CROP SYSTEMS
FOR SUSTAINABLE AGRICULTURE
IN THE NORTH-WESTERN FREE STATE,
SOUTH AFRICA

By

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Declaration

Declaration with regards to independent work:

I, Melanie de Bruyn (student number 2007031855), hereby declare that this research project submitted to the University of the Free State, for the degree Doctor of Philosophy majoring in Sustainable Agriculture is my own independent work. This research project was conducted through the University of the Free State, under the supervision of Prof Johan van Niekerk and co-supervised by Dr André Nel.

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Date

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“Yet not I, but through Christ in me”

- CityAlight -

Abstract

Introduction: The North-Western Free State is a main contributor of South Africa's maize production which has recently been put under enormous pressure by climate change, pests, diseases, economic factors and population growth. Crop diversification, by means of crop rotation, has potential to alleviate some of the challenges faced by the farmers and communities in the area. However, the effects of crop rotation are known to be site-specific. Therefore, the aim of this study was to determine the views and perspectives of local farmers on crop diversification as well as to determine the sustainability (in terms of soil health, nutrition, production and profitability) of different rotational systems specifically in the North-Western Free State.

Materials and methods: An interdisciplinary approach of social and natural science was taken to achieve the aim of this study. A unique questionnaire was designed, distributed and analysed to determine the views and perspectives of the local farmers on crop diversification. A field trial comparing different crop rotational systems was established on the farm Christinasrus and monitored for three consecutive seasons (2020/2021, 2021/2022 and 2022/2023). Soil, nutritional and yield data obtained from the trial were further analysed using descriptive and inferential statistics.

Results and discussion: North-Western Free State farmers had a positive perception towards crop diversification, with 87% of them rotating crops, showing movement from crop specialisation towards crop diversification. Rotational systems in the field trial maintained soil health, provided nutritional benefits and improved crop production and productivity. Seasonal variation (mainly rainfall) played a role on soil health, nutrition and crop production, with most aspects being negatively affected by above normal rainfall conditions.

Conclusion: This study provided insight into the effect of crop rotation specific to the North-Western Free State. The rotational systems investigated were viable, with potential for agricultural sustainability. The study recommends that maize rotational systems incorporating soybean and cover crop be implemented in the area to ensure sufficient and nutritious food, while conserving and improving the soil and environment.

Keywords: Crop rotation, maize production, North-Western Free State, soybean production, sustainable agriculture

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Acronyms

ANOVA	Analysis of variance
CA	Conservation agriculture
CDI	Crop diversity index
DALRRD	Department of Agriculture, Land Reform and Rural Development
Bt	*Bacillus thuringiensis*
FAO	Food and Agricultural Organisation of the United Nations
GIS	Geographic Information System
GM	Genetically modified
H3A	Haney, Haney, Hossner and Arnold
HI	Herfindahl index
HSHT	Haney soil health test
IAEA	International Atomic Energy Agency
IMV	Improved maize varieties
IPM	Integrated pest management
IQR	Interquartile range
LSD	Least significant difference
MCS	Maize-cover crop-soybean
MM	Monoculture maize
MMS	Maize-maize-soybean
MS	Maize-soybean
MLND	Maize lethal necrosis disease
NT	No-till
OPV	Open pollinated varieties
QTL	Quantitative trait loci
SAFEX	South African Futures Exchange
SAGL	South African Grain Laboratories
SAHRI	South African Herbicide Resistance Initiative
SANAS	South African National Accreditation System
SOP	Standard operating procedure
SPSS	Statistical Package for the Social Sciences
TDN	Total digestible nutritional value

UFS	University of the Free State
UN	United Nations
USAID	Unites States Agency for International Development
WEN	Water extractable nitrogen
WEOC	Water extractable organic carbon
WEON	Water extractable organic nitrogen

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Chapter 1

Introduction

1.1. Background

Maize was introduced into South Africa in 1655 and has since become one of the country's most important food crops (Sihlobo, 2018). It is the primary food of 80% of the country's population (Standard Bank, 2015). The Free State province is a major producer of the country's maize (Department of Agriculture, Land Reform and Rural Development [DALRRD], 2019). More specifically, the North-Western Free State, which forms part of the Nala municipality in the Lejweleputswa district, has a strong focus on maize as well as sunflower, soybean, peanuts and vegetables (DALRRD, 2019).

