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Tillage effects on soil quality and plant productivity in the Swartland region, South Africa

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By

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PhD

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Applicant:

Flackson Tshuma

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Tillage effects on soil quality and plant productivity, in crop production systems with and without the use of synthetic chemicals in the Swartland, South Africa

This is to certify that the above named applicant has completed the Coventry University Ethical Approval process and their project has been confirmed and approved as Medium Risk

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[redacted]

Abstract

Many farmers have stopped the practice of conventional tillage and have adopted conservation agriculture. Nonetheless, the practice of no-tillage in conservation agriculture can lead to weed and pest infestations, therefore most farms are currently managed using synthetic agrochemical (herbicide, insecticide, fungicide, and fertiliser) applications. Excessive utilisation of synthetic agrochemicals can be harmful to the environment. If the current conservation agriculture systems are to limit the environmental damage caused by synthetic inputs, then some form of tillage is likely to be necessary. Infrequent tillage practices could be adopted as a means of preventing intensive tillage and minimising problems associated with long-term conservation agriculture.

This research explored the effects of contrasting tillage regimes and agrochemical applications on soil quality, crop productivity, and weed dynamics in South Africa's Mediterranean climate zone. Seven tillage treatments, within a long-term (44-years) tillage experiment, were investigated: continuous mouldboard (MB), tine-tillage (TT), shallow tine-tillage (ST), no-tillage (NT), and infrequent tillage treatments: ST conducted once in two years (ST-NT), ST conducted once in three years (ST-NT-NT), and ST conducted once in four years (ST-NT-NT-NT). Three rates of synthetic agrochemical applications were used (standard, reduced, and minimum); the reduced and minimum rates involved the application of synthetic agrochemicals in combination with bio-chemicals (chemicals derived from natural compounds). It was hypothesised that infrequent tillage and application of reduced synthetic agrochemicals would improve soil quality, crop productivity and increase weed seedbank diversity relative to the NT and MB treatments.

Contrary to the research hypothesis, infrequent tillage practices failed to significantly reduce the stratification of soil chemical parameters and could not improve the soil microbial diversity and enzyme activity; wheat and canola yield and quality and weed seedbank diversity. The MB was able to prevent stratification and weed infestation but depleted the soil organic carbon and led to a reduced soil enzyme activity. Nonetheless, the combined results from the system with standard and reduced use of synthetic agrochemicals for 2018 and 2020 showed that there were no differences in

yield and grain quality in four of the seven tillage treatments. And no differences were found in canola seed yields in 2019. Further reduction in the application of synthetic agrochemicals, as was done in the system with minimum synthetic agrochemicals, did not yield positive crop productivity results due to severe weed problems.

Overall, results from this study highlight the importance of reducing both the intensity of tillage and the application of synthetic agrochemicals as doing so can improve soil quality and crop productivity. However, there are trade-offs. Some form of tillage is required to prevent nutrient stratification, but this should not be so intensive or frequent as to deplete the soil organic matter stocks. Also, the application of standard synthetic agrochemicals, as conducted in most conservation agriculture systems, can be reduced, but it is risky to completely avoid the synthetic agrochemicals as shown by crop failure in the system with minimum synthetic agrochemicals in 2020. Furthermore, results from the system with reduced synthetic agrochemicals shows that the Western Cape province has the potential to gradually introduce more agroecological farming practices in wheat and canola production by using bio-chemicals although further research is needed to optimise these approaches.

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First and foremost, I thank Jehovah God, the Almighty for the precious gift of life and for giving me hope, purpose and the ability to face many hurdles.

My story at Stellenbosch University began in 2010 when I was accepted for an MSc in Animal Sciences in the Faculty of AgriSciences. My financial situation wouldn't allow me to proceed with registration and thus I deferred the process until five years later when I enrolled for MSc in Sustainable Agriculture, where I met Dr Pieter A Swanepoel, who later became my mentor from then until now.

I am grateful to Dr P A Swanepoel for his role as my supervisor during my MSc and PhD studies as a *Matie* at Stellenbosch University. His vision, along with Dr Johan Labuschagne (Senior Scientist, Western Cape Department of Agriculture, Elsenburg) inspired and kick-started this research. Drs Francis Rayns and James Bennett (Centre for Agroecology, Water and Resilience - Coventry University) cemented the research and made this *dual PhD degree* (Stellenbosch and Coventry University dual PhD degree programme) a reality. These four individuals made an incredible supervisory team and provided guidance and constructive criticism throughout my study period at both Stellenbosch and Coventry Universities.

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List of Abbreviations

ANOVA	Analysis of variance
B	Boron
C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
CP	Conventional ploughing
Cu	Copper
DM	Dry matter
E	Evenness index
EDTA	Ethylenediaminetetraacetic acid
g	Gram
H'	Shannon-Wiener diversity index
ha	Hectare
K	Potassium
kg	Kilogram
m	Metre
MB	Mouldboard
Mg	Magnesium
mm	Millimetre
Mn	Manganese
N	Nitrogen
NT	No-tillage

ST-NT	Shallow tine-tillage, conducted once in two years in rotation with no-tillage
ST-NT-NT	Shallow tine-tillage, conducted once in three years in rotation with no-tillage
ST-NT-NT-NT	Shallow tine-tillage, conducted once in four years in rotation with no-tillage
P	Phosphorus
pH	The negative logarithm to the base ten of the hydrogen ion activity in the solution
S	Sulphur
SE	Standard error of the mean
SOC	Soil organic carbon
Spp.	Species
ST	Shallow tine-tillage
t	Ton
TT	Tine-tillage
Zn	Zinc

CHAPTER 1

General introduction

1.1 Background

Tillage has been practised for millennia through the use of simple implements which did not invert the soil (Lal et al., 2007). However, the industrial revolution led to the development, marketing and adoption of the modern-day mouldboard plough and the spreading of conventional tillage practices in most European countries (Derpsch, 2004) and the Americas (Lal et al., 2007). Industrialisation also led to the manufacture and distribution of tractors that could be used to pull the mouldboard plough, leading to increased tillage intensity (Baumhardt et al., 2015). During the same era, the manufacture of synthetic agrochemicals (fertilisers, herbicides, fungicides and insecticides) started (Timmermann and Félix, 2015).

The use of tractors, mouldboard plough and application of synthetic herbicides broadly resulted in significant increases in agriculture production (Timmermann and Félix, 2015). The success of the mouldboard plough led to its spread and adoption in various parts of the world, including Africa (Derpsch, 2004). However, the mouldboard plough inverts soil and mostly does not leave a surface that is conducive for seeding, therefore a couple of secondary tillage passes may be necessary to get a fine tilth for seeding (Laker and Nortjé, 2020). This multiple tillage practice not only leaves the soil bare and unprotected but also breaks down the soil structure and create a tough plough pan below the depth of regular tillage (Bogunovic et al., 2018; Hamza and Anderson, 2005). A plough pan limits root growth, and water and nutrient infiltration down the soil profile. Incidences of soil erosion, crusting and poor soil structure are often associated with the practice of intensive conventional tillage (Baumhardt et al., 2015; Bogunovic et al., 2018; Hamza and Anderson, 2005; Hösl and Strauss, 2016; Kladivko, 2001). In addition, conventional tillage practices can lead to reduced soil fertility through depletion of soil organic carbon (Tshuma et al., 2021) and reduced soil microbial diversity (Habig et al., 2018).

The benefits of conventional tillage are thus only temporary therefore the practice of reduced tillage, including no-tillage, is now being advocated as a better means of preserving soil quality. However, reduced tillage is generally unable to effectively control weeds and is primarily dependent on the use of synthetic agrochemicals such as herbicides and pesticides (Lal, 2009). Like the temporary benefits of intensive tillage, the use of synthetic agrochemicals in the past few decades has led to higher yields but has also resulted in the evolution of herbicide-resistant weeds such as ryegrass (*Lolium rigidum*) and hairy fleabane (*Conyza* spp.) (Heap, 2021; Ndou et al., 2021) and detrimental effects on beneficial insects (Pannell et al., 2014).

As the first European settlers started to farm in Africa, the use of the modern-day mouldboard plough was introduced. As in other places, conventional tillage with the mouldboard, and disc ploughs became the norm in South Africa. For example, the Europeans who settled in the Western Cape province of South Africa, produced wheat (*Triticum aestivum*) using conventional farming practices (Strauss et al., 2021b). Continued conventional tillage practices in the Western Cape province led to the deterioration of soil quality such that in the mid-1980s, most farmers observed declining yields and increased production costs to the extent that the economic viability of the production systems became questionable (Strauss et al., 2021b; Swanepoel et al., 2016). Farmers subsequently started to convert to no-tillage systems. To help local farmers to make the correct tillage choice, a long-term tillage experiment was started in 1976 at Langgewens Research Farm, in the Swartland, a winter cereal growing region of the Western Cape province. The experiment investigated the effects of various tillage treatments and cropping systems on soil quality and crop yield as well as the effects of different rates of fertiliser applications on soil quality and crop yield. The cropping system included wheat monoculture at first, and later also crop rotation, which involved: wheat, canola (*Brassica napus*) and a cover crop mixture. The tillage treatments included continuous no-tillage, tillage with a mouldboard plough, tine tillage, shallow tine tillage and three different infrequent tillage treatments.

By the year 2000, most farmers in the Western Cape province had changed their farming systems by adopting one or more aspects of conservation agriculture, which is based on three principles: (i) minimum mechanical soil disturbance, (ii) crop rotation or species diversification and (iii) permanent soil organic cover (FAO, 2017). As of the year 2020, 25% of commercial farmers in South Africa had fully adopted conservation agriculture, of which 83% of the farmers were in the Western Cape province (Strauss et al., 2021b). The positive effects of conservation agriculture on soil quality and plant productivity have been well documented (Alizadeh and Allameh, 2015; Fooladi Vanda et al., 2009; Montgomery, 2007; Six et al., 2004). Limitations, however, still remain.

The practice of no-tillage can, *inter alia,* lead to increased weed pressure (Yankov et al., 2015), nutrient stratification (Franzluebbers, 2002; Tshuma et al., 2021) and inability to adequately ameliorate soil acidification problems (Grove et al., 2007). Nutrient stratification can be problematic if the topsoil dries out, reducing the availability of immobile nutrients such as phosphorus (Shen et al., 2011). Soil acidification can also limit nutrient availability to plants, particularly during drier periods (Franzluebbers, 2002) and can result in reduced crop productivity. Also, soil compaction in a conservation agriculture system, which can be caused by the movement of farming implements (Swanepoel et al., 2015), can limit the movement of water and nutrients into the soil.

There is, therefore, a need to change the current farming systems to environmentally friendly ones. Strategic/ or occasional tillage, the deliberate one-off tillage conducted in a no-tillage field to solve a particular problem, may mitigate the problems associated with conservation agriculture (Dang et al., 2018; Labuschagne et al., 2020). Alternatively, farmers could minimise the use of synthetic agrochemicals by gradually adopting some agroecological farming principles within the current farming systems. Agroecology refers to a system of agriculture that does not involve any application of synthetic agrochemicals but rather focuses on applying ecological concepts and principles to the design and management of sustainable agroecosystems (Udall et al., 2015; Wibbelmann et al., 2013).

1.2 The long-term tillage experiment at Langgewens Research Farm

The long-term trial was laid out in a randomised block design with four replicated blocks. Each block had 14 plots and each plot measured 50 m x 6 m. The blocks were separated by a buffer zone of at least 9 m, and plots were separated by a 1 m buffer zone.

The primary tillage treatments included: the mouldboard plough (MB) which involved ploughing and inverting the soil to a depth of 200 mm; tine tillage (TT) which involved the use of non-soil inverting tine implements that ploughed to a depth of 150 mm, and no-tillage (NT) which did not include any primary tillage (Agenbag, 2012).

Initially, wheat was the only crop grown on the trial site. However, as production costs and soil deterioration increased in the Western Cape province, the cropping system and tillage treatments on the research site were changed to meet the needs of the local farming community. Crop rotation was introduced on the long-term trial site in 1990 such that the long-term experiment was split into continuous wheat production and a four-year rotation system where wheat was rotated with lupins (*Lupinus* spp.) and canola (*Brassica napus*). Four-year crop rotation sequences used were continuous wheat (wheat-wheat-wheat-wheat) and wheat-lupin-wheat-canola (Agenbag, 2012). The tillage treatments were changed to include shallow tine-tillage (ST) treatments, but the MB, TT and NT treatments in the continuous wheat system were still applied on the same plots as before (Agenbag, 2012). The shallow tine-tillage involved primary tillage with tine implements to a depth of 75 mm. Tillage rotations, herewith referred to as infrequent tillage was also started in 1990. The infrequent tillage treatments were: (i) ST every second year in rotation with NT, (<u>ST</u>-NT); (ii) ST every third year in rotation with NT, (ST-<u>NT</u>-NT); and (iii) ST every fourth year in rotation with NT, (ST-NT-<u>NT</u>-NT).

The agronomic practices such as fertilisation, weed and pest control, were conducted according to the advice from the Langgewens Technical Committee, which included agricultural researchers and industry experts. The application of herbicides, fertilisers, fungicides and insecticides were thus not constant from one season to another, but varied depending on the crops planted, seed variety and available synthetic agrochemicals. The quantity of herbicides and pesticides applied in all plots per growing season was, however, generally equal. Although there were no further changes in the tillage treatments, the research aims did change from time to time. For example, Maali and Agenbag, (2006) investigated the effects of tillage, crop rotation and nitrogen application rates on bread-baking quality of spring wheat, whilst Agenbag and Maree, (1989) investigated the effects of tillage on soil strength of simulated surface crusts in two cropping systems for wheat (*Triticum aestivum*). Fertilisation applications were therefore not constant due to the differing aims but generally ranged between 60 and 140 kg N ha^{-1}, and 14.5 kg P ha^{-1} per year, depending on the aims of the trials being conducted.

Increasing cases of insecticide and herbicide resistance (Heap, 2021) necessitated a further change in the management of the long-term trial site. In 2018, the use of bio-chemicals (referred to as **reduced** synthetic agrochemicals) was started on two of the four blocks but the tillage treatments were not changed (Figure 1.1).

Block 1		Block 2		Block 3		Block 4	
Standard synthetic agrochemicals		Reduced synthetic agrochemicals		Standard synthetic agrochemicals		Reduced synthetic agrochemicals	
14	MB	*15*	ST-NT-NT-NT	*42*	ST	*43*	ST-NT-NT-NT
13	ST	*16*	ST-NT	*41*	TT	*44*	ST-NT-NT
12	NT	*17*	NT	*40*	MB	*45*	NT
11	ST-NT	*18*	TT	*39*	ST-NT-NT-NT	*46*	NT
10	ST-NT-NT-NT	*19*	TT	*38*	NT	*47*	ST-NT
9	ST-NT-NT	*20*	ST-NT-NT-NT	*37*	ST-NT-NT	*48*	ST
8	MB	*21*	ST-NT-NT	*36*	ST-NT-NT	*49*	ST-NT-NT
7	TT	*22*	ST-NT	*35*	TT	*50*	MB
6	ST-NT-NT	*23*	ST-NT-NT	*34*	MB	*51*	ST-NT
5	ST-NT	*24*	NT	*33*	ST-NT	*52*	ST-NT-NT-NT
4	ST	*25*	MB	*32*	ST-NT	*53*	MB
3	ST-NT-NT-NT	*26*	ST	*31*	ST	*54*	ST
2	TT	*27*	ST	*30*	NT	*55*	TT
1	NT	*28*	MB	*29*	ST-NT-NT-NT	*56*	TT

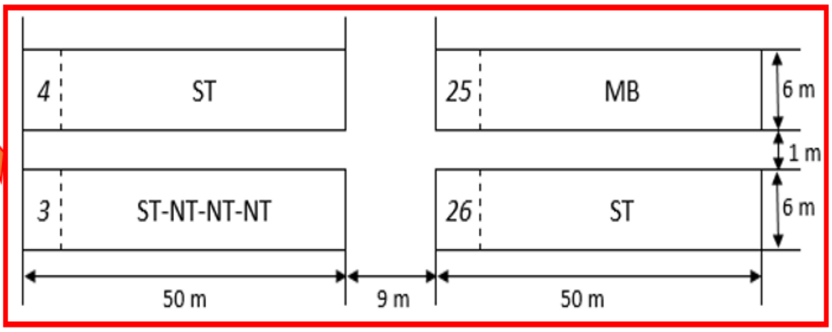

Figure 1.1: Layout of the long-term trial site at Langgewens Research Farm in 2018, showing the four blocks (1; 2; 3 and 4), and the level of synthetic agrochemicals (**Standard** synthetic chem; and **Reduced** synthetic chem). The system with standard synthetic agrochemicals was started in 1976 whereas the system with reduced synthetic agrochemicals was introduced on two of the four blocks in 2018. MB = ploughing with a mouldboard plough to a depth of 200 mm; TT = ploughing with a chisel plough to a depth of 150 mm; ST = ploughing with a chisel plough to a depth of 75 mm; NT = no-tillage; ST-NT = ploughing with a chisel plough to a depth of 75 mm once every two years in rotation with NT; ST-NT-NT = ploughing with a chisel plough to a depth of 75 mm once every three years in rotation with NT; ST-NT-NT-NT = ploughing with a chisel plough to a depth of 75 mm once every four years in rotation with NT. The numbers 1 to 56 represent the plots.

In 2019, further reduction on synthetic agrochemicals (referred to as **minimum** synthetic agrochemicals) was implemented such that each of the 56 plots had a 14 m x 6 m section (Figure S4) which only received a single application of synthetic agrochemicals at the beginning of the crop growing season.

As new improved seed cultivars became available (Nhemachena and Kirsten, 2017), the seeding densities varied from time to time depending on the seed variety recommendations but mainly was at a seeding rate of 100 kg ha^{-1} (Agenbag and Maree, 1991). For example, in 1986, the researchers aimed to achieve a population of 200 plants m^{-2}, therefore wheat was sown at a rate of 120 kg ha^{-1}. From 1997 to 2000, the spring wheat cultivar SST 57 was sown at a rate of 300 seed m^{-2} (Maali and Agenbag, 2003b). In 2018, the wheat cultivar SST 056 was planted at a rate of 100 kg ha^{-1} whereas in 2020, the wheat cultivar SST 0166 was planted at a rate of 90 kg ha^{-1}. Canola cultivar Alfa TT was planted in 2019 at a rate of 3.5 kg ha^{-1}. Row spacing was generally about 170 mm for wheat whereas it was about 300 mm for canola. Available data does not specify the exact cultivars which were planted throughout the years.

1.3 Rationale

Although most farmers in the Western Cape province of South Africa have adopted conservation tillage practices and moved away from intensive tillage with the mouldboard plough. The current conservation agriculture systems rely on synthetic agrochemicals for fertilisation, and weed and pest control. If current conservation agriculture systems in the Western Cape province are to become more environmentally friendly, then tillage is likely to be necessary. Currently, no published article shows that the Western Cape province has any agroecological farmed grain or canola. Yet in 2020, almost 100% of South Africa’s dryland canola and 52% of wheat was produced in the Western Cape province (Grain SA, 2021).

To reduce reliance on synthetic agrochemicals in conservation agriculture systems, farmers may have to include livestock and cover crops to control weeds (MacLaren et al., 2021). However, Strauss et al. (2021a) indicated that most farmers in the Western Cape province were reluctant to include cover crops such as annual medics and clovers in their crop rotation systems. Strategic tillage can be conducted in conservation agriculture systems but cannot offer a lasting solution as it is only performed when a problem has already been identified in the field. Infrequent tillage practices could be adopted as a means of regularly controlling weeds and incorporating soil amendments. Infrequent tillage is different from strategic tillage in that it refers to a pattern of planned tillage rotations involving a phase of no-tillage and a phase of tillage (Tshuma et al., 2021). The phase of no-tillage can be one, two, or three consecutive years which are followed by tillage.

A better understanding of the relationship between tillage frequency, soil quality and plant productivity is essential to promote tillage practices that may be adopted in farming systems without compromising on soil quality whilst enabling the reduction of synthetic agrochemical applications.

1.4 Research aim

This research aimed to establish an acceptable tillage frequency regime that can be adopted in the conservation agriculture systems to gradually minimise the application of synthetic agrochemicals in the Swartland region of South Africa. This research was conducted within a long-term (44-years) trial at Langgewens Research Farm.

1.5 Research objectives

To obtain answers concerning the aforesaid research aim; the specific objectives of the study were as follows:

i. To assess the effects of long-term infrequent tillage on the stratification of selected soil chemical parameters to a depth of 300 mm in a dryland crop rotation system.

ii. To assess the progressive impact of tillage practices and varied rate (**standard**, **reduced**, and **minimum**) of synthetic agrochemical application on soil microbial diversity indices and enzyme activity in a dryland crop rotation system.

iii. To determine the long-term (44-years) tillage effects on wheat grain yield in a dryland farming system.

iv. To determine the effects of tillage practices on wheat and canola yield and quality in a dryland crop rotation system that received, either **standard**, **reduced**, or **minimum** synthetic agrochemicals.

v. To determine the effects of long-term (44-years) tillage practices and short-term use of varied rates (**standard**, **reduced**, and **minimum**) of synthetic agrochemicals on the soil weed seedbank in a dryland crop rotation system.

1.6 Use of terminology

Throughout the thesis the bold terms: **standard**, **reduced**, and **minimum** represents the rate of synthetic agrochemical application:

i. **Standard**: synthetic agrochemicals were applied as would be applied on farms that follow conservation agriculture practices. The application of synthetic agrochemicals on the trial site was determined by the Langgewens Technical Committee according to best practices for the Swartland region.

ii. **Reduced**: half of the synthetic agrochemicals applied in the **standard** system were replaced with bio-chemicals. Therefore, a combination of synthetic agrochemical and bio-chemicals were applied on the allocated plots. In this thesis, the term *bio-chemical* does not imply organic certification but refers to products derived from natural compounds. A full list of chemicals applied is available in the appendix Tables S1-5.

iii. **Minimum**: Only one application of a broad-spectrum herbicide before planting, and no other chemical was applied.

iv. Tillage sequence: refers to the specific order in which the tillage treatments are conducted per each crop growing season/year. This can be continuous no-tillage; continuous mouldboard plough; or infrequent tillage.

1.7 Outline of the thesis

The thesis comprises eight chapters including the general introduction, literature review, five research chapters that are based on the objectives listed in section 1.4, and a general conclusions chapter. Except for Chapters 1, 2 and 8, the rest are structured as manuscripts for scientific publication with their abstracts, introduction, methodology, conclusions, and a list of references.

Chapter 2 provides a literature review on soil tillage and synthetic agrochemical application practices in various farming systems in South Africa and around the world. The chapter explains the shortcomings of the current tillage practices and the effects of repeated use of synthetic agrochemicals. It also provides some suggestions for overcoming the problems associated with frequent tillage and synthetic agrochemical application.

Chapter 3 addresses the first objective and assesses how some selected soil chemical parameters were stratified as a result of long-term (42-years) tillage practices in a dryland farming system at Langgewens Research Farm. This was done by collecting soil samples from 56 plots to a depth of 300 mm and assessing the quantity of the chemical parameters per depth increments of 0-50; 50-100; 100-150, and 150-300 mm. This chapter has been published as an original research article in *Soil and Tillage Research* which could be cited as: Tshuma, F., Rayns, F., Labuschagne, J., Bennett, J., Swanepoel, P.A., 2021. Effects of long-term (42 years) tillage sequence on soil chemical characteristics in a dryland farming system. Soil Tillage Res. 212, 1–9. https://doi.org/10.1016/j.still.2021.105064.

Chapter 4 addresses the second objective and investigates how soil microbial diversity indices and enzyme activity were affected by a combination of various tillage practices and rates (**standard**, **reduced**, and **minimum**) of synthetic agrochemical application in a dryland cropping system. This was achieved by collecting soil samples from 64 sub-plots to a depth of 150 mm during anthesis and analysing the soils for soil microbes and microbial enzymes. This chapter is currently in preparation for submission to a peer-reviewed journal for publication as an original research article.

Chapter 5 addresses the third objective and explores the history of wheat production trends at Langgewens Research Farm. Wheat grain yield data from a long-term (44-years) tillage trial were analysed and compared with current (2018-2020) yield responses of the same trial site. This chapter has been submitted to *Field Crops Research* for publication as an original research article.

Chapter 6 addresses the fourth objective and tests the hypothesis that infrequent tillage practices will lead to higher crop productivity relative to both continuous no-tillage and tillage with a mouldboard plough in a system with **reduced** synthetic agrochemicals. The productivity of wheat and canola under various rates of synthetic agrochemical were monitored and evaluated over three years (2018-2020). Aboveground biomass, grain and seed quality and yield parameters were assessed.

This chapter has been submitted for publication as an original research article and is currently under review in *Field Crops Research*.

Chapter 7 addresses the fifth objective and evaluates the weed seedbank dynamics in a dryland crop rotation system with varied rates of synthetic agrochemicals. The study seeks to determine if the weed seedbank species increases or decreases with a reduction in tillage frequency and application of synthetic agrochemicals. Diversity indices (Shannon-Wiener and Gini-Simpson) were computed and compared per tillage and agrochemical application. This chapter is currently in preparation for submission to a peer-reviewed journal for publication as an original research article.

Chapter 8 contains the general discussion, conclusions, and recommendations from the thesis.

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CHAPTER 2

Literature review

2.1 Introduction

During medieval times, land preparation for crop production was conducted through the practice of no-tillage and minimum tillage (Derpsch, 2004). For millennia, minimum tillage practices were conducted through the use of simple handheld sticks and implements such as the 'ard' which did not invert the soil (Lal, 2009; Lal et al., 2007). The ard led to the development of the soil inverting 'Roman plough' which was popular in the European countries in the 10th century. According to Derpsch (2004), the German, Dutch and British made some improvements to the plough in the 17th century leading to the shape of the mouldboard, which turned the soil by 135^{o}. The mouldboard plough is described as the only implement that could effectively control quack grass (*Agropyron repens*), a weed that had become problematic in Europe in the 18th century (Derpsch, 2004).

The success of the mouldboard plough in the European countries led to its use in parts of the world wherever the European powers went, including the Americas, Asia and Africa (Derpsch, 2004). In the United States of America, a mouldboard plough was designed by Thomas Jefferson and marketed by John Deer (Lal, 2009; Lal et al., 2007). With industrialisation and the development of tractors, the uptake and worldwide use of the mouldboard plough increased, leading to increased tillage frequency and depth (Hobbs et al., 2008; Kassam et al., 2009). Industrialisation also led to the manufacture of synthetic agrochemicals (fertilisers, insecticides, fungicides, and herbicides), which further contributed to the uptake and popularity of the mouldboard during the Green Revolution in the 1950s, a period marked by significant increases in agriculture production in many parts of the world (Timmermann and Félix, 2015).

Although the use of the mouldboard was 'successful' in Europe and other places, probably due to high rainfall, the same could not be achieved in the dry Southern Great Plains of the United States of America. Frequent, deep tillage of the virgin soils of the Great Plains in the 1930s greatly contributed to soil erosion and the devastating Dust

Bowl (Lal, 2009; Lee and Gill, 2015). The contrasting effects caused by frequent use of the mouldboard is indicative of a need to adjust tillage practices depending on locality and other factors such as rainfall, type of soil, tillage frequency and depth (Lee and Gill, 2015). Kassam et al. (2019) and Lal (2009) highlighted that the devastating effects of the Dust Bowl resulted in a mind shift from frequent tillage practices as practised in conventional tillage, to practices that minimise soil disturbance.

Some of the early forms of tillage implements are shown in Figures 2.1 and 2.2.

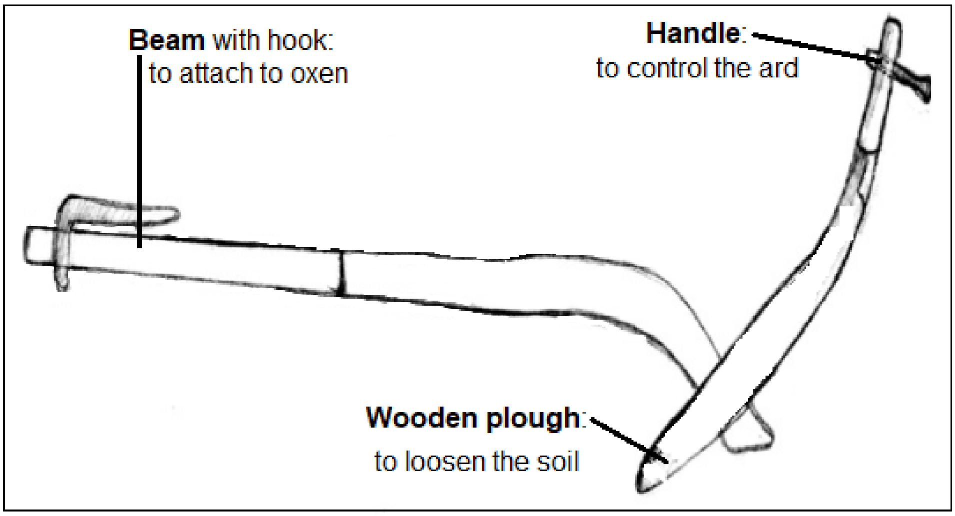

Figure 2.1: The 'ard', a primitive tillage tool from about 4,000 BCE (before common era); Adapted from Lal et al. (2007).

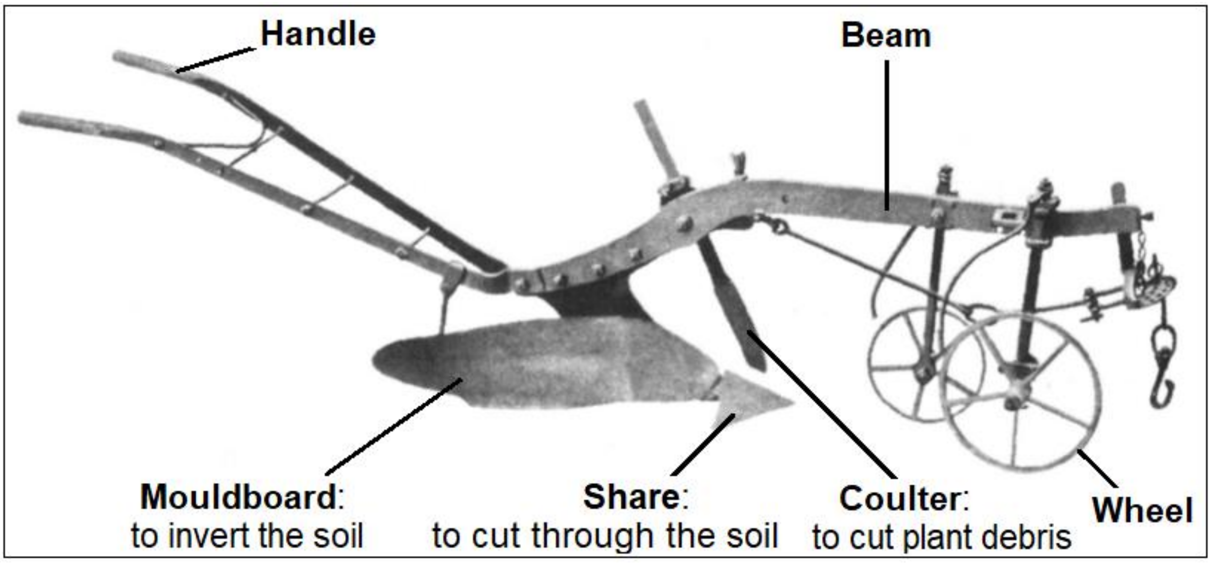

Figure 2.2: The horse-drawn, 19^{th}-century all-metal plough; Adapted from Mitchell, (1979).

2.2 Conventional tillage

Conventional tillage mainly represents tillage practices that cultivate the soil to depths of 200 – 250 mm thereby causing severe soil disturbances (Li et al., 2020). In some cases, rippers and subsoilers, which do not invert the soil, can be used to till soils to depths that are deeper than 250 mm. Conventional tillage comprises several tillage passes (primary and secondary) through the field during land preparation for the planting of crops. Primary tillage is conducted mainly by using an aggressive implement such as the mouldboard plough (Figure 2.3), disc plough, or chisel plough (Figure 2.4), to break the soil. The mouldboard causes soil inversion which buries and kills weeds and crop residues that are on the soil surface. However, the mouldboard can, depending on soil texture and water content, leave huge clods on the soil surface. These clods can prevent seed germination and establishment, therefore secondary tillage with a less aggressive implement is conducted to make to soil surface smooth and even, and ready for seeding. Laker and Nortjé (2020) stated that some farmers who practised conventional tillage in South Africa conducted up to eight secondary tillage passes in their fields before seeding. The tillage practices are normally performed before the arrival of the rains. Such frequent tillage practices not only pulverise the soil but also leave it bare and increase the chances of soil erosion by wind or rain.

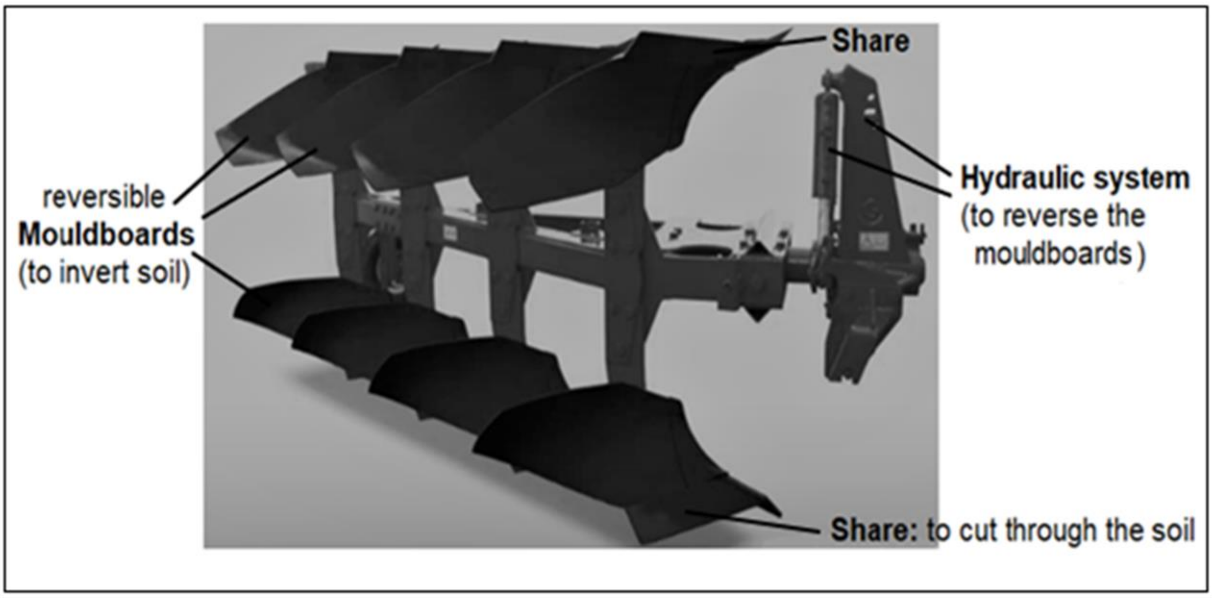

Figure 2.3: Modern, reversible hydraulic tractor-drawn plough with eight mouldboards; Adapted from Massey Ferguson (2016).

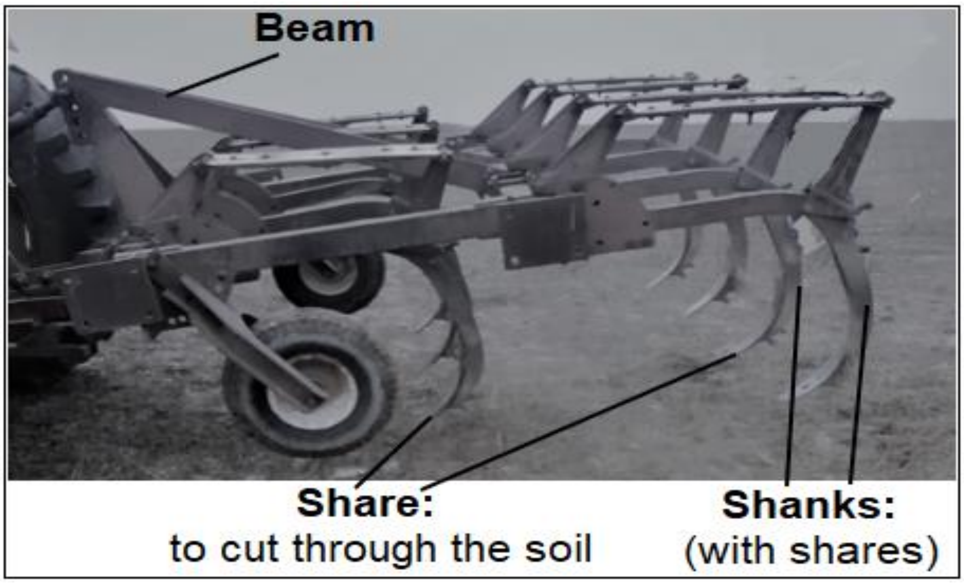

Figure 2.4: Non-soil inverting tractor-drawn chisel plough with seven shanks; (Photo credit: Tshuma F).

Although tillage can be an effective method of controlling weeds (Conyers et al. 2019; MacLaren et al. 2021), improving soil aeration and providing a suitable surface for planting crops, intensive tillage has led to massive erosion of the fertile topsoil and desertification such as evidenced by the Dust Bowl incident. Amongst other things, the practice of conventional tillage generally leads to soil organic carbon depletion (Tshuma et al., 2021), creating a tough plough pan below the depth of regular tillage (Laker and Nortjé, 2020). This reduces soil microbial diversity (Habig et al., 2018), and increases greenhouse gas emissions from the soil as well as the fossil fuel used during the many tillage operations (Strauss et al., 2021b). Unlike highly mechanised countries, the use of tractor-drawn tillage implements remains low in many parts of South Asia and Africa (Lal, 2009), especially in subsistence farming. However, animal-drawn soil inverting tillage implements are used, and these too expose the soil to degradation through erosion.

