	2.30	2.41	2.45^{b}
	Avg.	2.66^{ab}	2.54^{c}	2.60^{bc}	2.59^{bc}	2.70^{a}	2.61	**Avg.**	2.61^{a}	2.59^{a}	2.61^{a}	2.41^{b}	2.45^{b}	2.53
	$LSD_{(season1)(0.10)}$ = 0.045 cv = 1.4% $LSD_{(season2)(0.10)}$ = 0.077 cv = 2.3%							$LSD_{(season1)(0.10)}$ = 0.076 cv = 2.4% $LSD_{(season2)(0.10)}$ = 0.099 cv = 3.1%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
Averages followed by the same letter did not differ significantly

Table 4.30 : Average residue nitrogen content (%) of final wheat crop planted in residues of preceding summer and winter cropping sequences

Final wheat crop on 2nd season plantings — Summer block plantings (rows: Final wheat crop on 1st season plantings)

Crops	Dry bean	Maize	Sorghum	Soybean	Sun-flower	Avg.
Dry bean	0.393	0.422	0.441	0.400	0.437	0.419
Maize	0.435	0.344	0.375	0.604	0.481	0.448
Sorghum	0.417	0.370	0.393	0.512	0.428	0.424
Soybean	0.381	0.374	0.429	0.407	0.427	0.404
Sunflower	0.419	0.399	0.395	0.382	0.408	0.401
Avg.	0.409	0.382	0.407	0.461	0.436	0.410

$LSD_{(season1)(0.10)}$ = ns
$LSD_{(season2)(0.10)}$ = ns

Final wheat crop on 2nd season plantings — Winter block plantings (rows: Final wheat crop on 1st season plantings)

Crops	Vetch	Fallow	Fodder oats	Oats	Wheat	Avg.
Vetch	0.439	0.444	0.493	0.478	0.495	0.470
Fallow	0.526	0.413	0.499	0.484	0.639	0.512
Fodder oats	0.603	0.374	0.501	0.656	0.426	0.512
Oats	0.560	0.401	0.498	0.556	0.477	0.498
Wheat	0.421	0.416	0.465	0.819	0.444	0.513
Avg.	0.510^{ab}	0.410b^{c}	0.491^{bc}	0.599^{a}	0.496^{bc}	0.500

$LSD_{(season1)(0.10)}$ = ns
$LSD_{(season2)(0.10)}$ = 0.097
cv = 15.4%

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.31 : Average nitrogen harvest index (%) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	77	77	77	79	76	77	**Vetch**	77	72	66	64	70	70
	Maize	78	78	78	69	77	76	**Fallow**	66	76	72	66	62	68
	Sorghum	77	75	79	81	76	78	**Fodder oats**	71	80	68	57	72	70
	Soybean	79	82	76	75	77	78	**Oats**	66	75	69	56	68	67
	Sunflower	74	76	79	78	78	77	**Wheat**	75	72	74	43	68	66
	Avg.	77	78	78	76	77	77	**Avg.**	71[a]	75[a]	70[a]	57[b]	68[a]	68
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 8.07 cv = 7.7%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

4.4.5.3 Nitrogen use efficiency

For the purpose of this study nitrogen use efficiency percentage of grain ($NUE_{(grain)}$) was defined as the yield produced per unit nitrogen absorbed, or utilised by the plant to produce grain (Equation 3.9 in Chapter 3). The grain nitrogen use efficiency of final wheat planted on second season oats plots, was significantly lower than the $NUE_{(grain)}$ of wheat planted on the other four winter crop treatment plots (Table 4.32).

4.4.6 Precipitation use efficiency

Precipitation use efficiency (PUE) gives an indication of the effectiveness with which a crop uses precipitation and was calculated using equation 3.10 in Chapter 3. The grain yield of the final wheat crop planted in the residue of different cropping sequence plots was divided by precipitation received from harvest of the last crop in the sequence, to harvest of the final wheat. Table 4.33 indicates that the PUE of the final wheat was the same on all the plots in the summer blocks. Wheat planted on first season fallow winter plots used precipitation more efficiently than wheat planted on first season vetch, wheat and oats plots, while the PUE of wheat planted on second season oats plots, was less efficient than the other plots where vetch, fallow, fodder oats and wheat treatments were applied.

Table 4.32 : Average grain nitrogen use efficiency (%) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							Winter block plantings						
Final wheat crop on 1st season plantings	Crops	Dry bean	Maize	Sorghum	Soybean	Sun-flower	Avg.	Crops	Vetch	Fallow	Fodder oats	Oats	Wheat	Avg.
	Dry bean	3.4	4.1	3.7	3.9	3.7	3.8	Vetch	2.6	2.6	2.6	1.8	2.6	2.4
	Maize	4.1	3.5	3.7	3.4	3.6	3.6	Fallow	3.4	3.6	3.3	2.5	3.3	3.2
	Sorghum	3.6	4.1	3.9	3.7	3.4	3.7	Fodder oats	2.8	3.5	2.7	2.0	2.7	2.7
	Soybean	3.3	3.7	3.8	3.5	3.6	3.6	Oats	2.8	2.7	2.8	2.0	2.3	2.5
	Sunflower	3.9	3.1	3.3	3.2	3.3	3.4	Wheat	3.2	2.6	2.5	1.7	2.5	2.5
	Avg.	3.7	3.7	3.7	3.5	3.5	3.6	Avg.	3.0[a]	3.0[a]	2.8[a]	2.0[b]	2.7[a]	2.7
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = 0.43 cv = 12.9%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