Climate change is a concern for North-Western Free State agriculture as natural resources are being put under pressure (DALRRD, 2019). Extreme weather events evident include increased temperature and altered patterns of precipitation (Makate *et al.,* 2016). The province experienced a major drought, with the lowest average rainfall since 1904 being recorded in 2015, followed by two successive years of above average rainfall (DALRRD, 2019). These extreme conditions have negatively affected many stakeholders, resulting in increased food inflation and higher unemployment rates (DALRRD, 2019). Other challenges effecting agriculture in the area include: Diminishing soil fertility, environmental degradation, declining crop yields and increased production risks. (Makate *et al.,* 2016; Nel & Loubser, 2004). Furthermore, the extremely sandy soils of the North-Western Free State are associated with inherent compaction, low organic matter content, low nutrition and low water retention capability (Beukes *et al.,* 2019).

Crop diversification has potential to alleviate some of the many challenges faced by the farmers and communities of the North-Western Free State. Makate *et al.* (2016:2) defines crop diversification as "the practice of cultivating more than one variety of crops belonging to the same or different species in a given area in the form of rotations and or intercropping". Many farmers tend to focus their production on a single crop as to produce large quantities (Chambers, 2020). Monocropping, which is the term used for producing single crops, can lead to water loss, cause a decrease in nutrients and biodiversity of soils, and can result in an increase of diseases due to genetic similarity (Chambers, 2020).

The benefits associated with crop diversity can be linked to all three aspects of sustainable agriculture: Environmental, social and economic (Bobojonov *et al.,* 2012). Environmentally, crop diversity enhances soil health and reduces the risk of diseases, pests and weeds (Gurr *et al.,* 2016; Lin, 2011; Smith, Nel & Trytsman, 2019). Soil health is a term used to describe the general condition or quality of the soil resource (Kibblewhite, Ritz & Swift, 2008). The importance to maintain soil health stems from the need to sustain plant productivity, maintain or enhance water and air quality, and promote plant health (Doran & Zeiss, 2000). Crop diversification has shown potential to prevent soil deterioration, improve soil quality and fertility which in turn could improve sustainability and profitability of the crop diversification systems (Beukes *et al.,* 2019; Bobojonov *et al.,* 2012; Lin, 2011; Smith, Nel & Trytsman, 2019).

Crop diversification often results in higher crop yields and reduced production costs compared to monoculture crops (Nel & Loubser, 2004; Smith, Nel & Trytsman, 2019). Production risks are lowered through the inclusion of alternative crops with relatively low risk (Nel & Loubser, 2004). By securing their profits, farmers can easily respond to market changes, price fluctuations and stabilise their income (Bobojonov *et al.,* 2012). Furthermore, a profitable farming business can create employment opportunities, which remains the most sufficient way to alleviate poverty and inequality (Mashabela, 2017). In addition to the upliftment of the community, another important social aspect affected by crop diversification is food security (CropLife, 2014). A stable and increased crop production increases food availability and lowers food prices, ultimately improving food security (CropLife, 2014). Furthermore, the nutritional quality of crops has a direct effect on human nutrition (International Atomic Energy Agency [IAEA], 2020).