The practice of conventional tillage has been often accompanied by the repeated growing of the same crops year after year. For example, the first Europeans in South Africa in the 1650s introduced wheat (*Triticum aestivum*) for cultivation in the Western Cape province. However, they were only willing to sponsor and to buy wheat and no other crop from the farmers, therefore, wheat was grown in monoculture systems under conventional tillage practices until the 1980s (Swanepoel et al., 2016). Growing crops in a monoculture system can, *inter alia*, lead to the build-up of pests and weeds which may drastically reduce crop yield (Strauss, 2021). Considering the above, the practice of conventional tillage coupled with growing crops in monoculture systems is unsustainable and should be avoided. To minimise soil degradation through erosion, minimum tillage could be practised instead of intensive tillage.

2.3 Conservation tillage

Conservation tillage is a broad term that describes any tillage practice that seeks to minimise the degree of soil disturbance (Strauss et al., 2021b). Included as part of conservation tillage are minimum tillage, no-tillage, zero tillage, shallow tillage, and strip tillage (Hernanz et al., 2002; Leskovar et al., 2016; MacLaren et al., 2021; Pardo et al., 2019; Tshuma et al., 2021). The individual terms for conservation tillage have been described differently or interchangeably by the above authors. However, conservation tillage does not cause soil inversion, and deep tillage (>150 mm) is prevented. MacLaren et al. (2021) explained that minimum tillage involves the use of tines to loosen the soil to 100 mm depth, and no-tillage refers to direct drilling using a seed drill fitted with tine openers, whereas zero tillage refers to direct drilling using a seed drill fitted with disc openers. Tshuma et al. (2021) described shallow tillage as soil loosening with a tine implement to a depth of 75 mm. According to Kassam et al. (2019) and Lal (2009), the no-tillage system was started in the United States of America's maize (*Zea mays*) growing regions in response to the severe problem of soil erosion and slowly spread to other parts of the world. Conservation tillage relies on the use of special implements such as the seed drills fitted with tine or disc openers and these are not readily affordable by most resource-poor farmers, hence the adoption of conservation tillage is relatively low in Africa relative to other continents. The use of the primitive ard or hoe which were developed some 7 millennia ago is still being practised by the resource-poor farmers in Africa and South Asia (Lal, 2009; Lal et al., 2007).

Amongst other things, conservation tillage practices have led to marked improvements in soil quality through the build-up of soil organic matter, reduced greenhouse gas emissions from the soil and reduced use of fossil fuel, increased soil aggregate stability, and reduced chances of soil erosion (Labuschagne et al., 2020; Peixoto et al., 2020; Strauss et al., 2021a; Wang et al., 2020). Also, the practice of no-tillage can lead to increased soil microbial diversity and enzyme activity (Habig et al., 2018). Unlike the soil inverting conventional tillage practices, conservation tillage is not able to effectively incorporate soil amendments into the deeper soil or control weeds as the soil is not turned. For weed control, the success of conservation tillage practices is largely dependent on the use of synthetic herbicides. The practice of conservation tillage was made possible by the production and use of synthetic herbicides such as triazine, paraquat, and glyphosate, and roundup-ready crops (Lal, 2009). Round-up ready crops are genetically modified to be resistant to glyphosate-based herbicides.

2.4 Use of synthetic herbicides

In the past few decades, the use of synthetic agrochemicals in cropping systems has resulted in increased crop yields (Dahal and Dhakal, 2016; Foteinis and Chatzisymeon, 2016; Knapp and van der Heijden, 2018; Loaiza Puerta et al., 2018) because of their effective control of weeds, pests and provided nutrients to pants. Synthetic herbicides can kill weeds and their propagules (Gibson, 2010; Pardo et al., 2019) by targeting specific sites of action in the plants and causing malfunctioning of the plant cells or metabolic pathways (Ndou et al., 2021; Pieterse, 2010). Strauss et al., (2021a) highlighted that some farmers who practice conservation tillage, especially no-tillage, have taken measures to prevent excessive use of synthetic herbicides. However, the general repeated use of herbicides has led to the development of herbicide-resistant weeds such as ryegrass (*Lolium* spp.) (Heap, 2021), hairy fleabane (*Conyza* spp.) (Pieterse, 2010), and plantain (*Plantago lanceolata*) (Ndou et al., 2021). As more plants evolve herbicide resistance, weed scientists have the daunting task of identifying new modes of action that can be explored to chemically control weeds and pests (Westwood et al., 2018). In the last decade, there has been little development in the manufacture of new synthetic agrochemicals with different modes of action that can be used to replace current agrochemicals. The recent development of herbicide resistance seems to suggest that, even if new chemicals with different modes of action are discovered, plants may still be able to evolve and develop resistance (Westwood et al., 2018).

In addition to the declining effectiveness of the current synthetic agrochemicals, other studies show that the synthetic chemicals are harmful, not only to the environment (Lackmann et al., 2021; Udall et al., 2015) but to humans too (Alsen et al., 2021;

Krzastek et al., 2020; Lesseur et al., 2021). For example, the World Health Organisation’s International Agency for Research on Cancer (IARC) categorised glyphosate as probably carcinogenic to humans (IARC, 2015) due to increased incidences of illness amongst people exposed to the herbicide (Davoren and Schiestl, 2018). However, Andreotti et al. (2018), and Temple (2016) have since shown that glyphosate does not directly affect humans. Other studies have also confirmed that glyphosate does not directly affect humans but does upset the gut microbiome, which disrupts the diversity and balance of the microflora (Davoren and Schiestl, 2018; Patocka, 2018; Peillex and Pelletier, 2020), and metabolism thereby creating a perfect environment for the development of chronic diseases such as gastrointestinal disorders, diabetes, heart disease and cancer (Patocka, 2018). A study by Nazam et al. (2020) found that phosphorodithioate, the active ingredient found in pesticides such as dimethoate, can damage human DNA.

The development of herbicide resistance, coupled with a lack of new synthetic agrochemicals, as well as the potential damage posed by synthetic agrochemicals are indicative of the need to change our farming and tillage practices so that we can produce food without harming the environment and human health, and without reliance on synthetic agrochemicals. However, without chemical weed control, the practice of no-tillage may be difficult as weeds can easily proliferate when tillage is not conducted.

2.5 Conservation agriculture

The term *conservation agriculture* is at times confused with *conservation tillage*. The term *conservation tillage* has already been described in section 2.3 and is basically concerned with soil cultivations. On the contrary, the term *conservation agriculture* does not only refer to a tillage practice but is a set of management principles that are meant to minimise the negative effects of conventional tillage on the environment (Strauss et al., 2021a). According to the Food and Agriculture Organisation of the United Nations, conservation agriculture is a resource-saving agricultural production system that aims to attain production intensification and competitive yields while enhancing the natural resources base (FAO, 2017). The benefits of conservation agriculture can be realised if farmers adhere to three linked principles which should be implemented along with locally formulated, adapted crop management practices (Corsi and Muminjanov, 2019). Regarding the inclusion of locally adapted practices, Strauss et al. (2021a) stated that diversification of conservation agriculture systems can be increased by growing pasture and forage crops. This enables integration of livestock with the crop system which can increase the financial stability and profitability of the farming enterprise.

The three principles of conservation agriculture are (i) continuous minimum mechanical soil disturbance through the practice of no-tillage and direct seeding. The disturbed area for crop establishment must be less than 30% of the cropped area (ii) maintenance of permanent soil organic cover with crop residues and/or cover crops to the extent allowed by water availability, and (iii) species diversification through varied crop rotations, sequences and associations involving at least three different crops (Corsi and Muminjanov, 2019).

The International Institute of Rural Reconstruction (IIRR), together with the African Conservation Tillage Network (ACT), emphasised the importance of adopting simultaneous implementation of all the three principles of conservation agriculture by using an illustration of a three-legged cooking pot which is very common in many African households (Figure 2.5). They reasoned that the three-legged cooking pot would be best able to balance and stand on its own if it has all three legs (IIRR and ACT, 2005). If one of the legs is missing, it will be difficult for the cooking pot to remain in balance. Likewise, if farmers implement only one or two of the three conservation agriculture principles, their farms may fail to perform optimally. For example, if a farmer did not maintain permanent soil cover, the field may be subject to increased weed pressure or soil erosion as the soil will be unprotected.

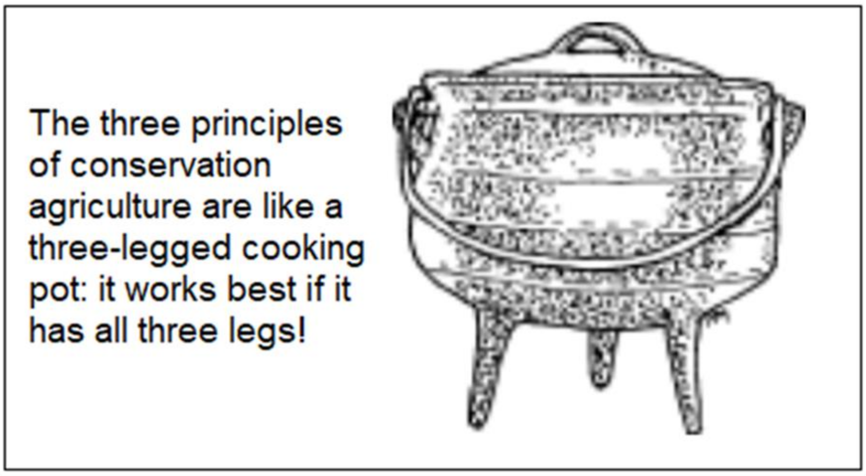

Figure 2.5: Illustration of a three-legged cooking pot (Source: IIRR and ACT (2005)).

In principle, the practice of no-tillage, retention of soil cover and crop diversification all aid in reducing soil exposure and thus minimise soil erosion by both wind and water (Derpsch et al., 2014). Maintenance of permanent soil cover also prevents weeds from intercepting sunlight and therefore inhibits weed growth (Strauss et al., 2021b). Growing different crop species or diversification helps to break the life cycle of crop-specific pests, therefore diversification is important for pest and disease control (IIRR and ACT, 2005; Strauss, 2021), and may help prevent nutrient loss (Rayns et al., 2010). Also, crop diversification enables the use of different herbicides to control weeds which may become problematic if crops are grown in monoculture (MacLaren et al., 2021).

2.5.1 Adoption of conservation agriculture

Conservation agriculture has been adopted and hailed as climate-smart agriculture in many parts of the world such as South and North America, Australia and New Zealand, Asia, Russia and Ukraine, Europe and Africa. (Kassam et al., 2019). Amongst other things, conservation agriculture has led to improvements in soil quality through increased carbon sequestration (Smith et al., 2017), reduced greenhouse gas emissions (Carbonell-Bojollo et al., 2019), soil water retention and increased crop yield (Strauss et al., 2021b; Swanepoel et al., 2017). In most parts of Africa, commercial farmers have adopted conservation agriculture. Nonetheless, the adoption of conservation agriculture by resource-poor small-scale farmers in Africa has been low (Corbeels et al., 2014; Swanepoel et al., 2017). For example, in Zambia, Kafwamfwa et al. (2017) reported that between 53 and 83% of small-scale farmers did not practice conservation agriculture due to severe weed problems. In Namibia, Taapopi et al. (2018) found that technological know-how, limited agricultural inputs and implements hindered the uptake of conservation agriculture by small-scale farmers. As in Namibia, small-scale farmers in the Eastern Cape province of South Africa cited a lack of finance and tillage implements as a hindrance to the uptake of conservation agriculture (Muzangwa et al., 2017).

Concerning the adoption of conservation agriculture by the commercial farmers in South Africa, Findlater et al. (2019) and Strauss et al. (2021b) noted that while the uptake is higher than that of small-scale farmers, most farmers have only adopted one or two aspects of conservation agriculture. As of 2020, 25% of South African commercial farmers had fully adopted conservation agriculture. However, the majority

(83%) of the commercial farmers that have adopted all three principles of conservation agriculture are based in the Western Cape province (Strauss et al., 2021b). Findlater et al. (2019) explained that some of the commercial farmers who practised conservation tillage regarded themselves as practising conservation agriculture. The same misconception of conservation agriculture was also found with small-scale farmers in the Eastern Cape province as noted by Muzangwa et al. (2017). This shows that researchers investigating the adoption of conservation agriculture must confirm which principles have been adopted by the farmers so that they may get accurate adoption figures. Inconsistency in studies and reports often leads to inaccurate data. For example, Kafwamfwa et al. (2017) noted that there were two conflicting reports on the adoption of conservation agriculture in Zambia. One report stated that in 2007, Zambia had around 120,000 farmers, including small-scale farmers, who practised some form of conservation agriculture whereas another report put the figure at 170,000. This discrepancy suggests greater need for consistency in the definition of conservation agriculture and more accurate research. In South Africa, the practice of no-tillage is the most adopted of the three principles of conservation agriculture (Findlater et al., 2019; Muzangwa et al., 2017; Strauss et al., 2021b).

The fact that most farmers in Africa, including South African farmers, have not fully adopted the three principles of conservation agriculture could be suggestive of great reliance on synthetic agrochemicals for fertilisation and control of weeds and pests.

2.5.2 Problems associated with conservation agriculture

Every system has its advantages and disadvantages. The advantages of conservation agriculture have been highlighted in section 2.5.1 above. The fact that conservation agriculture has been promoted as climate-smart agriculture (Corsi and Muminjanov, 2019) broadly suggests that its advantages outweigh its disadvantages. However, long-term no-tillage practices may lead to stratification of some soil nutrients (Tshuma et al., 2021), meaning that some layers of the soils, especially the topsoil, may have more nutrients than the lower soil profile. Nutrient stratification can become a problem when the topsoil becomes dry because immobile nutrients become unavailable for uptake by plant roots (Shen et al., 2011). When the topsoil is wet, plant roots can get both nutrients and water from the topsoil. However, if the topsoil becomes dry, plants roots tend to move deeper into the soil profile in search of water. Immobile nutrients such as phosphorus will remain bound by soil particles within the topsoil and therefore become unavailable for uptake by plants, leading to poor plant growth and productivity.

Many weeds can easily be controlled by tillage (Mahé et al., 2021), therefore, if no-tillage is practised, some weeds can proliferate and become a problem. Weed infestations have been reported as one of the reasons why the most resource-poor small-scale farmers have not been able to adopt conservation agriculture (Corbeels et al., 2014; Kafwamfwa et al., 2017). As stated in section 2.3, the practice of no-tillage is often accompanied by using synthetic herbicides for weed control.

Also, tillage can be vital for incorporating soil amendments such as lime, manure, and biochar. No-tillage does not cause much soil disturbance and cannot incorporate these soil amendments to deeper depths, therefore long-term no-tillage has been associated with an inability to ameliorate soil acidity problems (Grove et al., 2007; Tshuma et al., 2021).

Some fields under long-term no-tillage have been found to have soil compaction problems, which can be caused by the movement of farm vehicles and implements (Laker and Nortjé, 2020; Swanepoel et al., 2015). Soil compaction can limit the movement of water and nutrients into the soil, hinder root development, and ultimately reduce plant productivity.

2.5.3 The potential benefits of alternative tillage practices

To mitigate the use of synthetic herbicides, soil nutrient stratification, soil compaction weeds and other problems associated with long-term no-tillage, some tillage could be reintroduced in the no-tillage fields. Strategic tillage, also known as occasional tillage, could be conducted. Strategic tillage refers to the deliberate one-off tillage conducted in a no-tillage field to solve a particular problem. Some studies have already shown that strategic tillage does not degrade soil quality or decrease crop yield but can help with weed control, loosening of soil, and mitigate other problems associated with conservation agriculture (Dang et al., 2018; Labuschagne et al., 2020). However, the effectiveness of strategic tillage will also depend on the type of soil being ploughed.

Another option would be to conduct infrequent tillage. Unlike strategic tillage, infrequent tillage refers to a pattern of planned tillage rotations involving a phase of no-tillage and a phase of tillage (Tshuma et al., 2021). The phase of no-tillage can be one, two, or three consecutive years which are followed by tillage. The tillage phase can be vital in the mixing of soil amendments, prevention of soil nutrient stratification, and weed control, thereby resulting in a decrease in the application of synthetic herbicides. As reduced tillage can prevent soil erosion (Derpsch et al., 2014), the phase of no-tillage might enable the build-up of soil organic matter. Nonetheless, the overall tillage effects may differ according to site and soil types.

2.6 Conventional agriculture

Conventional agriculture, also referred to as industrial agriculture, is an umbrella term for all agricultural practices that use synthetic agrochemicals and/or genetically modified organisms (Berentsen et al., 1998; Curl et al., 2003; Kirchmann et al., 2016; Le Campion et al., 2020; Okur et al., 2015; Puech et al., 2014). Conservation agriculture is included or classified as conventional agriculture because synthetic agrochemicals are part and parcel of the system. Also, some farmers who practice conservation agriculture, plant genetically modified organisms such as Roundup-ready crops (Cuhra, 2015; Lal, 2009). In South Africa, white maize is the most common genetically modified crop which is commercially produced for human consumption (Ala-Kokko et al., 2021). However, some studies on conservation agriculture seem to suggest that conservation agriculture is different from conventional agriculture. The studies seem to consider conventional agriculture to be one that does not practice no-tillage, and crop rotation or diversification. For example, a questionnaire used by Findlater et al. (2019) requested farmers to classify their ‘farming system’ from a list of six options: conservation, conventional, precision, progressive, biological, and organic. The inclusion of both terms, *conservation* and *conventional* agriculture on the list seem to suggest that the two terms refer to different farming systems.

A report by Grigoras et al. (2012) states that: *“Conservation agriculture is an alternative to conventional agriculture …”.* A statement from Grabowski and Kerr, (2014) reads: *“most farmers were adamant that conservation agriculture could perform better than conventional agriculture only if they applied fertilizer or compost”*.

These examples indicate that the term *conventional agriculture* is possibly misunderstood by other researchers and would need to be clarified within the agricultural community. Overall, the use of synthetic agrochemicals and intensive tillage in conventional agriculture systems has led to soil degradation, loss of biodiversity, and increased susceptibility to disease (Wibbelmann et al., 2013).

2.6.1 Effects of conventional agriculture on soil physical and chemical parameters

The use of synthetic agrochemicals, especially inorganic/synthetic fertilisers can increase the availability of soil nutrients for plant uptake (Timmermann and Félix, 2015). However, excessive application of synthetic fertilisers in conventional agriculture has broadly led to a decline in soil quality in a cascading manner. Among other things, repeated application of synthetic fertilisers can lower the soil pH, which can limit the availability of essential nutrients such as phosphorus. A low soil pH can also increase aluminium ion (A^{3+}) availability, leading to aluminium toxicity (Shetty et al., 2021). Furthermore, a low soil pH can limit the availability of exchangeable calcium in the soil. Synthetic fertilisers can lead to the breakdown of soil crumbs and increase the chances of soil compaction and ultimately makes the soil infertile and unproductive. Unlike organic fertilisers, synthetic fertilisers mainly contain only a few nutrients, which do not build up the soil organic carbon, therefore soil structure may be weakened, and more nutrients can leach down the soil profile. Concerning tillage, intensive tillage can also lead to increased leaching of soil nutrients (Maali and Agenbag, 2003b).

2.6.2 Effects of conventional agriculture on soil biological parameters

Like synthetic fertilisers, the use of synthetic insecticides and fungicides have contributed to increased crop productivity (Timmermann and Félix, 2015; Wang et al., 2015). Nevertheless, their application can pollute the soil and groundwater, and negatively affect the diversity of the soil microbial community (Kobierski et al., 2020; Zhao et al., 2016). For example, Udall et al. (2015) stated that some neonicotinoid insecticides can negatively affect the soil microbial community. Soil microbes secrete enzymes that are essential for the biogeochemical processes such as decomposition of organic matter, humus formation, and nitrogen, phosphorus and carbon cycles (Błońska et al., 2017; Kwiatkowski et al., 2020). Therefore, a decrease in soil microbial biodiversity may reduce the overall soil microbial enzyme activity, which can lead to reduced nutrient cycling.

Conventional tillage practices can also affect soil microbial diversity and enzyme activity by breaking down or depleting the soil organic matter content (Huang et al., 2020; Zhang et al., 2019). Soil microbes depend on adequate soil organic matter levels; to conserve the soil organic matter, conservation tillage could therefore be conducted instead of intensive tillage.

2.6.3 Effects of conventional agriculture on weeds

Synthetic herbicides have also contributed to significant increases in crop productivity in the past few decades (Gibson, 2010; Pardo et al., 2019; Timmermann and Félix, 2015). However, conventional weed management systems mainly focus on reducing weed biomass and do not consider the importance of weed diversity. Increased weed diversity in cropping systems has recently been advocated as an indicator of agroecosystem sustainability (Storkey and Neve, 2018). The consistent use of synthetic herbicides over the past decades has promoted the adaptation of a few dominant weed species which are difficult to eradicate.

2.6.4 Effects of conventional farming on crop productivity

Crop productivity can be affected, *inter alia*, by tillage intensity, soil quality (physical, chemical, and biological), and weeds. As noted already, conventional agriculture practices have led to reduced soil quality and the development of herbicide-resistant weeds, which can decrease crop productivity. The overall benefit of conventional agriculture is short-lived. For example, a study by Wang et al. (2015) found that in a period of 25 years (1980 to 2005), fertiliser use in China increased by about 276%, while the total grain production increased by about 51%. During that period, fertiliser-use efficiency, which is expressed as grain production per unit of fertiliser applied, decreased by nearly 52%, from 32 to 15 kg kg^{-1}. One of the limiting factors associated with the continuous application of synthetic fertilisers is the development of aluminium toxicity which can inhibit the uptake, transport, and utilisation of essential nutrients such as phosphorus, potassium, calcium, magnesium, iron, molybdenum, and boron. Aluminium may also restrict root growth which in turn renders them inefficient in absorbing nutrients (Shetty et al., 2021). There is strong justification, therefore, for a shift away from conventional agriculture practices.

2.7 Agroecology

Unlike conventional agriculture, the term *agroecology* broadly refers to farming systems that do not use synthetic agrochemicals (Udall et al., 2015; Wibbelmann et al., 2013). The use of the term *agroecology* dates from the 1970s and it has had varying definitions over time and across cultures but most seem to acknowledge that agroecology should strive to balance the needs of communities and the integrity of ecosystems and thus, to develop sustainable systems of food production (Wibbelmann et al., 2013). Altieri, (1995) emphasised that agroecology goes beyond a one-dimensional view of agroecosystems but covers a wider context that includes ecological and social variables. According to the Food and Agriculture Organization of the United Nations, agroecology can be defined as:

"An integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of food and agricultural systems. It seeks to optimize the interactions between plants, animals, humans and the environment while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system" (FAO, 2018).

As in other farming systems, tillage can be conducted but the focus of agroecology is to naturally improve soil health and fertility through crop diversification, integration of crop and livestock systems, and use of manure and local crop varieties. Weed control is achieved mainly through tillage as synthetic herbicides are not applied. Instead of synthetic fertilisers, manure or compost and nitrogen-fixing legumes are used to improve soil fertility. Tillage is also used to incorporate soil amendments and to prepare a conducive seedbed. Farmers that practise agroecology do not need to be certified by any organisation (Wibbelmann et al., 2013), therefore agroecology empowers people to become their own agents of change. Agroecology consists of ten interlinked and interdependent elements: (i) diversity, (ii) synergies, (iii) recycling, (iv) efficiency, (v) resilience, (vi) co-creation and sharing of knowledge (vii) human and social values, (viii) culture and food traditions (ix) responsible governance, and (x) circular and solidarity economy (FAO, 2018).

To illustrate the interconnectedness; an agricultural system with a high species diversity can have strong synergies, which enables the recycling of nutrients and enhance ecosystem services, including pollination, natural predation, and soil health, and therefore the system becomes efficient and resilient. A resilient system will be able to recover from disturbances that may be caused by drought, floods, pests, and disease attacks. Agroecology, with its emphasis on great species diversity, has a greater chance of imitating nature through the recycling of nutrients and water. The inclusion of deep-rooted plants in agroecology ensures that nutrients are not lost through leaching and thus maintain soil health. A study by Swanepoel and Tshuma, (2017) found that the removal of deep-rooted natural vegetation and its replacement with shallow-rooted cash crops contributed to the development of soil sodicity problems in the Western Cape province of South Africa. The soil sodicity problems prevented the regeneration of annual medics (*Medicago* spp.) during the pasture phase of crop rotation.

Agroecology does not provide farmers with a fixed ideology but rather combines traditional and indigenous knowledge, producers' and traders' practical knowledge, and global scientific knowledge to create solutions that are specific and beneficial to both the farmer and the environment (Wibbelmann et al., 2013). The co-creation and sharing of knowledge are, therefore, vital in agroecology as specific solutions are needed for each specific environment. For example, different areas have different soil types, rainfall, and indigenous crops, therefore, context-specific solutions are needed. The flexibility of conducting tillage to incorporate soil amendments and to control weeds is vital for reducing the use of synthetic agrochemicals, which might be difficult to achieve if the current conservation agriculture practices are not improved to include some form of tillage.

Included within the agroecological farming system is organic, biodynamic, and any other farming practices that do not use synthetic agrochemicals.

2.7.1 Organic, and biodynamic agriculture

Organic agriculture was established as a concept in Europe in the early 20th century (Heckman, 2006), long before the use of the word 'agroecology'. Unlike the broad term, *agroecology*, organic agriculture involves certification of a farm, adhering to some requirements, and maintaining a strict code of practice (Wibbelmann et al., 2013). The Codex Alimentarius Commission defined organic agriculture as:

"*A holistic production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological* *activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, cultural, biological and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system,*" (FAO/WHO Codex Alimentarius Commission, 2007).

The definition provided highlights that farms must have optimum nutrient and energy flow and should minimise risk through the implementation of crop rotations that include legumes to bring symbiotically fixed nitrogen into the system. As the use of synthetic agrochemicals is not permitted, soil fertilisation is achieved by the application of manure, and other approved amendments, as well as through crop diversification and growing of nitrogen-fixing legumes. Additionally, tillage, crop rotation, mulching, and cover cropping can suppress weeds, and reduce weed populations in the subsequent crops (Kobierski et al., 2020). Instead of insecticides, biological pest control and integrated pest management can add to the benefits of organic production. Tillage can also be used to incorporate the organic soil amendments within the soil.

Although over or under application is possible, the application of organic soil amendments normally results in improved soil conditions due to increased microbial activity and diversity (Kobierski et al., 2020; Okur et al., 2015) that improve soil structure and thereby create more stable systems (Loaiza Puerta et al., 2018; Scialabba et al., 2010). As synthetic fertilisers are not utilised, contamination of natural resources is reduced, soil erosion is minimised as infiltration rate and water holding capacity are increased, and use of non-renewable energy is decreased (Scialabba et al., 2010). Nevertheless, the process of certification can be expensive and so the organic produce may be targeted towards a particular niche market and not the general consumers.

Like organic agriculture, biodynamic agriculture has its own certifying bodies and does not utilise synthetic agrochemicals and aim to keep farms as part of the natural environment. Its emphasis is on building up soil quality through the addition of compost, animal and green manures, crop rotations, and diversifying crops and livestock (Reganold, 1995). Although tillage is conducted for seedbed preparation and weed control as practised in any other agroecological farming system, biodynamic agriculture is listed by Wibbelmann et al. (2013) as alternative agriculture. A major difference between biodynamic agriculture and other agroecological systems is that biodynamics is based on esoteric, spiritual physical principles such as involving cosmic factors (position of the moon relative to the sun) to estimate appropriate planting dates (Reganold, 1995).

2.7.1.1 Reduced tillage in organic agriculture

Traditionally, tillage with a mouldboard plough is common practice in organic agriculture systems to control weeds. However, the use of the mouldboard plough has already been shown to cause the breakdown of soil aggregates, deplete soil organic matter and increase chances of soil erosion (Lal et al., 2007). Therefore, some research has focused on assessing the possibility of implementing conservation tillage practices in organic agriculture systems (Bond and Grundy, 2001; Krauss et al., 2020; Loaiza Puerta et al., 2018; Peigné et al., 2018; Weber et al., 2017). All these studies found that the practice of reduced tillage resulted in greater improvement in soil organic matter content. Nonetheless, Peigné et al. (2018) observed that wheat grain yield did not differ ($P>0.05$) between the fields under reduced tillage and those that were ploughed with a mouldboard. They reasoned that soil compaction, which was greater in fields with reduced tillage, could have negatively affected yield in those fields by hindering root development. Compaction is thought to have been caused by farm implements as they conducted weeding (four to five times during the growing season) through the use of shallow harrows (Peigné et al., 2018).

Regardless of the yield similarities, these studies broadly show that there is a possibility of further improving soil quality in organic fields by reducing tillage intensity and frequency. Furthermore, the studies seem to indicate that agroecological principles could be gradually adopted in food production systems that are currently heavily reliant on synthetic agrochemicals. For example, wheat and canola (*Brassica napus*) are currently produced under conventional agriculture systems in the Western Cape province. Instead of solely applying synthetic herbicides, weeds could be partly controlled by the use of shallow tine weeders or harrows. As already indicated in section 2.7, agroecology does not require one to be certified but empowers farmers to be agents of change. Farmers could gradually change their farming systems to become more environmentally friendly until they become certified if they so desire. However, there are trade-offs to the application of reduced tillage as shown by Peigné et al. (2018). Soil organic matter can increase, but also compaction and weed infestation. The success of such weed control measures may also depend on the topography, implements availability and condition of the soil in the field.

2.8 Farming systems common in South Africa

Most farmers in South Africa apply synthetic agrochemicals in their fields, therefore, conventional farming is more common than farming systems that do not involve the use of synthetic agrochemicals. Most commercial farmers have, however, stopped conventional tillage and adopted no-tillage practices (Strauss et al., 2021a). As briefly stated in section 2.2, conservation agriculture was introduced to local farmers when conventional tilling of monoculture systems became unsustainable (Strauss et al., 2021b; Swanepoel et al., 2016). And, grain yields in monoculture systems declined due primarily to the build-up of weeds (MacLaren et al., 2021), pests and diseases (Strauss, 2021) and declining soil organic matter (Dube et al. 2020). Soil erosion had become a major contributor to land degradation such that laws were put in place to try and minimise soil erosion. Rabie, (1974) explained that the Soil Conservation Act 76 of 1969 came into operation in 1970 and it prohibited cultivation on any land that had a slope of 2% or more unless contours were put in place. Le Roux et al. (2008) estimated that more than 70% of South Africa is affected by varying intensities of soil erosion.

The adoption of conservation tillage systems was also driven by economic factors. The deregulation of the agricultural economy in the 1990s meant that farmers could no longer get subsidies from the government. Also, rising input costs and low commodity prices prompted many farmers to change their tillage practices and introduce crop rotation (Strauss et al., 2021a; Swanepoel et al., 2016). Some farmers, along with the departments of agriculture in the Western Cape and KwaZulu-Natal provinces encouraged other farmers to adopt conservation agriculture as a means of improving soil quality. Consequently, by the early 2000s, most farmers had adopted components of conservation agriculture (Strauss et al., 2021a; Swanepoel et al., 2016). Of the nine provinces of South Africa, the Western Cape province has the highest adoption rate of conservation agriculture (Swanepoel et al., 2017).

2.9 Cropping systems in the Western Cape province

The Western Cape province is situated on the south-western coast of South Africa and has an area of about 129,449 km^2. It stretches about 400 km northwards along the Atlantic Ocean and about 500 km eastwards along the Indian Ocean. Due to its diverse topography and the effects of the surrounding ocean currents, the climatic conditions are generally more diverse than in any other province in South Africa. Most areas within the province receive an annual rainfall of between 350 and 1,000 mm, but this is extremely variable between years and can be as low as 60 mm or peak at 3,345 mm per year (ARC-ISCW, 2014).

The Western Cape province produces about 50% of South Africa's wheat and almost 100% of dryland canola (Grain SA, 2021). Wheat is grown in rotation with a variety of crops including canola, lupins (*Lupinus* spp.), annual medics (*Medicago* spp.), clovers (*Trifolium* spp.), barley (*Hordeum vulgare*), triticale (×*Triticosecale*), lucerne (*Medicago sativa*) and oats (*Avena sativa*). Wheat, barley, triticale, oats, canola, and lupins are the cash crops, of which wheat and barley are the most marketable and profitable, and therefore, are the most produced in the province (Strauss et al., 2021a). The annual medics, clovers, and lucerne are used as pasture for livestock, mainly sheep. Lucerne is, however, rarely grown in the Swartland due to its rainfall requirements. The rainfall distribution of the Swartland limits the growing of lucerne in a dryland farming system. Of all the crops that are grown in these regions, the most profitable crop rotations in the Swartland regions are those that involved wheat grown in rotation with canola, annual medics, and lupins (Knott et al., 2017). Considering that only one crop can be grown per season, some economically viable four-year crop rotations for the region are typically: wheat-medic-wheat-medic; wheat-canola-wheat-lupins; and canola-wheat-wheat-wheat. Knott et al. (2017) also found that in drier seasons, the crop rotation, wheat-medic-wheat-medic, led to higher returns relative to the other two crop rotations. The only broadleaf plant which is both adapted to the climatic conditions of the Western Cape province, and marketable is canola, hence canola is produced in relatively higher quantity than lupins in this region (Strauss et al., 2021a). A major limitation to the crop rotation systems of the Western Cape province is the lack of other suitable broadleaf crops that can be incorporated to increase the overall diversity of the cropping system. Also, some farmers do not want to integrate livestock into their conservation agriculture systems, and therefore are reluctant to include the annual medics and clovers in their crop rotation systems (Strauss et al., 2021a).

To generate scientific information that could be used in the agricultural industry, several research farms, including Langgewens Research Farm, were established in various locations within the Western Cape province. The research farms provided science-based solutions in response to challenges faced by farmers in the various regions (Western Cape Government, 2021). This included the establishment of several long-term trials to facilitate the study of the effects of management on soil and crop performance. For example, a long-term tillage experiment was established in 1976 to investigate the tillage effects on soil quality and crop productivity.

2.10 Synthesis

The history of tillage has shown us that tillage is not new in the field of agriculture. However, ancient farmers only practised minimum tillage using simple tools that were available during their time. Industrialisation led to the production of powerful tillage implements and tractors, as well as synthetic agrochemicals, which led to increased tillage intensity. Although the use of powerful mechanical tillage implements and synthetic agrochemicals led to a marked increase in crop production, the overall benefits have dwindled over the last few decades. Amongst other things, intensive tillage has led to massive soil degradation by soil erosion and depletion of soil organic matter, whereas repeated use of synthetic agrochemicals has resulted in the evolution of insecticide and herbicide-resistant insects and weeds. Unlike intensive tillage, the practice of no-tillage has led to improvements in soil quality but contributed to excessive use of synthetic agrochemicals. There is, therefore, a need to re-evaluate the current farming practices and to develop ways to grow crops without total reliance on synthetic agrochemicals. Both the quantity of synthetic agrochemicals and the intensity of tillage need to be reduced so that our farming may become sustainable.

The long-term (44-years) trial at Langgewens Research Farm could be used to assess the effects of long-term tillage treatments and synthetic agrochemicals on soil quality, crop productivity and weeds dynamics. Synthetic agrochemicals applications on this long-term trial could be adjusted to include environmentally friendly bio-chemicals. The adjustments may enable the investigation of the combined effects of long-term tillage and short-term agrochemical applications and possibly help farmers to adjust their farming practices towards agroecology.

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CHAPTER 3

Effects of long-term (42 years) tillage sequence on soil chemical characteristics in a dryland farming system

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NB: Adjustments were made in this thesis to the published article. An erratum is provided on page 196 in the appendix section.

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3.2.4 Data analysis

The Variance Estimation, Precision and Comparison (VEPAC) package of STATISTICA™ software version 13.5.0.17 (TIBCO Software Inc.) was used to analyse the data using the Restricted Maximum Likelihood (REML) procedure, with the assumption of compound symmetry or equicorrelation between depth measures. The REML procedure was chosen instead of the maximum likelihood procedure because it provides unbiased estimates of variance and covariance related parameters at small sample sizes (Fleming et al., 2019). Tillage sequence, sampling depth and their interactions were specified as fixed effects in order to take the repeated measures into account. Block was specified as a random effect whilst sampling depth was regarded as the time factor for the repeated measures. All parameters were subjected to a test of normality using the normal probability plots of raw residuals. Where the F-test was significant, the mean separation was performed using Fisher's least significance difference (LSD) test at a 5% significance level. Data that did not meet the assumptions of an analysis of variance were log-transformed, and back-transformed data are presented in figures. Tillage sequence was specified as the fixed effect and block as the random effect for SOC stock and nutrient stratification ratios.

3.3 Results

3.3.1 Effect of tillage on soil chemical characteristics

A significant interaction between tillage sequence and sampling depth was apparent for the distribution of most of the soil nutrients (Table 3.1). For nutrients where no interaction ($P > 0.05$) was recorded, the soil depth effect was significant in all cases, except for Cu and Mn. Tillage effects were significant ($P < 0.05$) only for Cu.

3.3.2 Soil pH_{KCl}

The MB treatment resulted in a similar ($P > 0.05$) pH_{KCl} across all the soil depths from 0 – 300 mm (Figure 3.1). Apart from the MB treatments, the ST treatment resulted in more stratification ($P < 0.05$) than the other treatments as the 50 – 100 mm depth layer had a higher pH_{KCl} than that of the other treatments at the corresponding depth. The TT treatment did not lead to the effective mixing of layers and pH_{KCl} was as stratified as the NT treatment ($P > 0.05$).