Table 4.33 : Average precipitation use efficiency (kg ha^{-1} mm^{-1}) of final wheat crop planted in residues of preceding summer and winter cropping sequences

	Final wheat crop on 2nd season plantings													
	Summer block plantings							**Winter block plantings**						
Final wheat crop on 1st season plantings	**Crops**	**Dry bean**	**Maize**	**Sorghum**	**Soybean**	**Sun-flower**	**Avg.**	**Crops**	**Vetch**	**Fallow**	**Fodder oats**	**Oats**	**Wheat**	**Avg.**
	Dry bean	0.27	0.29	0.29	0.29	0.26	0.28	**Vetch**	0.32	0.34	0.33	0.25	0.35	0.32^{bc}
	Maize	0.29	0.29	0.28	0.25	0.29	0.28	**Fallow**	0.38	0.41	0.37	0.29	0.37	0.36^{a}
	Sorghum	0.26	0.29	0.28	0.28	0.27	0.27	**Fodder oats**	0.33	0.41	0.33	0.26	0.35	0.33^{ab}
	Soybean	0.27	0.29	0.26	0.27	0.27	0.27	**Oats**	0.32	0.36	0.32	0.26	0.29	0.31^{c}
	Sunflower	0.28	0.30	0.30	0.28	0.28	0.29	**Wheat**	0.38	0.32	0.35	0.24	0.32	0.32^{bc}
	Avg.	0.27	0.29	0.28	0.27	0.27	0.27	**Avg.**	0.35^{a}	0.37^{a}	0.34^{a}	0.26^{b}	0.34^{a}	0.33
	$LSD_{(season1)(0.10)}$ = ns $LSD_{(season2)(0.10)}$ = ns							$LSD_{(season1)(0.10)}$ = 0.02 cv = 5.7% $LSD_{(season2)(0.10)}$ = 0.05 cv = 10.9%						

Underlined values = final wheat planted on monoculture crops
Avg. = Average
ns= not significant
Averages followed by the same letter did not differ significantly

4.4.7 Correlation between yield contributing components of final wheat crop

Correlations were calculated between selected components (plant, yield, quality, nitrogen use and precipitation use) of the final wheat crop planted on winter and summer treatment plots to determine the influence of the different components on one another (Tables 4.34 and 4.35). A highly significant positive correlation ($P \leq 0.01$; $r=0.994$) was observed between precipitation use efficiency (PUE) and grain yield of wheat planted on all the preceding crop treatments. A stronger correlation was observed between PUE and hectolitre mass of final wheat on winter crops ($P \leq 0.01$; $r=0.512$), than between PUE and hectolitre mass of final wheat on summer crops ($P \leq 0.05$; $r=0.214$). Precipitation use efficiency of final wheat on winter crop treatment plots correlated positively ($P \leq 0.01$) with protein and grain nitrogen ($r=0.279$ and $r=0.289$ respectively), in contrast with the negative correlation ($P \leq 0.01$) observed between PUE, protein and grain nitrogen of final wheat planted on summer crop treatments. These correlations can be ascribed to the 10 or 12 month period between the harvest of second season summer crops and planting of the final wheat, compared to the six month period between harvest of the second season winter crops and planting of the final wheat crop.

Significant correlations ($P \leq 0.01$) were also observed between soil water and soil nitrogen in both the summer blocks and winter blocks ($r=0.273$ and $r=0.326$ respectively). The correlation between soil water and final wheat seedling survival was significant ($P \leq 0.01$; $r=0.324$) in winter treatment blocks, but non-significant in summer treatment blocks.

These correlations confirmed that wheat is highly dependent on the availability of soil water and nitrogen to ensure economic grain yields (Purchase et al. 2000, Otto 2007, ARC-SGI 2013).

Table 4.34 : Correlation between yield contributing components of final wheat crop planted on summer treatments blocks

	Grain yield	Biomass yield	Residue yield	TKM	Harvest index	HLM	Protein %	FN	Biomass N %	Grain N %	Soil N %	Seedling survival rate
Biomass yield	0.141											
Residue yield	-0.033	0.984**										
TKM	0.196	-0.252*	-0.291**									
Harvest index	0.190	-0.762**	-0.810**	0.313**								
HLM	0.236*	-0.085	-0.132	0.469***	0.271**							
Protein %	-0.409**	-0.076	0.010	-0.536***	-0.207*	-0.597**						
Falling number	-0.046	0.206*	0.218*	-0.186	-0.217*	-0.176	0.201*					
Biomass N%	-0.060	-0.003	0.015	-0.058	-0.022	-0.083	0.204*	0.021				
Grain N%	-0.425**	0.019	0.105	-0.523**	-0.267**	-0.480**	0.851**	0.141	0.198			
Soil N%	0.011*	0.100**	0.094	-0.231	-0.086	-0.343**	0.132	0.129	0.033	0.217*		
Seedling survival rate	-0.112	0.522**	0.543**	-0.397**	-0.487**	-0.230*	0.131	0.184	-0.001	0.209*	0.175	
% Vol. soil water	-0.146	0.027	0.048	-0.127	-0.151	-0.241	0.084	0.172	-0.198	0.097	0.273**	0.137
PUE	0.994**	0.155	-0.017	0.172	0.166	0.214*	-0.385**	-0.046	-0.053	-0.404**	0.022	-0.082