1.2 Problem statement

Maize is a valuable crop, providing for a significant amount of the country's food. A major portion of this maize is produced in the North-Western Free State. It is important to enhance and maintain the productivity of maize in the area to ensure South Africa's food security. That said, it is also important to bear in mind that the maize market should be protected from overproduction which would result in a drop in commodity price making it less profitable and non-viable for the farmer to farm. Crop diversity is a proposed method of sustainable agriculture that has potential to maintain soil health as well as increase crop yields and profitability. Crop diversity has the potential to spread the farmers' risks as the event of an over production of two or more crops is highly unlikely. Furthermore, crop diversity is likely to improve employment rates and provide nutritional maize which ultimately promotes food security. The need has arisen to further investigate and add to the limited research results available regarding crop diversification on soil health, maize nutrition, maize yields and profitability in the North-Western Free State.

1.3 Aim and objectives

The aim of the study was to determine the perception of North-Western Free State farmers on crop diversification as well as to determine the sustainability of different rotational systems in the area. The following objectives were devised in order to meet the aim of the study:

- Determine the views and perspectives of North-Western Free State farmers on crop diversification
- Determine the effect of crop rotation on soil health in the North-Western Free State
- Determine the nutritional benefits of maize-soybean systems in the North-Western Free State
- Determine the production and productivity of maize and soybean grown in rotation in the North-Western Free State
- Provide guidelines for sustainable rotational systems in the North-Western Free State

1.4 Research questions

In response to the research aim and objectives the following research questions were derived:

- What are the views and perspectives of North-Western Free State farmers on crop diversification?
- Does crop rotation effect soil health in North-Western Free State?
- Do maize-soybean rotational systems in the North-Western Free State provide nutritional benefits?
- Does crop rotation improve the production and productivity of maize and soybean in the North-Western Free State?
- What sustainable rotational system guidelines can be followed in North-Western Free State?

1.5 Significance of the study

Crop diversification has the potential to accelerate the achievement of a greatly needed environmental, economic and social sustainability – the three pillars of sustainable agricultural development (Bobojonov *et al.,* 2012). In addition, the potential of crop diversification supports the second strategic development goal of “zero hunger” (United Nations [UN], 2020). It more specifically supports the target of goal 2.4

which states that: “By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaption to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality” (UN, 2020).

1.6 Layout of chapters

Chapter 1: Introduction

The introduction provided a general description of the study. The problem statement, aim and objectives and research questions were included. Furthermore, the significance of the study was discussed.

Chapter 2: Literature review

The literature review was laid out using a funnel technique. The broader aspects included maize production in South Africa, maize morphology and its growth cycle. The literature was narrowed down to include the factors affecting maize production and strategies to improve it.

Chapter 3: Sample collection and methodology

Chapter 3 discussed the sample collection and methodology. An interdisciplinary approach of social and natural sciences was taken to achieve the aim of this study. The site description, target population and trial layout were discussed in this chapter.

Chapter 4: Views and perspectives of North-Western Free State farmers on crop diversification

This chapter used a mixed method approach to determine the views and perspectives of farmers on crop diversification in the North-Western Free State. The analysis and results were discussed.

Chapter 5: The effect of crop rotation on soil health in the North-Western Free State

In Chapter 5, natural science methods were used to determine the effect of crop rotation on soil health in the North-Western Free State. The analysis and results were discussed.

Chapter 6: Nutritional benefits of maize-soybean rotational systems in the North-Western Free State

In Chapter 6, natural science methods were used to determine nutritional benefits of maize-soybean rotational systems in the North-Western Free State. The analysis and results were discussed.

Chapter 7: Production and profitability of maize and soybean grown in rotation in the North-Western Free State

In Chapter 7, production and profitability of maize and soybean grown in rotation in the North-Western Free State were analysed. The results were discussed.

Chapter 8: Association between soil health, nutritional value and maize production in different rotational systems in the North-Western Free State

Chapter 8 looked at the association between soil health, nutritional value and production of maize in different crop rotation systems in the North-Western Free State. The analysis and results were discussed.

Chapter 9: Conclusion

In the final chapter, the overall observations were summarised and guidelines were provided for farmers in the North-Western Free State.