Table 3.1: The F-values with degrees of freedom, and P-values from the mixed model ANOVA for the soil nutrients, as affected by the tillage sequence, sampling depth and by the tillage sequence x depth interactions at the Langgewens long-term tillage trial in 2018; Significant treatments ($P < 0.05$) are highlighted in bold.

Soil nutrient	Tillage sequence		Sampling depth		Tillage sequence x depth interaction	
	$F(6,18)$	P	$F(3,9)$	P	$F(18,165)$	P
pH_{KCl}	1.384	0.274	102.97	**<0.001**	5.206	**<0.001**
Exchangeable acidity	3.297	**0.023**	18.39	**<0.001**	2.084	**0.009**
Log(Soil organic C)	6.471	**0.001**	164.48	**<0.001**	5.217	**<0.001**
Exchangeable Ca	1.962	0.125	131.73	**<0.001**	5.135	**<0.001**
Log(Exchangeable Mg)	2.043	0.112	119.54	**<0.001**	5.063	**<0.001**
Log(Exchangeable K)	1.767	0.163	366.66	**<0.001**	1.259	0.221
Log(Exchangeable Na)	1.025	0.441	39.86	**<0.001**	1.576	0.071
Log(Cation exchange capacity)	2.515	0.060	176.98	**<0.001**	7.022	**<0.001**
Extractable P	2.946	**0.035**	73.08	**<0.001**	3.171	**<0.001**
Log(Extractable S)	0.407	0.865	31.33	**<0.001**	0.447	0.975
Log(Extractable Cu)	3.632	**0.015**	0.73	0.559	0.173	0.999
Extractable Mn	2.117	0.102	0.36	0.786	0.198	0.999
Extractable Zn	1.792	0.157	99.70	**<0.001**	2.044	**0.010**
Log(Extractable B)	2.056	0.110	50.66	**<0.001**	1.109	0.347

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CHAPTER 4

Relating soil microbial diversity and enzyme activity to different tillage practices and agrochemical applications in a dryland cropping system

Abstract

The soil microbial community is essential for soil nutrient cycling. However, frequent tillage and the use of synthetic agrochemicals can reduce soil microbial diversity and enzyme activity. In this study, the effects of four tillage treatments (continuous mouldboard plough, shallow tine tillage, no-tillage and infrequent tillage), and three rates of synthetic agrochemicals (standard, reduced and minimum) on soil microbial diversity and enzyme activity were investigated between 2018 and 2020 in South Africa's Mediterranean climate zone. The reduced and minimum synthetic agrochemicals comprised varied rates of synthetic and bio-chemicals. It was hypothesised that a reduction in tillage frequency, and quantity of synthetic agrochemicals application, will lead to greater microbial diversity and enzyme activity. Soil samples were collected from the 0-150 mm layer of a field trial under a dryland crop rotation system in the Swartland region. Soil microbial species richness and abundance were measured by using the Shannon–Wiener diversity and Evenness indices. The activities of four microbial enzymes: β-glucosidase, acid and alkaline phosphatase, and urease, were used to evaluate ecosystem functioning. Microbial diversity was not affected by the tillage or synthetic agrochemical application treatments. However, microbial enzyme activity generally increased with a reduction in tillage and synthetic agrochemical application. The ploughed treatment led to the least ($P<0.05$) microbial enzyme activity relative to other tillage treatments whereas the system with standard synthetic agrochemicals led to the lowest ($P<0.05$) microbial enzyme activity relative to reduced and minimum systems. We recommend farmers opt for minimum tillage and reduced application of synthetic agrochemicals.

4.1 Introduction

Soil microbial communities can be influenced, *inter alia*, by tillage (Kobierski et al., 2020), synthetic agrochemical applications (Zhao et al., 2016), and soil organic matter content (Huang et al., 2020; Zhang et al., 2019). Any change in soil organic matter dynamics can affect the soil microbial community.

The soil microbial community is involved in biogeochemical processes such as decomposition of organic matter, humus formation, and nitrogen, phosphorus and carbon cycles (Błońska et al., 2017; Kwiatkowski et al., 2020). To maintain the complex biogeochemical processes that occur within the soil ecosystem, a diverse microbial community is required. Microbial diversity is important for soil health (Tahat et al., 2020), provides stability to the soil food web and ensures that various soil minerals and nutrients which are critical for plant growth and productivity are recycled (Błońska et al., 2017; Kwiatkowski et al., 2020). Soil microbes are sensitive to pollution and other environmental changes (Habig et al., 2018; Swanepoel et al., 2021) and are easily modified by alterations in the soil environment. A change in the microbial community or diversity may affect the soil microbial enzyme activities.

Soil enzymes are biological catalysts that conduct or control nutrient cycling reactions that occur in the soil, and are mainly produced by soil microbes but also secreted by plant roots (Huang et al., 2020). Soil microbial diversity and enzyme activity can be used as bio-indicators of the soil quality status (Habig et al., 2018; Tahat et al., 2020). The benefits of soil enzyme activity in assessing changes or imbalances that may affect soil quality and crop productivity have been widely studied (Bielińska and Mocek-PŁóciniak, 2012; Błońska et al., 2017; Harasim et al., 2020; Kobierski et al., 2020; Kwiatkowski et al., 2020). The activity of soil enzymes such as β-glucosidase, urease, and alkaline and acid phosphatase which are involved in the cycling of soil carbon, nitrogen and phosphorus, respectively, can be used along with soil microbial diversity to assess soil quality (Habig et al., 2018).

Application of synthetic agrochemicals (fertilisers, herbicides, fungicides and pesticides) can pollute the soil and groundwater, and negatively affect the diversity of the soil microbial community (Kobierski et al., 2020; Zhao et al., 2016) and ultimately affect soil enzymes. In addition, synthetic fertilisers can lower the soil pH (Zhao et al., 2016). Intensive tillage can increase soil organic matter decomposition and reduce microbial diversity. Conversely, reduced tillage, including no-tillage, does not mix the soil profiles and can result in increased soil organic matter immobilisation and microbial diversity (Kobierski et al., 2020; Piazza et al., 2020; Strauss et al., 2021a).

Most studies of soil microbial communities and soil enzyme activity have investigated or reported the effects of conventional and minimum tillage treatments (Bielińska and Mocek-PŁóciniak, 2012; Błońska et al., 2017; Habig et al., 2018; Harasim et al., 2020; Huang et al., 2020; Kobierski et al., 2020; Mashavakure et al., 2018; Melero et al., 2009; Zhong et al., 2016). To our knowledge, there have been no studies on the soil microbial community and soil enzymes, which have investigated the effects of infrequent tillage practices together with the application of varying rates of synthetic agrochemicals. Infrequent tillage refers to a 'pattern' of alternating tillage practices which include a phase of tillage and another of no-tillage (Tshuma et al., 2021). The phase of no-tillage can be one, two, or three consecutive years, which are followed by a year in which tillage is conducted. The aim of this study was therefore to assess the progressive impact of tillage practices and varied rates of synthetic agrochemical application on soil microbial diversity and enzymatic activity in a dryland cropping system. It was hypothesised that a reduction in the quantity of synthetic agrochemicals applied, and no-tillage or infrequent tillage practices will lead to greater microbial diversity and enzyme activity.

4.2 Materials and methods

4.2.1 Site description

The research was conducted at Langgewens Research Farm (33°17ˈ0.78ˈˈ S, 18°42ˈ28.09ˈˈ E) of the Western Cape Department of Agriculture, in the Swartland region of South Africa. The Swartland region has a Mediterranean-type climate with a wet winter and hot, dry summer. The trial site has a mean annual rainfall of 395 mm, of which approximately 80% falls between April and September, the growing season for this region (ARC-Small Grain Institute, 2020). The trial site is located on a shallow (300 mm) lithic soil locally known as a Glenrosa-soil form (Soil Classification Working group, 1991) or internationally, as Haplic Cambisols (IUSS Working Group WRB, 2015). The soil had a 14.7% clay content (excluding the gravel and stone content), whilst the gravel and stone content in the A horizon is 44.6% (Maali and Agenbag 2003).

4.2.2 Trial history and treatments

The study was conducted within a long-term trial, which was established in 1976. Fifty-six plots, each measuring 50 m x 6 m, were laid out within four replicated blocks. The blocks were separated by a buffer zone of at least 9 m, and plots were separated by a 1 m buffer zone. Wheat (*Triticum aestivum*) was rotated with canola (*Brassica napus*) and lupins (*Lupinus* spp.) in a four-year cycle; wheat-canola-wheat-lupin. From the beginning of the long-term trial, seven tillage treatments were investigated, however, the current experiment (microbial study between 2018 and 2020) only considered four of the seven tillage treatments (Table 4.1). The tillage treatments were chosen based on the degree of soil disturbance, from most intensive (as caused by the mouldboard plough) to the least (as caused by no-tillage). Based on the four selected tillage treatments, only 32 of the 56 plots were used in this study.

Table 4.1: Summary of the four tillage treatments, abbreviations and the implements used at Langgewens Research Farm. All plots were sown with a no-till drill.

Tillage treatment	Abbreviation	Tools used and tillage intensity
Mouldboard	MB	Ploughing with a chisel (tine) plough to a depth of 150 mm, followed by the mouldboard plough to a depth of 200 mm and field cultivator to a depth of 50 mm.
Shallow tine-tillage	ST	Tillage with a chisel plough to a depth of 75 mm followed by a non-selective pre-plant herbicide.
No-tillage	NT	Tillage was not conducted. Non-selective pre-plant herbicides were used to control the weeds and volunteer plants
ST applied every 4th year in rotation with NT	ST-NT-NT-NT	Tillage with a chisel plough to a depth of 75 mm was conducted once every four years.

Prior to the current experiment, lime (4000 kg ha^{-1}) was evenly broadcast within this trial site in 2016 to raise the soil pH across all treatments. In March 2018, the soil pH_{KCl} at the trial site was found to be slightly below 5.0. Detailed information regarding the seven tillage treatments and soil chemical parameters of this study site is available in Tshuma et al. (2021).

Three rates of synthetic agrochemical application were also investigated: **standard**, **reduced**, and **minimum**. In this article, the bold terms **standard**, **reduced**, and **minimum**, represent the rates of synthetic agrochemical application. Initially, only synthetic agrochemicals were applied on this trial site. The use of varied rates of synthetic agrochemicals; **reduced** and **minimum** were only introduced in 2018 and 2019, respectively.

From 2018, sixteen of the 32 plots received the **standard** synthetic agrochemicals as determined by the Langgewens Technical Committee, according to best practices common in the region (ARC-Small Grain Institute, 2020; FERTASA, 2016). The remaining 16 plots received the **reduced** synthetic agrochemicals, in which, some of the synthetic agrochemicals were replaced with bio-chemicals. All bio-chemicals were manufactured and supplied by RealIPM. In this article, the term, bio-chemical does not imply organic certification but refers to products derived from natural compounds. Bio-chemicals that were used were *Trichoderma asperellum*, silicic acid, and triacontanol and bull kelp (*Nereocystis luetkeana*) extracts. Bio-chemicals were mainly for improving plant health and pest and disease control. They were applied twice within 30 days in the wheat crops of 2018 and 2020. In the canola crop of 2019, the bio-chemicals were applied three times within 90 days. A full list of chemicals applied is available in supplementary Tables S1-5*.*

In 2019 and 2020, all 32 plots were divided into two subplots, separated by a buffer zone of 1 m. One sub-plot measured 35 m x 6 m and continued to receive either the **standard** or **reduced** synthetic agrochemicals. The second subplot measured 14 m x 6 m and received a single application of a broad-spectrum herbicide at the beginning of the planting season with no additional chemicals other than fertiliser and, will be referred to as the system with **minimum** synthetic agrochemicals.

The seeds planted in the systems with **reduced** and **minimum** synthetic agrochemicals were treated with the bio-chemical *Trichoderma asperellum* before planting. Furthermore, the systems with **reduced** and **minimum** synthetic agrochemicals received a mixture of synthetic fertiliser and pelletised chicken manure.

Half of the synthetic fertiliser quantity applied to the **standard** treatment was replaced with pelletised chicken manure.

Wheat cultivar SST 056 was planted on 11th May 2018 at a rate of 100 kg ha^{-1}. Canola cultivar Alfa TT was planted on 30th April 2019 at a rate of 3.5 kg ha^{-1}. The wheat cultivar SST 0166 was planted on 12th May 2020 at a rate of 90 kg ha^{-1}.

After crop harvesting, the trial site remained fallow through the dry summer period (November to April), therefore, to prevent sprouting of summer weeds, all plots were treated with non-selective herbicides. Crop residues were not removed from the plots and remained on the soil surface until the start of the growing season when tillage treatments were conducted.

4.2.3 Assessments

4.2.3.1 Soil microbial functional diversity and evenness

Soil augers (90 mm Ø) were used to aseptically collect soil samples in August of each year from 2018 to 2020 during the flowering stage of crops. Random soil samples were collected at a depth of 0-150 mm from each plot. The soil samples were divided into two batches: one for soil microbial enzyme activity analysis, and the other for microbial functional diversity analysis. Freshly collected soils were kept cool at 4-6 °C until analysis.

The carbon source utilisation profiles (or functional diversity) of soil microbial populations were determined by using the number of different substrates utilized (species richness) in the Biolog Ecoplates^{TM} (Garland and Mills, 1991). For soil microbial analyses, 10 g soil was added to 90 ml sterile distilled water (Buyer and Drinkwater, 1997) shaken and inoculated into Biolog EcoPlates^{TM} (Biolog® Inc., Hayward, CA, USA) that contained 31 wells with a range of carbon sources plus a control well, in triplicate. The plates were incubated at 28°C and the optical density was measured twice daily for 7 days at 590 nm to determine the average well colour development within each plate (Winding and Hendriksen, 1997). The rate of carbon source utilisation was indicated by the reduction of the tetrazolium dye found at the bottom of each well. This indicator dye changed from colourless to purple as soon as the individual carbon sources were utilised by the microbial communities. The

Shannon-Weaver diversity index (H') was subsequently calculated by using the rate of carbon utilisation in the wells.

$$H' = -\sum_{i=1}^{s} (Pi)(\ln Pi)$$

where: P*i* = a*i* / ∑a = the proportional turbidity observed in the i^{th} well and a*i* = the turbidity of the i^{th} well and ∑a = the total turbidity observed in all sample wells (Lahav and Steinberger, 2001), s = the number of species.

The Evenness index (E) was calculated to determine the proportion of each species in the soil, that is, the index (E) is a measure of how evenly the populations of the different microbial species are in the soil (Habig et al., 2018; Habig and Swanepoel, 2015). The Evenness index was calculated as:

$$J' = \frac{H'}{\ln (S)}$$

where: H' = Shannon-Weaver diversity index, and s = the number of species.

4.2.3.2 Soil microbial enzyme activity

Four key enzymes were used as indicators of soil microbial activity: β-glucosidase, acid and alkaline phosphatase, and urease. Collected soil samples were air-dried at 40 °C for 48 hours and sieved through a 2 mm sieve before analyses. β-glucosidase and phosphatase activities were calculated according to Dick et al. (1996), by spectrophotometrically determining the release of p-nitrophenyl after the incubation of soil with p-nitrophenyl glucoside and p-nitrophenyl phosphate, respectively, at a wavelength of 410 nm. The amount of p-nitrophenol released per hour was calculated with reference to a standard calibration graph obtained from p-nitrophenol standards. Urease activity was determined using the method of (Kandeler and Gerber, 1988), where released ammonia was spectrophotometrically measured after the incubation of soil samples with a urea solution at a wavelength of 690 nm. The urea content was calculated with reference to a standard calibration graph obtained from urea standards.

4.2.4 Data analyses

The experiment was designed as a randomised complete block design with a split-plot arrangement. Tillage sequences were the main plots whilst the levels of synthetic agrochemical applications were the sub-plots, with the growing season as an additional factor. From 2018 to 2020, samples were collected from the systems with **standard** and **reduced** synthetic agrochemicals. However, in 2019 and 2020, samples were also collected from the system with **minimum** synthetic agrochemicals, therefore, data from 2018 to 2020 growing seasons (from the systems with **standard** and **reduced** synthetic agrochemicals) was analysed separately from the 2019 and 2020 data. Furthermore, the system with **minimum** synthetic agrochemicals had twice as many samples than those from the systems with **standard** and **reduced** synthetic agrochemicals, hence the 2019 to 2020 data was unbalanced.

For the 2018 to 2020 data, the Variance Estimation, Precision and Comparison (VEPAC) package of STATISTICA™ software version 13.5.0.17 (TIBCO Software Inc.) was used to fit mixed-effects models to the data using the Restricted Maximum Likelihood (REML) procedure (Type III decomposition). The mixed-effects model was used because data were repeatedly collected from the same plots over time, whereas the REML procedure was used because it provides unbiased estimates of variances and covariances. Tillage sequence, growing season, rate of synthetic agrochemical application, and their interactions were specified as fixed effects. Plot was specified as a random effect nested in block (to account for repeated measures). The unbalanced 2019 to 2020 data were analysed with a mixed model ANOVA in *R* Version 4.0.2 (2020-06-22), using the *lmer* package, with tillage sequence and crop management system as the fixed effects. To account for repeated measures, plot was specified as a random effect nested in block. The Kenward-Roger's estimation procedure was used to account for the unbalanced data and heteroskedasticity.

F-tests were used to assess whether fixed effects were significant at 5% level. Post-hoc pairwise comparisons of means were performed using Fisher's least significance difference (LSD) test at a 5% significance level. All parameters were subjected to a test of normality using the normal probability plots of raw residuals. Also, the Shapiro-Wilk W-test for normality was performed on the residuals for each analysis.

4.3 Results

4.3.1 Soil microbial diversity (H') and evenness (E)

The Shannon-Wiener diversity index (H') of soil microbes in the systems with **standard** and **reduced** synthetic agrochemicals was affected ($P<0.05$) by the growing season but not by the tillage treatments or level of synthetic agrochemical application (Table 4.2). In this article, the growing season factor includes both the effect of growing season and crop because two years with wheat and one with canola were sampled. Microbial diversity did not differ ($P>0.05$) in 2019 (2.5) and 2020 (2.4) but was lowest ($P<0.05$) in 2018 (2.0). In general, the Shannon-Wiener diversity index ranged between 2.2 in the ST and ST-NT-NT-NT treatments, and 2.4 in the MB treatment. Each of the systems (**standard** and **reduced**) had a Shannon-Wiener diversity index of 2.3 (results not shown).

Microbial Evenness in the systems with **standard** and **reduced** synthetic agrochemicals was not affected ($P>0.05$) by any treatment (Table 4.2). Nonetheless, the MB and infrequent tillage treatment ST-NT-NT-NT both resulted in an Evenness index of 0.8, whilst the NT and ST treatments had 0.78 and 0.77 respectively (results not shown). Analysis of the 2019 and 2020 data from the systems with **standard**, **reduced** and **minimum** synthetic agrochemicals revealed that both the Shannon-Wiener diversity and Evenness indices were not affected by any treatment (Table 4.2).

The Shannon-Wiener diversity index ranged between 2.4 in the MB, ST, and ST-NT-NT-NT treatments, and 2.5 in the MB treatment. The Shannon-Wiener diversity index for the three systems of synthetic agrochemical applications; **standard**, **reduced** and **minimum**, were 2.5, 2.4 and 2.5, respectively (results not shown).

Table 4.2: The F-values with degrees of freedom, and P-values from the mixed model ANOVA for the soil microbial diversity (Shannon-Wiener diversity) and Evenness indices for 2018 to 2020 growing seasons (system with **standard** and **reduced** synthetic agrochemicals), and 2019 to 2020 growing seasons (system with **standard**, **reduced** and **minimum** synthetic agrochemicals) as affected by the tillage sequence, rate of synthetic agrochemical application and growing season and their interactions at Langgewens Research Farm. Boldfaced P-values denote significant effects at P<0.05.

Parameter	Tillage sequence (T)		Agrochemical application (A)		Growing season (G)		T x A		T x G		A x G		T x A x G	
	F(3,6)	*P*	*F*(1,2)	*P*	*F*(2,4)	*P*	*F*(3,6)	*P*	*F*(6,12)	*P*	*F*(2,4)	*P*	*F*(6,12)	*P*
2018 to 2020 data (standard and **reduced)**														
Shannon-Wiener diversity index	1.16	0.40	0.04	0.87	15.9	**0.01**	1.22	0.38	1.57	0.24	3.04	0.16	0.58	0.74
Evenness index	0.78	0.55	0.14	0.75	3.67	0.12	1.96	0.22	0.68	0.67	0.24	0.80	0.88	0.54
2019 and 2020 data (standard, **reduced** and **minimum)**														
Shannon-Wiener diversity index	1.36	0.32	2.14	0.26	0.40	0.57	0.17	0.98	1.89	0.21	0.87	0.50	1.39	0.24
Evenness index	0.17	0.92	0.13	0.88	0.09	0.79	1.68	0.23	1.47	0.29	1.18	0.41	1.66	0.15

4.3.2 Soil microbial enzyme activity

β-glucosidase and acid phosphatase activities in the systems with **standard** and **reduced** synthetic agrochemicals (2018 to 2020) were not affected (P>0.05) by any treatment (Table 4.3). β-glucosidase activity ranged between 690 (in the MB) and 1001 µg g^{-1} h^{-1} in the NT treatments. Its activity in the two systems (**standard** and **reduced**) was 794 and 945 µg g^{-1} h^{-1}, respectively. Acid phosphatase activity in the **standard** and **reduced** systems was 2655 and 3309 µg g^{-1} h^{-1} respectively and ranged between 2511 (in the MB) and 3280 µg g^{-1} h^{-1} in the ST treatments (results not shown).

Growing season was significant for the alkaline phosphatase and urease activities (Table 4.3). The 2020 growing season led to the highest (P<0.05) alkaline phosphatase and urease activity (725 µg g^{-1} h^{-1} and 38 µg g^{-1} $2h^{-1}$, respectively) whereas no differences (P>0.05) were found between 2018 (299 µg g^{-1} h^{-1} and 25 µg g^{-1} $2h^{-1}$, respectively) and 2019 (359 µg g^{-1} h^{-1} and 27 µg g^{-1} $2h^{-1}$, respectively).

Analysis of the 2019 and 2020 data from the three systems; **standard**, **reduced,** and **minimum**, showed that the activity of all the four enzymes was generally greater (but not always significant) in the systems with **reduced** and **minimum** synthetic agrochemicals than in the **standard** system. Enzyme activity was generally lowest (P>0.05) in the MB treatment relative to other tillage treatments. Only β-glucosidase and acid phosphatase were affected (P<0.05) by the tillage treatment (Table 4.4). β-glucosidase and acid phosphatase activities follow a similar trend in the three systems of synthetic agrochemical applications. In the system with **standard**, and **reduced** synthetic agrochemicals, their activity remained uniform (P>0.05) across all four tillage treatments. But in the system with **minimum** synthetic agrochemicals, their activity was lowest (P<0.05) in the MB treatment and did not differ (P>0.05) in the ST, ST-NT-NT-NT and NT treatments (Table 4.5).

Table 4.3: The F-values with degrees of freedom, and P-values from the mixed model ANOVA for the soil microbial enzyme activity for 2018 to 2020 growing seasons (systems with **standard** and **reduced** synthetic agrochemicals), as affected by the tillage sequence, rate of synthetic agrochemical application, growing season and their interactions at Langgewens Research Farm. Boldfaced P-values denote significant effects at P<0.05.

	Tillage sequence (T)		Agrochemical application (A)		Growing season (G)		T x A		T x G		A x G		T x A x G	
Soil enzyme	*F*(3,6)	*P*	*F*(1,2)	*P*	*F*(2,4)	*P*	*F*(3,6)	*P*	*F*(6,12)	*P*	*F*(2,4)	*P*	*F*(6,12)	*P*
2018 to 2020 data (standard and **reduced)**														
β-glucosidase (μg g^{-1} h^{-1})	3.11	0.11	1.40	0.36	1.39	0.35	0.35	0.79	0.42	0.85	0.78	0.52	0.38	0.88
Acid phosphatase (μg g^{-1} h^{-1})	4.31	0.06	1.47	0.35	1.73	0.29	0.75	0.56	0.51	0.79	0.91	0.47	0.36	0.89
Alkaline phosphatase (μg g^{-1} h^{-1})	0.21	0.89	1.57	0.34	71.9	**0.001**	0.49	0.70	2.33	0.10	0.10	0.91	0.63	0.70
Urease (μg g^{-1} $2h^{-1}$)	0.30	0.82	3.18	0.22	8.99	**0.03**	1.11	0.42	0.17	0.98	0.96	0.46	0.35	0.90

Table 4.4: The F-values with degrees of freedom, and P-values from the mixed model ANOVA for the soil microbial enzyme activity for 2019 to 2020 growing seasons (systems with **standard**, **reduced** and **minimum** synthetic agrochemicals) as affected by the tillage sequence, rate of synthetic agrochemical application, growing season and their interactions at Langgewens Research Farm. Boldfaced P-values denote significant effects at P<0.05.

Soil enzyme	Tillage sequence (T)		Agrochemical application (A)		Growing season (G)		T x A		T x G		A x G		T x A x G	
	F(3,8)	*P*	*F*(2,3)	*P*	*F*(1,3)	*P*	*F*(6,9)	*P*	*F*(3,8)	*P*	*F*(2,3)	*P*	*F*(6,63)	*P*
2019 and 2020 data (standard, **reduced** and **minimum)**														
β-glucosidase (μg g^{-1} h^{-1})	9.86	**0.004**	5.36	0.11	0.73	0.46	1.20	0.38	1.32	0.33	0.08	0.93	0.48	0.82
Acid Phosphatase (μg g^{-1} h^{-1})	4.79	**0.03**	1.11	0.46	2.84	0.20	0.33	0.91	1.67	0.25	0.45	0.68	0.20	0.97
Alkaline Phosphatase (μg g^{-1} h^{-1})	1.23	0.36	4.36	0.17	40.8	**0.01**	1.06	0.45	1.66	0.25	0.67	0.58	0.58	0.75
Urease (μg g^{-1} $2h^{-1}$)	0.61	0.63	0.67	0.59	17.7	**0.03**	0.44	0.84	0.83	0.51	0.12	0.89	0.66	0.68

Table 4.5: Soil microbial enzyme activity ± standard error of the mean, for the 2019 and 2020 growing seasons as affected by the tillage sequence treatment in the systems with **standard**, **reduced** and **minimum** synthetic agrochemicals at Langgewens Research Farm. For each microbial enzyme activity, the different superscripts across the rows and columns denote significant differences per synthetic agrochemical application and tillage treatments, respectively (P<0.05). MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage.

Tillage sequence	Agrochemical applications		
	Standard	**Reduced**	**Minimum**
β-glucosidase activity ($\mu g\ g^{-1}\ h^{-1}$)			
MB	679 ± 51.79^{cd}	783 ± 55.51^{cd}	703 ± 33.46^{d}
ST	$963 \pm 109.2b^{bcd}$	943 ± 105.2^{bcd}	1139 ± 92.82^{ab}
ST-NT-NT-NT	802 ± 108.6^{cd}	952 ± 150.2^{bcd}	1162 ± 78.90^{ab}
NT	$987 \pm 84.48b^{cd}$	1066 ± 114.8^{abc}	1353 ± 64.77^{a}
Acid phosphatase activity ($\mu g\ g^{-1}\ h^{-1}$)			
MB	2286 ± 118.1^{b}	2938 ± 293.5^{ab}	2492 ± 94.12^{b}
ST	3288 ± 365.9^{ab}	3471 ± 492.5^{ab}	3616 ± 335.5^{a}
ST-NT-NT-NT	2637 ± 107.0^{ab}	3680 ± 599.1^{a}	3258 ± 345.3^{a}
NT	2776 ± 76.06^{ab}	3578 ± 505.7^{a}	3345 ± 348.6^{a}

On considering the effects of the tillage treatments in the three systems: **standard**, **reduced** and **minimum**, the activities of both, β-glucosidase and acid phosphatase were similar (P>0.05) in the MB treatment (Table 4.5). However, in the NT and infrequent tillage treatment ST-NT-MT-NT, the activity of β-glucosidase was significantly greater (P<0.05) in the system with **minimum** synthetic agrochemicals than in the **standard** system. The activity of acid phosphatase remained the same (P>0.05) in all three systems regardless of the tillage treatment.

The activity of alkaline phosphatase and urease in the systems with **standard**, **reduced** and **minimum** synthetic agrochemicals were only affected by the growing season (Table 4.4). Increased (P<0.05) alkaline phosphatase and urease activity were recorded in the 2020 growing season relative to the 2019 season. In 2020, the alkaline phosphatase and urease activities were 759 µg g^{-1} h^{-1} and 39 µg g^{-1} $2h^{-1}$, respectively, compared to 424 µg g^{-1} h^{-1} and 28 µg g^{-1} $2h^{-1}$ in 2019. When broadly considering the tillage treatments, the alkaline phosphatase activity increased (P>0.05) with a reduction in tillage frequency such that its activity increased from 506 µg g^{-1} h^{-1} in the MB treatment to 663 µg g^{-1} h^{-1} in the NT treatment. Urease activity was lowest (P>0.05) in the MB treatment (30 µg g^{-1} $2h^{-1}$) and highest (P>0.05) in the ST treatment which had 36 µg g^{-1} $2h^{-1}$, (results not shown).

4.4 Discussion

Our study showed that the soil microbial diversity (Shannon-Wiener diversity index) in the different tillage treatments ranged between 2.0 and 2.5 and was generally lowest in 2018 (P<0.05) and higher in 2019 and 2020. These diversity indices broadly show that the trial site has a moderate diversity of microbes. Magurran and McGill, (2011) considered that Shannon-Wiener diversity values that are closer to 2.5 indicate a moderately diverse community and values of 1.5 and less indicate a less diverse community, whereas those closer to 3.5 indicate a highly diverse community. Results of our Shannon-Wiener diversity indices are similar to the findings by Habig et al. (2018), and Habig and Swanepoel (2015) who found microbial diversity indices that mostly ranged between 2.0 and 2.6. Results from this study also show that individual tillage treatments did not significantly affect microbial diversity, such that the intensive MB, infrequent tillage ST-NT-NT-NT and NT treatments, all broadly led to similar (P>0.05) diversity indices. These results differ from those of other studies which found higher diversity indices in the reduced tillage treatments relative to the intensive MB treatment (de Quadros et al., 2012; Habig et al., 2018; Habig and Swanepoel, 2015; Tahat et al., 2020). Although we could not find an exact explanation as to why the microbial diversity did not differ between different tillage treatments, some studies have shown that cereal fields under conventional tillage tended to have more microbial diversity than NT fields due to higher C: N ratios which provides more substrate to microorganisms (de Quadros et al., 2012; Habig and Swanepoel, 2015). In this trial, wheat was grown in 2018 and 2020 and thus could have contributed to the overall microbial diversity in the fields under the MB treatment.

Furthermore, there were no differences (P>0.05) in microbial diversity indices in fields under the three rates of synthetic agrochemical applications: **standard**, **reduced** and **minimum**. Whilst most studies of soil microbes show that microbes' sensitivity to changes in abiotic conditions renders them as useful bio-indicators of soil quality (Habig et al., 2018; Habig and Swanepoel, 2015; Mendes et al., 2013; Tahat et al., 2020), our results on the microbe diversity indices were not able to pick up the changes in the soil environment due to both the tillage treatments and the varying rate of synthetic agrochemical application. Similarly, the microbial Evenness index (E) was not affected by any treatment. The reason for the lower E index was not clear. The application of *Trichoderma asperellum* as a bio-chemical control agent on the seeds planted in the systems with **reduced** and **minimum** synthetic agrochemicals could have altered the soil microbial diversity, as *Trichoderma asperellum* is known to provide plant immunity by killing other soil microbes (Mukherjee et al., 2012), but more evidence is needed. It is, therefore possible that soil microbes needed more time to adapt to the new environment which contains the bio-chemicals. De Quadros et al., (2012) and Habig and Swanepoel, (2015) acknowledged that soil microbial diversity and composition in agricultural soils does not depend solely on management, but also on soil features and type, separation distances between the trial plots, application of fertilizers and herbicides, and the complex interactions between different microbial populations.

Analysis of soil enzymes (β-glucosidase, acid and alkaline phosphatase, and urease) broadly showed that soil enzyme activity increased with a reduction of both synthetic agrochemicals and tillage intensity. Although not always significant, the activity of all four enzymes was generally lowest in the MB treatment relative to other tillage treatments. Also, the system with **standard** synthetic agrochemicals led to the lowest (P>0.05) enzyme activities relative to the systems with **reduced** and **minimum** synthetic agrochemicals. Significant differences (P<0.05) between the system with **standard** and **minimum** synthetic agrochemicals were observed for β-glucosidase in the NT and infrequent tillage treatment ST-NT-NT-NT (Table 4.5). These results are similar to the findings by Habig et al.,(2018), and Habig and Swanepoel, (2015) in that the MB treatment generally resulted in the lowest β-glucosidase relative to reduced tillage. β-glucosidase and acid phosphatase are involved in carbon and phosphorus cycling, respectively, and are highly active when mulch is readily available on the soil surface due to reduced degrees of soil disturbance (Bielińska and Mocek-PŁóciniak, 2012; Habig and Swanepoel, 2015). Acid phosphatase was more active than alkaline phosphatase in the cycling of phosphorus probably due to the low soil pH_{KCl} (<5) of the trial site. Acid phosphatase has its optimum activity in acidic conditions whilst alkaline phosphatase is more active in alkaline conditions (Antonious et al., 2020; Chen et al., 2019).

Mixing of synthetic agrochemicals and bio-chemicals in the system with **reduced** synthetic chemicals could have also contributed to the lack of significant differences in microbial enzyme activity between the systems with **standard** and **reduced** synthetic chemicals. When synthetic agrochemicals were avoided as in the system with **minimum** synthetic agrochemicals, the enzyme activity was relatively higher and sometimes significantly, than the system with **standard** synthetic agrochemicals. These results seem to suggest that the application of synthetic agrochemicals can pollute the soil and lead to reduced microbial enzyme activity. On the contrary, a reduction in synthetic agrochemicals, as evidenced in the system with **minimum** agrochemicals, may reduce pollutants and increase microbial enzyme activity (Kobierski et al., 2020; Zhao et al., 2016). In addition, the application of herbicides to control summer weeds during the fallow period (November to April) could have negatively affected the microbial community and overall enzyme activity.

Future studies could consider investigating the effects of tillage treatments in systems with **standard** and **minimum** synthetic agrochemical application over a longer (5 to 10 years) period to give adequate time for microbes to adjust to the new environment. In the current farming systems, the practice of mixing manure with chemical fertiliser to balance nutrient supply to the crop is considered as normal practice; future studies could monitor the trends in microbial diversity and enzyme activities in systems that apply animal manures and other sources of nutrients such as composted wastes without mixing with other sources of nitrogen.

4.5 Conclusions

Results from this study contradicted our hypothesis that greater microbial diversity can be achieved by reducing the rate of synthetic agrochemical application in the fields. A reduction in tillage intensity and synthetic agrochemical applications did not affect (P>0.05) the microbial diversity indices. We noted that microbial diversity was affected by the growing season and that the study site broadly has a moderately diverse microbial community. However, we found that microbial enzyme activity generally increased with a reduction in tillage and application of synthetic agrochemicals. The system with **minimum** synthetic agrochemicals had a greater microbial enzyme activity than the system with **standard** synthetic agrochemicals. We suggest that a combination of minimum tillage and **reduced** synthetic agrochemical use has potential for improving soil microbial activity in cropping systems, but this requires further exploration experimentally.

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CHAPTER 5

Effects of long-term (44-years) tillage sequences on wheat grain yield in a dryland farming system in South Africa

Abstract

Long-term no-tillage, and continuous tillage with a mouldboard plough may negatively affect crop productivity. Infrequent tillage practices could be used to ameliorate some problems associated with long-term no-tillage. Effects of tillage sequences on wheat productivity were assessed between 1976 and 2020 in South Africa's Mediterranean climate zone. Four continuous tillage treatments were investigated: mouldboard (MB), tine-tillage (TT), shallow tine-tillage (ST), and no-tillage (NT); and three infrequent tillage treatments: ST conducted once in two years (ST-NT), ST conducted once in three years (ST-NT-NT), and ST conducted once in four years (ST-NT-NT-NT). Two crop management systems were also investigated: wheat monoculture and crop rotation. The study aimed to determine the long-term (44-years) tillage effects on wheat grain yield in a dryland farming system. We evaluated the long-term yield responses and hypothesised that, with time, the (i) monoculture system will lead to reduced grain yield, (ii) MB treatment will lead to reduced grain yield, (iii) infrequent tillage practices will improve grain yield relative to continuous NT. Our results show that; (i) the monoculture system led to reduced grain yield over time. (ii) Compared to other tillage treatments in the monoculture system, the MB treatment led to the highest ($P<0.05$) grain yields. However, in the crop rotation system, the NT treatment was the best option as it was environmentally sustainable and led to a high grain yield ($P>0.05$) relative to other tillage treatments. (iii) The infrequent tillage sequences failed to significantly improve the grain yield relative to continuous NT. Our study highlights that infrequent tillage treatments were no better than the NT practice. We recommend that farmers opt for NT and crop rotation to ensure sustainability.