** = P≤0.01
* = P≤0.05

Table 4.35 : Correlation between yield contributing components of final wheat crop planted on winter crop treatment blocks

	Grain yield	Bio-mass yield	Residue yield	TKM	Harvest. index	HLM	Protein %	FN	Biomass N %	Grain N %	Soil N%	Seedling survival rate
Biomass yield	0.129											
Residue yield	-0.162	0.957**										
TKM	0.388**	-0.007	-0.129									
Harvest index	0.679**	-0.565**	-0.762**	0.343**								
HLM	0.512**	-0.155	-0.309**	0.490**	0.485**							
Protein %	0.277**	0.050	-0.019	-0.117	0.155	0.019						
Falling number	-0.141	0.129	0.174	-0.144	-0.208*	-0.229*	0.011					
Biomass N%	-0.196*	0.194	0.258*	-0.097	-0.277**	-0.345**	-0.194	0.093				
Grain N%	0.289*	0.131	0.057	-0.137	0.109	0.035	0.843**	0.009	-0.105			
Soil N%	-0.118	0.038	0.073	-0.190	-0.117	-0.175	0.071	0.061	0.058	0.063		
Seedling survival rate	0.129	0.441**	0.400**	0.048	-0.228*	0.104	0.170	-0.119	-0.213*	0.271**	0.009	
% Vol. soil water	-0.110	-0.056	-0.025	0.070	-0.088	0.051	-0.027	0.192	-0.213*	-0.008	0.326**	0.324**
PUE	0.999**	0.127	-0.164	0.390**	0.680**	0.512**	0.279**	-0.135	-0.194	0.289**	-0.113	0.123

** = P≤0.01
* = P≤0.05

4.6 Conclusion

The main objective of this chapter was to evaluate the impact of different cropping sequences on the growth of wheat as target crop in a conservation tillage system in the Eastern Free State. Six parameters, namely soil, plant, yield, quality grading, nitrogen use and precipitation use were evaluated. This was done to test the hypothesis that wheat growth will be influenced by preceding cropping sequences in a CA system.

It is well known that the annual yield of crops in the Eastern Free State fluctuates considerably due to variation in rainfall. Average annual rainfall was in 2008, 2009 and 2011 between 102 and 159 mm less than the long-term average rainfall of 709 mm. The average rainfall of 2010 was 869 mm. Rainfall recorded in January and December 2010 was exceptionally high (296 mm and 200 mm respectively). When soybean and dry bean crops were harvested in March 2010, pod shattering occurred due to rain.

Crops are sensitive to water stress during grain filling. The grain filling period of winter crops are between October and November. Rainfall recorded for these two months was from 2008 to 2011, 23% to 64% less than the long term average of 171 mm. The lower rainfall had a negative impact on grain yields of oats and wheat.

Only preceding summer crop sequences showed a significant ($P \leq 0.1$) influence on the yield parameters of the final wheat crop. Final wheat had fewer plants and ears m^{-2}, as well as a lower biomass and residue yield m^{-2} when it was planted on preceding sorghum × soybean, maize × sunflower and soybean × maize sequences. Results of final wheat on preceding sorghum × soybean sequence plots were always the lowest, but did not differ significantly from the other two sequences. The harvest index (%) and TKM results were significantly higher when the final wheat crop was planted on preceding sorghum × soybean sequence plots. Fewer plants, with less in-row competition for water and nutrients, had most probably been responsible for the higher TKM of the final wheat crop planted on these plots.

It was found that the final wheat crop planted in the residue of second season oats treatments had significantly ($P \leq 0.1$) lower seedling numbers, with fewer ears m^{-2} and a lower grain yield. The nitrogen use parameters indicated that these wheat plants also had a lower precipitation use efficiency and grain nitrogen use efficiency, which resulted in significantly lower grain protein. Rotation with oats is often recommended to reduce Take-all (*Gaeumannomyces graminis* var. *tritici)*, a soil-borne disease of wheat. However, results of this study indicated that oats has the potential to reduce the yield of wheat in a rotation system unless it is used as break crop to reduce Take-all.

Nel et al. (2003) found that wheat after sunflower in a rotation system yielded significantly more than wheat after fallow and other summer crops. This study confirmed that the final wheat crop had a significantly higher number of ears m^{-2}, as well as grain nitrogen use efficiency and grain protein when planted on second season sunflower plots. The yield of the final wheat crop on these plots did, however, not differ significantly from wheat on other second season summer crop plots.

The results showed that preceding crop sequences can have a significant influence on the growth of wheat as target crop in a CA system in the Eastern Free State. More research is needed to identify crop sequences that have a synergistic effect on wheat.