Chapter 2

Literature review

2.1 Introduction

Plant domestication is “a co-evolutionary process that occurs when wild plants are brought into cultivation by humans” (Purugganan, 2019:1). It is considered one of the most important developments of human history (Diamond, 2002). The domestication of plants has led to civilisation as we know it, including the rapid growth of technology and its consequence on agricultural development (Tenaillon & Charcosset, 2011).

Maize (*Zea mays*) domestication is thought to have occurred about 9 000 years ago in Mexico (Tenaillon & Charcosset, 2011). Figure 2.1 illustrates how maize has now become one of the most important crops worldwide, cultivated across a range of latitudes, altitudes, moisture regimes and soil types (Mejía, 2003; Smale & Jayne, 2003). The annual maize production in 2020 was 1 162 352 997 (one billion one hundred and sixty-two million three and hundred fifty-two thousand nine hundred and ninety-seven) tons (Knoema, 2022a).

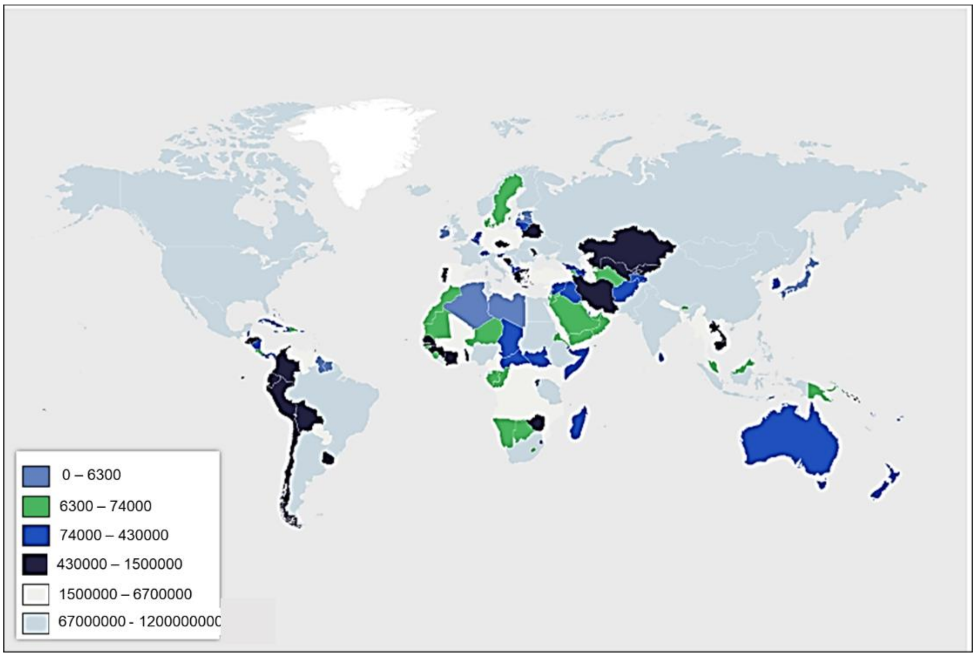

Figure 2.1: Maize production (tons) throughout the world in 2020 (Food and Agricultural Organisation of the UN [FAO], 2022a; Knoema, 2022a)

2.2 Maize production in South Africa

Maize, which was introduced to South Africa in 1655 by the Portuguese, fast became the country's staple food and cash crop (Burtt-Davy, 1914; Sihlobo, 2018). In a book by Burtt-Davy (1914:7) it was mentioned that: "No country in the world is better suited to maize-growing on a large scale than South Africa; it has an ample average rainfall, at the right season of the year, and phenomenally favourable winter weather for the natural production of the quality of grain most suitable for shipment." Now, 100 years later, all nine provinces of South Africa are successfully producing maize (Figure 2.2). Most of South Africa's maize comes from what is known as the 'maize quadrangle' (Figure 2.3), which includes the Highveld of Mpumalanga Province, the provinces of Gauteng and the North West, and the northern half of the Free State Province (Nortjè & Laker, 2021).