5.1 Introduction

Historically, most small grain producers in the Mediterranean region of South Africa relied on conventional tillage with mouldboard and disc ploughs to grow crops in monoculture systems (Strauss et al., 2021b). However, over time, grain yields in these monoculture systems declined due primarily to the build-up of weeds (MacLaren et al., 2021), pests and diseases (Strauss, 2021), and declining soil organic carbon (Dube et al. 2020). Further pressure on these conventional production systems came with the deregulation of the agricultural economy in the 1990s. Farmers had to become self-sufficient as they could no longer get subsidies from the government. This prompted many farmers to change their tillage practices and introduce crop rotation. Relatedly, the farmer-driven conservation agriculture (CA) adaptation activities and the departments of agriculture in the Western Cape and KwaZulu-Natal provinces encouraged farmers to adopt CA as a means of improving soil quality (Strauss et al., 2021b). Consequently, by the early 2000s, most farmers had adopted components of CA (Swanepoel et al., 2016).

Conservation agriculture is based on three principles namely, minimum soil disturbance, maintenance of permanent soil cover and crop rotation (FAO, 2010). As of 2020, 25% of commercial grain farmers in South Africa have adopted all three principles of CA but at least 40% have adopted one of the three principles (Strauss et al., 2021b). Unlike the rest of South Africa, most small grain producers in the Mediterranean climate region (Western Cape province) have adopted at least two principles of CA. Minimum disturbance of soil is the most widely adopted component of CA, whilst the maintenance of permanent soil cover is the least adopted (Findlater et al., 2019). The hot dry summers of the Mediterranean climate of the Swartland region in the Western Cape province are not conducive for the growing of cover crops in rainfed farms (Swanepoel et al., 2016). Producers can only retain the stubble from a previous season to cover soil. The comprehensive adoption of CA can reduce weed pressure (MacLaren et al., 2021; Pittelkow et al., 2015), lead to an improvement in soil structure, an increase in soil organic carbon stocks and increased crop yield. Crop rotations may help prevent nutrient loss (Rayns et al., 2010), loosen the soil and break disease and insect pest cycles (Schillinger and Paulitz, 2018). In contrast, the adoption of only one or two components of CA may lead to poor control of weeds and a reduction in yields (Findlater et al., 2019; MacLaren et al., 2021; Pittelkow et al., 2015).

Typical CA systems in the Western Cape province include crop rotations involving wheat (*Triticum aestivum*), canola (*Brassica napus*), barley (*Hordeum vulgare*) and/or legumes such as lucerne (*Medicago sativa*), lupins (*Lupinus* spp.) and annual medic (*Medicago* spp.). The Western Cape province produces about 50% of South Africa's wheat and 99% of canola (Liebenberg et al., 2020). Common four-year crop rotation systems in the Swartland region are wheat-canola-wheat-lupin (WCWL) and wheat-medic-wheat-medic (WMWM). Rotation of cereals with a broadleaf crop is important as it enables the use of different selective herbicides to eliminate grass weeds that are difficult to control in systems with cereals only. Wheat, barley, and canola are the cash crops, whilst the legumes are used as pasture.

A reduction in tillage can lead to the proliferation of weeds (MacLaren et al., 2021; Udall et al., 2015). Tillage, particularly soil inversion practices with a mouldboard plough is one method farmers can consider to control weeds (MacLaren et al., 2021). However, the continued use of the mouldboard plough may lead to a general decline in soil quality through, amongst other things, the depletion of soil organic carbon stocks, breakdown of soil aggregates and increased soil erosion which may ultimately lead to reduced crop yields. The negative effects of the mouldboard plough have been well documented (Dendooven et al., 2012; Derpsch, 2004; Hobbs et al., 2008; Swanepoel et al., 2015). To minimise soil degradation through tillage, the use of reduced tillage, including no-tillage, has increased.

Although most producers in the Western Cape province have adopted no-tillage, a few practice strategic tillage by conducting occasional/strategic tillage (Findlater et al., 2019), especially in sandy no-tillage fields. Strategic tillage refers to one-off tillage, which is intentionally applied to alleviate specific problems that are associated with no-tillage (Blanco-Canqui and Wortmann, 2020), *inter alia*, weed infestation, soil compaction, soil nutrient stratification and to incorporate soil amendments like limestone (Liebenberg et al., 2020; Tshuma et al., 2021). The benefits of strategic tillage have recently been documented (Blanco-Canqui and Wortmann 2020; Conyers et al. 2019; Dang et al. 2018; Kirkegaard et al. 2014; Peixoto et al. 2020). Apart from strategic tillage, infrequent tillage could also be considered as an option for alleviating some of the problems associated with no-tillage with the intention of improving crop productivity. Unlike strategic tillage, infrequent tillage is not a one-off practice. There are specific tillage rotations that are followed. Infrequent tillage involves the application of alternating tillage practices (involving tillage and no-tillage) on one specific field. The phase of no-tillage of a particular field can be one, two or three consecutive no-tillage years which are followed by a year in which tillage is conducted, and then reverting to a phase of no-tillage. Some limited short-term research on infrequent tillage has been conducted in the Western Cape province (Agenbag 2012; Maali and Agenbag 2003, 2006), however, globally there is a paucity of information on the effects of the long-term infrequent tillage practices on wheat yield.

This research aimed to determine the effects of long-term (44-years) tillage practices on wheat grain yield in a dryland farming system. The objective was to examine and evaluate the long-term wheat grain yield responses from a trial site located at Langgewens Research Farm, in South Africa. It was hypothesised that with time, (i) the monoculture system will lead to reduced wheat grain yield, (ii) continuous ploughing with a mouldboard plough will lead to reduced wheat grain yield, (iii) the infrequent tillage practices will improve wheat grain yield relative to continuous no-tillage.

5.2 Materials and methods

5.2.1 Site description

The research was conducted at Langgewens Research Farm (33°17ˈ0.78ˈˈ S, 18°42ˈ28.09ˈˈ E) of the Western Cape Department of Agriculture, in the Swartland region of South Africa (Figure 5.1). The Swartland region has a Mediterranean-type climate. The Köppen-Geiger climate classification is Csa (warm temperate climate with hot, dry summer). Langgewens receives an average long-term (55 years) annual rainfall of 395 mm (standard deviation = 101 mm), of which approximately 80% falls during the growing season between April and September.

The trial site has a 300 mm shallow lithic soil, locally known as a Glenrosa-soil form (Soil Classification Working group, 1991) or internationally, as Haplic Cambisols (IUSS Working Group WRB, 2015). The soil has a 14.7% clay content (excluding the gravel and stone content), whilst the gravel and stone content in the A horizon is about 45% (Maali and Agenbag, 2003a).

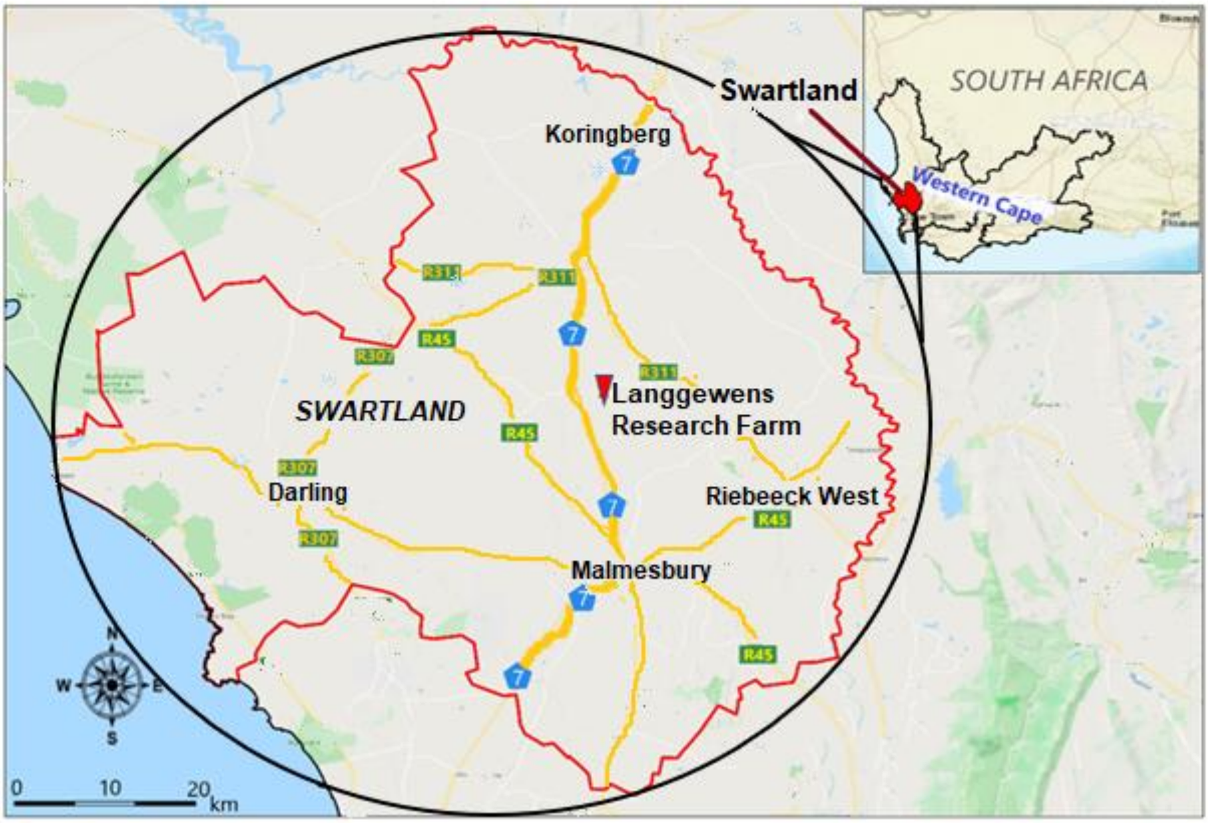

Figure 5.1: The location of Langgewens Research Farm relative to major roads and towns in the Swartland region, in the Western Cape province of South Africa, (Map courtesy of the Western Cape Department of Agriculture, South Africa).

5.2.2 Trial history and treatments

The trial was laid out in a randomised block design with four replicated blocks. Each block had 14 plots and each plot measured 50 m x 6 m. The blocks were separated by a buffer zone of at least 9 m, and plots were separated by a 1 m buffer zone. Seven tillage treatments were investigated and are summarised in Table 5.1.

Tillage trials were started in 1976 with only one cropping system (wheat monoculture) on the four blocks. In 1990, each of the blocks was equally split into two sections and a second cropping system (crop rotation) was randomly introduced on one section whilst the other section continued with the wheat monoculture system. In the crop rotation system, wheat was rotated with lupins and canola. The four-year crop rotation sequences used were continuous wheat (WWWW) and wheat-lupin-wheat-canola (WLWC) (Agenbag 2012; Maali and Agenbag 2006).

Table 5.1: Summary of tillage treatments, abbreviation and the implements used. All plots were sown with a no-till drill.

Tillage treatment	Abbreviation	Tools used and tillage intensity
Mouldboard	MB	Ploughing with a chisel (tine) plough to a depth of 150 mm, followed by the MB plough to a depth of 200 mm and field cultivator to a depth of 50 mm
Tine-tillage	TT	Tillage with a chisel plough to a depth of 150 mm, followed by field cultivator to a depth of 50 mm
Shallow tine-tillage	ST	Tillage with a chisel plough to a depth of 75 mm followed by a non-selective pre-plant herbicide
No-tillage	NT	Tillage was not conducted. Non-selective pre-plant herbicides were used to control weeds and volunteer plants
ST applied every 2nd year in rotation with NT	ST-NT	Tillage with a chisel plough to a depth of 75 mm conducted once every 2 years.
ST applied every 3rd year in rotation with NT	ST-NT-NT	Tillage with a chisel plough to a depth of 75 mm conducted once every 3 years.
ST applied every 4th year in rotation with NT	ST-NT-NT-NT	Tillage with a chisel plough to a depth of 75 mm conducted once every 4 years.

Over the years, various sub experiments were conducted within the overall design to explore fertiliser rates. The quantity of fertiliser applied on the trial site therefore varied with time. In summary, 55 kg N ha^{-1} was applied each season in all plots from 1976 to 1980. In 1980 and 1982, 65 kg N ha^{-1} was applied in each plot followed by 80 and 100 kg N ha^{-1} per plot in 1983 and 1984, respectively. Some N-fertiliser trials conducted in the 1990s required the application of three different levels of fertiliser such that the plots were split into three sections. The sections received 60, 100 and 140 kg N ha^{-1} and 10 kg P ha^{-1}. From 2014 onwards 65 kg N ha^{-1} was applied. Liming and pesticide applications were conducted as recommended by the research farms' Technical Committee in line with standard practice for the area at the time (ARC-Small Grain Institute, 2020; FERTASA, 2016). Calcitic lime (2000 kg ha $^{-1}$) was applied in all plots in 1999, 2001, 2005 and 2016. An additional 2000 kg ha^{-1} of dolomitic lime was also applied in 2016. Agronomical practices concerning planting densities, post-emergence weed control, insect and disease control and liming were kept constant across all tillage treatments.

Instead of wheat, black oats (*Avena strigosa*) were grown on all plots on this trial site in 2011 and 2012 as a means of controlling weeds. In 2013, cover crops mixtures were grown on all plots in different species combinations instead of wheat. Ten cover crops species were grown, namely black oats, forage barley (*Hordeum vulgare*), annual ryegrass (*Lolium multiflorum*), stooling rye (*Festuca arundinacea*), clovers (*Trifolium* spp.), vetch (*Vicia sativa*), oat (*Avena sativa*), mustard (*Brassica* spp.), triticale (× *Triticosecale*), and sulla (*Hedysarum coronarium*). The cover crop mixtures (species combinations) were equally replicated per tillage treatment to prevent giving an unfair advantage to one treatment over the other, which could distort future grain yields.

Tillage treatments were typically conducted after the first autumn rains (usually in April) and seeding was mostly conducted within the first two weeks of May of each year. The MB treatment mostly incorporated crop residues into the soil. The TT and ST treatments loosened the soil to depths of 150 and 75 mm, respectively and lead to some incorporation of crop residues into the soil. The NT treatment led to some dragging of crop residues, therefore, in some years (depending on quantity), the stubble of the previous crop was burnt before seeding.

Grain harvesting was done in October or early November of the same year. A plot harvester was used to harvest a strip of 1.25 m × 50 m along the centre of each plot. However, a plot harvester could not be used in 2018 as a severe windstorm led to crop damage just before harvesting. Therefore, 50 visibly undamaged wheat spikes were randomly collected from each plot and used to determine the average weight of seeds per spike. The weight of seeds per spike and the number of wheat ear-bearing tillers per m^2 were used to estimate wheat grain yield. Grain yield from each plot was standardised to 12% water content. The seed varieties that were planted within the trial site changed with time as new, improved varieties became available.

5.2.3 Data analyses

Linear regression was carried out with STATISTICA^{TM} software version 13.5.0.17 (TIBCO Software Inc.) to assess the association between the seasonal rainfall (April to September) and the wheat grain yield for the data from 1996 when the infrequent tillage treatments were started, through to 2020. Grain yield was the response variable, while seasonal rainfall and tillage treatments were the predictor variables. Scatter plots and coefficient of determination (R^2) were computed for each tillage treatment. Furthermore, scatter plots for the two extreme tillage treatments (Intensive tillage with MB and NT sequences), were also computed using data from 1976 to 2020. The trend of the long-term (1976 to 2020) wheat grain yield data was summarised and presented as rolling four-year yield averages because the crop rotation system used (WWWW and WCWL) had a four-year cycle.

The wheat grain yield data from 1976 to 2013 was only available as mean annual yield values per tillage treatment and crop management system. To test whether the overall means across the span of the experiment were different for each tillage treatment, the wheat grain yield data from the randomised complete block design were analysed with a mixed model ANOVA in *R* Version 4.0.2 (2020-06-22), using the *lmer* package, with tillage sequence and crop management system (monoculture and crop rotation) as the fixed effects and block as the random factor. The mean annual wheat grain yields in each tillage treatment were considered as replicates. To enable comparison of the tillage treatments in the two crop management systems, the Kenward-Roger's estimation procedure was used to account for the unbalanced data and heteroskedasticity.

Complete wheat yield data sets, comprising the yield per plot, tillage treatment and crop management system, were available for four growing seasons: 2014, 2016, 2018 and 2020. The Variance Estimation, Precision and Comparison (VEPAC) package of STATISTICA was used to fit mixed-effects models to the data using the Restricted Maximum Likelihood (REML) procedure (Type III decomposition). Tillage sequence, and growing season (year), and their interactions were specified as fixed effects. Plot was specified as a random effect nested in block (to account for repeated measures).

F-tests were used to assess whether fixed effects were significant at 5% level. Post-hoc pairwise comparisons of means were performed using Fisher's least significance difference (LSD) test at a 5% significance level. All parameters were subjected to a test of normality using the normal probability plots of raw residuals. Also, the Shapiro-Wilk W-test for normality was performed on the residuals for each analysis.

5.3 Results

5.3.1 Seasonal rainfall and wheat grain yield

There was a positive correlation *F* (1,26) = 9.56, P<0.05 between seasonal rainfall and wheat grain yield. The association between the seasonal rainfall and wheat grain yield had R^2 values that ranged from 21%, (r(27) = 0.46, P< 0.05) in the ST-NT sequence to 37%, (r(27) = 0.62, P<0.05) in the MB sequence. Thus, less than 38% of the variation in grain yield can be explained by the variation in seasonal rainfall, for each of the tillage treatments. The scatter plots for the two extreme treatments (MB and NT sequences) are shown in Figure 5.2.

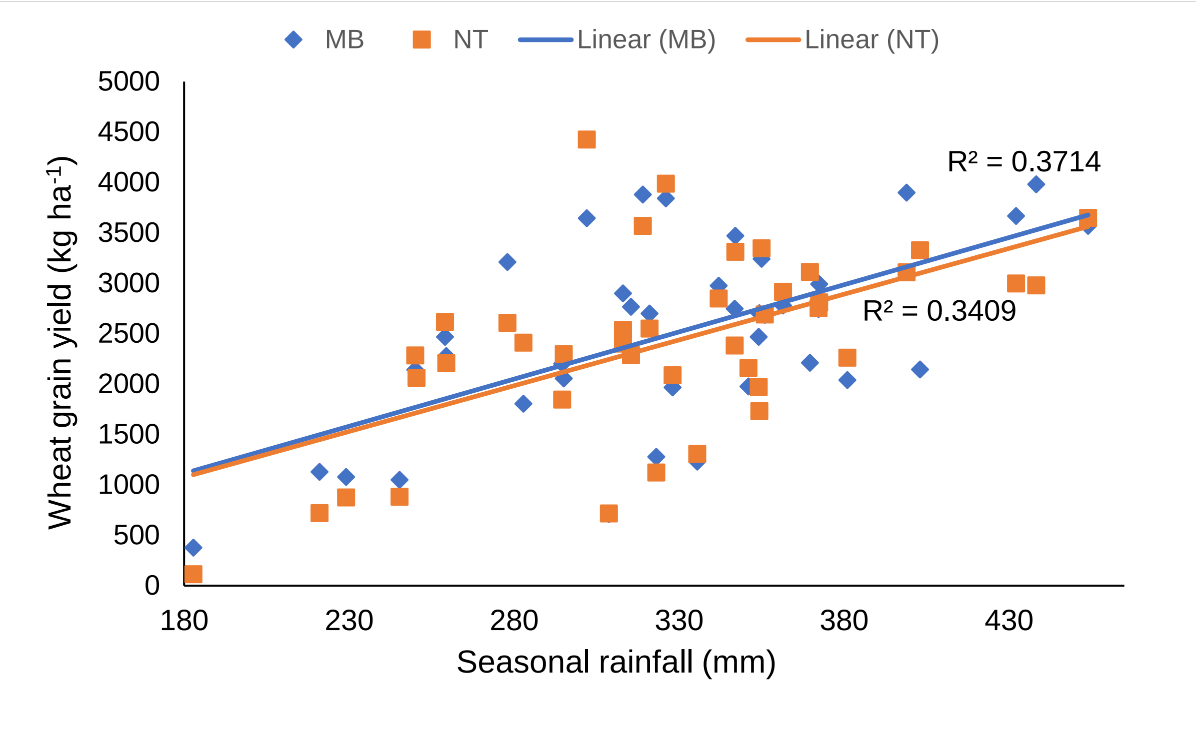

Figure 5.2: The relationship between seasonal rainfall (April – September) and wheat grain yield in the mouldboard (MB) and no-tillage (NT) sequences at the long-term (1976 - 2020) trial site at Langgewens Research Farm in the Swartland region, South Africa.

5.3.2 Long-term wheat grain yield (1976 – 2020)

The overall wheat grain yield increased with time across all tillage treatments within both the monoculture and crop rotation systems (Figure 5.3). For the monoculture system, there was no distinct pattern in the trend of the wheat grain yield due to the tillage sequences. Initially, the wheat grain yield generally decreased and then, over

10 years, consistently increased with an increase in the quantity of N-fertiliser applied. In the early to mid-1990s, the grain yield in the monoculture reached a peak and then declined with time until the monoculture practice was stopped in 2010 (Figure 5.3a). The introduction of infrequent tillage practice in 1996 did not lead to an improvement in wheat grain yield but rather a further decline. In almost all the monoculture trial period, the mouldboard (MB) sequence led to the highest ($P>0.05$) wheat grain yield relative to other tillage treatments (Figure 5.3a and 5.4). Overall, the three infrequent tillage treatments did not lead to higher grain yields F (6,26) = 1.14, $P > 0.05$ relative to no-tillage (NT), tine-tillage (TT) and shallow tine-tillage (ST) (Figure 5.4). The infrequent tillage ST-NT-NT generally led to the lowest ($P<0.05$) grain yield in the wheat monoculture system but did not differ ($P>0.05$) from other infrequent tillage treatments (Figure 5.4).

For the crop rotation system, wheat grain yields fluctuated with time but there was relative yield stasis from 1990 to 2010 and then a sharp increase in yields from 2014 to 2020 (Figure 5.3b). Cover crops were grown in all plots for three consecutive years, from 2011 to 2013 on the trial site, therefore there was no wheat grain yield during that period. From the inception of the crop rotation system (in 1990) to 1997, the NT, TT and MB led to relatively similar grain yields. From 1997 to 2009, the NT sequence treatment led to higher grain yields, closely followed by the TT sequence treatment. The grain yield then substantially increased from 2014 to 2020 across all tillage treatments. After 2018, all tillage treatments except the ST-NT sequence led to grain yields greater ($P>0.05$) than that in the MB sequence. The three infrequent tillage sequences generally resulted in lower grain yields than all other tillage treatments but improved with time.

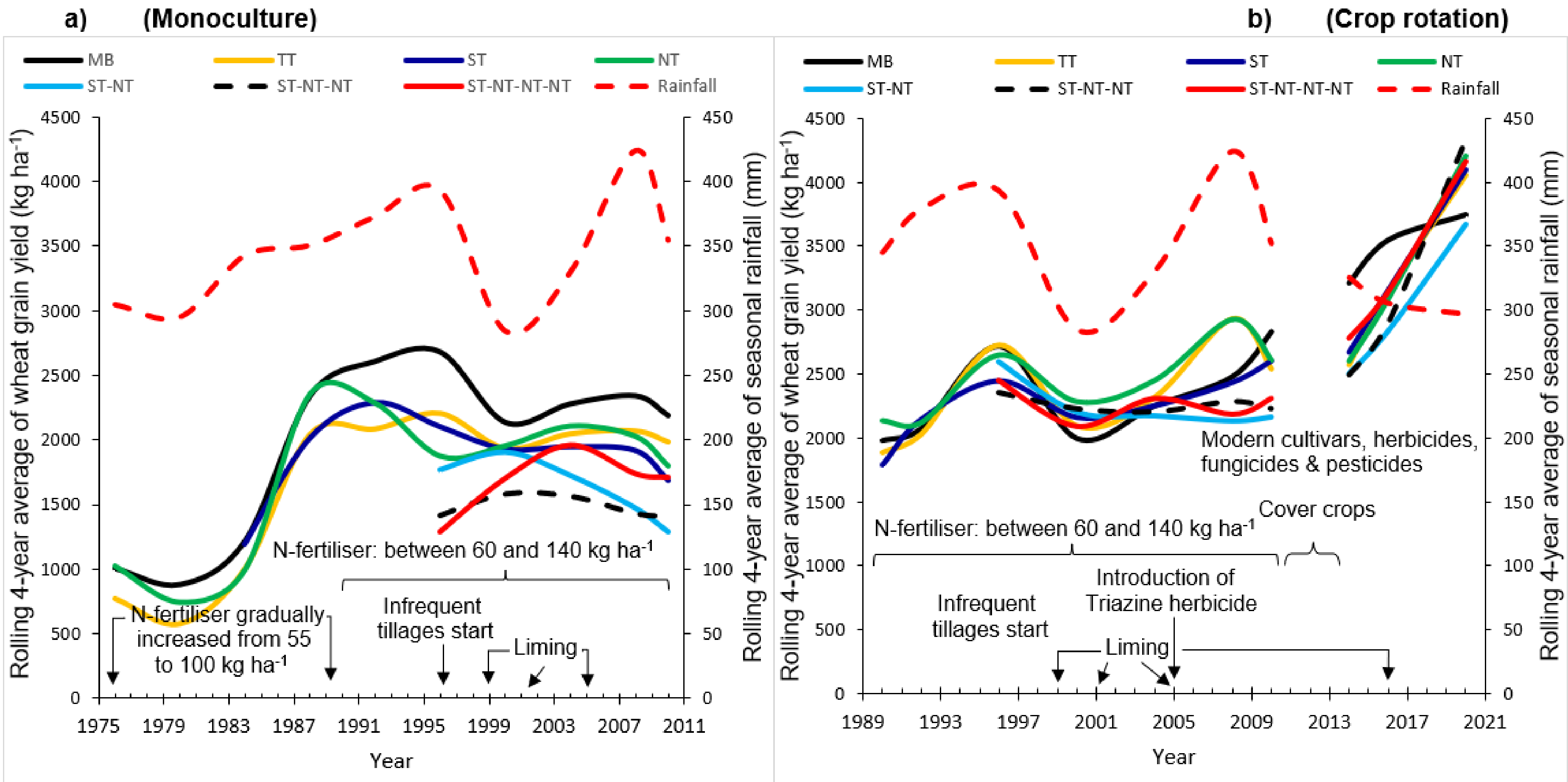

Figure 5.3: Rolling 4-year averages of the long-term wheat grain yield and seasonal rainfall (April – September) in the (**a**) monoculture system from 1976 to 2010 and (**b**) crop rotation (WCWL) system from 1990 to 2020 at Langgewens Research Farm. From 1990 to 2010, N-fertiliser ranged between 60 and 140 kg ha^{-1} in the wheat crop, however, 65 kg ha^{-1} was applied from 2014 onwards. See also, (Supplementary Figures S1 and S2).

The ST-NT sequence, however, consistently resulted in a lower grain yield from 2004 until 2020. The differences in the grain yield trend (Figure 5.3b) were, however, small and led to a lack of significant differences in the overall yields between the tillage treatments in the crop rotation system (Figure 5.4).

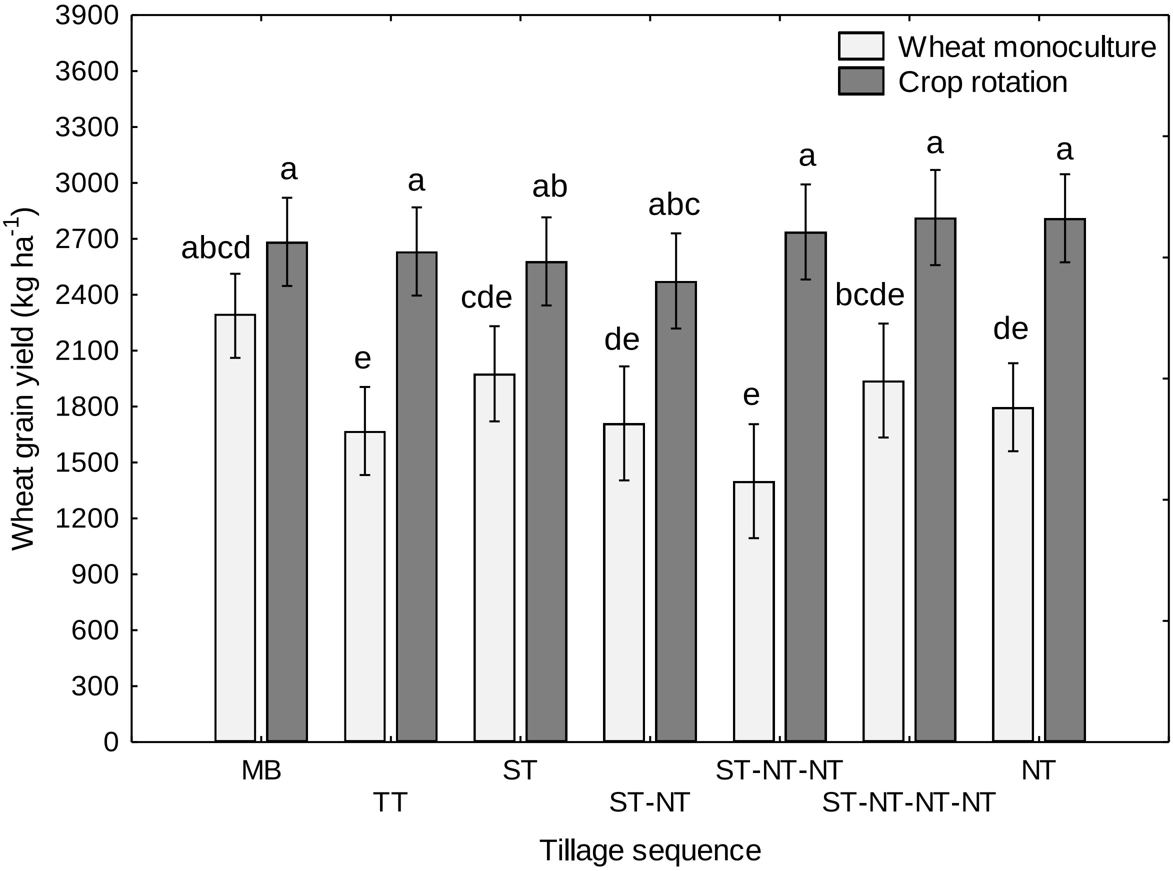

Figure 5.4: The long-term mean wheat grain yield in the wheat monoculture (1976 to 2010) and crop rotation systems (1990 to 2020) at Langgewens Research Farm as influenced by the tillage sequence and crop management system. Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage, Crop rotation = wheat-canola-wheat-cover crops. The different letters on top of the bars denote a significant difference (P<0.05).

5.3.3 Wheat grain yield – 2014 to 2020

Wheat grain yield was affected (P<0.05) by the interaction between tillage sequence and the growing season. Despite the long period (44 years) of continuous intensive tillage with the MB plough, the wheat grain yield in the MB sequence was highest in both 2014 (3210 kg ha^{-1}) and 2016 (3880 kg ha^{-1}) but not in 2018 and 2020 (Figure

5.5). Except in 2020 when the MB sequence resulted in the lowest (P>0.05) yield, the infrequent tillage treatment ST-NT sequence consistently led to the lowest wheat grain yields in all years.

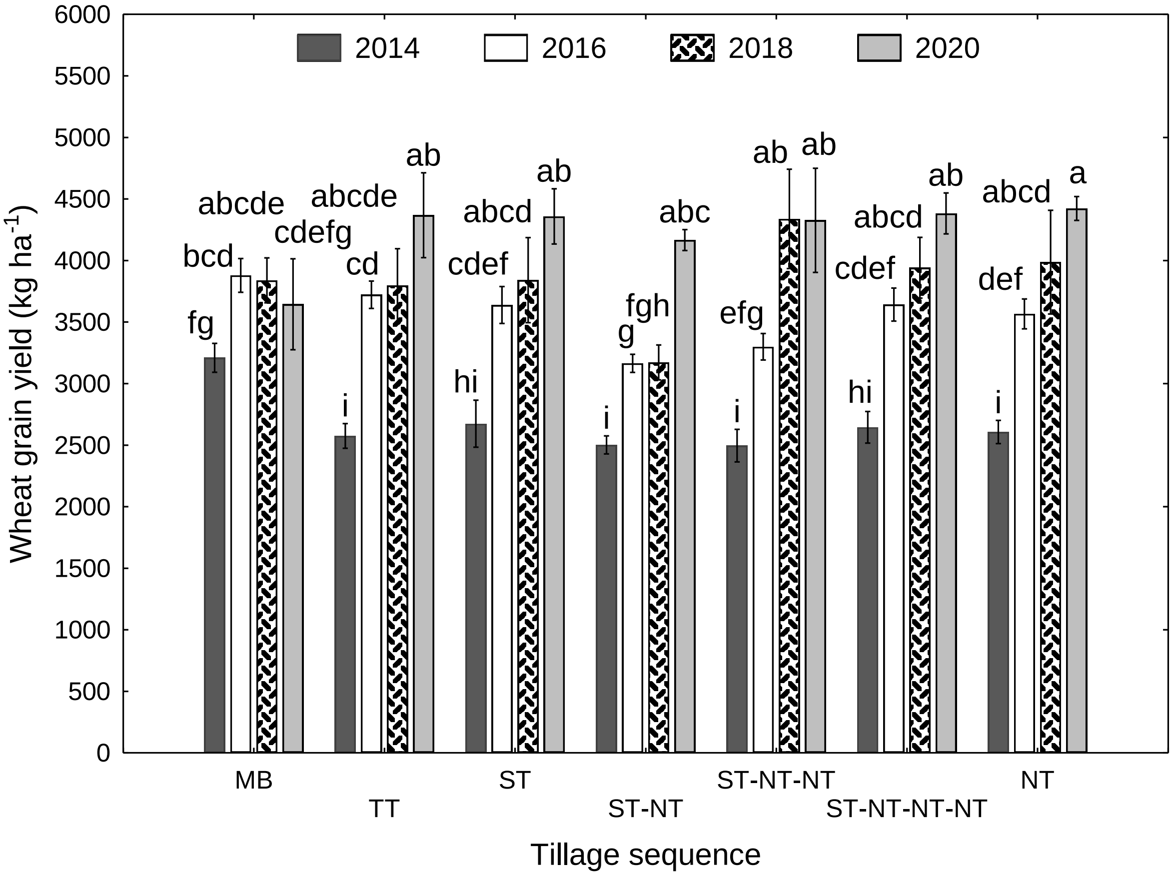

Figure 5.5: The wheat grain yield in 2014, 2016, 2018 and 2020, as influenced by the interaction between tillage sequence and year (growing season) at Langgewens Research Farm. Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The different letters on top of the bars denote a significant difference (P<0.05).

Unlike the infrequent tillage treatment ST-NT, the infrequent tillage sequence ST-NT-NT-NT led to grain yields that were similar (P>0.05) to the highest yielding treatments in all years, except for 2014. In 2018 and 2020, there were no differences (P>0.05) in wheat grain yield between any tillage treatments per growing season, except for the treatment ST-NT in 2018 and MB in 2020, (Figure 5.6). In 2020, the wheat grain yield was more than 4000 kg ha^{-1} in all tillage treatments, except in the MB sequence. Overall, there was a general increase (P<0.05) in grain yield from 2014 (2673 kg ha^{-}

^{1}) to 2020 (4238 kg ha^{-1}). The 2020 growing season had 59 and 19% more grain than 2014 and 2016, respectively.

5.4 Discussion

5.4.1 Effects of seasonal rainfall on wheat grain yield

Our results concerning the relationship between seasonal rainfall (April to September) and wheat grain yield were similar to the findings by Kloppers (2014) for the Swartland region. Also similar to our results, Crookes et al. (2017) stated that seasonal rainfall from 1996 to 2015 had a positive relationship with wheat grain yield at Langgewens Research Farm. In our study, the relationship between seasonal rainfall and wheat grain yield shows that other factors may have affected the wheat grain yields in the Swartland region. Amongst other things, yield can be affected by the seed variety, available soil water (Schillinger et al., 2008), distribution of the rainfall (Kloppers, 2014), soil nutrients and environmental temperature (Gooding et al., 2003). Water availability is crucial during the grain filling phase and can affect grain yield (Abid et al., 2017). In the Swartland region, grain filling mostly occurs in September, therefore, a good amount of available stored soil water or rainfall in September is needed for a higher grain yield.

The positive correlation between the seasonal rainfall and wheat grain yield could be part of the reason why the grain yield increased or decreased with an increase or decrease in seasonal rainfall (Figure 5.3). The effects of seasonal rainfall on grain yield may have contributed to the differences in grain yield between 2014 and 2016, and similarity in 2016 and 2018 (Figure 5.5). The drought experienced in the 2015 growing season resulted in low crop residues and ground cover, which could have affected the 2016 growing season. The 2016 and 2018 growing seasons had higher seasonal rainfall, with 319 and 326 mm, respectively, compared to 278 mm in 2014, and had greater ($P>0.05$) grain yield than that obtained in 2014. In both years, the monthly rainfall during the growing season was greater than 35 mm, except for April and September 2014, and May 2016 which had 16.8, 13.2 and 4.0 mm, respectively.

The introduction and use of improved seed varieties could, *inter alia*, have also led to increased grain yield, especially after 2014 when a decrease in rainfall did not lead to a decrease in grain yield. Furthermore, the 2020 growing season had less seasonal rainfall (306 mm) than 2018 (326 mm) and 2016 (319 mm) but had a similar ($P>0.05$)

grain yield to that of 2018 and greater ($P<0.05$) than 2016 (Figure 5.6). There is little difference between the three rainfall values, suggesting that the observed differences in yield between these time points cannot be explained by rainfall alone but potentially also by the use of improved herbicides, pesticides and seed varieties. Nhemachena and Kirsten (2017) and Tadesse et al. (2018) noted that the improvements in seed varieties in South Africa was slow but contributed to increased wheat grain production with time. In addition, the substantial increase in wheat grain yield across all tillage treatments could also be attributed to the positive effects of growing cover crops for three consecutive years within this trial site. Smit et al. (2021) stated that the use of cover crop mixtures can increase soil available nitrogen, soil organic matter and improve the utilisation of rain, which can lead to increased productivity of the following crops.