4.7 References

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CHAPTER 5

MOST PROFITABLE CROPPING SEQUENCE WITH WHEAT AS TARGET CROP IN A CONSERVATION TILLAGE SYSTEM

5.1 Introduction

Crop production occurs in an ever changing environment. Annually, producers have to attend to numerous factors that influence their management decisions. Some factors are within their control, but many are not. The weather, market conditions, input costs, year-to-year changes in yields, crop prices, government policies and new technologies represent broad categories of externalities that producers must deal with on a continuous basis (Helmers et al. 2001, Tanaka et al. 2002). This is a huge challenge, especially against the background that producers' decisions are carried out in a financial environment of diminishing economic returns. Planning and precaution taken, or not taken, to minimise risk can make the difference between success and failure (Binding et al. 1993).

Diversification implies an increase in the type and number of crop species within a cropping system to reduce economic risk (Helmers et al. 2001, Nel and Loubscher 2004, Nel 2005). In theory diversification of crops in a rotation system may reduce risk because a year of low returns for one crop may be offset by high returns from another crop (Helmers et al. 2001). The risk benefits of crop diversification are generally well understood, but the additional effect of rotational cropping on risk is less understood (Helmer et al. 2001). Rotation risk involves two components. The first risk component is associated with the fact that rotation of one crop after another can have a stabilising (risk reducing), or destabilising (risk increasing) effect on yield. The second risk component centers on the net-return benefits of rotations which results from higher yields or lower input costs (Helmer et al. 2001).

Cropping system risks result from variability in returns across time and arise from year-to-year changes in yields, crop prices and production costs (Helmer et al 2001). Risk must be quantified in order to evaluate whether various risk management tools and strategies are effective in achieving producers' risk reduction goals (Harwood et al. 1999).

Different approaches are used by economists to capture decision making in risky situations. The safety first method are applicable where the survival of an individual, or business is the main concern. This method involves choosing the set of activities (in this study cropping sequence) with the smallest probability of yielding an expected return below a specified disaster level of return (Harwood et al. 1999). This approach has been successfully used in research to evaluate the risk of different rotation systems (Helmer et al 2001, Nel and Loubscher 2004).

Adoption of crop rotation systems has been moderate and recent in the dryland wheat production areas of South Africa (Smit et al. 2010). Rotation systems are usually fixed and the grain crops in the rotation portfolio of the Eastern Free State include maize, soybean, dry bean, sunflower and wheat, with a fallow period in some of the systems. Typical crop rotation systems used in the region are summarised in Table 5.1 (Heckroodt and Odendaal 2000).

The hypothesis for the study was that different cropping sequences would influence the growth and profitability of wheat as the final crop in a conservation tillage system. The objective of this chapter was to determine the profitability and production risk of 50 cropping sequences.

Table 5.1 Crop rotation systems used by grain producers in the Eastern Free State

Crop rotation system	Cultivated area (%)						
	Time-span (years)	Area used (%)	Maize	Sun-flower	Soy-bean	Dry bean	Wheat
soybean × maize × maize	3	100	67	0	33	0	0
sunflower × maize × maize	3	100	67	33	0	0	0
dry bean × maize × maize	3	100	67	0	0	33	0
dry bean × soybean × maize × maize	3	100	67	0	17	17	0
wheat × fallow × maize	3	66	33	0	0	0	33
wheat × fallow × sunflower × maize	4	75	25	25	0	0	25
wheat × fallow × dry bean × maize	4	75	25	0	0	25	25
wheat × fallow × soybean × maize	4	75	25	0	25	0	25
wheat × wheat × fallow × maize	4	75	25	0	0	0	50
wheat × wheat × fallow × sunflower × maize	5	80	20	20	0	0	40
wheat × wheat × fallow × dry bean × maize	5	80	20	0	0	20	40
wheat × wheat × fallow × soybean × maize	5	80	20	0	20	0	40
wheat × wheat × fallow × maize × maize	5	80	40	0	0	0	40
wheat × wheat × fallow × sunflower × maize × maize	6	83	33	17	0	0	33
wheat × wheat × fallow × dry bean × maize × maize	6	83	33	0	0	17	33
wheat × wheat × fallow × soybean × maize × maize	6	83	33	0	17	0	33

5.2 Procedure

The experimental layout and crop treatments are described in Chapter 3 (section 3.5). Four summer crops, namely maize, sunflower, soybean and dry bean were chosen from the Eastern Free State crop rotation portfolio, while sorghum was included to evaluate its potential as a rotation crop in the region. Winter crop treatments included wheat and oats, as well as two fodder crops (vetch and fodder oats) and a fallow period. The vetch and fodder oats treatments were sprayed with Glyphosate (Round-up^{TM}) before seed set to mimic the on-farm situation where these crops would have been used for animal grazing.

Production costs and prices of the different crop treatments were obtained from VKB Agriculture Pty LTD. Production costs included seed, fertiliser, pesticides, fuel, repair costs, contractors, crop insurance and interest on operational capital loans. On-farm production cost was used for grazing crops and the value of hay was not taken into account for any of the crops. Silo handling cost and transport differential cost were deducted from pricing when relevant. Annual net return was calculated with the following equation:

$$\text{Annual net return per crop} = (\text{crop yield} \times \text{price}) - \text{production cost} \qquad (5.1)$$

Average net return and the total profit or loss of individual crop rotation systems were calculated with equations 5.2 and 5.3.

$$\text{Average net return of rotation system} = \frac{\text{Annual net return of } (\text{crop } 1 + \text{crop } 2 + \text{crop } 3)}{3} \qquad (5.2)$$

$$\text{Total profit/loss} = \text{Annual net return of } (\text{crop } 1 + \text{crop } 2 + \text{crop } 3) \qquad (5.3)$$

The safety first method was used for the evaluation of the financial risks of the different cropping sequences in the study. The choice of a disaster target level for this method is arbitrary. An amount of R1,000 was chosen as the minimum profit needed by a producer to cover fixed costs (Heckroodt 2013 Personal Communication[1]). Risks of individual rotation systems were calculated by totaling the Rand deficits for all the years where net returns fell below R1,000.