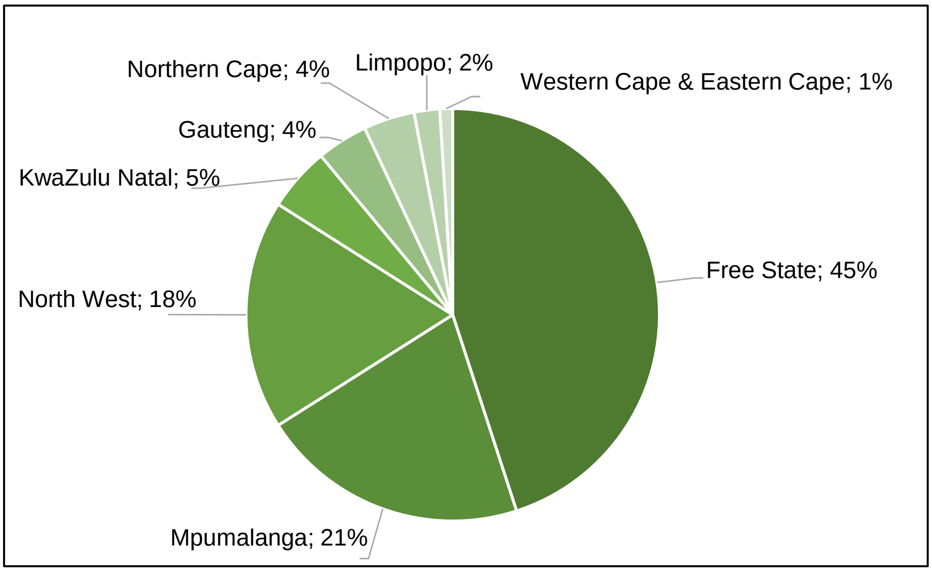

Figure 2.2: Provincial contribution to the South African 2020 maize production (South African Grain Laboratories [SAGL], 2020a)

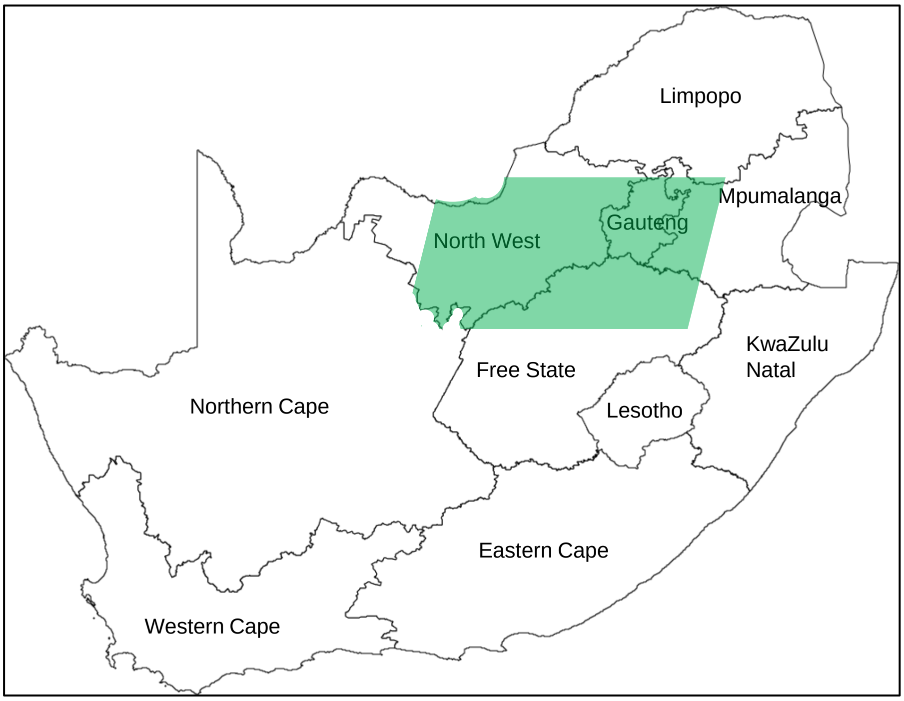

Figure 2.3: South Africa’s ‘maize quadrangle’ including the Highveld of Mpumalanga Province, the provinces of Gauteng and the North West, and the northern half of the Free State Province (illustration by M de Bruyn)