5.4.2 Effects of growing wheat in a monoculture system

The wheat monoculture data shows that there was an initial decrease in wheat grain yield from the inception of the trial (in 1976) to 1980, followed by a general increase from 1980 to 1990 (Figure 5.3a). Various factors could have contributed to the initial decline in wheat grain yield. For example, Agenbag and Maree, (1991) explained that previous management practices and low rainfall in 1978 and 1979 affected the wheat grain yield. It is, therefore, plausible that the initial decrease in grain yield could have been caused by the poor supply of nitrogen. Also, the low yields could have been a result of the wheat disease, take-all, which is caused by the fungus *Gaeumannomyces graminis* var. *tritici*. Take-all can be severe in soils of low fertility (Kwak and Weller, 2013). The increase in the wheat grain yield coincides with rising N-fertiliser application, which was only implemented after 1980. These results are similar to those obtained by other researchers (Agenbag 2012; Litke et al. 2018; Maali and Agenbag 2003; Tabak et al. 2020) who stated that the grain yield increased with an increase in N-fertiliser application.

Frequent, intensive tillage with implements such as the mouldboard and disc ploughs have been identified as major contributors to soil degradation through the depletion of soil organic carbon (Tshuma et al., 2021) and erosion of the fertile topsoil (Dendooven et al., 2012; Derpsch, 2004; Hobbs et al., 2008; Swanepoel et al., 2015) and increased greenhouse gas emission due to both the burning of extra fossil fuel to achieve the cultivations, and emissions from the soil (Carbonell-Bojollo et al., 2019; Rutkowska et al., 2018). Soil degradation may lead to reduced crop productivity, however, in this research, intensive tillage with the MB plough led to the opposite. This long-term research shows that the MB treatment generally resulted in the highest yields (although not always significantly different) (Figure 5.3a and 5.4a). Higher yields in conventional tillage with a mouldboard plough, relative to no-tillage practices, were also observed by Maali and Agenbag (2003) and other researchers across the globe (Litke et al., 2018; Panasiewicz et al., 2020; Pittelkow et al., 2015). Tillage with a mouldboard plough can increase soil aeration and nutrient mineralisation which could have contributed to higher grain yield as more nutrients become available for plant uptake (Blevins and Frye, 1993). Also, the MB sequence may result in higher yields when there is adequate soil moisture (Maali and Agenbag, 2003a). The MB plough is also an effective means of controlling weeds (Lal et al., 2007; MacLaren et al., 2021) when compared to other tillage treatments, aiding with improved crop productivity. Similar to our results, Seepamore et al. (2020) found that the grain yield can increase with increased tillage intensity.

Long-term trials have some limitations in that they have a propensity to have some variables changed with time, such that a proper analysis of results may be negatively impacted. Chmielewski and Potts (1995) and a report by Rothamsted Research (2012) shows that the long-term trials at Rothamsted Research Farm in the UK underwent some adjustments with the addition or removal of fertilisers and division of fields into different sections to enable fallowing for weed control. Likewise, several adjustments were made within our trial site over the years. For example, wheat was not grown in all plots for three consecutive years from 2011 to 2013 to control weeds. Also, the monoculture system within our trial site was ended in 2010 as the production costs increased along with an increased build-up of weeds (Agenbag, 2012; Dube et al., 2020; Swanepoel et al., 2016). An evaluation of a crop rotation study which was initiated in 2007 at two different locations in the Mediterranean climate region of South Africa, namely, Langgewens Research Farm (the same place as our experiment but on a different trial site) and Tygerhoek Research Farm (in the Southern Cape region) also showed that the wheat monoculture system resulted in more weeds than in the crop rotation system (MacLaren et al., 2021). Likewise, in Poland, an evaluation of a 29-year-old cereal monoculture system by Woźniak, (2019) showed that the monoculture system resulted in lower wheat grain yield and quality when compared to a crop rotation system. Woźniak, (2020, 2019) attributed the reduced yield to increased weed and disease infestation.

5.4.3 Effects of tillage and crop rotation systems on wheat grain yield

The overall mean grain yield analysis (Figure 5.4) shows that the tillage treatments did not affect (P>0.05) yield in the crop rotation system. Tillage treatments have led to varied grain yield results in different growing seasons but in the same fields. Various long-term tillage trials involving crop rotations also had contrasting tillage effects on wheat grain yield. In Australia, grain yield data collected in 17 growing seasons from a system with a canola-wheat-pulse rotation, showed that conventional tillage led to higher yields (P<0.05) compared to NT (Armstrong et al., 2019). A different long-term trial (16 years) involving sugar beet (*Beta vulgaris*), maize and wheat, also in Australia showed that there were no grain yield differences (P>0.05) between tillage treatments for 14 years (Neugschwandtner et al., 2015). In Switzerland, a 50-year-old tillage trial showed that soil tillage system had no effect (P>0.05) on wheat grain yield for a period of 39 years (1977–2016) (de Cárcer et al., 2019). A 14-year-old trial in the United States of America showed that tillage affected grain yield (Schlegel et al., 2018). In other trials, significant differences due to tillage were found in some growing seasons but not in others (Maali and Agenbag, 2003a; Ozpinar, 2006). Jug et al. (2011) found that tillage treatments affected (P<0.05) grain yield. The contrasting grain yield results indicate that, in addition to tillage, other factors also contribute to grain yield, such as the distribution and amount of seasonal, pest and disease occurrence.

In agreement with other studies (Nhemachena and Kirsten, 2017; Woźniak, 2019, 2020), the crop rotation system in this long-term research led to increased wheat grain yield relative to the monoculture system (Figure 5.3 and 5.4). From 1989 to 2009, there was relatively little difference between wheat grain yield from the monoculture and crop rotation systems. However, after 2010, the differences became pronounced. The increase in wheat grain yields in the long-term research could be because of a variety of factors *inter alia*, improved seed cultivars, farm management practices, herbicides, fungicides, pesticides, increased fertiliser rates, use of cover crop mixtures and improved farming implements (Findlater et al., 2018b). In a review of commercial wheat production and breeding in South Africa, Nhemachena and Kirsten (2017) found that dryland wheat productivity increased from less than 500 kg ha^{-1} in 1936 to more than 3500 kg ha^{-1} in 2015, partly as a result of sowing improved seed cultivars.

However, the dryland wheat grain yields in South Africa are lower than that of the major wheat-producing countries in the world due, amongst other things, to the slower wheat breeding progress in South Africa (Nhemachena and Kirsten, 2017; Tadesse et al., 2018).

The introduction of crop rotation enabled the use of different specific herbicides which could not be used in the monoculture system (MacLaren et al., 2021). For example, when triazine herbicides, which could not be applied in wheat monoculture, were introduced in 2005 in the canola phase of the crop rotation system, there was a marked improvement in wheat grain yield in the season that followed. The inclusion of legumes in the crop rotation system probably increased the soil nitrogen content (Das et al., 2018) and availability for crops, leading to improved crop yields. Also, the crop rotation system enabled better control of weeds and pests by disrupting the weed and pest life cycles (Schillinger and Paulitz, 2018). Regardless of the positive effects of using different herbicides in the crop rotation system from 2005 to 2010, the grain yield did not increase as much as it did from 2014 to 2020. We believe that the three years of continuous cover crops from 2011 to 2013 could have contributed to the increase in grain yields.

5.4.4 Effects of the infrequent tillage on wheat grain yield

The infrequent tillage treatments, which were expected to alleviate some of the problems associated with NT, failed to improve the wheat grain yield relative to the NT treatment in both the monoculture and crop rotation systems in this long-term trial. Wheat grain yield was generally greater in the MB sequence (although not always significantly so) whilst the ST-NT sequence gave the lowest yields (again, not always significantly different). Agenbag (2012) also found similar results in that there were no significant differences in wheat grain yield between the infrequent tillage sequences and the NT sequence. In our trial, it took 18 years (1996 to 2014) for the infrequent tillage sequence ST-NT-NT-NT to equal the rolling 4-year grain yield of the NT sequence (Figure 5.3b).

Literature on infrequent tillage is limited, therefore an assessment of strategic tillage could be beneficial. A literature review of 30 strategic tillage studies across the world revealed that for a period of two to three years after the strategic tillage, crop yield did not significantly change from that of the NT treatment in 80%, decreased in 5% and increased in about 15% of the cases (Blanco-Canqui and Wortmann, 2020). Likewise, several other studies on strategic tillage (Conyers and Dang 2014; Dang et al. 2018; Kirkegaard et al. 2014) have also indicated that crop yield was, in most cases, neither improved nor decreased. Although the infrequent tillage practices can help to incorporate soil amendments (Tshuma et al., 2021), the results presented in this paper indicate that they could not significantly increase crop yield relative to the NT treatment.

5.4.5 Implications of tillage practices

Grain yield in the MB treatment was not always significantly higher than the yield in the NT and ST-NT-NT-NT treatments, therefore, intensive tillage with the MB plough may be unnecessary as it can be environmentally unsustainable. Conventional tillage with the MB plough requires more fuel and can increase greenhouse gas emissions by more than 50% when compared to reduced tillage practices (Carbonell-Bojollo et al. 2019; Rutkowska et al. 2018). Furthermore, intensive tillage can lead to the deterioration of soil quality, including reduced soil organic carbon stocks, extractable phosphorus stocks and soil organic carbon stratification ratios (Franzluebbers, 2002; Tshuma et al., 2021). In this research, the NT and infrequent tillage treatment ST-NT-NT-NT can be better options than the MB treatment as they can improve soil quality (Tshuma et al. 2021) by enabling the build-up of soil organic matter. However, the NT treatment may be the best option overall ahead of both the MB and infrequent tillage treatments because it is the least costly financially, requiring less fuel (leading to reduced greenhouse gas emission) and labour costs associated with the purchase and maintenance of tillage implements.

5.5 Conclusions

Our results broadly show that the long-term wheat grain yield was affected by a variety of factors, *inter alia*, use of improved seed varieties, fertiliser applications, different herbicides, growing of cover crops, seasonal rainfall and tillage. Wheat grain yield was generally higher in the crop rotation system than in the monoculture system. Grain yield in the monoculture system decreased with time and the system was subsequently discontinued (1976 to 2010). Compared to other tillage treatments in the monoculture system, the MB sequence led to relatively higher yields, however, in the crop rotation system, there were no overall yield differences. Although ploughing with the mouldboard led to high yields, it was not the most cost-effective treatment overall. Ploughing with the mouldboard may lead to increased soil erosion, greenhouse gas emission, global warming, and depletion of soil organic carbon. Our results show that the infrequent tillage sequences did not significantly increase the wheat grain yield when compared to the NT sequence. We, therefore, recommend that wheat producers opt for NT and crop rotation to ensure sustainability and avoid intensive tillage.

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CHAPTER 6

Can infrequent tillage practices compensate for reduced synthetic agrochemical application in a dryland cropping system?

Abstract

Tillage practices and continuous application of synthetic agrochemicals can hinder crop productivity. However, there is a paucity of information on the effects of infrequent tillage and reduced synthetic agrochemicals on crop productivity. Four continuous tillage treatments: mouldboard ploughing, tine-tillage, shallow tine-tillage, no-tillage; and three infrequent tillage treatments: shallow tine-tillage conducted once in two years, shallow tine-tillage conducted once in three years, and shallow tine-tillage conducted once in four years were assessed within a long-term (44-years) trial site in South Africa. The study aimed to determine the effects of tillage practices on wheat and canola yield and quality in a dryland crop rotation system that received varied rates of synthetic agrochemicals (standard, reduced, or minimum). It was hypothesised that infrequent tillage treatments will lead to improved crop yield and quality whilst using a reduced quantity of synthetic agrochemicals. In the system with reduced synthetic agrochemicals, the mouldboard, no-tillage, and infrequent tillage treatments had similar ($P>0.05$) yields. When comparing the systems with standard, and reduced synthetic agrochemicals, the combined 2018 and 2020 wheat grain yield and quality did not differ ($P>0.05$) in four of the seven tillage treatments. And no differences were found in canola seed yields in 2019. This study highlights that infrequent tillage treatments did not reduce the yield or quality compared to no-tillage but were in some cases more effective at preventing yield reductions resulting from reduced agrochemical application. We recommend that farmers opt for infrequent or no-tillage practices when applying a reduced quantity of synthetic agrochemicals.

6.1 Introduction

Different tillage intensities and frequencies may positively or negatively affect soil quality. For example, the mouldboard plough may be effective in controlling weeds as it turns the soil and buries and kills the weeds and their seeds to a depth where they cannot germinate (Conyers et al. 2019; MacLaren et al. 2021). Tillage may also bring buried viable weed seeds to the surface where they can germinate. However, continuous intensive tillage with aggressive implements such as the mouldboard may lead to the breakdown of soil aggregates (Bottinelli et al., 2017; Gao et al., 2017). The smaller soil aggregates can increase the chances of soil erosion by wind and water, leading to loss of the fertile topsoil (Bogunovic et al., 2018; Vach et al., 2018) and decline in soil quality (Derpsch, 2004). Soils of poor quality tend to lead to poor crop productivity. To improve soil quality, reduced tillage, including no-tillage has been widely advocated and adopted in South Africa (Findlater et al., 2018) and across the world (Derpsch, 2004).

The benefits of no-tillage have been widely published (Bottinelli et al., 2017; Gao et al., 2017; Kibet et al., 2016; Swanepoel et al., 2015; Tshuma et al., 2021; Vach et al., 2018). Amongst other things, no-tillage can lead to improved soil aggregate stability, reduced soil erosion, improved water infiltration, increased soil microbial activity and a reduced carbon footprint. Despite the benefits, prolonged no-tillage has been associated with increased weed pressure, soil nutrient stratification, inability to incorporate lime and fertiliser to a deeper depth, and soil compaction (Blanco-Canqui and Wortmann, 2020; Conyers et al., 2019; Dang et al., 2018; Liebenberg et al., 2020). Producers who practise no-tillage may be forced to rely on synthetic herbicides to control weeds. Excessive and repeated use of synthetic herbicides has led to the development of herbicide-resistant weeds, such as ryegrass (*Lolium* spp.) (Pieterse, 2010), plantain (*Plantago lanceolata* L.) (Ndou et al., 2021) and horseweed (*Conyza* spp.) (Heap, 2021). Furthermore, agrochemicals (synthetic herbicides, fungicides and pesticides) have been blamed for increasing environmental damage (Lackmann et al., 2021; Le Du-Carrée et al., 2021) by killing beneficial insects and harming human health (Curl et al., 2003). There is, therefore, a need to reduce the quantity of synthetic agrochemicals (herbicides, pesticides and fertilisers) applied in agriculture and to convert current farming systems to more environmentally friendly agroecological farming systems (MacLaren et al., 2020). One option for reducing the quantity of synthetic agrochemicals can be to substitute them with some environmentally friendly bio-chemicals or organic compounds. In this article, the term ‘bio-chemical’ refers to chemical inputs derived from natural compounds (Supplementary Table S2-6).

Crop rotation can also facilitate weed control (MacLaren et al., 2021). Crop rotation enables the different selective herbicides to eliminate weeds that are difficult to control when found in a monoculture system. Also, crop rotations may help prevent nutrient loss (Rayns et al., 2010), loosen the soil and break disease and insect pest cycles (Schillinger and Paulitz, 2018).

An alternative method to reduce weed pressure in a no-tillage system is to conduct strategic tillage. Blanco-Canqui and Wortmann, (2020) described strategic tillage as one-off tillage, which is intentionally applied to solve specific problems that are identified in a no-tillage field. Reducing weeds through strategic tillage may enable a reduction in the application of herbicides. The benefits of strategic tillage have been well documented (Blanco-Canqui and Wortmann, 2020; Conyers et al., 2019; Dang et al., 2018; Kirkegaard et al., 2014; Labuschagne et al., 2020; Peixoto et al., 2020).

Apart from strategic tillage, infrequent tillage could also be considered as an option for alleviating some of the problems associated with no-tillage to improve crop productivity. Unlike strategic tillage, infrequent tillage involves the application of alternating tillage practices which include tillage and no-tillage (Tshuma et al., 2021). The phase of no-tillage can be one, two, or three consecutive years which are followed by a year in which tillage is conducted. Some research on infrequent tillage has been conducted in the Western Cape region of South Africa (Agenbag, 2012; Maali and Agenbag, 2006; Maali and Agenbag, 2003). However, globally there is a paucity of information on the effects of infrequent tillage practices on crop yield and quality in systems that apply varied rates of synthetic agrochemicals.

This research aimed to determine the long-term effects of different tillage practices on wheat and canola yield and quality in a dryland crop rotation system that applies **standard**, **reduced**, or **minimum** rates of synthetic agrochemicals. In this article, these terms (when highlighted in bold) represent the level of synthetic agrochemical application. Three objectives were examined by determining the effects of the tillage practices on (i) aboveground plant biomass production, (ii) seed and grain yield, and (iii) seed and grain quality. It was hypothesised that infrequent tillage would ameliorate some problems (including weeds) associated with long-term no-tillage practices and lead to improved crop yield and quality whilst using a **reduced** quantity of synthetic agrochemicals.

6.2 Materials and methods

6.2.1 Site description

The research was conducted at Langgewens Research Farm (33°17ˈ0.78ˈˈ S, 18°42ˈ28.09ˈˈ E) of the Western Cape Department of Agriculture, in the Swartland region of South Africa (Supplementary Figure S3). The Swartland region has a Mediterranean-type climate with a wet winter and hot, dry summer. Langgewens receives a mean annual rainfall of 395 mm, of which approximately 80% falls between April and September, the growing season for this region (ARC-Small Grain Institute, 2020). The trial site has a shallow (300 mm) lithic soil locally known as a Glenrosa-soil form (Soil Classification Working group, 1991) or internationally, as Haplic Cambisols (IUSS Working Group WRB, 2015). The soil had a 14.7% clay content (excluding the gravel and stone content), whilst the gravel and stone content in the A horizon is 44.6% (Maali and Agenbag 2003).

6.2.2 Trial history and treatments

The long-term research trial within which this current experiment was conducted was established in 1976. The trial was laid out in a randomised block design with four replicated blocks. Each block had 14 plots and each plot measured 50 m x 6 m. The blocks were separated by a buffer zone of at least 9 m, and plots were separated by a 1 m buffer zone. Initially, wheat (*Triticum aestivum*) was grown in monoculture on the trial site. In 1990, the trial was split into two cropping systems. One involved wheat monoculture production and the other involved a four-year rotation of wheat, canola (*Brassica napus*), and lupins (*Lupinus* spp.) in the sequence wheat-canola-wheat-lupin. The wheat monoculture system was ended in 2010. Seven tillage treatments were investigated (Table 6.1).

The research described in this article was conducted between 2018 and 2020. The tillage sequences remained unchanged, but the crop management system was changed in 2018. Four of the eight replications were allocated to continue with a crop management system with the **standard** synthetic agrochemicals. The **standard** application of synthetic agrochemicals was determined by the Langgewens Technical

Committee according to best practices for the region (ARC-Small Grain Institute, 2020; FERTASA, 2016).

Table 6.1: Summary of tillage treatments, abbreviations and the implements used at Langgewens Research Farm. All plots were sown with a no-till drill.

Tillage treatment	**Abbreviation**	**Tools used and tillage intensity**
Mouldboard	MB	Ploughing with a chisel (tine) plough to a depth of 150 mm, followed by the mouldboard plough to a depth of 200 mm and field cultivator to a depth of 50 mm.
Tine-tillage	TT	Tillage with a chisel plough to a depth of 150 mm, followed by field cultivator to a depth of 50 mm.
Shallow tine-tillage	ST	Tillage with a chisel plough to a depth of 75 mm followed by a non-selective pre-plant herbicide.
No-tillage	NT	Tillage was not conducted. Non-selective pre-plant herbicides were used to control the weeds and volunteer plants
ST applied every 2nd year in rotation with NT	ST-NT	Tillage with a chisel plough to a depth of 75 mm was conducted once every two years.
ST applied every 3rd year in rotation with NT	ST-NT-NT	Tillage with a chisel plough to a depth of 75 mm was conducted once every three years.
ST applied every 4th year in rotation with NT	ST-NT-NT-NT	Tillage with a chisel plough to a depth of 75 mm was conducted once every four years.

The remaining four replications were allocated to a crop management system with **reduced** application of synthetic agrochemicals. Some of the synthetic agrochemicals were replaced by bio-chemicals, therefore, the quantity of synthetic agrochemicals applied was reduced. In this article, the term *bio-chemical* does not imply organic certification. The bio-chemicals that were introduced were *Trichoderma asperellum* (to help with control of soil-borne diseases), silicic acid (to promote plant resistance to both biotic and abiotic stress) and triacontanol and bull kelp (*Nereocystis luetkeana*) extracts (to promote photosynthesis and plant growth). The bio-chemicals were manufactured and supplied by Real IPM *(*A full list of chemicals applied is available in the supplementary Tables S1-5*)*.

In 2019 and 2020, all plots were further divided into two subplots which were separated by a buffer zone of 1 m (Supplementary Figure S4). One sub-plot measured 35 m x 6 m and remained as the crop management system with either **standard** or **reduced** synthetic agrochemicals. The second subplot measured 14 m x 6 m and received a single application of herbicide at the beginning of the trial and will be referred to as the crop management system with **minimum** synthetic agrochemicals.

Due to severe weed infestation in the crop management system with **reduced**, and **minimum** synthetic agrochemicals in 2019, weed control was conducted by hand pulling. A second application of herbicide was made to prevent total failure of the canola crop in the system with **minimum** synthetic agrochemicals. However, in 2020, the wheat crop in the system with **minimum** synthetic agrochemicals received only one application of herbicide.

The seeds planted in the crop management system with **reduced**, and **minimum** synthetic agrochemicals were treated with the bio-chemical *Trichoderma asperellum* before planting. After planting, the bio-chemicals were applied twice within 30 days in the wheat crops of 2018 and 2020. In the canola crop of 2019, the bio-chemicals were applied three times within 90 days. Pelleted chicken manure was combined with 50% chemical fertiliser and applied to the crops in the management systems with **reduced** and **minimum** application of synthetic agrochemicals. Overall, nitrogen fertiliser was applied at 65 and 75 kg N ha^{-1} in the wheat and canola crops, respectively according to guidelines for the region (FERTASA, 2016) (Supplementary Table S7). Phosphorus and potassium were applied according to soil test results.

Wheat cultivar SST 056 was planted on 11th May 2018 at a rate of 100 kg ha^{-1}. Canola cultivar Alfa TT was planted on 30th April 2019 at a rate of 3.5 kg ha^{-1}. In 2020, wheat cultivar SST 0166 was planted on 12th May at a rate of 90 kg ha^{-1}. Harvesting was conducted at the end of October of each year.

6.2.3 Assessments

6.2.3.1 Aboveground biomass and wheat ear-bearing tillers

The aboveground biomass of wheat and canola was determined at 90 days after crop establishment (DAE), and physiological maturity. Plant samples were cut to ground level from eight rows of 1 m length from each plot and dried in an oven at 60 °C for 72 hours to determine the dry matter (DM).

The number of wheat ear-bearing tillers was determined by collecting samples from eight rows of 1 m length which were cut to ground level before harvesting.

6.2.3.2 Wheat grain and canola seed yield

In 2018, there was a severe windstorm, which led to crop damage just before harvesting that made conventional yield assessments impossible. Therefore, 50 visibly undamaged wheat spikes were randomly collected from each plot and used to determine the average weight of seeds per spike. The weight of seeds per spike and the number of wheat ear-bearing tillers per m^2 were used to estimate wheat grain yield (kg ha^{-1}). In 2019 and 2020, a Hege 140 plot combine was used to harvest a strip of 1.25 m x 35 m and 1.25 m x 14 m along the centre of each plot where canola or wheat was grown to determine the seed yield.

6.2.3.3 Wheat grain and canola seed quality

Wheat and canola seed samples were subjected to quality analyses by using a near Infrared (NIR) grain analyser (model IM 9500, Perten Instruments, Waltham, USA). Protein content (%), hectolitre mass (kg hL^{-1}) and thousand kernel mass (g) were determined for wheat. The oil content and the thousand seed mass (g) were determined for canola seed. Both oil and seed protein values are reported on a dry matter basis.

6.2.4 Data analyses

For the 2018 and 2020 wheat data, the Variance Estimation, Precision and Comparison (VEPAC) package of STATISTICA™ software version 13.5.0.17 (TIBCO Software Inc.) was used to fit mixed-effects models to the data using the Restricted Maximum Likelihood (REML) procedure (Type III decomposition). Tillage sequence, growing season, crop management system, and their interactions were specified as fixed effects. Plot was specified as a random effect nested in block (to account for repeated measures). The 2019 canola data contained unbalanced data and was analysed with a mixed model ANOVA in *R* Version 4.0.2 (2020-06-22), using the *lmer* package, with tillage sequence and crop management system as the fixed effects and block as the random factor. To enable the comparison of unbalanced tillage treatments in the three crop management systems (**standard**, **reduced**, and **minimum**), the Kenward-Roger's estimation procedure was used to account for the unbalanced data and heteroskedasticity.

F-tests were used to assess whether fixed effects were significant at 5% level. Post-hoc pairwise comparisons of means were performed using Fisher's least significance difference (LSD) test at a 5% significance level. All parameters were subjected to a test of normality using the normal probability plots of raw residuals. Also, the Shapiro-Wilk W-test for normality was performed on the residuals for each analysis.

6.3 Results

6.3.1 Wheat crops

The aboveground biomass of wheat was assessed in the crop management systems with **standard** and **reduced** synthetic agrochemicals. At 90 DAE, the aboveground biomass was not affected ($P>0.05$) by any treatment interactions (Table 6.2). However, there was a difference ($P<0.05$) in biomass yield between 2018 and 2020. The aboveground biomass production was 89% more in 2018 (7117 kg DM ha^{-1}) than in 2020 (3760 kg DM ha^{-1}). In 2018, the aboveground biomass production ranged from 6312 kg DM ha^{-1} in the TT treatment to 7803 kg DM ha^{-1} in the <u>ST</u>-NT treatment (the underlined treatment in the sequence indicates the tillage treatment conducted for the growing season).

In 2020, the aboveground biomass ranged from 3395 kg DM ha^{-1} in the MB treatment to 3993 kg DM ha^{-1} in the <u>ST</u>-NT-NT-NT treatment. There was 21% more ($P<0.05$) aboveground biomass produced in the system with the **standard** synthetic agrochemicals than in the system with **reduced** synthetic agrochemicals (results not shown). Also in 2020, the experiment in the system with **minimum** synthetic agrochemicals was terminated at 90 DAE due to severe weed infestation.

Table 6.2: The F-values with degrees of freedom, and P-values from the mixed model ANOVA for the wheat crop productivity parameters as affected by the tillage sequence, crop management system and growing season and their interactions. Boldfaced P-values denote significant effects at P<0.05.

	Tillage sequence (T)		Management system (M)		Growing season (G)		T x M		T x G		M x G		T x M x G	
Parameter	*F*(6,12)	*P*	*F*(1,2)	*P*	*F*(1,2)	*P*	*F*(6,12)	*P*	*F*(6,68)	*P*	*F*(1,2)	*P*	*F*(6,68)	*P*
Biomass at 90 DAE (kg DM ha^{-1})	1.04	0.45	0.12	0.76	31.2	**0.03**	2.23	0.11	0.91	0.52	2.75	0.24	0.51	0.79
Biomass at plant maturity (kg DM ha^{-1})	1.67	0.21	2.96	0.23	0.01	0.92	1.17	0.38	2.55	0.08	0.18	0.72	0.41	0.86
Tillers (m^{-2})	2.90	0.06	6.93	0.12	10.8	0.08	2.96	0.05	1.24	0.35	0.59	0.52	0.68	0.67
Grain yield (kg ha^{-1})	1.98	0.15	3.08	0.22	28.7	**0.03**	2.02	0.14	0.59	0.74	1.24	0.38	1.18	0.38
Thousand seed mass (g)	1.84	0.17	0.33	0.62	0.24	0.66	1.20	0.37	0.80	0.59	0.03	0.87	0.57	0.75
Grain protein content (%)	4.18	**0.02**	1.04	0.42	64.3	**0.002**	0.62	0.72	1.00	0.47	1.93	0.30	0.72	0.65
Hectolitre mass (g)	3.12	0.06	0.04	0.86	4.48	0.17	1.73	0.20	0.83	0.57	5.89	0.14	0.72	0.64

At plant physiological maturity, the aboveground biomass of wheat was not affected ($P>0.05$) by any treatment (Table 6.2). The biomass, however, tended to be greater ($P>0.05$) in 2020 than in 2018, and in the system with **standard** application of synthetic agrochemicals than in the system with **reduced** synthetic agrochemicals. The mean aboveground biomass in the systems with **standard** and **reduced** synthetic agrochemicals were 7043 and 5985 kg DM ha^{-1}, respectively (results not shown).

The number of ear-bearing tillers was not affected ($P>0.05$) by any treatment (Table 6.2). Like the aboveground biomass at 90 DAE, the number of ear-bearing tillers tended to be greater ($P>0.05$) in the system with **standard** application of synthetic agrochemicals than in the system with **reduced** synthetic agrochemicals. The mean number of ear-bearing tillers in the systems with **standard**, and **reduced** synthetic agrochemicals was 209 and 182 tillers m^{-2}, respectively (results not shown).

Wheat grain yield was affected ($P<0.05$) by the growing season (or year) (Table 6.2). The mean grain yield was 15% more ($P<0.05$) in 2020 (3916 kg ha^{-1}) than in 2018 (3418 kg ha^{-1}). In 2018, the wheat grain yield tended to be higher (but not always significant) in the infrequent tillage treatment ST-NT-<u>NT</u>-NT followed by the ST treatment and was lowest in the <u>ST</u>-NT treatment (the underlined letters in the tillage sequence represent the tillage treatment conducted in that growing season) (Figure 6.1). In 2020, the wheat grain yield tended to be higher ($P>0.05$) in the ST treatment followed by the infrequent tillage treatment ST-NT-NT-<u>NT</u> and was lowest ($P>0.05$) in the MB and ST-<u>NT</u> treatments, which both had 3659 kg ha^{-1}. Although not significant, the wheat grain yield was higher in the system with the **standard** synthetic agrochemicals than in the system with **reduced** synthetic agrochemicals.

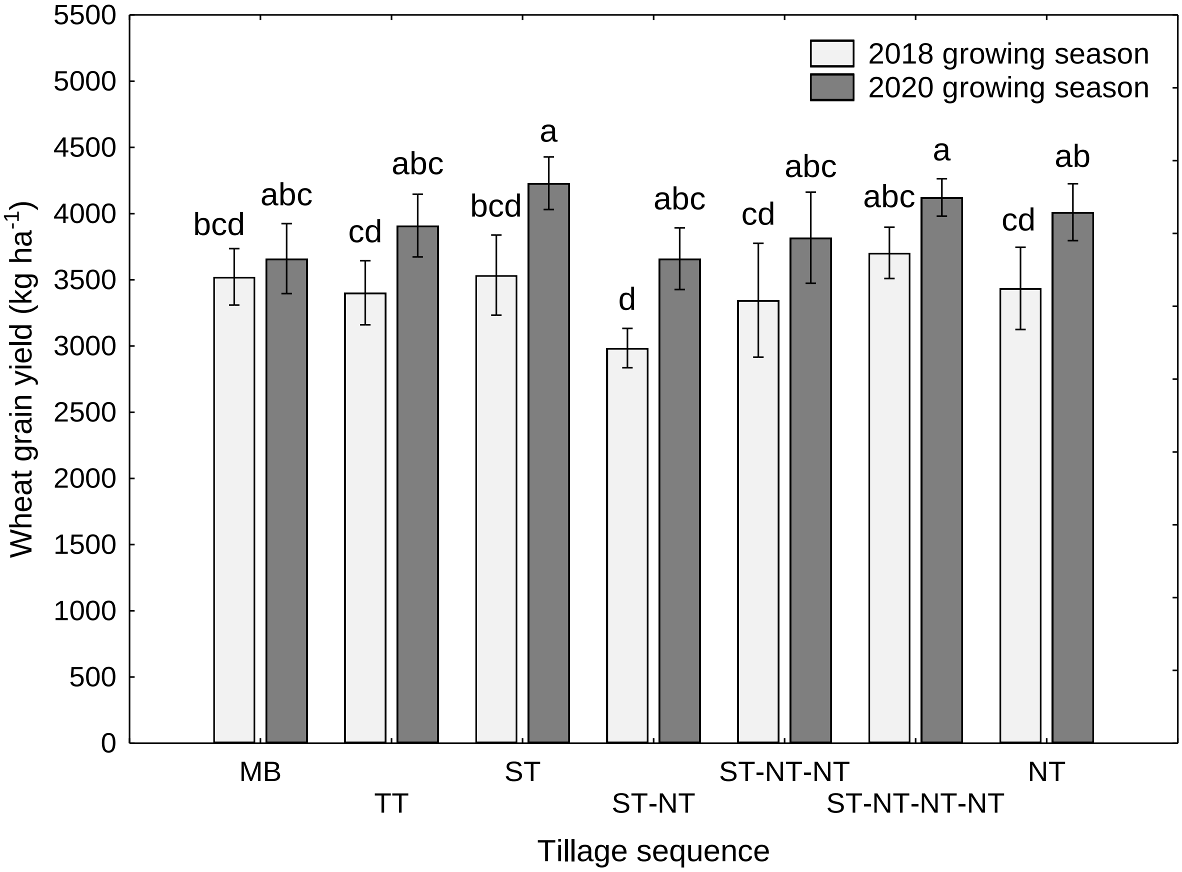

Figure 6.1: Wheat grain yield (average of the two agrochemical levels) in 2018 and 2020 as influenced by the growing season in each tillage treatment at Langgewens Research Farm. The different letters on top of the bars denote a significant difference (P<0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage.

Concerning the tillage treatments in the system with **reduced** synthetic agrochemicals, the infrequent tillage treatment ST-NT-NT-NT (3466 kg ha^{-1}) led to a higher grain yield (but not always significant) than the MB (3205 kg ha^{-1}) and NT (2883 kg ha^{-1}) treatments in 2018 (Figure 6.2). In 2020, the ST treatment led to the highest grain yield (P<0.05) with 3230 kg ha^{-1} followed by the infrequent treatment ST-NT-NT-NT (3466 kg ha^{-1}) and MB (3206 kg ha^{-1}). For the two-growing seasons, the only difference between the system with **standard**, and **reduced** synthetic agrochemicals was in the infrequent tillage treatment ST-NT-NT in 2018 (Figure 6.2).

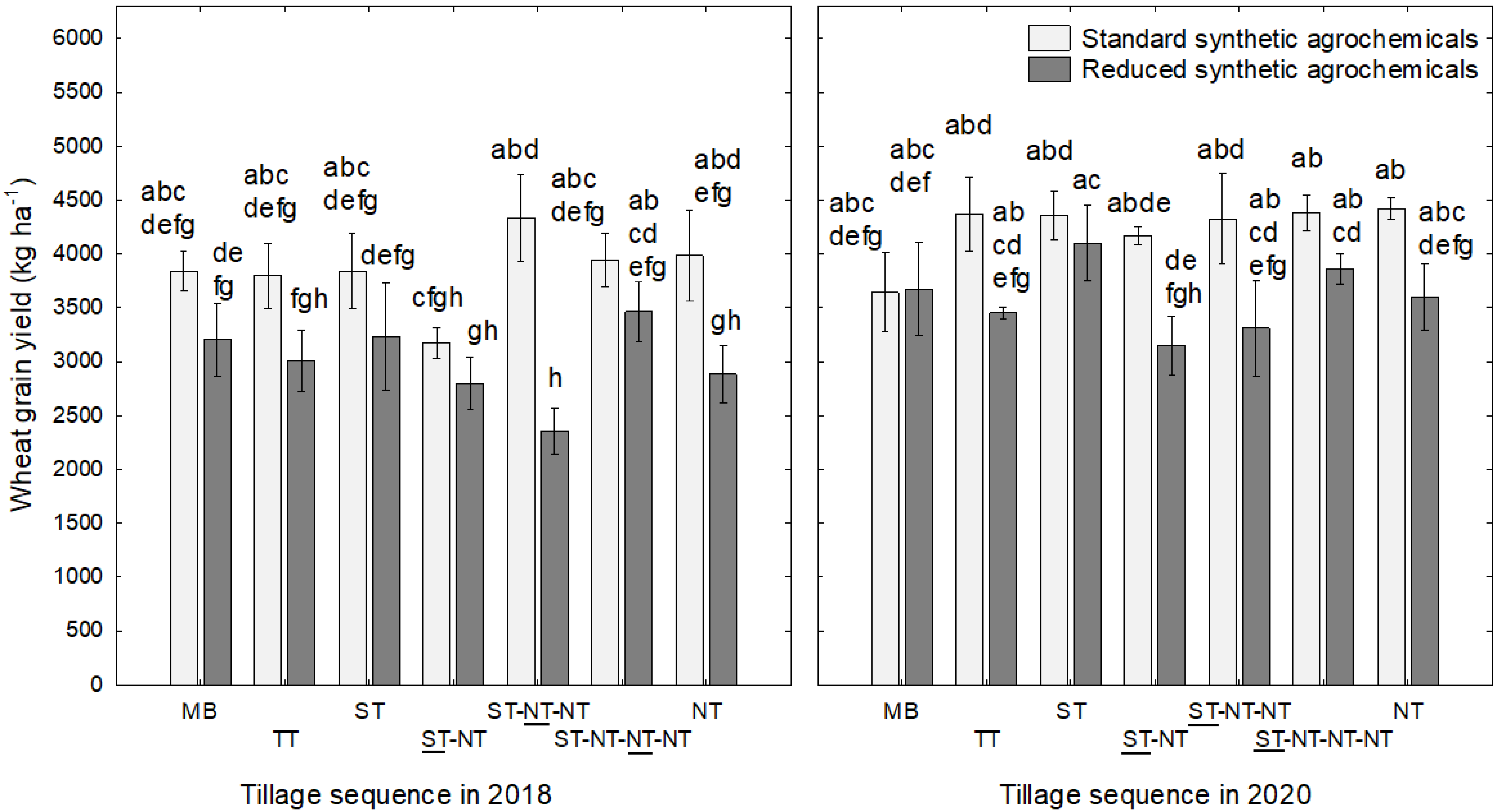

Figure 6.2: Wheat grain yield in 2018 and 2020 as influenced by the growing season per tillage sequence and crop management system at Langgewens Research Farm. The different letters on top of the error bars denote a significant difference (P<0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the treatment for each year.