5.3 Results and Discussion

The total net return of a crop rotation system is influenced by the variation in year-to-year yields, prices and production costs of crops in the system (Helmer et al. 2001). Planting of first season summer crops in the study started in December 2008 and the

[1]J Heckroodt. VKB Agriculture Pty LTD

final wheat crop was harvested in December 2011. Annual yields of the different cropping sequences, including the final wheat crop, are listed in Tables 5.2 and 5.3. Preceding monoculture sequences were underlined to indicate it as such.

A huge variation between yields of summer crops was observed in the 2010 season (Table 5.2). Heavy rain occurred at harvest time and resulted in pod shattering of second season dry bean and soybean treatments, which led to significantly lower yields (0.49 ton ha $^{-1}$ and 1.58 ton ha^{-1} respectively). Second season yields of sunflower and sorghum treatments had to be written off due to bird damage. Maize was the only second season summer crop treatment with a stable and higher average yield of 4.12 ton ha^{-1} in 2010.

The average grain yield of the final wheat crop on preceding summer crop sequences was 2.52 ton ha^{-1} (Table 5.2) compared to the much lower grain yield of 1.94 ton ha^{-1} (Table 5.3) produced on preceding winter crop sequence plots. The longer fallow period (12 months) between second season summer crops and final wheat plantings could be a possible cause for the difference between yields of the final wheat crop in summer and winter blocks. However, the final wheat crop yield did not differ significantly between plantings on different crop treatment plots within summer and winter blocks. Monoculture in preceding sequences also had no impact on the yield of the final wheat crop.

The lowest second season oats yield (0.84 ton ha^{-1}) was obtained on the monoculture oats plots (Table 5.3), while the lowest second season wheat yield (1.08 ton ha-1) was produced on preceding oats plots.

Table 5.2 : Average annual yield of different crop sequences in a three year rotation system on preceding summer crop treatment blocks

Crop sequence of the three year rotation			Annual yield (ton ha^{-1}) of crops in the rotation		
Crop 1	**Crop 2**	**Crop 3**	**Season 1**	**Season 2**	**Season 3**
Dry bean	Dry bean	Wheat	3.21	0.49	2.46
Maize	Dry bean	Wheat	3.94	0.49	2.61
Sorghum	Dry bean	Wheat	2.48	0.49	2.39
Soybean	Dry bean	Wheat	2.64	0.49	2.41
Sunflower	Dry bean	Wheat	2.93	0.49	2.57
Dry bean	Maize	Wheat	3.21	4.12	2.65
Maize	Maize	Wheat	3.94	4.12	2.59
Sorghum	Maize	Wheat	2.48	4.12	2.63
Soybean	Maize	Wheat	2.64	4.12	2.64
Sunflower	Maize	Wheat	2.93	4.12	2.69
Dry bean	Sorghum	Wheat	3.21	Bird damage	2.61
Maize	Sorghum	Wheat	3.94	Bird damage	2.55
Sorghum	Sorghum	Wheat	2.48	Bird damage	2.55
Soybean	Sorghum	Wheat	2.64	Bird damage	2.38
Sunflower	Sorghum	Wheat	2.93	Bird damage	2.70
Dry bean	Soybean	Wheat	3.21	1.58	2.57
Maize	Soybean	Wheat	3.94	1.58	2.26
Sorghum	Soybean	Wheat	2.48	1.58	2.38
Soybean	Soybean	Wheat	2.64	1.58	2.43
Sunflower	Soybean	Wheat	2.93	1.58	2.58
Dry bean	Sunflower	Wheat	3.21	Bird damage	2.33
Maize	Sunflower	Wheat	3.94	Bird damage	2.59
Sorghum	Sunflower	Wheat	2.48	Bird damage	2.42
Soybean	Sunflower	Wheat	2.64	Bird damage	2.46
Sunflower	Sunflower	Wheat	2.93	Bird damage	2.50
Average grain yield of final wheat planting on preceding summer crop sequences in 2011					**2.52**
$LSD_{(final\ wheat\ crop)\ (0.10)}$ = ns					

Table 5.3 : Average annual yield of different crop sequences in a three year rotation system on preceding winter crop treatment blocks