Maize is mainly used for human consumption (normally ground into meal and other products) and as animal feed, either whole, ground or crushed (Ranum, Peña-Rosas & Garcia-Casal, 2014). White maize is preferred for human consumption while yellow maize and maize stover is the main source of animal feed (Mashingaidze, 2006). Other uses of maize include being a source of alcoholic beverages, industrial uses and ethanol production (Muroyiwa & Mushunje, 2017). More recently the use of maize for fuel production has increased with a focus on producing environmentally friendly biofuel (Muroyiwa & Mushunje, 2017).

2.3 Maize morphology

Maize is a monecious annual plant with a single predominant stem and distichous leaves (Alarcón, Lloret & Salguero, 2014; Majía, 2003). Although monecious, maize is generally cross-pollinated (Miya, 2015). The anthers at the tip of the male inflorescence are responsible for producing pollen which fertilizes the female inflorescence, the ears (Figure 2.4). The leave blades are adapted for maximum absorption of sunlight which is thought to result in the plants’ modified photosynthetic pathway which allows the plant to produce more dry matter per unit of water transpired than most other plants (Majía, 2003).

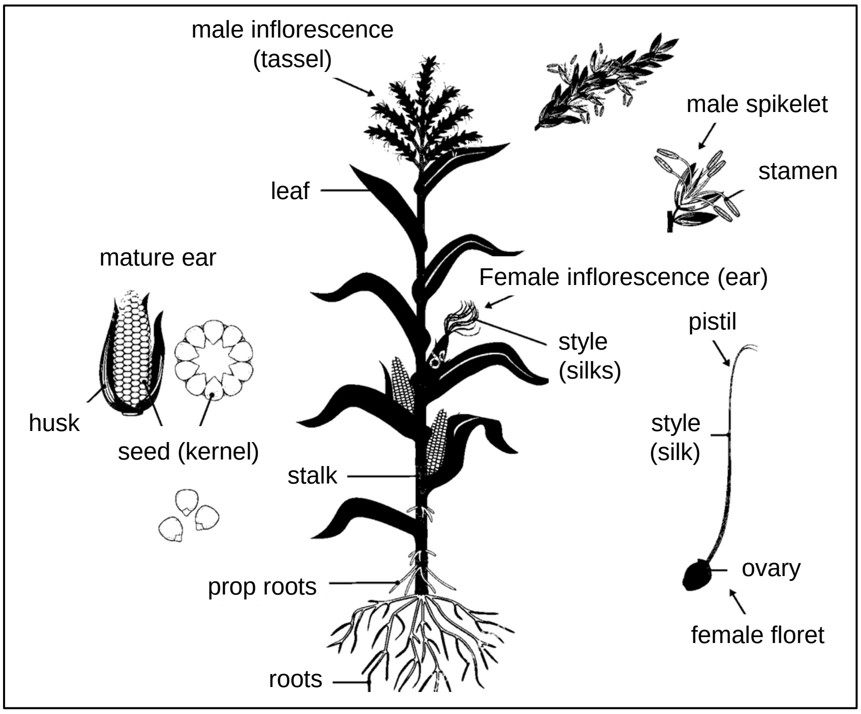

Figure 2.4: Morphology of the maize plant (adapted from Majía (2003))

The maize primary root is a cylindrical structure forming many lateral roots as it grows (Alarcón, Lloret & Salguero, 2014). Figure 2.5 illustrates a mature maize plants' fibrous root system consisting of many shoot-borne (adventitious) roots growing both horizontally and vertically, on top and below the soil (Alarcón, Lloret & Salguero, 2014; Feldman, 1994). The roots on top of the soil are specialised brace roots which provide plant anchorage (Reneau *et al.*, 2020). The root system of an average maize plant grows about 5,50 m^3 with an average horizontal spread of 1,00 m and vertical growth of less than 1,50 m (Feldman, 1994).