Over the two-growing seasons, the mean grain yield in the system with the **standard** synthetic agrochemicals was highest (P>0.05) in the tillage treatment ST-NT-NT (4332 kg ha^{-1}) followed by NT (4205 kg ha^{-1}) and ST-NT-NT-NT (4162 kg ha^{-1}) treatments (results not shown).

The thousand kernel mass and hectolitre mass were both not affected (P>0.05) by any treatment (Table 6.2). The thousand kernel mass ranged from 37 to 39 g whilst the hectolitre mass ranged between 82 and 83 g hL^{-1} in both growing seasons.

Both the tillage sequence and growing season affected (P<0.05) the wheat grain protein content (Table 6.2). The grain protein content in the systems with **standard** and **reduced** synthetic agrochemicals did not differ (P>0.05) within each tillage treatment but differed (P<0.05) between different tillage treatments (Figure 6.3).

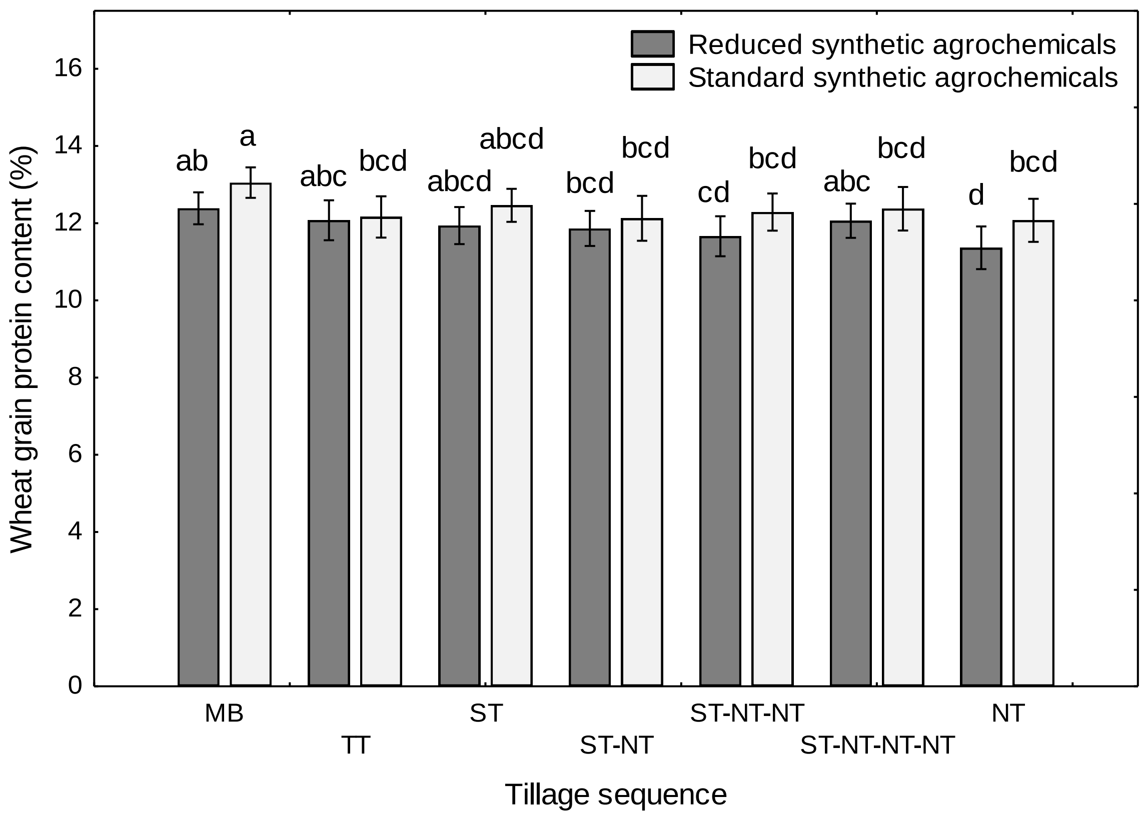

Figure 6.3: Wheat grain protein content of samples collected in 2018 and 2020, as influenced by the tillage sequence and crop management system at Langgewens Research Farm. The different letters on top of the bars denote a significant difference (P<0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage.

In the system with **standard** synthetic agrochemicals, all tillage treatments, except the MB, led to similar (P>0.05) grain protein content. In the systems with the **reduced** synthetic agrochemicals, the grain protein content in the MB, TT, ST, ST-NT, and ST-NT-NT-NT treatments did not differ (P>0.05). Concerning the effects of the growing season, 2018 led to a grain protein content (13.3%) which was 22% more than the protein content in the grains from the 2020 growing season (10.9%). In both growing seasons, the MB and NT treatments resulted in the highest and lowest (but not always significant) grain protein content.

6.3.2 Canola crop

At 90 DAE, the aboveground biomass was affected (P<0.05) by tillage sequence (Table 6.3). The MB treatment resulted in the highest (P<0.05) aboveground biomass with 7146 kg ha^{-1}. No differences (P>0.05) were found between the other tillage sequences which led to biomass that ranged from 5812 to 6078 kg ha^{-1}.

Table 6.3: The F-values with degrees of freedom, and P-values from the mixed model ANOVA for the canola crop productivity parameters as affected by the tillage sequence, crop management system and their interactions. Boldfaced p-values denote significant effects at P<0.05. Biomass = kg DM ha^{-1}.

	Tillage sequence (T)		Management system (M)		T x M	
Parameter	*F*(6,17)	*P*	*F*(2,3)	*P*	*F*(12,73)	*P*
Biomass at 90 DAE	3.42	**0.02**	0.18	0.84	1.05	0.42
Biomass at plant maturity	1.20	0.06	9.33	**0.05**	1.20	0.30
Seed yield (kg ha^{-1})	6.68	**0.001**	73.8	**0.01**	1.52	0.13
Seed oil content (%)	10.6	**<0.001**	5.67	0.14	0.81	0.64
Thousand seed mass (g)	2.74	0.05	0.11	0.90	0.67	0.78

At physiological maturity, the crop management system affected (P<0.05) the aboveground biomass (Table 6.3). The system with **standard** application of synthetic agrochemicals resulted in greater (P<0.05) aboveground biomass than the systems with **reduced**, and **minimum** synthetic agrochemicals, by 19% and 34% respectively. The systems with **reduced**, and **minimum** synthetic agrochemicals did not differ (P>0.05) from each other.

Canola seed yield was affected (P<0.05) by both the crop management system and tillage sequence (Table 6.3). Seed yield generally decreased with a reduction in synthetic agrochemical application such that the system with **standard** application of synthetic agrochemicals had the highest yield (P<0.05). Canola seed yield in the system with **standard** synthetic agrochemicals was less but did not differ (P>0.05) from the system with **reduced** application of synthetic agrochemicals. The lowest (P<0.05) canola seed yield occurred in the system with **minimum** synthetic agrochemicals. The system with the **reduced** synthetic agrochemicals had a seed yield (2284 kg ha^{-1}) which was 9% and 46% more than the yield in the systems with **standard** (2092 kg ha^{-1}), and **minimum** (1569 kg ha^{-1}) synthetic agrochemicals (results not shown). For all the seven tillage treatments, there were no differences (P>0.05) in seed yield between the systems with **standard** and **reduced** synthetic agrochemicals (Figure 6.4). The NT, MB, TT, and infrequent tillage treatment ST-NT-<u>NT</u> resulted in greater seed yield (P>0.05) in the system with **reduced** synthetic agrochemicals relative to the system with the **standard** synthetic agrochemicals (the underlined letters in the tillage sequence denotes the tillage treatment conducted). In the system with **reduced** synthetic agrochemicals, the NT and infrequent tillage sequence ST-NT-<u>NT</u> led to higher (but not always significant) canola seed yield than other tillage treatments.

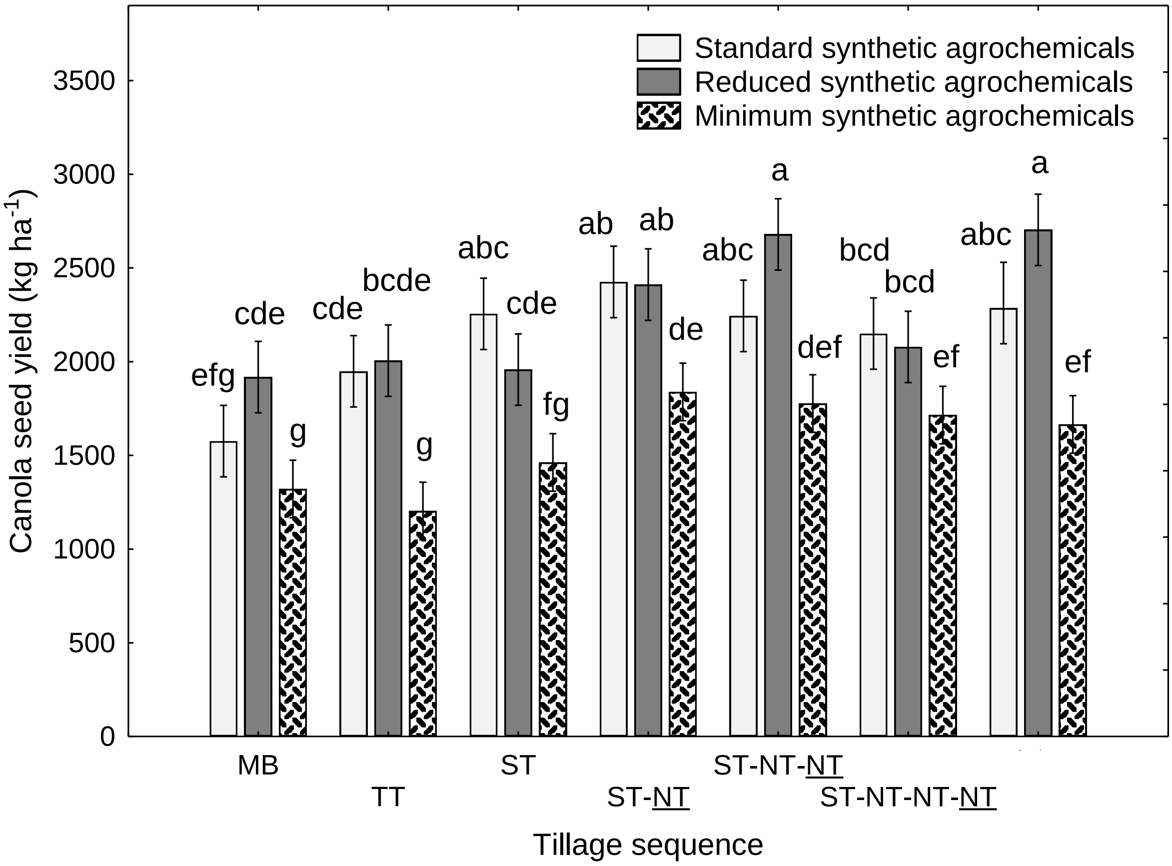

Figure 6.4: Canola seed yield as affected by tillage sequence and crop management system at Langgewens Research Farm in 2019. The different letters on top of the bars denote a significant difference (P<0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the tillage treatment for 2019.

Canola seed oil yield was affected (P<0.05) by tillage sequence (Table 6.3). The canola seed oil content ranged between 36.4% in the MB treatment (standard synthetic agrochemicals) and 42.8% in the NT treatment (reduced synthetic agrochemicals) (Figure 6.5). Relative to the system with the standard synthetic agrochemicals, the system with reduced synthetic agrochemicals led to a higher (P>0.05) seed oil content in all tillage treatments. The tillage treatments MB, TT, ST-NT, and ST-NT-NT-NT resulted in seed oil content that did not differ (P>0.05) in the three crop management systems, **standard**, **reduced** and **minimum**.

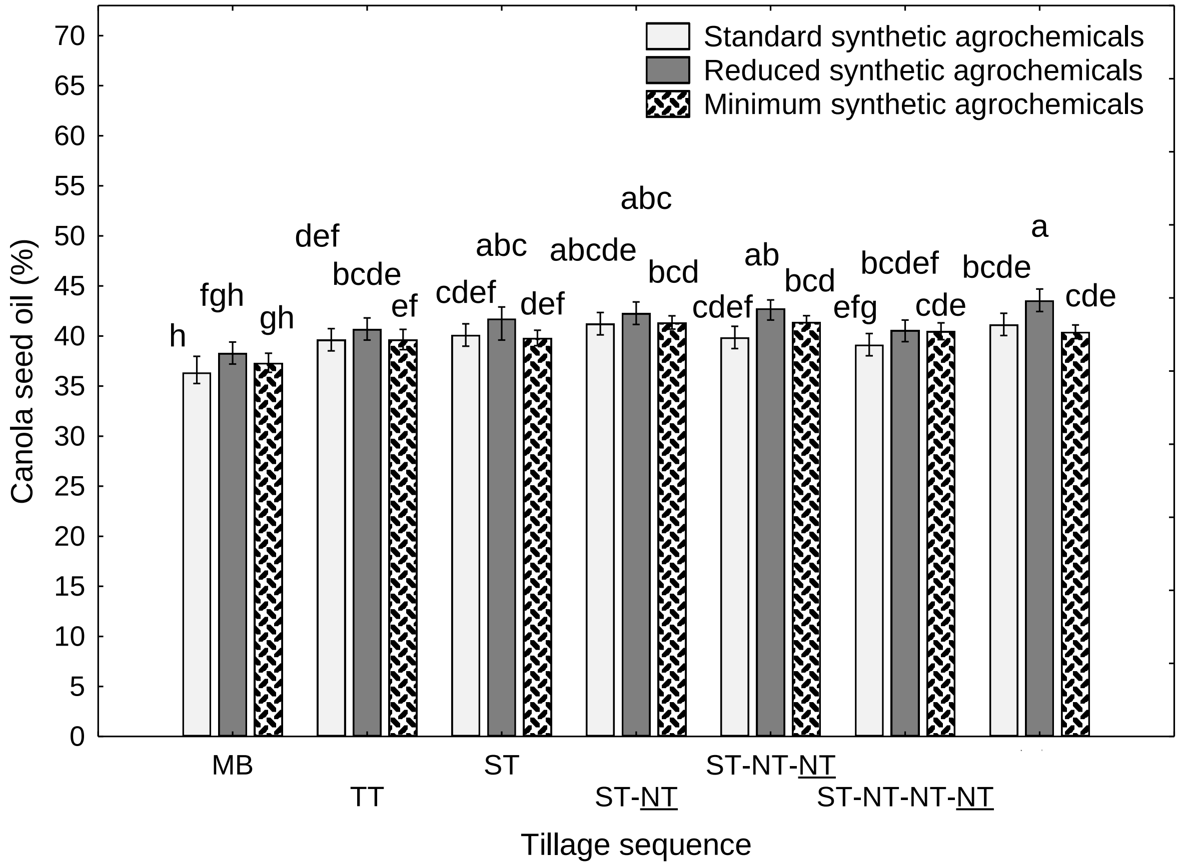

Figure 6.5: Canola seed yield as affected by tillage sequence in each crop management system at Langgewens Research Farm in 2019. The different letters on top of the bars denote a significant difference (P<0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The underlined treatment in the sequence indicates the tillage treatment for 2019.

No differences (P>0.05) were found in the thousand seed mass (2.6 - 2.7 g) of canola.

6.4 Discussion

It is generally acknowledged that the use of synthetic agrochemicals leads to increased crop yields, at least in the short to medium term (Dahal and Dhakal, 2016; Foteinis and Chatzisymeon, 2016; Knapp and van der Heijden, 2018; Loaiza Puerta et al., 2018). However, some argue that the use of synthetic agrochemicals has led to the degradation of the soil (Dahal and Dhakal, 2016; Swanepoel et al., 2015; Udall et al., 2015), water (Foteinis and Chatzisymeon, 2016) and increased greenhouse gas emissions (H. P. J. Smit et al., 2021). In this research, the crop management system with the **standard** synthetic agrochemicals generally led to higher (P>0.05) wheat and canola biomass production, and grain yield, than the systems with **reduced**, and **minimum** synthetic agrochemicals. The yield differences between the systems with **standard**, and **reduced** synthetic agrochemicals were expected as populations of soil microorganisms and beneficial insects need time to adapt to the new environment (Cormack, 2006). The process of converting from **standard** synthetic agrochemicals to agrochemical-free or certified organic farming is marked by a general decline in crop yield in the initial years (Cormack, 2006).

Our results from the systems with **standard**, and **reduced** synthetic agrochemicals, however, show that it is possible to reduce the quantity of synthetic agrochemicals that are applied in the fields. Except for the system with **minimum** synthetic agrochemicals, there were generally no grain or seed yield differences (P>0.05) between the crop management system with **standard** and **reduced** synthetic agrochemicals in all growing seasons. The only difference between the system with **standard**, and **reduced** synthetic agrochemicals was in the <u>ST</u>-NT treatment in 2018. In 2019, canola seed yield was highest (P<0.05) in the NT and ST-NT-<u>NT</u> treatments relative to the MB, TT and ST-NT-NT-<u>NT</u> treatments in the system with reduced synthetic agrochemicals (Figure 6.4). Nonetheless, canola was only grown over one season, therefore, definitive conclusions cannot be made about the effects of treatments on canola.

Concerning treatments that involved some form of minimum or no-tillage, and **reduced** synthetic agrochemicals, the ST and ST-NT-NT-NT treatments resulted in relatively higher yields (P>0.05) than other tillage treatments for wheat in both 2018 and 2020. The ST-NT-NT and NT treatments did this for canola (Figure 6.4). Importantly, this shows that it is possible to reduce both tillage and synthetic agrochemicals without resulting in yield losses. Nonetheless, it should be noted that bio-chemicals were each applied twice in the wheat crop and thrice in the canola crop. The bio-chemicals were likely to be more effective for pest and disease control rather than in aiding crop growth through weed suppression. There was no noticeable pest or disease attack within any part of the trial site, but weeds were problematic in the systems with **reduced**, and **minimum** synthetic agrochemicals.

Our results on wheat grain yield in the crop management system with the **standard** synthetic agrochemicals (Figures 6.1 and 6.2) were in agreement with results by

Agenbag (2012) who found no differences ($P>0.05$) in grain yield between the NT and infrequent tillage treatments. In other studies involving one-off tillage practices (occasional or strategic tillage), crop yield neither improved nor decreased significantly from that of the NT treatment (Blanco-Canqui and Wortmann, 2020; Conyers and Dang, 2014; Dang et al., 2018; Kirkegaard et al., 2014). These results seem to indicate that the infrequent tillage practices do not negatively affect crop yield. However, if the application of herbicides is reduced sufficiently, as in the management system with **minimum** synthetic agrochemicals, there is a greater chance of crop failure as evidenced in 2019 and 2020. This seems to suggest that tillage alone at the start of the growing season may not be adequate in crop production as weeds can become a major challenge during the growing season. In a study conducted in the UK, Cormack (2006) states that cultivation with a tined weeder and limited hand pulling can be an effective method of controlling weeds. Regardless of the differences in the climatic conditions between the UK and South Africa, cultivation with a tined weeder and hand pulling (in addition to any initial tillage that occurs at the start of the season) could be effective in weed control in South Africa. Currently, tine weeding is not being practised in commercial wheat farming in South Africa. To reduce the application of synthetic agrochemicals, some work may need to be done to adjust row spacing to enable passage of the tine weeder. Although cultivation can bring the buried viable weed seeds to the surface where they can germinate, it is the weeds that have already germinated and established that can negatively affect crop growth. Canola (Figure 6.4) in the system with **reduced** synthetic agrochemicals compared well with canola in the system with the **standard** synthetic agrochemicals partly due to weed control by hand pulling. Hand pulling of weeds was not done in the wheat crop of 2020, leading to crop failure in the system with **minimum** synthetic agrochemicals. Weed control by hand pulling is possible in arable farming systems but is costly as it requires a lot of labour.

The thousand kernel mass and hectolitre mass of the wheat grains were not affected ($P>0.05$) by the tillage treatments, either in 2018 or 2020. Our findings on the thousand kernel mass are similar to the results obtained by Taner et al. (2015) and Seepamore et al. (2020). In South Africa, wheat of good quality should have a hectolitre mass of at least 74 kg hL^{-1}. The hectolitre mass obtained in this trial had an average mass of 82.1 kg hL^{-1}. Wheat grain protein content is also an important quality factor in wheat grading. In South Africa, a wheat grain protein content of at least 10% is required for a good grading. In this research, the 2018 and 2020 wheat grain protein contents were greater than 10.4% in each of the seven tillage treatments which means that the wheat grains from all tillage sequences were generally of good bread baking quality. In both growing seasons, the highest and lowest ($P<0.05$) wheat grain protein content were in the MB and NT treatments respectively, possibly due to increased nutrient mineralisation in the MB ploughed fields (Labuschagne et al., 2020).

Canola seeds of better quality in terms of percentage oil content and thousand seed mass were produced in the infrequent tillage and NT treatments. The MB treatments led to the production of canola seeds of relatively lower quality. The current canola grading system in South Africa does not incentivise increased seed oil or protein content (Swanepoel and Labuschagne, 2020).

Although synthetic agrochemicals in crop production can be effective in weed and pest control their excessive use can be detrimental, not only to the environment (Lackmann et al., 2021; Udall et al., 2015) but to humans (Alsen et al., 2021; Krzastek et al., 2020; Lesseur et al., 2021). For example, the pesticide, dimethoate (active ingredient phosphorodithioate), which was applied on the wheat crop of 2018, can damage human DNA (Nazam et al., 2020) and some European countries have proposed banning the pesticide. Also, there is increased concern about the direct and indirect negative effects of the herbicide, glyphosate, on human health (IARC, 2015). Although some studies argue that there is no direct link between glyphosate and human cancer (Andreotti et al., 2018; Temple, 2016), the World Health Organisation's International Agency for Research on Cancer (IARC) categorised glyphosate as probably carcinogenic to humans (IARC, 2015) due to increased incidences of illness amongst people exposed to the herbicide (Davoren and Schiestl, 2018). Some researchers argue that although glyphosate does not directly affect humans, it negatively affects the gut microbiome which disrupts the microflora diversity and balance (Davoren and Schiestl, 2018; Patocka, 2018; Peillex and Pelletier, 2020), and metabolism thereby creating a perfect environment for the development of chronic diseases such as gastrointestinal disorders, diabetes, heart disease and cancer (Patocka, 2018). It is, therefore, important to replace some synthetic agrochemicals with bio-chemicals in food production. Long-term studies are needed to evaluate the trade-offs between the cost of bio-chemicals and environmental benefits so that more producers can be motivated to use fewer synthetic agrochemicals.

The economic feasibility of using bio-chemicals in arable farming was beyond the scope of this research but would need to be evaluated to encourage producers to reduce the quantity of synthetic agrochemicals they apply. In addition, the farming problems cannot be overcome by the simple substitution of individual inputs. Therefore, to reduce reliance on synthetic agrochemicals, it may be beneficial to change the management strategies to include livestock, competitive crops, cover crops, plant density and row spacing (MacLaren et al., 2021).

6.5 Conclusions and practical implications

The infrequent tillage practices were not different from continuous NT treatments in wheat grain and canola seed yield, and quality. When the use of synthetic agrochemicals is **reduced**, infrequent tillage treatments are more effective than NT for wheat production, but the NT treatment worked best for canola production. The results show that it is unnecessary to conduct intensive tillage with the MB plough as it did not result in significantly higher yields, relative to the infrequent tillage and NT treatments in both systems with **standard** and **reduced** synthetic agrochemicals. Also, it is possible to reduce the quantity of synthetic agrochemicals that are applied to crops by replacing them with bio-chemicals without significant changes in grain or seed yields and quality. However, reducing the quantity of synthetic agrochemicals (as in the systems with **reduced** or **minimum** agrochemicals) may mean that any form of tillage conducted at the beginning of the growing season will not be adequate for weed control. Therefore, weed control could be achieved through cultivation with tined weeders as well as a variety of integrated weed control strategies such as the inclusion of livestock, use of competitive crop varieties, cover crops, and appropriate row spacing and plant density.

We recommend that farmers prevent intensive tillage and adopt NT or infrequent tillage practices during the process of converting from **standard** to **reduced** use of synthetic agrochemicals. Future studies should evaluate the economic feasibility of applying bio-chemicals in arable farming and the weed pressure over the long run when **reduced** use of synthetic agrochemicals is followed.

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CHAPTER 7

Can infrequent tillage practices affect soil weed seedbank diversity in a dryland crop rotation system?

Abstract

Weed seedbank diversity can be used as an indicator of agroecosystem sustainability. However, tillage and synthetic agrochemicals can affect the soil weed seedbank diversity by either promoting the germination or extinction of seeds. In this study, the effects of seven tillage treatments within a long-term (44-years) tillage trial (mouldboard plough, tine tillage, shallow-tine (ST) tillage, no-tillage (NT), ST every two years in rotation with NT, ST every three years in rotation with NT, and ST every four years in rotation with NT), and three rates of synthetic agrochemicals (standard, reduced and minimum), on weed seedbank were investigated between 2018 and 2020 in South Africa's Mediterranean climate zone. It was hypothesised that: (i) infrequent tillage practices, and (ii) the system with reduced synthetic agrochemicals will increase the soil weed seedbank diversity compared to the MB, and NT treatments, and the systems with standard synthetic agrochemicals, respectively. Weed seedbank density, Shannon-Wiener, and Gini-Simpson diversity indices, species richness and Pielou's evenness index were assessed for each treatment. Twenty-one weed species were identified across all treatments with *Lolium rigidum* and *the Conyza* species being the dominant weeds, however, soil weed seedbank diversity did not differ ($P>0.05$) (i) in the MB, NT, and infrequent tillage practices, and (ii) in the systems with reduced and standard synthetic agrochemicals. The similarity ($P>0.05$) between the standard and reduced systems seems to suggest that it is possible to successfully farm with reduced synthetic agrochemicals. Overall, this long-term trial site broadly had a low weed seedbank species diversity (Shannon-Wiener diversity indices <1.5), probably due to the continuous application of synthetic agrochemicals over a long period.

7.1 Introduction

A ‘weed’ refers to any plant that grows where it is not wanted (Hussey et al., 1997). Most weeds in field cropping systems are resilient with good root and seed production abilities, can efficiently utilise nutrients, and outcompete or out-grow the crop (Gibson, 2010). Weed control in field cropping systems is mainly achieved by tillage and use of herbicides and mainly focuses on reducing the number of weeds, rather than promoting weed diversity. Increased weed seedbank diversity has recently been advocated as an indicator of agroecosystem sustainability (Storkey and Neve, 2018). The soil weed seedbank comprises any viable seeds that have recently fallen on the soil surface together with those that have accumulated in the soil over several years (Mahé et al., 2021). Cropping systems with higher soil weed seedbank diversity are associated with being more agronomically and environmentally sustainable than those with lower weed diversity (Liebman et al., 2021; Neve et al., 2018).

A higher weed seed diversity is important as it ensures increased plant diversity which prevents the population growth of a few dominant species (Liebman et al., 2021; Storkey and Neve, 2018). On the contrary, a lower plant diversity can lead to the proliferation of a few adapted species, which may quickly develop some resistance to herbicides. The weed flora diversity can promote ecosystem services through increased natural predation of both weeds and pests (Neve et al., 2018; Storkey et al., 2018).

Tillage can control weeds by killing or burying weeds, their seeds and propagules to depths that prevent their germination (MacLaren et al., 2021; Mahé et al., 2021). Tillage may also bring up viable buried weed seeds to the surface. In general, different tillage operations can affect the soil weed seedbank by either promoting the germination of some seeds or causing the death of other seeds (Romaneckas et al., 2021). Most weeds with small seeds tend to require less or partial soil cover and therefore germinate in no-tillage fields. Weeds with bigger seeds tend to germinate in conventionally tilled fields as they may require total cover by the soil (Pardo et al., 2019). Larger seeds also have more sprouting energy than smaller seeds which enable them to germinate in conventionally tilled soils (Romaneckas et al., 2021). Despite the potential benefits of tillage in weed control, excessive tillage can lead to the breakdown of soil structure (Bottinelli et al., 2017; Gao et al., 2017), depletion of soil organic carbon (Tshuma et al., 2021) and increased soil erosion (Bogunovic et al., 2018; Vach et al., 2018). The classic case of the deadly Dust Bowl of the 1930s in the United States of America was partly due to extensive deep tillage (Lee and Gill, 2015). To improve and preserve soil quality, no-tillage has been promoted and adopted across the world (Strauss et al., 2021a, 2021b). The practice of no-tillage can, however, lead to increased weed pressure as farmers are forced to rely on herbicides for weed control. Strategic tillage and infrequent tillage practices can be used for weed control. Strategic or occasional tillage refers to one-off tillage which is conducted in no-tillage fields to ameliorate a specific problem (Blanco-Canqui and Wortmann, 2020). On the contrary, infrequent tillage is not one-off tillage but a pattern of tillage rotations that involve a phase of tillage and a phase of no-tillage (Tshuma et al., 2021). Conducting strategic and infrequent tillage could reduce the need to apply synthetic herbicides.

Synthetic herbicides can effectively control weeds by killing the weeds and their propagules (Gibson, 2010; Pardo et al., 2019). If applied before the reproductive stage, herbicides can prevent weed seed production and thereby limit seeds that are added to the soil seedbank. However, the continuous, excessive use of synthetic herbicides has led to reduced weed diversity, and the development of herbicide resistant weeds (Heap, 2021). Therefore, farmers need to implement more integrated weed control strategies, which includes application of herbicides with different modes of action (but not at excessive rates), physical pulling or slashing of weeds, mulching (Mashingaidze et al., 2017), planting of competitive crop varieties (Gibson, 2010; Mahé et al., 2021), tillage (but not excessive), use of natural predators such as grazing livestock, and crop rotation (MacLaren et al., 2021). Crop rotation involving species that are not related, such as rotation of cereals with a broadleaf crop, enables the use of different selective herbicides which can prevent the domination of a few weed species and may promote greater weed diversity. Furthermore, the use of competitive crops in a rotation system can disrupt the weed life cycle (Schillinger and Paulitz, 2018), by providing quick shading and thereby preventing weeds from intercepting sunlight.

The study of the soil weed seedbank can provide a good indicator of the effectiveness of the weed management strategies applied in the field (Pardo et al., 2019). Long-term experiments can provide vital information about tillage effects on weed infestations.

However, worldwide, few long-term tillage experiments have focused on weed seedbank studies (Pardo et al. 2019). Furthermore, to our knowledge, no published article discusses the infrequent tillage effects on soil weed seedbank in systems that apply varied rates of synthetic agrochemicals (fertilisers herbicides, fungicides, and insecticides).

In this research, we aimed to determine the effects of long-term (44 years) tillage practices and short-term use of varied rates of synthetic agrochemicals on the soil weed seedbank in a dryland crop rotation system. It was hypothesised that: (i) infrequent tillage practices will lead to increased soil weed seedbank diversity compared to both continuous tillage and no-tillage practices, and (ii) the system with **reduced** synthetic agrochemicals will lead to increased soil weed seedbank diversity compared to the systems with **standard** and **minimum** synthetic agrochemicals.

7.2 Materials and methods

7.2.1 Trial site description

The research was conducted at Langgewens Research Farm (33°17ˈ0.78ˈˈ S, 18°42ˈ28.09ˈˈ E) of the Western Cape Department of Agriculture, in the Swartland region of South Africa. The Swartland region has a Mediterranean-type climate. The Köppen-Geiger climate classification is Csa (warm temperate climate with hot, dry summer). Langgewens receives an annual rainfall of 395 mm, of which approximately 80% falls between April and September, the growing season for this region (ARC-Small Grain Institute, 2020). The trial site has a 300 mm shallow lithic soil, locally known as a Glenrosa-soil form (Soil Classification Working group, 1991) or internationally, as Haplic Cambisols (IUSS Working Group WRB 2015). The soil had approximately 14.7% clay content (excluding the gravel and stone content), whilst the gravel and stone content in the A horizon is 45% (Maali and Agenbag 2003).

7.2.2 Trial history and treatments

The long-term research trial within which this current trial was conducted was established in 1976. Fifty-six plots, each measuring 50 m x 6 m, were laid out within four replicated blocks. The blocks were separated by a buffer zone of at least 9 m, and plots were separated by a 1 m buffer zone. The research described in this paper was conducted between 2018 and 2020. Wheat (*Triticum aestivum*) was rotated with canola (*Brassica napus*) and lupins (*Lupinus* spp.) in a four-year cycle; wheat (2018)-

canola (2019)-wheat (2020)-legume cover (2021). Seven tillage treatments (Table 7.1), and three rates of synthetic agrochemicals applications were investigated; **standard**, **reduced**, and **minimum**. In this article, each of the bold terms represents the rates of synthetic agrochemical application between 2018 and 2020. The systems with **reduced** and **minimum** synthetic agrochemicals were only started in 2018 and 2019, respectively.

Table 7.1: Summary of tillage treatments, abbreviations and the Implements used at Langgewens Research Farm. All plots were sown with a no-till drill.

Tillage treatment	Abbreviation	Tools used and tillage intensity
Mouldboard	MB	Ploughing with a chisel (tine) plough to a depth of 150 mm, followed by the mouldboard plough to a depth of 200 mm and field cultivator to a depth of 50 mm.
Tine-tillage	TT	Tillage with a chisel plough to a depth of 150 mm, followed by field cultivator to a depth of 50 mm.
Shallow tine-tillage	ST	Tillage with a chisel plough to a depth of 75 mm followed by a non-selective pre-plant herbicide.
No-tillage	NT	Tillage was not conducted. Non-selective pre-plant herbicides were used to control the weeds and volunteer plants
ST applied every 2nd year in rotation with NT	ST-NT	Tillage with a chisel plough to a depth of 75 mm was conducted once every two years.
ST applied every 3rd year in rotation with NT	ST-NT-NT	Tillage with a chisel plough to a depth of 75 mm was conducted once every three years.
ST applied every 4th year in rotation with NT	ST-NT-NT-NT	Tillage with a chisel plough to a depth of 75 mm was conducted once every four years.

Twenty-eight of the 56 plots received a **standard** application of synthetic agrochemicals as determined by the Langgewens Technical Committee, according to practices common in the region (ARC-Small Grain Institute, 2020; FERTASA, 2016).

The remaining 28 plots received a **reduced** application of synthetic agrochemicals, in which some of the synthetic agrochemicals were replaced with bio-chemicals. In this article, the term, *bio-chemical* does not imply organic certification but refers to products derived from natural compounds. Bio-chemicals that were introduced are *Trichoderma asperellum*, silicic acid, and triacontanol and bull kelp (*Nereocystis luetkeana*) extracts. In the wheat crops of 2018 and 2020, the bio-chemicals were applied twice within 30 days. In the canola crop of 2019, the bio-chemicals were applied three times within 90 days. Bio-chemicals were used to promote plant health and growth and acted as substitutes for synthetic insecticides, fungicides, and fertilisers. All bio-chemicals were manufactured and supplied by Real IPM (A full list of chemicals applied is available in the supplementary Tables S1-5).

In 2019 and 2020, all 56 plots were divided into two subplots which were separated by a buffer zone of 1 m. One sub-plot measured 35 m x 6 m and continued to receive either the **standard** or **reduced** synthetic agrochemicals. The second subplot measured 14 m x 6 m and received a single application of herbicide and will be referred to as the system with **minimum** application of synthetic agrochemicals.

The seeds planted in the systems with **reduced**, and **minimum** synthetic chemicals were treated with the bio-chemical *Trichoderma asperellum* before planting. Furthermore, the systems with **reduced** and **minimum** synthetic agrochemicals received a mixture of 50% synthetic fertiliser and pelletised chicken manure. Wheat cultivar SST 056 was planted on 11th May 2018 at a rate of 100 kg ha^{-1}. Canola cultivar Alfa TT was planted on 30th April 2019 at a rate of 3.5 kg ha^{-1}. The wheat cultivar SST 0166 was planted on 12th May 2020 at a rate of 90 kg ha^{-1}.

All crops were harvested at the end of October of each year, however, in 2020, the wheat crop in the system with **minimum** synthetic agrochemicals was infested with weeds and terminated by mowing 90 days after crop emergence. It is important to note that after crop harvesting, the trial site remained fallow through the dry summer period (November to April); to prevent sprouting of summer weeds all plots were therefore treated with non-selective herbicides.

7.2.3 Assessments

Soil weed seedbank samples were collected in March of each year, before conducting any tillage treatments, and the arrival of the first rains (usually in April) which could trigger germination of seeds. Soil weed seedbanks can be assessed by the emergence method and/ or direct extraction of seeds from soil (Liebman et al., 2021). We chose the seedling emergence method as it is regarded as a reliable method of determining the composition of viable seeds from the soil seedbank (Esmailzadeh et al., 2011; Reinhardt and Leon, 2018). The method can also indicate the potential weed pressure in a given year (MacLaren et al., 2021).