Crop sequence of the three year rotation			Annual yield (ton ha^{-1}) of crops in the rotation		
Crop 1	**Crop 2**	**Crop 3**	**Season1**	**Season 2**	**Season 3**
Vetch	Vetch	Wheat	Grazing	Grazing	1.89
Vetch	Fallow	Wheat	Grazing	No crop	1.99
Vetch	Fodder oats	Wheat	Grazing	Grazing	1.93
Vetch	Oats	Wheat	Grazing	1.29	1.46
Vetch	Wheat	Wheat	Grazing	1.88	2.07
Fallow	Vetch	Wheat	No crop	Grazing	2.21
Fallow	Fallow	Wheat	No crop	No crop	2.40
Fallow	Fodder oats	Wheat	No crop	Grazing	2.15
Fallow	Oats	Wheat	No crop	1.32	1.72
Fallow	Wheat	Wheat	No crop	3.12	2.17
Fodder oats	Vetch	Wheat	Grazing	Grazing	2.03
Fodder oats	Fallow	Wheat	Grazing	No crop	2.42
Fodder oats	Fodder oats	Wheat	Grazing	Grazing	1.91
Fodder oats	Oats	Wheat	Grazing	1.27	1.52
Fodder oats	Wheat	Wheat	Grazing	2.04	2.06
Oats	Vetch	Wheat	1.56	Grazing	1.88
Oats	Fallow	Wheat	1.56	No crop	2.09
Oats	Fodder oats	Wheat	1.56	Grazing	1.86
Oats	Oats	Wheat	1.56	0.84	1.52
Oats	Wheat	Wheat	1.56	1.08	1.71
Wheat	Vetch	Wheat	2.68	Grazing	2.25
Wheat	Fallow	Wheat	2.68	No crop	1.90
Wheat	Fodder oats	Wheat	2.68	Grazing	2.03
Wheat	Oats	Wheat	2.68	1.13	1.44
Wheat	Wheat	Wheat	2.68	1.40	1.90
Average grain yield of final wheat planting on preceding winter crop sequences in 2011					**1.94**
LSD$_{\text{(final wheat crop) (0.10)}}$ = ns					

Although final wheat crop yield did not differ significantly between preceding treatment plots, the highest yield (2.42 ton ha^{-1}) was recorded on the fodder oats × fallow plots Table 5.3).

The first summer and winter crops were planted in December 2008 and July 2009 respectively, while the final wheat crop was planted in July 2011 and harvested in December 2011. Table 5.4 summarises the total production costs and prices of individual crops. Weed control cost for fallow periods between harvest of second season crops (summer crops = 12 months and winter crop = 6 months) and planting of the final wheat crop was also included in Table 5.4 (indicated with *). The yield data of Tables 5.2 and 5.3 was used together with the information in Table 5.4 to calculate the total profit or loss (Equations 5.1 to 5.3) of the 50 cropping sequences in the study.

Table 5.4 : Total production costs and produce prices from 2008 to 2011

Total production cost (R ha^{-1})				Price (R ton^{-1}) of crop		
Preceding sequences			Final wheat	Preceding sequences		Final wheat
Summer	**2008**	**2009**	**2010**	**2009**	**2010**	**2011**
Dry bean	R 8,061.00	R 6,160.00	* R 379.32	R 3,035.00	R 4,631.00	R 3,341.00
Maize	R 5,233.00	R 3,552.00	* R 379.32	R 1,288.25	R 911.72	R 3,341.00
Sorghum	R 4,186.40	R 2,841.60	* R 379.32	R 1,264.00	R 1,464.09	R 3,341.00
Soybean	R 4,911.00	R 3,532.95	* R 379.32	R 3,175.25	R 2,486.12	R 3,341.00
Sunflower	R 5,089.00	R 2,714.00	* R 379.32	R 2,514.38	R 2,999.88	R 3,341.00
Winter	**2009**	**2010**	**2011**	**2009**	**2010**	**2011**
Vetch	R 573.45	R 675.24	* R 189.66	Grazing	Grazing	R 3,341.00
Fodder oats	R 1,146.90	R 1,350.47	* R 189.66	Grazing	Grazing	R 3,341.00
Oats	R 2,696.34	R 2,963.54	* R 189.66	R 1,297.47	R 2,170.08	R 3,341.00
Wheat	R 3,370.42	R 3,704.43	R 4,467.00	R 1,923.61	R 2,600.24	R 3,341.00
Fallow	R 448.00	R 379.32	* R 189.66	No crop	No crop	R 3,341.00

*Fallow period between second season crops and the final wheat crop

Variation in production cost and prices can have a huge impact on crop rotation risk. The production costs of summer crops in 2008 were between R1,344.80 and R2,375.00 higher than the following year (Table 5.4). This was as a direct result of a weaker Rand, which caused higher fuel and fertiliser prices (Heckroodt 2013 Personal Communication[1]).

Cropping sequences with an accumulated net return of higher than R1,000 can be seen as rotations with lower production risks (Table 5.5). Of the cropping sequences 32 showed an average net return of between R354.32 and R2,516.59, with a total profit margin of between R1,062.97 and R7,549.76 (Table 5.5). Fourteen of the 32 cropping sequences had a total profit of more than R3,000 ha^{-1}, while a further 11 cropping sequences could obtain a total profit of more than R2,000 ha^{-1}. More than R1,000 ha^{-1} profit was obtained by 7 cropping sequences.

The profit margin of an individual crop in a rotation system can play an important role in the total profit of the system. Soybean was the only crop that showed a net profit in both of the first two growing seasons of the study. The first 11 rotation systems in Table 5.5 accumulated a total profit of above R3,600 in the three study years and soybean formed part of 6 of these rotation systems.