Although some of the tillage treatments from the previous season could have buried some seeds to a greater depth or brought buried seeds to the surface, we collected soil samples to a depth of 50 mm. The 50 mm depth was chosen because seeds that are buried within this depth have a greater chance of germinating and contributing to the weed pressure during the growing season (MacLaren et al., 2021).

In 2018 and 2019, one composite soil sample comprising ten soil cores (42 mm in diameter, i.e., 0.0139 m^2 field area) was collected from each of the 56 plots to a depth of 50 mm and air-dried. In 2020, a total of 112 composite soil samples were collected (the 56 plots were split into two sections in 2019 but were sampled separately for the first time in 2020). The composite soil samples were each placed in plastic seedling trays of 330 mm length x 280 mm width x 110 mm height, on a 40 mm thick layer of sterilised sand. The trays with the soil samples were placed under shade nets to prevent contamination of samples by wind-dispersed seeds whilst enabling the soil to warm and cool with changes in ambient temperature. Overhead micro-sprinklers were used to irrigate the samples for eight minutes each day to promote germination. In addition, trays with sterilised sand only were placed under the same shade nets and used as controls to monitor contamination with external seeds. Every week, all seed trays were checked for seedling emergence. The seedlings were allowed to develop until the species could be identified, counted, and removed from the trays. This process was repeated several times until no new seedlings emerged.

When new seedlings had stopped emerging, the soil in the trays was stirred (during the late spring to early summer; September to October) to bring any non-germinated seeds to the surface to promote germination and the emergence of all viable seeds. Weed identification and enumeration were stopped at end of October as we were interested in weeds that directly affect crop growth and harvest (April to October). Common weeds were identified to species level and other weeds, to genus level. A small percentage (0.03%) of seedlings could not be identified but were included in the species richness calculation (Díaz-Villa et al., 2003).

We assessed the weed species response to tillage and level of synthetic agrochemical application by determining the weed seedbank density, species richness, Shannon-Wiener diversity index (H') (Magurran and McGill, 2011), Simpson diversity index/Gini-Simpson (1 − Simpson's original index) (Simpson, 1949), and Pielou's evenness index (J') (Pielou, 1975). Although both diversity indices (Shannon-Wiener and Gini-Simpson) are generally used to measure the diversity of species in an ecosystem (Roswell et al., 2021), they were both included in this article as they account for different variables. The Shannon-Wiener diversity index accounts for both the species richness and evenness whereas the Gini-Simpson index specifically measures the probability that two individuals, drawn randomly from the sample, will be of different species (Roswell et al., 2021).

7.2.4 Data analyses

Seedbank data from the systems with **standard** and **reduced** synthetic agrochemicals from 2018 to 2020 was analysed separately from the seedbank data collected from the system with **minimum** synthetic agrochemicals in 2020. The seedbank data for the 2020 growing season was unbalanced as the system with **minimum** synthetic agrochemicals had twice as many samples as each of the systems with **standard** and **reduced** synthetic agrochemicals. Data analyses were carried out with STATISTICA™ software version 13.5.0.17 (TIBCO Software Inc.). Although the system with **minimum** synthetic agrochemicals was only evaluated in 2020, one-way ANOVAs were used to compare the mean seedbank species density of the system with **minimum** synthetic agrochemicals to the three-year means of the systems with **standard** and **reduced** synthetic agrochemicals. Post-hoc pairwise comparisons of means were performed using Fisher's least significance difference (LSD) test at a 5% significance level. Where the ANOVA residuals were not normally distributed, the non-parametric Kruskal-Wallis H test was performed and then post-hoc pairwise comparisons of means were performed using the Z' values at a 5% significance level.

Furthermore, the Variance Estimation, Precision and Comparison (VEPAC) package was used to fit mixed-effects models to the 2018 to 2020 data from the systems with **standard** and **reduced** synthetic agrochemicals using the Restricted Maximum

Likelihood (REML) procedure (Type III decomposition). Tillage sequence, level of synthetic agrochemical application, growing season, and their interactions were specified as fixed effects. To account for repeated measures, plot was specified as a random effect nested in block. The 2020 seedbank data were analysed with a mixed model ANOVA in *R* Version 4.0.2 (2020-06-22), using the *lmer* package with tillage sequence and level of synthetic agrochemical application (**standard**, **reduced**, and **minimum**), and their interactions as the fixed effects and block as the random factor. To enable comparison of the tillage treatments and the three levels of synthetic agrochemical applications, the Kenward-Roger's estimation procedure was used to account for the unbalanced data and heteroskedasticity.

F-tests were used to assess whether fixed effects were significant at 5% level. Post-hoc pairwise comparisons of means were performed using Fisher's least significance difference (LSD) test at a 5% significance level. All variables were subjected to a test of normality using the normal probability plots of raw residuals. Also, the Shapiro-Wilk W-test for normality was performed on the residuals for each analysis.

7.3 Results

7.3.1 Weed seedbank species

From soil samples collected from the systems with **standard** and **reduced** synthetic agrochemicals, twenty-one weed species germinated and emerged from the growing trays in the mesh tunnel (Table 2). Twenty species were identified, and one could not be identified and was labelled as unknown. Amongst the most dominant weed species across all treatments were ryegrass (*Lolium rigidum*), hairy fleabane (*Conyza* spp.), knotweed (*Polygonum aviculare* L.) and woodsorrel (*Oxalis* spp.) (Table 2). These weed species accounted for 63, 13, 7 and 5% of the mean weed seedbank density from the trays (across all treatments) in the mesh tunnel, respectively. Although the system with **minimum** synthetic agrochemicals was only sampled in 2020, the mean weed seedbank density from this system was compared to the three-year mean weed seedbank densities of the systems with **standard** and **reduced** synthetic agrochemicals. Except for ryegrass, hairy fleabane, creeping wood sorrel and the common milk thistle (*Sonchus oleraceus* L.), there were no significant differences between the weed seedbank densities in the systems with **standard**, **reduced** and **minimum** synthetic agrochemicals (Table 2).

Table 7.2: Three year mean densities (m^{-2}) of weed seedbank in soil samples collected across all tillage treatments from the systems with **standard** and **reduced** synthetic agrochemicals at Langgewens Research Farm in March of each year from 2018 to 2020. Samples from the system with **minimum** synthetic agrochemicals were only collected in 2020, therefore the mean seedbank density is for one growing season. SE = standard error of the mean; **Standard**, **reduced**, **minimum** = level of synthetic agrochemical application; n/a = not applicable. The different superscripts in each row denote a significant difference (P<0.05).

Weed species	Common name	Mean weed seedbank count (m^{-2}) ± SE		
		Standard	**Reduced**	**Minimum**
Lolium spp.	Ryegrass	798 ± 104.7[b]	2464 ± 284.7[b]	3689 ± 505.3[a]
Conyza spp.	Hairy fleabane	458 ± 80.6[ab]	339 ± 53.9[b]	687 ± 82.2[a]
Polygonum aviculare L.	Knotweed	277 ± 76.7[a]	332 ± 78.5[a]	264 ± 89.7[a]
Oxalis spp.	Woodsorrel	285± 77.4[a]	299 ± 84.4[a]	6 ± 3.33[b]
Crassula spp.	Pygmy weed	142 ± 35.2[a]	131 ± 27.5[a]	115 ± 23.1[a]
Raphanus raphanistrum L.	Wild radish	52 ± 9.43[a]	58 ± 10.83[a]	30 ± 11.6[a]
Cardamine hirsuta L.	Hairy bittercress	60 ± 17.4[a]	31 ± 14.01[a]	n/a
Bulbostylis capillaris (L.) Kunth ex C.B.Clarke	Tufted hair-sedge	29 ± 6.60[a]	39 ± 23.2[a]	13 ± 5.55[a]
Oenothera biennis L.	Evening primrose	29 ± 9.64[a]	33 ± 9.42[a]	48 ± 20.1[a]
Chenopodium carinatum R.Br.	Green goosefoot	34 ± 27.5[a]	5 ± 2.04[a]	34 ± 18[a]
Gnaphalium pensylvanicum Willd.	American cudweed	10 ± 4.19[a]	23 ± 7.25[a]	8 ± 3.01[a]
Chenopodium album L.	Fat hen	12 ± 3.83[a]	16 ± 5.91[a]	19 ± 5.96[a]
Corrigiola littoralis L.	European corrigiola	16 ± 6.70[a]	10 ± 5.49[a]	21 ± 9.51[a]
Gnaphalium uliginosum L.	Marsh cudweed	9 ± 2.93[a]	9 ± 2.93[a]	9 ± 3.71[a]
Chenopodium murale (L.) S. Fuentes	Nettle-leaf goosefoot	4 ± 1.87[a]	13 ± 8.03[a]	19 ± 9.47[a]
Tribulus terrestris L.	Caltrop	4 ± 2.23[a]	10 ± 3.41[a]	13 ± 4.55[a]
Euphorbia inaequilatera Sond.	Prostrate spurge	2 ± 1.72[a]	6 ± 2.79[a]	n/a
Malva parviflora L.	Small-flowered mallow	3 ± 1.91[a]	4 ± 1.87[a]	10 ± 5.65[a]
Medicago spp.	Medics	3 ± 2.58[a]	4 ± 2.24[a]	31 ± 15.59[a]
Sonchus oleraceus L.	Common milk thistle	1 ± 0.86[b]	1 ± 0.86[b]	31 ± 7.99[a]
Unknown		1 ± 0.43[a]	1 ± 0.43[a]	n/a

Concerning the system with **minimum** synthetic agrochemicals, ryegrass had the highest weed seedbank density (Table 7.2) and was also the most dominant in the field (personal observation). Eighteen weed species germinated and emerged from the soil samples collected from the system with **reduced** synthetic agrochemicals. Although ryegrass had the highest seedbank density, the grass species had a relatively small effect on the overall weed seedbank species diversity, when compared to the broadleaves. The broadleaves accounted for 86% (18 species) of the weed species that emerged from the germinating trays in the mesh tunnel (Table 7.2).

7.3.2 Weed seedbank density

The interaction between the growing season and rate of synthetic agrochemical application affected ($P<0.05$) the weed seedbank density in the systems with **standard** and **reduced** synthetic agrochemicals (Table 7.3). Except for 2019, the soil weed seedbank density did not differ ($P>0.05$) in the system that received the **standard** and **reduced** synthetic agrochemicals (Figure 7.1). In 2019, the weed seedbank density in the system with **reduced** synthetic agrochemicals (4230 seeds m^{-2}) was 269% more ($P<0.05$) than the seedbank density in the system with **standard** synthetic agrochemicals (1145 seeds m^{-2}). When broadly considering the tillage treatments in the systems with **standard**, and **reduced** synthetic agrochemicals, the MB and ST-NT-NT treatments led to the lowest and highest ($P<0.05$) mean weed seed densities than all other treatments (results not shown). In the 2020 growing season, the weed seedbank density was not significantly affected by any treatments. However, the MB and TT treatments generally led to the lowest and highest mean weed seedbank densities, respectively (results not shown).

Table 7.3: The F-values with degrees of freedom, and P-values from the mixed model ANOVA for the weed seedbank study at Langgewens Research Farm, as affected by the tillage sequence, level of synthetic agrochemical application (**standard**, and **reduced**) and growing season (2018 to 2020) and their interactions. Boldfaced p-values denote significant effects at P<0.05.

Parameter	Tillage sequence (T)		Agrochemical application (A)		Growing season (G)		T x A		T x G		A x G		T x A x G	
	F(6,12)	*P*	*F*(1,2)	*P*	*F*(2,4)	*P*	*F*(6,12)	*P*	*F*(12,24)	*P*	*F*(2,4)	*P*	*F*(12,24)	*P*
Weed seedbank density	3.58	**0.03**	2.54	0.25	5.56	0.07	0.91	0.52	1.38	0.24	11.5	**0.02**	1.45	0.21
Species richness	3.35	**0.04**	0.001	0.93	49.1	**0.002**	0.39	0.87	0.84	0.61	0.36	0.72	0.73	0.71
Shannon-Wiener diversity index	3.02	**0.04**	1.10	0.41	39.7	**0.002**	0.98	0.48	0.82	0.63	0.82	0.50	0.92	0.54
Gini-Simpson's diversity index	3.10	**0.04**	2.73	0.24	27.3	**0.005**	1.50	0.26	1.16	0.37	1.17	0.40	0.93	0.54
Pielou's evenness index	2.40	0.09	2.89	0.23	5.33	0.07	1.56	0.24	1.61	0.15	1.57	0.31	0.88	0.58

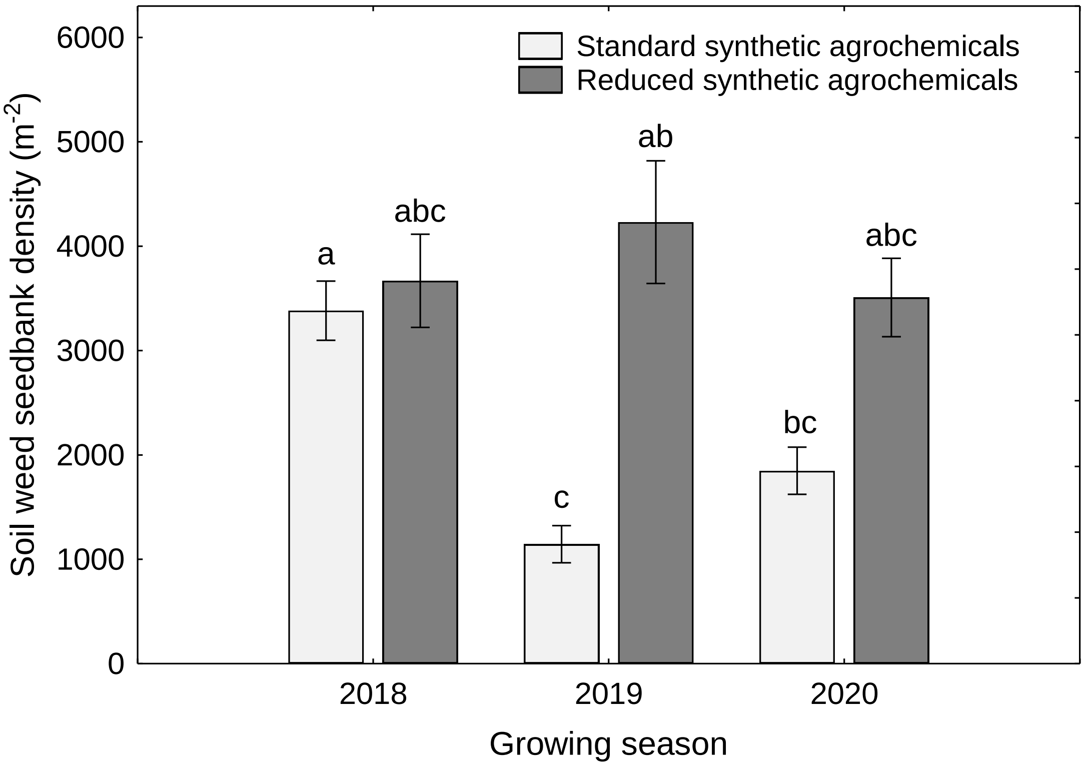

Figure 7.1: The soil weed seedbank density as affected by the interaction between growing season and application of synthetic agrochemicals at Langgewens Research Farm, South Africa. The different letters on top of the bars denote a significant difference (P<0.05). Crops grown in 2018 = wheat; 2019 = canola; 2020 = wheat. Error bars denote the standard error of the mean.

7.3.3 Species richness

In the systems with **standard**, and **reduced** synthetic agrochemicals, the species richness was affected (P<0.05) by the growing season, and tillage sequence (Table 7.3). The species richness was generally higher during the wheat phase (P<0.05) in 2018, followed by 2020 and was lowest during the canola phase in 2019. Concerning tillage, the TT and ST-NT-NT treatments led to the highest (P<0.05) and lowest mean species richness across all treatments. The variation in weed seedbank species richness in each growing season is shown in Figure 7.2.

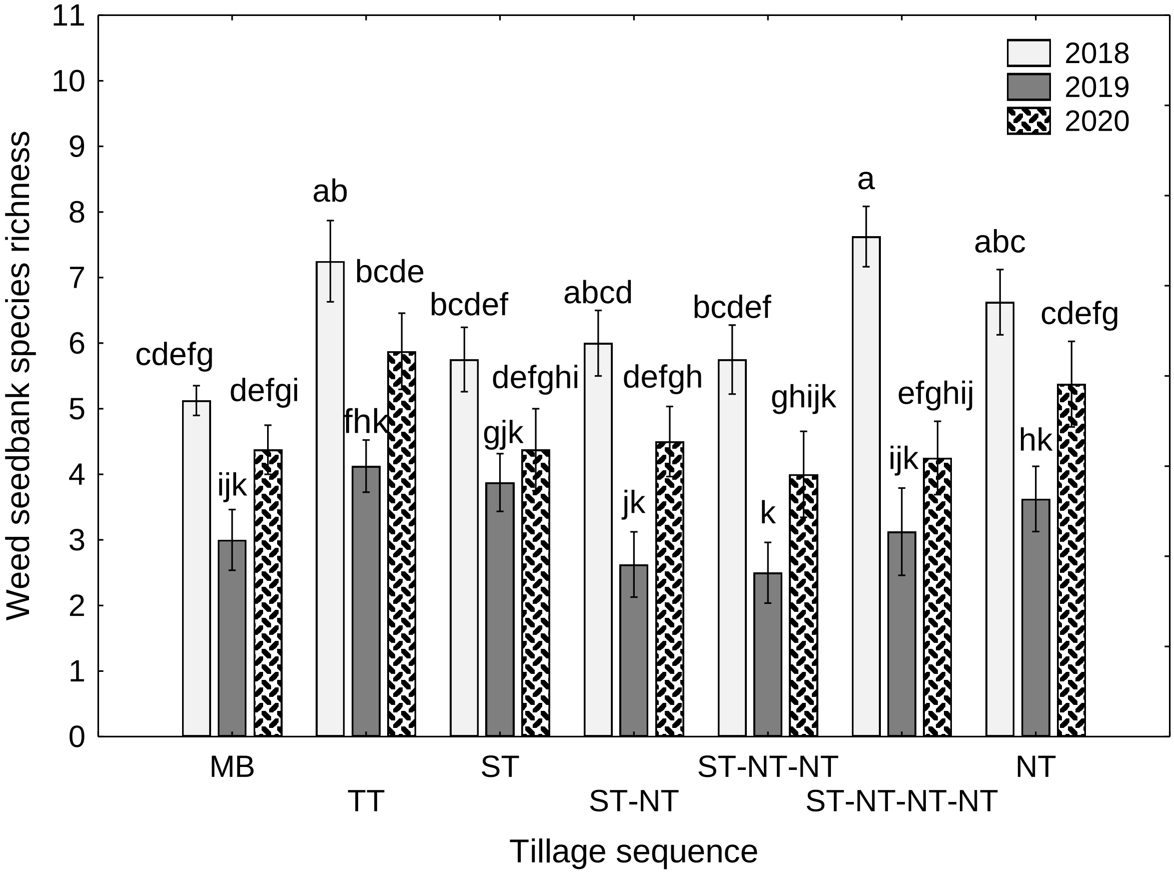

Figure 7.2: The mean weed seedbank species richness as affected by tillage sequence and growing season in the systems with **standard** and **reduced** synthetic agrochemicals at Langgewens Research Farm. The different letters on top of the bars denote a significant difference (P<0.05). Error bars denote the standard error of the mean. MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. Crops grown in 2018 = wheat; 2019 = canola; 2020 = wheat.

The weed seedbank species richness in the system with **standard** and **reduced** synthetic agrochemicals fluctuated with the growing season and tillage treatment. However, the species richness did not differ (P>0.05) in 2018 and 2020 in the MB, TT, ST, ST-NT, and NT tillage treatments. The species richness in 2018 was always greater (P<0.05) than that in 2019 across all tillage treatments. Except for the MB and ST tillage treatments, huge differences between 2018 and 2019 were noted in all the other tillage treatments (Figure 7.2). Although the species richness was greater in 2020 than in 2019, there were no significant differences in the MB, ST, ST-NT-NT, and ST-NT-NT-NT tillage treatments. For the 2020 growing season only, the weed seedbank species richness was not affected (P>0.05) by any treatment. However, the species richness tended to be lower (P>0.05) in the system with **minimum** synthetic agrochemicals than in the system with **standard** and **reduced** synthetic agrochemicals. The weed species that grew in the three systems were broadly similar across all treatments, except for three weed species (hairy bittercress, prostrate spurge, and an unknown grass species) that were not found in the system with **minimum** synthetic agrochemicals (Table 7.2).

7.3.4 Diversity indices

The Shannon-Wiener, and Gini-Simpson diversity indices for the systems with **standard**, and **reduced** synthetic agrochemicals were both affected (P<0.05) by the growing season, and tillage sequence (Table 7.4). Both the Shannon-Wiener and Gini-Simpson diversity indices fluctuated with time in each tillage treatment and had a similar trend. The 2018 growing season led to the highest (P<0.05) diversity indices for both the Shannon-Wiener and Gini-Simpson (1.63 and 0.77) indices followed by 2020 (1.28 and 0.69) and then 2019 (0.93 and 0.52) which had the lowest indices, respectively. Notable differences between 2018 and 2019 were in the infrequent tillage treatments (ST-NT, ST-NT-NT, and ST-NT-NT-NT) where the diversity indices (Shannon-Wiener and Gini-Simpson) were higher in 2018 than in 2019 by (149 and 105%), (165 and 137%) and (97 and 58%), respectively. For both indices, no differences (P>0.05) were found between the 2018 and 2020 growing seasons in the MB, TT, ST, ST-NT, ST-NT-NT, and NT treatments.

When broadly considering the overall means for the three growing seasons, the TT tillage treatment led to the highest Shannon-Wiener and Gini-Simpson diversity indices (1.50 and 0.73) but did not differ (P>0.05) from the indices in the MB (1.25 and 0.67), ST (1.30 and 0.68), ST-NT-NT-NT (1.03 and 0.66)) and NT (1.37 and 0.68) treatments, respectively. The lowest (P<0.05) diversity indices were in the ST-NT-NT tillage treatment which had a Shannon-Wiener and Gini-Simpson diversity index of 1.03 and 0.52, respectively. For the 2020 growing season only, the weed seedbank species Shannon-Wiener and Gini-Simpson diversity indices had a similar trend and were both not significantly affected by any treatment. However, the diversity indices (Shannon-Wiener and Gini-Simpson) tended to be highest (P>0.05) in the NT treatment (1.46 and 0.71) and lowest in the ST-NT-NT treatment (1.08 and 0.57), respectively (results not shown).

Table 7.4: Mean diversity indices (Shannon-Wiener, and Gini-Simpson) in the systems with **standard**, and **reduced** synthetic agrochemicals as affected by the growing season (2018 to 2020) and tillage sequence at Langgewens Research Farm. For each diversity index, the different superscripts across the rows and columns denote significant differences per growing season and tillage treatments, respectively ($P<0.05$). MB = Mouldboard at 200 mm depth; TT = Tine-tillage at 150 mm depth; ST = Shallow tine-tillage at 75 mm depth; NT = No-tillage. The figures in the table are mean ± standard error of the mean.

Treatment	Growing season		
	2018	2019	2020
Shannon-Wiener diversity index			
MB	1.49 ± 0.056^{abcdef}	0.93 ± 0.170^{hij}	1.33 ± 0.093^{cdefgh}
TT	1.79 ± 0.060^{ab}	1.22 ± 0.125^{defgh}	1.50 ± 0.092^{abcde}
ST	1.54 ± 0.093^{abcde}	1.16 ± 0.101^{efgh}	1.21 ± 0.138^{defgh}
ST-NT	1.63 ± 0.068^{abcd}	0.66 ± 0.187^{ij}	1.30 ± 0.135^{cdefgh}
ST-NT-NT	1.47 ± 0.123^{abcdefg}	0.55 ± 0.172^{j}	1.06 ± 0.169^{fghi}
ST-NT-NT-NT	1.85 ± 0.052^{a}	0.94 ± 0.209^{hij}	1.20 ± 0.186^{defgh}
NT	1.69 ± 0.080^{abc}	1.05 ± 0.172^{ghi}	1.38 ± 0.149^{bcdefg}
Gini-Simpson diversity index			
MB	0.75 ± 0.020^{abc}	0.56 ± 0.086^{def}	0.71 ± 0.036^{abcde}
TT	0.81 ± 0.008^{ab}	0.66 ± 0.054^{abcde}	0.73 ± 0.024^{abcd}
ST	0.75 ± 0.023^{abc}	0.65 ± 0.033^{abcde}	0.64 ± 0.052^{abcde}
ST-NT	0.78 ± 0.011^{ab}	0.38 ± 0.100^{fg}	0.69 ± 0.042^{abcde}
ST-NT-NT	0.71 ± 0.043^{abcd}	0.30 ± 0.090^{g}	0.56 ± 0.065^{def}
ST-NT-NT-NT	0.82 ± 0.008^{a}	0.52 ± 0.102^{ef}	0.63 ± 0.092^{bcde}
NT	0.78 ± 0.020^{ab}	0.57 ± 0.090^{cde}	0.67 ± 0.056^{abcde}

7.3.5 Pielou's evenness index

The Pielou's evenness index was not affected ($P>0.05$) by any treatments across all the growing seasons. However, the Pielou's evenness index in the systems with **standard** and **reduced** synthetic agrochemicals (2018 to 2020 growing seasons) tended to be higher but not significant in the MB and TT tillage treatments. The index values generally ranged between 0.73 in the ST-NT-NT treatment and 0.89 in both the MB and TT treatments. For the 2020 growing season only, the index values generally ranged between 0.80 in both the ST-NT-NT and ST-NT-NT-NT tillage treatments, and 0.89 in the MB treatment (results not shown).

7.4 Discussion

Mahé et al. (2021) stated that weed seedlings may emerge within a short (in the first month) or long (after several years) period. However, in this study, only seedlings that emerged during the growing season (April and October) of each year from 2018 to 2020 were considered as they represent weed seedlings that could directly affect crop growth and harvesting within each growing season. Ryegrass and hairy fleabane were two of the most common weeds in our germination experiment in the mesh tunnel (Table 7.2). These weeds also germinated and emerged along with wheat and canola crops in the field. Other studies show that ryegrass can adapt to tillage type and herbicide use (Heap, 2021; Kirkegaard et al., 2014; MacLaren et al., 2021). Similarly, it was noted that ryegrass was the most dominant weed across all agrochemicals application systems, but especially in the system with **minimum** synthetic agrochemicals (Table 7.2 and *in situ* assessment). The abundance of ryegrass in the system with **minimum** synthetic agrochemicals contributed to the wheat crop failure in this system in 2020.

Although the total number of seedlings that emerged from each tray does not reflect the total density of viable seeds in the soil (Mahé et al., 2021), it was considered to be indicative of total viable seeds that could emerge in the field and was used to determine the weed seed bank density per m^2. In this study, the weed seedbank density was affected ($P<0.05$) by the interaction between the growing season and the level of synthetic agrochemical application. Storkey and Neve (2018) explained that the use of synthetic herbicides is broadly intended to reduce weed density, therefore, it would be expected for a system that applies **standard** synthetic agrochemicals to have less weed seedbank density than one that applies a **reduced** quantity of synthetic agrochemicals. Nonetheless, in our study, the system that received a complete application of synthetic agrochemicals (**standard**) had a relatively similar weed seedbank density with a system that received half the quantity of synthetic agrochemicals (**reduced**), except in 2019. The general insignificant differences in weed seedbank density between the two systems (**standard** and **reduced**) may be indicative of the possibility to successfully farm with less application of herbicides. In effect, it may be unnecessary to apply **standard** synthetic herbicides if the weed seedbank density remains unchanged.

In the systems with **standard**, and **reduced** synthetic agrochemicals, the MB treatment led to the lowest ($P<0.05$) mean weed seed densities relative to all other treatments. Our results are in agreement with the findings by Hernández Plaza et al. (2015), Nichols et al. (2015) and Feledyn-Szewczyk et al. (2020) who found more seeds in the NT than in the conventionally tilled fields but are in contrast to those found by Romaneckas et al. (2021) and MacLaren et al. (2021). Like MacLaren et al. (2021), we believe that the contrasting results were due to the site-specificity of weed-tillage-rotation interactions.

Some studies show that tillage can significantly affect the weed seedbank species richness (Benvenuti and Pardossi, 2017; Pardo et al., 2019; Romaneckas et al., 2021). Studies by Schwartz-Lazaro and Copes (2019) and Hossain Mobarak et al. (2021) show that reduced tillage can increase the variety of species that germinate. However, Cordeau et al. (2020) found contradicting results over different seasons. At the beginning of their study, they noted that tillage significantly increased the weed species richness. In a different season, the tillage treatments did not affect ($P>0.05$) the species richness. They attributed the differences to the use of herbicides. They stated that herbicide use in one of the seasons homogenised initially contrasting weed flora. Our results are similar to those found by Cordeau et al. (2020) in that the tillage treatments had varied effects on the seedbank species richness. Although the species richness was generally greater during the wheat phase (2018 and 2020) than in the canola phase (2019), Figure 7.2 shows that there were no significant differences in species richness between the tillage treatments in 2020, but differences ($P<0.05$) were found 2018 and 2019. Concerning species richness, our results were not significant but are similar to those found by Schwartz-Lazaro and Copes (2019) and Hossain Mobarak et al. (2021) in that the species richness was mostly greater in the NT and infrequent tillage treatment ST-NT-NT-NT than in the intensive MB treatments. We suspect that the application of synthetic herbicides during the fallow period between November and April could have contributed to our varied results. Furthermore, the systems with **reduced** and **minimum** synthetic agrochemicals were only started in 2018 and 2019, respectively. Therefore, the relatively short time that these two agrochemical regimes had been in place could have affected the overall species richness as the legacy effect of persistent soil weed seedbank might have contributed to the seedlings that germinated during the trial (Storkey and Neve, 2018).

Although diversity indices were originally formulated for ecology studies (Magurran, 2004), they have been adopted in different diversity studies, including in the arable cropping system. The Shannon-Wiener diversity values mostly range between 1.5 and 3.5 and are rarely greater than four (Magurran, 2004). The index increases as both the richness and the evenness of the community increase, therefore, values that are closer to 3.5 indicate a highly diverse community, whereas values closer to 2.5 indicate a moderately diverse community and values of 1.5 and less indicate a less diverse community in the soil seed bank (Magurran, 2004). In our study, the Shannon-Wiener diversity values ranged between 0.55 (in the ST-NT-NT treatment in 2019) to 1.85 (in the ST-NT-NT-NT treatment in 2018) (Table 7.4). Although the tillage treatments significantly affected the Shannon-Wiener diversity index in the systems with **standard** and **reduced** synthetic agrochemicals, the overall three-year means for each tillage treatment were close to or less than 1.5, which is indicative of a less diverse and environmentally unsustainable community (Liebman et al., 2021; Storkey and Neve, 2018).

The Gini-Simpson diversity index range from 0 to 1. A value closer to one is indicative of a high probability of randomly drawing two different species from a sample population (Roswell et al., 2021). In our trial, the Gini-Simpson values ranged between 0.3 (in the ST-NT-NT treatment in 2019) to 0.82 (in the ST-NT-NT-NT treatment in 2018) (Table 7.4). The Gini-Simpson was generally high or low when the Shannon-Wiener index was also high or low, respectively. Fifty-seven per cent of the Gini-Simpson indices recorded in Table 7.4 had values less than 0.7, indicating that there was less than 70% chance of randomly drawing two different weed species from most of the plots. Only 10% of the Gini-Simpson values (Table 7.4) were above 0.8 and these were recorded during the 2018 growing season; (TT = 0.81 and ST-NT-NT-NT =0.82). These values generally show that regardless of the effects of tillage, the weed seed species diversity of the whole trial area is low. We suspect that the use of herbicides during the last 44-years of this tillage trial could have led to the overall decline in the weed species diversity and richness. Storkey and Neve (2018) and Liebman et al. (2021) noted that prolonged use of herbicides may favour the growth and proliferation of a few adapted, dominant weed species that can outgrow/outcompete other plants or crops in the field, leading to low species richness and biodiversity.

The Pielou's evenness index was not affected (P>0.05) by any treatment and was broadly similar across all treatments. The index values ranged between 0.73 and 0.89. Pielou (1975) stated that the index values range between 0 and 1, values closer to zero indicate low evenness whilst values closer to one indicate more evenness. The index values from our trial broadly show that the species evenness was in most plots were moderate. The same species germinated and grew in most of the treatments (Table 7.2); however, ryegrass was dominant in the plots that received **minimum** synthetic agrochemicals (Table 7.2 and *in situ* assessment). Some studies on soil weed seedbank do not report on the effects of tillage on seedbank species evenness (Ball, 1992; Mahé et al., 2021; Romaneckas et al., 2021; Rotchés-Ribalta et al., 2017; Santín-Montanyá et al., 2018; Schwartz-Lazaro and Copes, 2019; Sosnoskie et al., 2006). However, studies on the effects of cropping system diversity by Liebman et al. (2021) and Sosnoskie et al. (2006) show that the weed seedbank studies can be affected by the diversity of the cropping system and the application of agrochemicals. In our trial, the cropping system was uniform, therefore, the application of herbicides could have partly influenced the seedbank species evenness.

Future studies on soil seedbank should incorporate and investigate the tillage effects on weed seedbank species evenness. Also, the studies could look at the effects of the tillage treatments when no herbicides are applied during the fallow period, between November and April. Instead of herbicide application, mechanical weed control by mowing could be implemented during the fallow period in areas that are not undulating. Alternatively, some livestock, such as sheep, could be introduced into the system (for controlled grazing) during the fallow period. In the future, the use of tine cultivators/weeders could be considered as alternatives for weed control.

7.5 Conclusions

Results from this study contradicted both our hypotheses that (i) infrequent tillage practices will lead to increased soil weed seedbank diversity compared to both continuous tillage and no-tillage practices, and (ii) the system with **reduced** synthetic agrochemicals will lead to increased soil weed seedbank diversity compared to the systems with **standard** and **minimum** synthetic agrochemicals. The weed seedbank diversity remained relatively similar across all tillage treatments in the systems with **standard** and **reduced** synthetic agrochemicals. In effect, we noted that the whole long-term trial site generally had a low weed seedbank species diversity as indicated by the low Shannon-Wiener diversity indices (<1.5), probably because of continuous application of synthetic agrochemicals over a long period. While diversity did not change, species assemblage potentially could have changed.

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CHAPTER 8

General conclusions

8.1 Introduction

The use of synthetic agrochemicals (fertilisers, fungicides, insecticides, and herbicides) in conventional agriculture has had positive results in food production. For example, the Green Revolution in the 1950s resulted in significant increases in food production (DeLong et al., 2015; Timmermann and Félix, 2015). The benefits of conventional agriculture have, however, been questioned in the past few decades as the quantity of the synthetic agrochemicals required to grow the same quantity of food keeps rising. Wang et al. (2015) explained that the use of synthetic fertilisers in China increased by 276% in a period of 20 years (1980 to 2005), while the total grain production only increased by about 51%. A general reduction in the effect of the extra agrochemicals was observed in different parts of the world and for various crops. DeLong et al. (2015) indicated that agriculture productivity growth declined from about 2% during the Green Revolution, to about 1% yields per year and that yields had become constant despite the application of synthetic agrochemicals. For example, rice yields were observed to have plateaued in the Republic of Korea, and wheat in northwest Europe and India. The extensive application of synthetic fertilisers has, *inter alia*, largely contributed to the acidification of agricultural lands and the decline in soil fertility. Repeated use of synthetic insecticides and herbicides can be detrimental to beneficial insects (Pannell et al., 2014), decreases the biodiversity of weed flora (Liebman et al., 2021; Storkey and Neve, 2018), and lead to the evolution of insects, pathogens and weeds that have resistance to these agrochemicals (Heap, 2021; Ndou et al., 2021).

Like synthetic agrochemicals, conventional tillage practices have contributed to increased food production but also land degradation. Amongst other things, conventionally tilled soils are prone to soil organic carbon depletion (Tshuma et al., 2021), reduced soil microbial diversity (Habig et al., 2018), and compaction (Laker and Nortjé, 2020). On the contrary, long-term conservation tillage practices can, *inter alia,* lead to improved soil quality by increasing the soil aggregate stability (Labuschagne et al., 2020a), but can cause soil nutrient stratification (Tshuma et al., 2021) and weed infestation (Kafwamfwa et al., 2017).

In South Africa, many farmers have stopped the practice of conventional tillage and have adopted conservation agriculture practices (Strauss et al., 2021b). Nonetheless, conservation agriculture practices, like other conventional agriculture practices, are currently heavily associated with synthetic agrochemical applications. If the current conservation agriculture systems in South Africa and the rest of the world are to limit the environmental damage caused by artificial inputs, then some form of tillage is likely to be necessary.

This research intended to enhance our understanding of the relationship between tillage frequency, soil quality and plant productivity in farming systems that do not entirely rely on the application of synthetic agrochemicals. Specifically, this research aimed to establish an acceptable tillage frequency regime that can be adopted in conservation agriculture systems to gradually minimise the application of synthetic agrochemicals in the Western Cape province of South Africa.

The research was conducted within a long-term (44-years) trial site at Langgewens Research Farm in the Swartland region, South Africa.

8.2 Summary of the research findings

The research findings are discussed below and are presented in sequence according to the five objectives listed in Chapter 1 of this thesis.

Chapter 3 addressed the first objective, which was to assess the effects of long-term infrequent tillage on the stratification of selected soil chemical parameters to a depth of 300 mm. Seven tillage treatments, which included the mouldboard plough, no-tillage, and infrequent tillage, were investigated. It was hypothesised that infrequent tillage practices will ameliorate some of the nutrient stratification problems that are associated with long-term no-tillage in dryland farming systems. Relative to other tillage treatments, the study described in Chapter 3 showed that infrequent tillage practices were able to reduce ($P>0.05$) the stratification of soil organic carbon, exchangeable magnesium, cation exchange capacity and zinc. Nonetheless, infrequent tillage practices were no better ($P>0.05$) than the no-tillage treatment as infrequent tillage could not effectively ameliorate the stratification of key soil chemical parameters such as pH and extractable phosphorus and did not increase the stocks and stratification ratios of soil organic carbon. Overall, infrequent tillage failed to ameliorate the stratification problems relative to no-tillage but showed potential to do so as it reduced the stratification of some parameters. Further research is required, and future studies could investigate the effectiveness of infrequent tillage treatments when the tillage implement is adjusted to cultivate to a deeper depth.

Chapter 4 addressed the second objective, which was to assess the impact of tillage practices and varied rates (**standard**, **reduced**, and **minimum**) of synthetic agrochemical application on soil microbial diversity indices and enzyme activity in a dryland cropping system. It was hypothesised that soil microbial diversity and enzyme activity would increase with a reduction in synthetic agrochemicals application and tillage intensity. In contrast to results from other soil microbial studies (de Quadros et al., 2012; Habig et al., 2018; Habig and Swanepoel, 2015; Tahat et al., 2020), the different rates of synthetic agrochemical application and tillage treatments did not affect ($P>0.05$) the soil microbial diversity (Shannon-Weiner and Evenness) indices. However, the activity of key soil microbial enzymes (β-glucosidase, acid and alkaline phosphatase, and urease) generally increased with a reduction of both synthetic agrochemicals and tillage intensity. Although not always significant, the activity of all four enzymes was generally lowest in the mouldboard treatment relative to other tillage treatments.

These results broadly show that intensive tillage with a mouldboard plough could negatively affect soil enzyme activity. Also, a reduction in tillage intensity and application of synthetic agrochemicals could contribute to the enhancement of soil biological parameters.

Chapter 5 addressed the third objective, which was to determine the long-term (44-years) tillage effects on wheat (*Triticum aestivum*) grain yield in a dryland farming system. This chapter explored the history of wheat production trends at the long-term trial site at Langgewens Research Farm and compared it to the current (2018-2020) yield responses of the same trial site. The long-term trial site initially cultivated wheat in monoculture and later changed to include a crop rotation system. Therefore, this aspect of the study hypothesised that with time, (i) the monoculture system will lead to reduced grain yield relative to crop rotation, (ii) the mouldboard treatment will lead to reduced grain yield relative to no-tillage and infrequent tillage, and (iii) the infrequent tillage practices will improve grain yield relative to continuous no-tillage.

It was observed that wheat grain yield in the monoculture system declined with time and was generally lower than that of the crop rotation system. These results are similar to the findings by Woźniak, (2020, 2019) who also found that the monoculture system resulted in yield reduction. In this long-term trial site, the monoculture system was stopped in 2010 partly due to weed infestation and reduced grain yield. Concerning grain yield in the mouldboard treatment, the chapter described how the mouldboard treatment resulted in a relatively high yield, similar (P>0.05) to that of the no-tillage and infrequent tillage treatments. Results from this study also contradicted the third hypothesis in this chapter in that infrequent tillage treatments did not significantly increase wheat grain yield relative to continuous mouldboard or no-tillage treatments.

Although continuous tillage with a mouldboard plough led to similar (P>0.05) grain yield as the no-tillage and infrequent tillage treatments, it can, *inter alia*, lead to an increased likelihood of soil structure breakdown, soil erosion, depletion of soil organic carbon, increased fuel use and greenhouse gas emission (Carbonell-Bojollo et al., 2019; Rutkowska et al., 2018). On the contrary, no-tillage and infrequent tillage practices can, amongst other things, improve soil quality and reduce greenhouse gas emissions (Strauss, 2021). Therefore, it would be best to opt for no-tillage or infrequent tillage and crop rotation to ensure sustainability.

Chapter 6 addressed the fourth objective, which was to determine the effects of tillage practices on wheat and canola (*Brassica napus*) yield and quality in a dryland crop rotation system that received, either **standard**, **reduced**, or **minimum** synthetic agrochemicals. This chapter focused on crop data from 2018 to 2020 growing seasons and tested the hypothesis that infrequent tillage practices will lead to higher crop productivity relative to both continuous mouldboard and no-tillage treatments in a system with **reduced** synthetic agrochemicals. Results from the system with **reduced** synthetic agrochemicals show that grain yield did not differ (P>0.05) between continuous mouldboard, no-tillage, and infrequent tillage treatments. Also, when comparing the systems with **standard** and **reduced** synthetic agrochemicals, there were no differences (P>0.05) in wheat grain or canola seed yield in four of the seven tillage treatments in 2018, five out of seven in 2019 and three out of seven in 2020.

Although infrequent tillage practices did not lead to higher crop productivity as hypothesised, it resulted in no reduction in yield or quality compared to no-tillage. Most importantly, infrequent tillage treatments were in some cases more effective at preventing yield reductions resulting from **reduced** agrochemical application. These results broadly indicate that it is possible to reduce the quantity of synthetic agrochemicals that are applied in the field cropping systems whilst conducting minimum soil disturbance.

Chapter 7 addressed the fifth objective, which was to determine the effects of long-term (44-years) tillage practices and short-term use of varied rates (**standard**, **reduced**, and **minimum**) of synthetic agrochemicals on the soil weed seedbank in a dryland crop rotation system. Recent studies on soil weed seedbanks state that cropping systems with higher soil weed seedbank diversity are associated with being more agronomically and environmentally sustainable than those with lower weed diversity (Liebman et al., 2021; Storkey and Neve, 2018). It was hypothesised that: (i) infrequent tillage practices will lead to increased soil weed seedbank diversity compared to both continuous tillage and no-tillage practices, and (ii) the system with **reduced** synthetic agrochemicals will lead to increased soil weed seedbank diversity compared to the systems with **standard** and **minimum** synthetic agrochemicals. This chapter showed that twenty-one weed species were identified across all treatments with *Lolium rigidum* and the *Conyza* species being the dominant weeds, however, soil weed seedbank diversity did not differ (P>0.05) in (i) the mouldboard, no-tillage, and infrequent tillage practices, and (ii) in the systems with **reduced** and **standard** synthetic agrochemicals.

It was observed that this long-term trial site broadly had a low weed seedbank species diversity (Shannon-Wiener diversity indices <1.5), probably due to the continuous application of synthetic agrochemicals over an extended period. Nevertheless, the similarity (P>0.05) between the **standard** and **reduced** systems seems to suggest that it is possible to successfully farm with reduced synthetic agrochemicals.

8.3 General conclusions

8.3.1 Effects of the tillage treatments

Four continuous tillage treatments: mouldboard ploughing (MB), tine-tillage (TT), shallow tine-tillage (ST), and no-tillage (NT) and three infrequent tillage treatments:

ST every two years in rotation with NT (ST-NT), ST every three years in rotation with NT (ST-NT-NT), and ST every four years in rotation with NT (ST-NT-NT-NT), were investigated. The effects of the tillage treatments varied but it was broadly observed that the intensive mouldboard treatment resulted in relatively similar grain yield ($P>0.05$) to that of the no-tillage and infrequent tillage treatments. However, soil analysis revealed that the soil organic carbon stocks and extractable phosphorus were significantly lower in the mouldboard ploughed plots relative to that in the no-tillage and infrequent tillage treatments. Although the tillage treatments did not affect ($P>0.05$) soil microbial diversity, microbial enzyme activity increased with a reduction in tillage frequency and intensity and was lowest ($P<0.05$) in the mouldboard treatment. A high soil organic carbon stock is indicative of soil fertility (Xu et al., 2018; Zhao et al., 2015). Higher enzyme activity can also indicate soil nutrient availability for crop uptake (Habig et al., 2018).

This work shows that a reduction in tillage intensity could be important in increasing soil fertility and thus improving sustainability of farming systems. However, there are some trade-offs to reducing tillage intensity as it led to stratification of some soil chemical parameters such as pH and extractable phosphorus which may limit crop productivity. The mouldboard treatment was the only treatment that was able to prevent nutrient stratification for most parameters such as pH, soil organic carbon (SOC), extractable P, exchangeable Ca and Mg and cation exchange capacity (CEC). The infrequent tillage treatments were able to reduce the degree of stratification of some soil nutrients relative to no-tillage, but the differences were not significant. Weed seedbank species were, however, not affected by the tillage treatment, but weed density was lowest in the mouldboard treatment and highest in the tine-tillage treatment.

Regarding crop productivity in this trial, the plots that received the mouldboard treatment had no stratification problems but led to the same wheat grain yield as that in the no-tillage plots (which had nutrient stratification) probably due to adequate rainfall and nutrient supply through fertilisers. The problem of nutrient stratification normally becomes apparent when the topsoil becomes dry and immobile nutrients become unavailable for plant uptake.

8.3.2 Effects of varied rates of synthetic agrochemical application

Three rates of synthetic agrochemicals were investigated: **standard**, **reduced,** and **minimum**. The combined wheat crop productivity results for 2018 and 2020 showed that there were no differences in yield and grain quality in four of the seven tillage treatments (Figure 6.1). And no differences were found in canola seed yields (Figure 6.4). Thus, most of the crop yield results indicated no significant differences between the system with **standard** and **reduced** synthetic agrochemicals. Soil biology analysis revealed that the system with **standard** synthetic agrochemicals led to the lowest ($P<0.05$) microbial enzyme activity relative to **reduced** and **minimum** systems. Also, the systems with **standard** and **reduced** synthetic agrochemicals led to similar ($P>0.05$) weed seedbank species diversity. The lack of significant crop yield and quality and weed seedbank species diversity differences between the systems with **standard** and **reduced** synthetic agrochemicals is suggestive of the potential to produce crops whilst reducing the synthetic agrochemical applications. The bio-chemicals applied in the system with **reduced** synthetic agrochemicals were effective in protecting the crops and could be considered as a means of reducing the use and reliance on synthetic agrochemicals in conventional cropping systems.

Nonetheless, further reduction in the application of synthetic agrochemicals, as was done in the system with **minimum** synthetic agrochemicals, did not yield positive crop productivity results due to severe weed problems. In 2019, harvest in the system with **minimum** synthetic agrochemical was only possible because an additional application of synthetic herbicides was conducted. In 2020, no additional synthetic agrochemical was applied, resulting in weed infestation and total wheat crop failure.

8.3.3 Synthesis

Overall, results from this study broadly highlight the importance of reducing both the intensity of tillage and the application of synthetic agrochemicals. A reduction of the two parameters can improve soil quality and crop productivity. However, there are trade-offs. A balance is required, such that some form of tillage is required to prevent nutrient stratification, but this should not be so intensive or frequent as to deplete the soil organic carbon stocks. Also, the application of **standard** synthetic agrochemicals as conducted in most conservation agriculture systems can be reduced, but not to the extent of completely avoiding the synthetic agrochemicals as shown by the total failure of the wheat crop in the system with **minimum** synthetic agrochemicals in 2020. In this research, it was expected that the infrequent tillage treatments and **reduced** synthetic agrochemicals would provide the required balance. However, infrequent tillage practices failed to significantly increase wheat grain yield and quality relative to the no-tillage and mouldboard treatments just as it failed to ameliorate the stratification of key soil chemical parameters. Nonetheless, results from the system with **reduced** synthetic agrochemicals shows that the Western Cape province has the potential to gradually introduce agroecological farming practices in wheat and canola production through the use of bio-chemicals. This research could be of benefit to all farmers who intend to make their farming systems more sustainable and environmentally friendly. However, the adoption of such farming principles is most likely to be high only if the farming enterprise is economically viable.

8.4 Recommendations

Considering the conclusions drawn from this study, several recommendations and suggestions for future research were made, and include those listed below:

i) It was expected that the infrequent tillage treatments would ameliorate some of the problems associated with long-term no-tillage. However, the infrequent tillage treatments generally failed to improve soil quality and crop yield relative to no-tillage, possibly because of the shallow tine-tillage implements which were set to cultivate to a depth of only 75 mm and could not facilitate the redistribution of soil chemical parameters down the soil profile. It is worth investigating whether the stratification could be reduced by using a tine-tillage implement which is set to cultivate to a depth of 150 mm instead of 75 mm. This may require changing the tillage treatment at the long-term tillage site from ST-NT-NT-NT to TT-NT-NT-NT.

ii) The systems with **standard** and **reduced** synthetic agrochemicals generally resulted in similar grain yield and microbial diversity indices. The similarities between the two systems could be indicative of the possibility of applying fewer synthetic agrochemicals in cropping systems. However, it is plausible that there could be clear distinctions between the two systems if the use of synthetic herbicides during the fallow period is reduced by implementing some integrated management systems including the introduction of livestock such as sheep to graze during the fallow period. The short-term aim is not to completely stop the use of synthetic herbicides, but to minimise their application. Therefore, grazing, and mowing, which has not been tried on the trial site could be explored to control summer weeds during the fallow period (November to March). Synthetic herbicides could thus be applied only prior to planting.

iii) It was noted that the long-term trial site broadly has a low pH_{KCl} (<5.0) which could be a result of a variety of factors, including the continued application of synthetic fertilisers over the last 44-years, which have also probably contributed to low weed seedbank species diversity (Shannon-Wiener diversity indices <1.5). The application of organic manure could aid in raising soil pH on this trial site. However, the practicality of applying manure will depend not only on the availability and cost of manure or organic soil amendments but on a change of mindset by local commercial farmers so that they may integrate livestock as part of conservation agriculture. Strauss et al., (2021a) explained that not all farmers in the Western Cape province favour integrating livestock in the cropping systems.

iv) This research involved the use of bio-chemicals in the systems with **reduced** and **minimum** synthetic agrochemicals, however, the economic feasibility of applying these bio-chemicals could not be evaluated. Future studies could conduct the economic feasibility of the experiment and compare the outcomes with that of the current conservation agriculture system.

v) Also, financial, and other barriers to the adoption of agroecological farming principles (including reductions to the use of synthetic agrochemicals) could be explored using social science methodology including surveys and case study interviews.

vi) In addition to soil microbial diversity and enzyme activity analysis, future studies could also investigate the effects of applying the bio-chemicals on nematode community structure. It would be valuable to study changes in these parameters over the longer-term following modifications in the agrochemical programmes.

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APPENDIX

Erratum for Chapter 3

Additional information was added to Chapter 3, a published article to correct and explain some concepts as well as to standardize the chapter with the rest of the thesis.

Specifically, changes were made to:

- Table 3.1: Additional information about the type of ANOVA was added to the table title. The values of the degrees of freedom were also added to the table.
- Table 3.2: Errors were made in presenting the information about extractable P and Cu; hence it was removed from the table.
- Table 3.3: Units of measurements were added.
- Section 3.2.3 (Soil sample collection): The reason for choosing the method proposed by Franzlubbers (2002) to calculate soil stratification ratios was added. The time of soil sampling with regards to the previous crop (wheat) was also provided.
- Section 3.2.4 (Data analysis): More information was added to explain the reason why REML was used in data analysis. Also added was the information on how nutrient conversions were made.
- In the conclusions section, additional information was added to support the use of infrequent tillage in reducing SOC stratification.

Supplementary material for Chapters: 4, 5, 6 and 7

Table S1: Synthetic agrochemicals (excluding fertilisers) applied on the 2018 wheat crop, in the management system with the **standard** use of synthetic agrochemicals at Langgewens Research Farm.

Chemicals applied	Active ingredient	Quantity
Glyphosate 360	Glyphosate	2 l ha^{-1}
Sakura	Pyroxasulfone	125 g ha^{-1}
Resolve	Rimsulfuron; thifensulfuron methyl	750 ml ha^{-1}
Dimethoate	Phosphorodithioate	750 ml ha^{-1}
Prosper Trio	Spiroxamine; tebuconazole; triadimenol	500 ml ha^{-1}

Table S2: Synthetic and bio-chemicals (excluding fertilisers) applied on the 2018 and 2020 wheat crop, in the management system with **reduced** use of synthetic agrochemicals at Langgewens Research Farm.

Chemicals applied	Active ingredient	Quantity
Synthetic chemicals		
Glyphosate 360	Glyphosate	2 l ha^{-1}
Sakura	Pyroxasulfone	125 g ha^{-1}
Bio-chemicals		
Real Trichoderma	*Trichoderma asperellum*	100 ml ha^{-1}
SeaBrix	*Nereocystis luetkeana; triacontanol*	2 l ha^{-1}
Fulvic Acid	Fulvic acid	1 l ha^{-1}
NewSil	Silicic acid	500 ml ha^{-1}

Table S3: Synthetic agrochemicals (excluding fertilisers) applied on the 2020 wheat crop, in the management system with the **standard** use of synthetic agrochemicals at Langgewens Research Farm.

Chemicals applied	Active ingredient	Quantity
Glyphosate 360	Glyphosate	2 l ha^{-1}
Sakura	Pyroxasulfone	125 g ha^{-1}
Resolve	Rimsulfuron; thifensulfuron methyl	750 ml ha^{-1}
Aurora	Carfentrazone – ethyl (Triazolinone)	10 g ha^{-1}
Abacus Advance	Pyraclostrobin; epoxiconazole (triazole)	1 l ha^{-1}
Mospilan	Acetamiprid (Acetamidine)	50 g ha^{-1}
Duette Ultra	Epoxiconazole (triazole); Thiophanate-methyl (benzimidazole)	550 ml ha^{-1}

Table S4: Synthetic agrochemicals (excluding fertilisers) applied on the 2019 canola crop, in the management system with the **standard** use of synthetic agrochemicals at Langgewens Research Farm.

Chemicals applied	Active ingredient	Quantity applied
Glyphosate 360	Glyphosate	2 l ha^{-1}
Sluggit	Metaldehyde	8 kg ha^{-1}
Atraflo	Atrazine	2 l ha^{-1}
Kerb Flo	Propyzamide	1.9 l ha^{-1}

Table S5: Synthetic and bio-chemicals (excluding fertilisers) applied on the 2019 canola crop, in the management system with **reduced** use of synthetic agrochemicals at Langgewens Research Farm.

Chemicals applied	Active ingredient	Quantity
Synthetic chemicals		
Glyphosate 360	Glyphosate	2 l ha^{-1}
Kerb Flo	Propyzamide	1.9 l ha^{-1}
Sluggit	Metaldehyde	8 kg ha^{-1}
Bio-chemicals		
Real Trichoderma	*Trichoderma asperellum*	100 ml ha^{-1}
SeaBrix	*Nereocystis luetkeana; triacontanol*	2 l ha^{-1}
Fulvic Acid	Fulvic acid	1 l ha^{-1}
NewSil	Silicic acid	500 ml ha^{-1}

Table S6: Synthetic agrochemicals (excluding fertilisers) applied on the 2019 canola crop, in the management system with **minimum** use of synthetic agrochemicals at Langgewens Research Farm.

Chemicals applied	Active ingredient	Quantity
Glyphosate 360	Glyphosate	2 l ha^{-1}
Kerb Flo	Propyzamide	1.9 l ha^{-1}

Table S7: Quantity of fertiliser (N: P: K) applied between 2018 and 2020 in the management systems with **standard**, **reduced**, and **minimum** use of synthetic agrochemicals at Langgewens Research Farm.

Fertiliser component	Fertiliser component applied (kg ha^{-1})					
	2018 (Wheat)		2019 (Canola)		2020 (Wheat)	
	Standard	**Reduced**	**Standard**	**Reduced**	**Standard**	**Reduced** & **Minimum**
Nitrogen	65	65	70	70	65	65
Phosphorous	12.5	13	12.5	13	12.5	13
Potassium	0	1.2	0	1.2	0	1.2

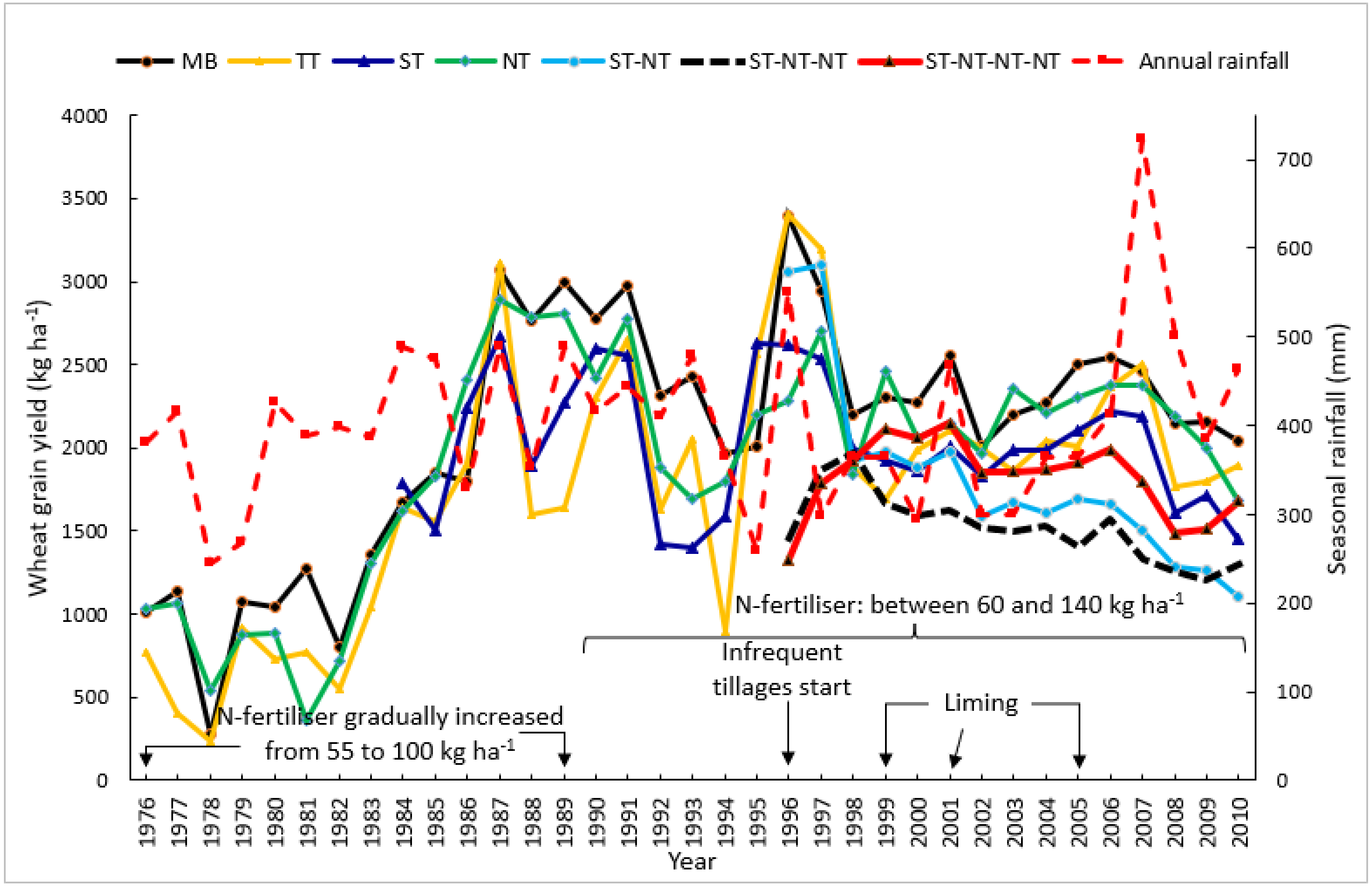

Figure S1: The long-term wheat grain yield and seasonal rainfall (April – September) in the monoculture system from 1976 to 2010 at Langgewens Research Farm. N-fertiliser applications ranged between 60 and 140 kg ha^{-1}.

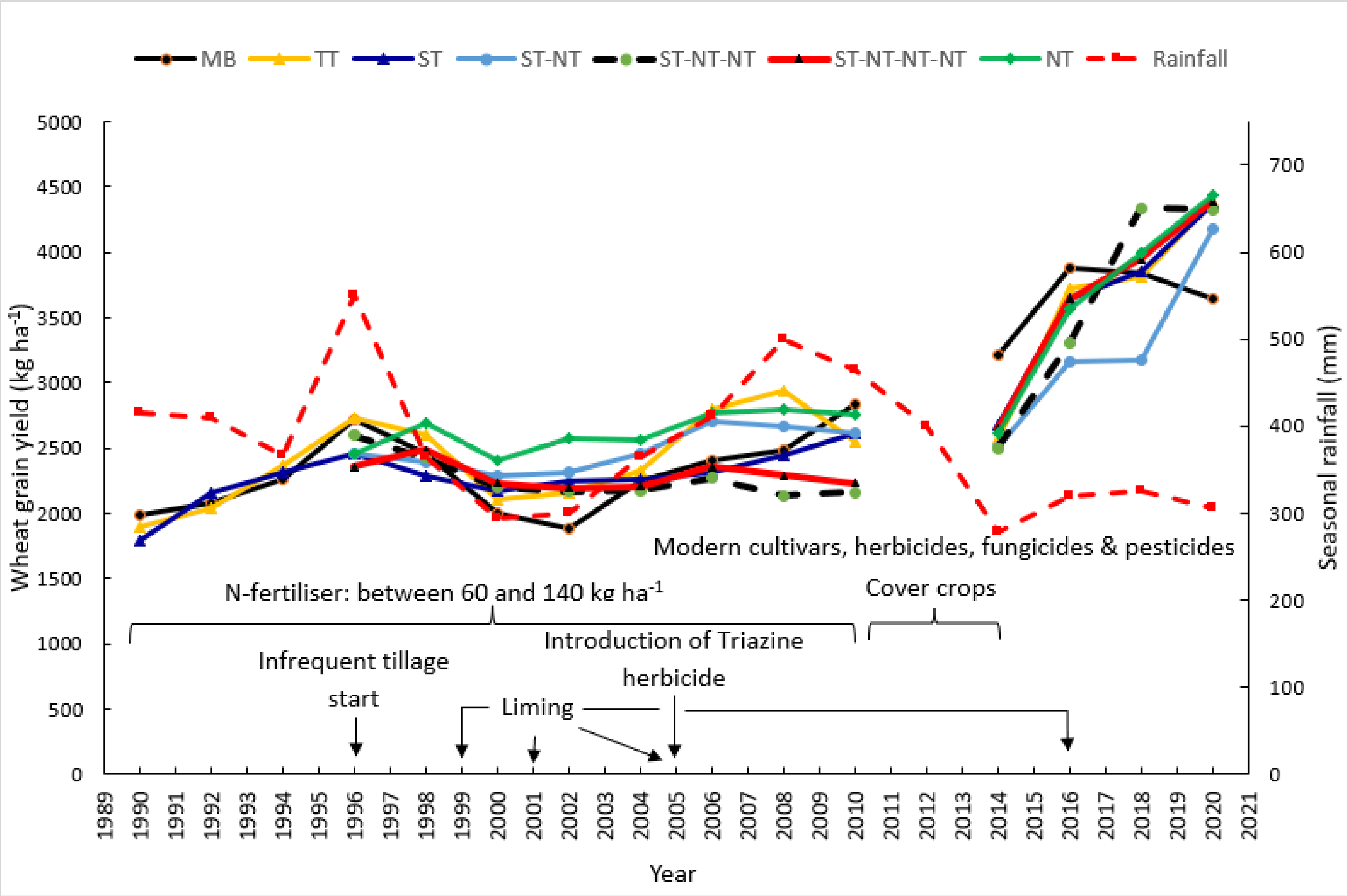

Figure S2: The long-term wheat grain yield and seasonal rainfall (April – September) in the crop rotation (WCWL) system from 1990 to 2020 at Langgewens Research Farm. 1990 to 2010, N-fertiliser ranged between 60 and 140 kg ha^{-1} in the wheat crop, however, 65 kg ha^{-1} was applied from 2014 onwards.

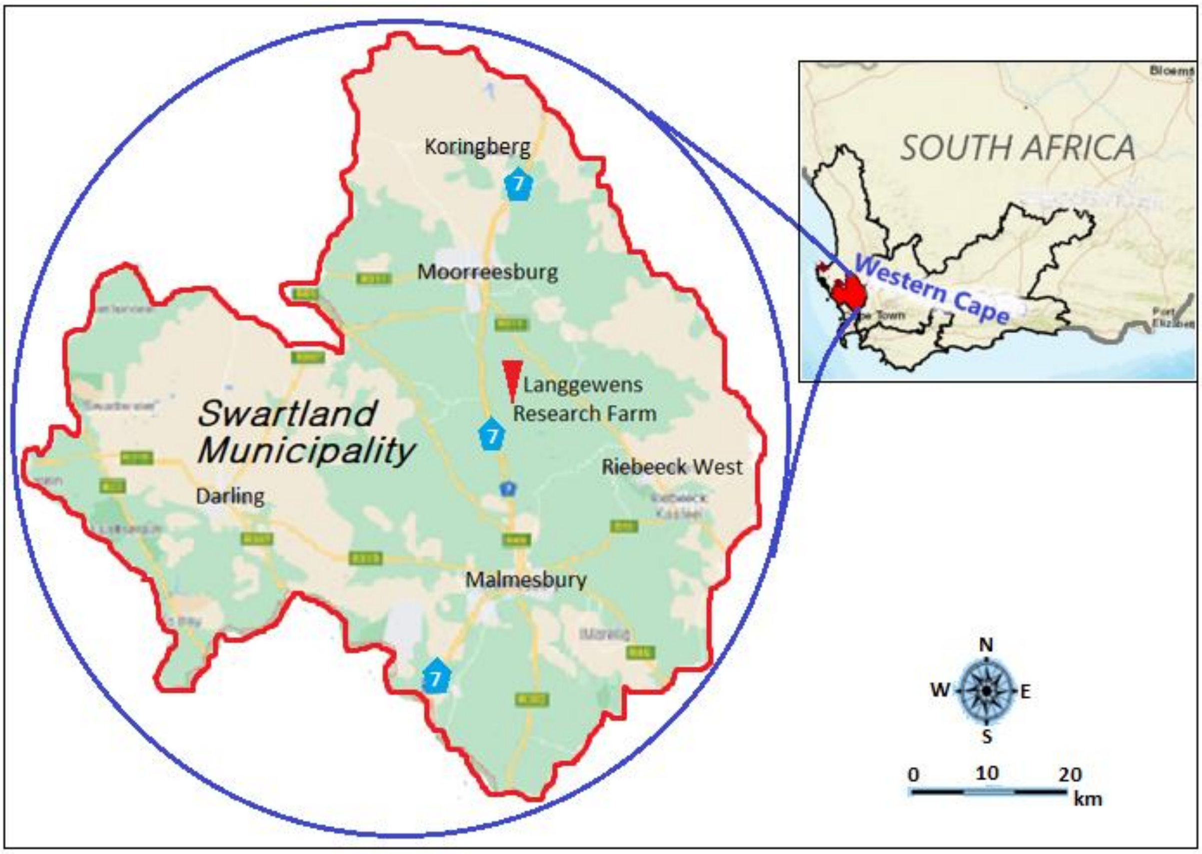

Figure S3: The location of Langgewens Research Farm in the Swartland region, in the Western Cape province of South Africa. Map adapted from Tshuma et al. (2021).

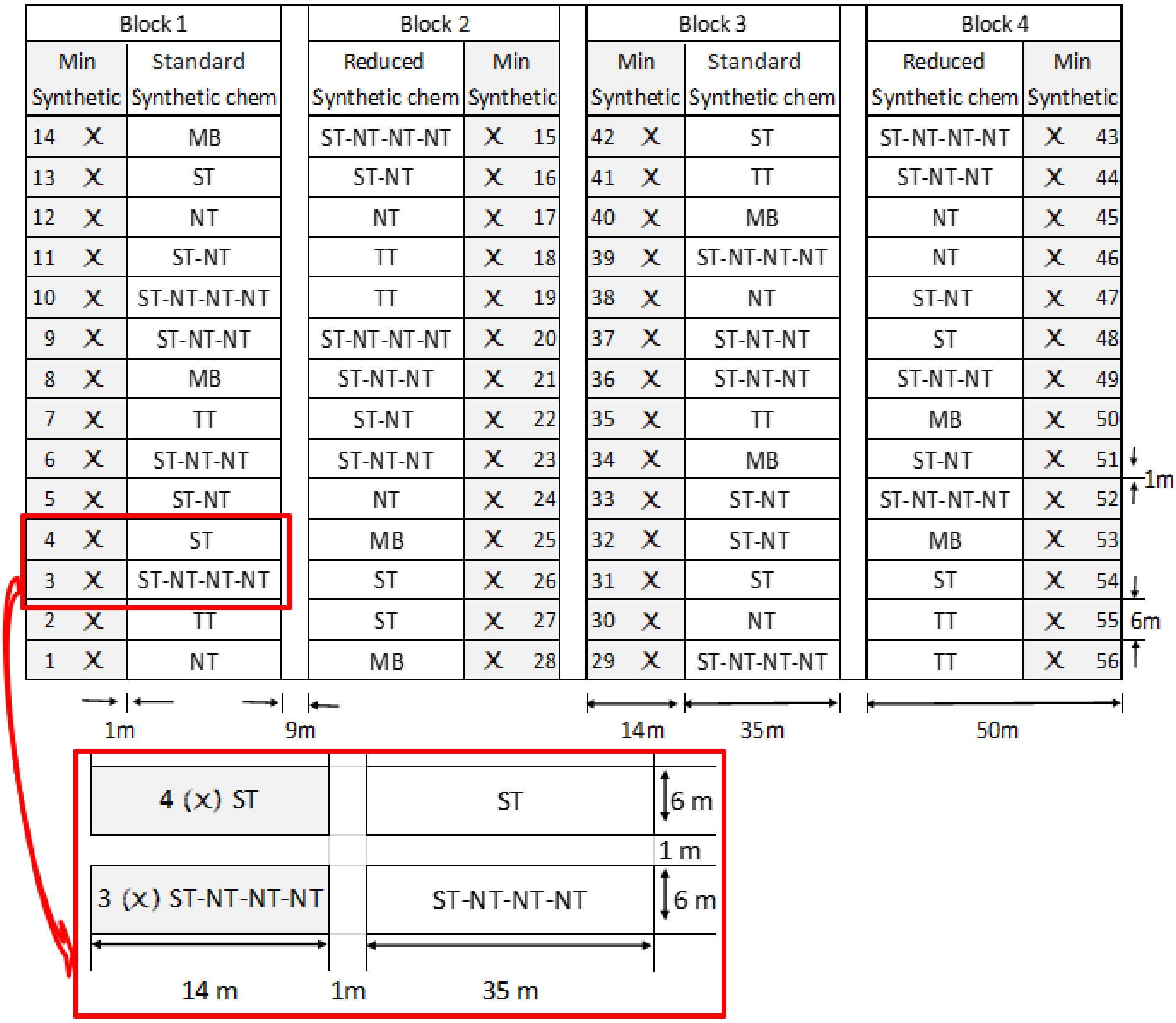

Figure S4: Layout of the trial site at Langgewens Research Farm showing the four blocks (1; 2; 3 and 4), the 35 m and 14 m sections of the plots which have the three crop management systems (Min synthetic; **Standard** synthetic chem; and **Reduced** synthetic chem). The numbers 1 to 56 represent the plots; Min = **minimum**; chem = chemical; X = sections of the plots that had a **minimum** application of synthetic chemical per planting season in 2019 and 2020. The tillage sequences are written in the unshaded part of each plot.

Journal paper: Author contribution agreement form

Paper title	Effects of long-term (42 years) tillage This item has been removed due to 3rd Party Copyright. The unabridged version of the thesis can be found in the
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Abstract	No-tillage can improve soil quality but can also increase the stratification of soil chemical parameters. Nutrient uptake by crops might be limited when nutrients are stratified, especially in semi-arid or Mediterranean regions. To reduce stratification, infrequent tillage could be considered. However, there is a paucity of information on the effects of long-term infrequent tillage on the stratification of soil chemical parameters. This study aimed to assess the effects of long-term infrequent tillage on the stratification of selected soil chemical parameters to a depth of 300 mm. The research was conducted on a long-term (42 years) research site at Langgewens Research Farm in South Africa. Seven tillage treatments were investigated: continuous mouldboard ploughing to a depth of 200 mm, tine-tillage to 150 mm, shallow tine-tillage to 75 mm, no-tillage, shallow tine-tillage every second year in rotation with no-tillage, shallow tine-tillage every third year in rotation with no-tillage and shallow tine-tillage every fourth year in rotation with no-tillage. Tillage treatments had differential effects on the distribution of soil chemical parameters. The mouldboard plough prevented stratification of most soil chemical parameters, such as soil acidity, soil organic carbon (SOC), extractable P, exchangeable Ca and Mg and cation exchange capacity (CEC). However, mouldboard ploughing also led to significantly lower SOC stocks and extractable P stocks. The SOC stocks and extractable P stocks of the no-tillage treatment were not significantly different from those of the infrequent tillage treatments. Overall, the infrequent tillage treatments were no better ($P > 0.05$) than the no-tillage treatment as infrequent tillage could not effectively ameliorate the stratification of most soil chemical parameters and did not increase the stocks and stratification ratios of SOC and extractable P.
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Where is the manuscript in the thesis?	Chapter 3

Authorship contribution statement

Johan Labuschagne manages the long-term tillage trials at Langgewens Research Farm. Pieter Swanepoel, Johan Labuschagne, Francis Rayns, and James Bennett contributed to the study conception. Flackson Tshuma along with PS, JL, FR and JB contributed to the study design. FT conducted the research under the guidance of PS, JL, FR and JB. FT collected soil samples with help from assistants from the Western Cape Department of Agriculture. FT also undertook the data analysis with support from the Stellenbosch University Centre for Statistical Consultation. FT drafted the manuscript. PS, JL, FR and JB edited and provided critical analysis and revisions to the manuscript. All authors read and approved the final manuscript.

Author agreement for the use of this collaborative work in PGR's Name PhD thesis

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