Thirteen preceding winter crop sequences (highlighted) were included in the 32 lower risk crop rotations listed in Table 5.5. Fallow periods often form part of the more popular crop rotation systems in the Eastern Free State. Although it was indirectly part of the preceding summer crop × final wheat sequences in the summer blocks, it was applied as an individual treatment in the winter crop sequences on winter blocks. The fallow-wheat-wheat rotation was rated third in Table 5.5, with a total profit of R6,643.29. A fallow treatment was used in 62% of the preceding winter crop sequences in Table 5.5 – 23 % was as first treatment and 39% as second treatment.

The study evaluated sorghum as a potential alternative summer crop in rotations for the Eastern Free State. Sorghum was part of five of the first 24 cropping sequences in

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[1]J Heckroodt. VKB Agriculture Pty LTD

Table 5.5 : Different cropping sequences rated according to average net return and total profit

Rating	Rating of crop sequences		
	Crop sequence	Average net return	Total profit
1	Soybean-maize-wheat	R 2,516.59	R 7,549.76
2	Soybean-soybean-wheat	R 2,346.33	R 7,038.98
3	Fallow-wheat-wheat	R 2,214.43	R 6,643.29
4	Sunflower-maize-wheat	R 2,174.43	R 6,523.28
5	Sunflower-soybean-wheat	R 2,115.53	R 6,346.60
6	Dry bean-maize-wheat	R 1,930.95	R 5,792.86
7	Dry bean-soybean-wheat	R 1,905.47	R 5,716.41
8	Wheat-vetch-wheat	R 1,353.29	R 4,059.86
9	Soybean-sunflower-wheat	R 1,343.36	R 4,030.09
10	Maize-maize-wheat	R 1,251.25	R 3,753.75
11	Soybean-sorghum-wheat	R 1,211.74	R 3,635.21
12	Sunflower-sorghum-wheat	R 1,170.27	R 3,510.80
13	Wheat-wheat-wheat	R 1,167.22	R 3,501.66
14	Wheat-fallow-wheat	R1,062.14	R 3,186.43
15	Sorghum-maize-wheat	R 997.67	R 2,993.01
16	Sunflower-sunflower-wheat	R 990.07	R 2,970.20
17	Vetch-wheat-wheat	R 986.48	R 2,959.44
18	Maize-soybean-wheat	R 947.35	R 2,842.05
19	Fodder oats-wheat-wheat	R 922.87	R 2,768.62
20	Soybean-dry bean-wheat	R 895.41	R 2,686.23
21	Wheat-fodder oats-wheat	R 883.20	R 2,649.61
22	Fallow-fallow-wheat	R 874.69	R 2,624.08
23	Dry bean-sorghum-wheat	R 871.11	R 2,613.33
24	Sorghum-soybean-wheat	R 782.86	R 2,348.59
25	Sunflower-dry bean-wheat	R 675.75	R 2,027.26
26	Fodder oats-fallow-wheat	R 664.00	R 1,992.00
27	Dry bean-sunflower-wheat	R 601.82	R 1,805.45
28	Fallow-vetch-wheat	R 564.46	R 1,693.37
29	Wheat-oats-wheat	R 505.85	R 1, 517.54
30	Oats-fallow-wheat	R 454.70	R 1,364.09
31	Vetch-fallow-wheat	R 376.27	R 1,128.82
32	Dry bean-dry bean-wheat	R 354.32	R 1,062.97

■ Winter crop sequences

Table 5.5. This crop has to compete with maize in the human consumption and animal feed markets. In contrast with maize, it has a higher risk of yield loss to bird damage, which makes it a less attractive option for producers. This was confirmed in the study when maize yielded a stable 3.94 ton ha^{-1} and 4.12 ton ha^{-1} in 2009 and 2010, while sorghum yielded 2.48 ton ha^{-1} in 2009, but had to be written off in 2010 due to bird damage.

Cropping sequences with an accumulated risk below R1,000 were rated from lowest to highest risk (1 to 18) in Table 5.6. Twelve of the 18 crop rotations (67%) had preceding winter crop sequences (highlighted). Oats was used in seven of the 12 preceding winter cropping sequences and five of those sequences showed a total loss of between R375.49 and R1,301.64 in the study (Table 5.6). The results suggested that oats should only be used in rotation systems if it is needed as a break against soil borne diseases of wheat.

Table 5.6 : Cropping sequences rated according to profit or loss and risk accumulated returns below R1000

Rating	Rating of crop sequences according risk-accumulated returns below R1000			
	Crop sequence	**Average net return**	**Total profit/loss**	**Risk-accumulated returns below R 1000**
1	Maize-sunflower-wheat	R 278.49	R 835.46	R -164.54
2	Fallow-fodder oats-wheat	R 272.56	R 817.68	R -182.32
3	Fallow-oats-wheat	R 210.83	R 632.48	R -367.52
4	Maize-sorghum-wheat	R 191.41	R 574.22	R - 425.78
5	Vetch-vetch-wheat	R 166.27	R 498.80	R -501.20
6	Fodder oats-vetch-wheat	R 131.03	R 393.09	R -606.91
7	Oats-vetch-wheat	R 122.19	R 366.56	R -633.44
8	Vetch-fodder oats-wheat	R -14.26	R -42.79	R -1042.79
9	Maize-dry bean-wheat	R -91.51	R -274.53	R -1274.53
10	Sorghum-sorghum-wheat	R -106.72	R -320.16	R -1320.16
11	Oats-fodder oats-wheat	R -125.16	R -375.49	R -1375.49
12	Oats-wheat-wheat	R -140.78	R -422.34	R -1422.34
13	Vetch-oats-wheat	R -142.24	R -426.73	R -1426.73
14	Sorghum-sunflower-wheat	R -208.96	R -626.89	R -1626.89
15	Fodder oats-fodder oats-wheat	R -227.69	R -683.06	R -1683.06
16	Fodder oats-oats-wheat	R -281.04	R -843.12	R -1843.12
17	Oats-oats-wheat	R -433.88	R -1,301.64	R -2301.64
18	Sorghum-dry bean-wheat	R -634.64	R-1,903.93	R -2903.93

■ Winter crop sequences

5.4 Conclusion

It was confirmed that the total profit of a crop rotation system, with wheat as target crop, can be influenced by preceding cropping sequences. Of the 50 crop rotations 32 had a total profit margin higher than R1,000 ha^{-1}. The highest total profit of R7,549.76 ha^{-1} was obtained with a soybean × maize × wheat rotation, while the sorghum × dry bean × wheat rotation had a total loss of -R1,903.93. Maize had a stable yield over two seasons, while the yield of the other four summer crops in the study posed a higher production risk under rainfall conditions (pod shattering in dry bean and soybean crops), and potential bird damage situations (sunflower and sorghum). Production costs of summer crops were influenced negatively in 2008 by a weaker Rand, while the prices of soybean and maize decreased between the first two cropping seasons with R689.13 and R376.53, respectively.

Production risks can be addressed with more diverse crop rotation systems. More research is needed to identify potential crops to be included in rotation systems of the Eastern Free State.

5.5 References

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CHAPTER 6

SUMMARY AND RECOMMENDATIONS

Crop rotation is one of the pillars of conservation agriculture, especially in countries like Australia and the United States of America, where no-till systems are employed successfully. A lack of reliable information on the most beneficial crops to be planted in a rotational system has often been claimed as one of the reasons for poor adoption of no-till systems in the Eastern Free State. The main purpose of this study was to evaluate the effect of 50 cropping sequences on the growth and profitability of wheat in a conservation tillage system in the Eastern Free State of South Africa.

A crop sequence trial was done for three consecutive years at the ARC-Small Grain Institute at Bethlehem. The crop matrix trial design was used and six parameters, namely soil, plant, nitrogen use, precipitation use, yield and quality grading were evaluated to quantify the effect of preceding crop sequences on wheat.

Total annual rainfall figures for 2009 and 2011 were lower than the long term average, while the total rainfall of 2010 was 160 mm higher than the long-term average of 709 mm. Grain filling of winter crops usually occurs during October and November. Rainfall recorded for these two months from 2009 to 2011 was 23% to 64% less than the average long-term total of a 171 mm. High rainfall was received during harvest of soybean and dry bean in March 2010, and it caused pod shattering, thus lower grain yields. High rainfall was recorded in December 2010 and it reduced any potential effect of preceding N fixing crops such as soybean, dry bean and vetch on the soil fertility status of the trial site.

The soybean × maize × wheat rotation produced the highest total profit of R7,549.76 ha^{-1} over the three year period. The N fixing ability of soybean crops play an important role in the profitability and sustainability of any rotation system. However, skilled management practices are needed to prevent pod shattering and yield loss. Maize was the summer crop with the most stable yield over two seasons, while the wheat yield fluctuated due to water stress which occurred during October and November. More research is needed to confirm these results and to determine any potential synergistic effects of a preceding soybean and maize sequence on wheat in a rotation system.

Only summer crop sequences had a significant influence on the yield components of the final wheat crop. A lower ($P \leq 0.1$) number of plants m^{-2} and ears m^{-2}, as well as lower biomass and residue yields m^{-2} were obtained when wheat was planted on the sorghum × soybean, maize × sunflower and soybean × maize plots. Results of the sorghum × soybean sequence plots always showed the poorest response, but did not differ significantly ($P > 0.1$) from the other two sequences. The lower number of final wheat plants on these plots had a significantly higher TKM and harvest index. This was probably the result of lesser in-row competition for water and nutrients.

Although the yield of the final wheat crop planted on second season summer treatment plots did not differ significantly, a higher number ($P \leq 0.1$) of ears m^{-2} was recorded on the second season sunflower plots. Similar to another study in the region, wheat from these plots also showed a better $N_{(grain)}$ use efficiency, with a significant higher grain protein content.

Oats was unsuccessful as a preceding winter crop treatment. A significant ($P \leq 0.1$) lower number of wheat seedlings, with fewer ears and a lower grain yield were recorded per unit area on second season oats residues. The final wheat crop utilised precipitation and N less efficiently ($P \leq 0.1$) resulting in a lower accumulation of grain protein at the end of the season. Oats should only be used in rotation systems as a break crop to reduce Take-all, a soil-borne disease of wheat.

The crop matrix technique, which was used for the first time in the country, proved to be a reliable method to generate more information on cropping sequences in the same trial over a much shorter period. The technique has been used successfully in the United States of America and Australia to identify more crops adaptable to specific regions. Multi-disciplinary research teams are working together in these countries on the different mechanisms that cause positive or negative effects of certain crop sequences. Such an approach can be valuable for future research in the Eastern Free State.