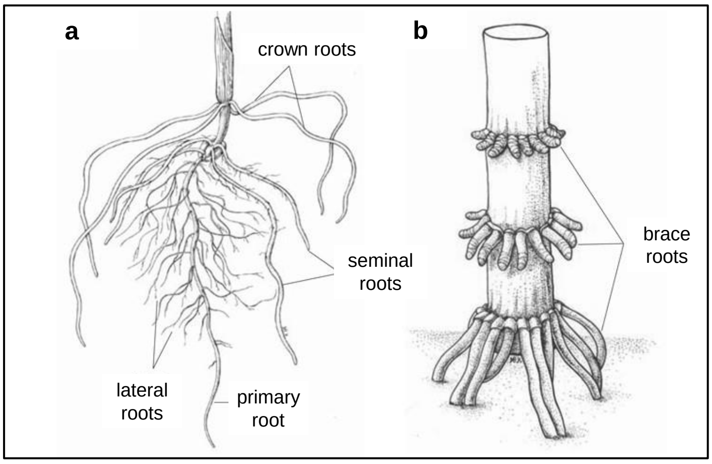

Figure 2.5: Root of a maize plant: a) fibrous root system and b) maize stem with brace roots for anchorage (Hochholdinger, 2009)

The plant colour and size as well as the kernel type and size of maize vary (Majía, 2003). The average height of a maize plant is 2,40 m, producing one to four ears per plant (Majía, 2003). The maize kernel is made up of a pericarp, endosperm and embryo (germ) (Majía, 2003). The use of maize is generally associated with the endosperm properties of the maize kernel, resulting in five types: Pop kernels, flint kernels, floury kernels, dented kernel and waxy kernels (Majía, 2003).

Maize can be classified by colour, ranging from white to yellow to red to black, with white and yellow being the most common (Ranum, Peña-Rosas & Garcia-Casal, 2014). The majority of maize in America is yellow compared to Africa where white maize is more popular (Ranum, Peña-Rosas & Garcia-Casal, 2014). The yellow colouring of maize is as a result of increased β-carotene and β-cryptoxanthin, vitamin A precursors, which give off a carotenoid pigment (Ranum, Peña-Rosas & Garcia-Casal, 2014).

2.4 Growth cycle of maize

Maize cultivars are classified as short, medium, or long season cultivars according to the duration of their growth cycle (Miya, 2015). The average maize growth cycle, as shown in Figure 2.6, is normally 120 – 140 days starting with the planting of a maize seed (Dlamini, 2015; Moeletsi, 2010). The maize seed starts to grow as soon as water is absorbed and emerges from the soil approximately five days later (Dlamini, 2015). It takes 15 – 25 days for the maize plant to establish itself before it enters the vegetative stage (Dlamini, 2015). The vegetative stage is dominated by the production of leaf collars, each new leaf collar indicates a new vegetative stage until the tassel emerges and maximum height is reached, about 25 – 40 days later (Dlamini, 2015; Montgomery, 2014). Once the tassel is completely visible the silks are formed, this flowering phase of the reproductive development lasts 15 – 20 days (Dlamini, 2015). Yield formation is the longest part of the cycle, about 35 – 45 days, during which the maize kernels are filled (Wang, Kang & Moreno, 1999). The ripening stage is the final stage and takes about 10 – 15 days (Dlamini, 2015). The maize plant is ready to be harvested at a moisture level below 15% (Adu *et al.,* 2014).

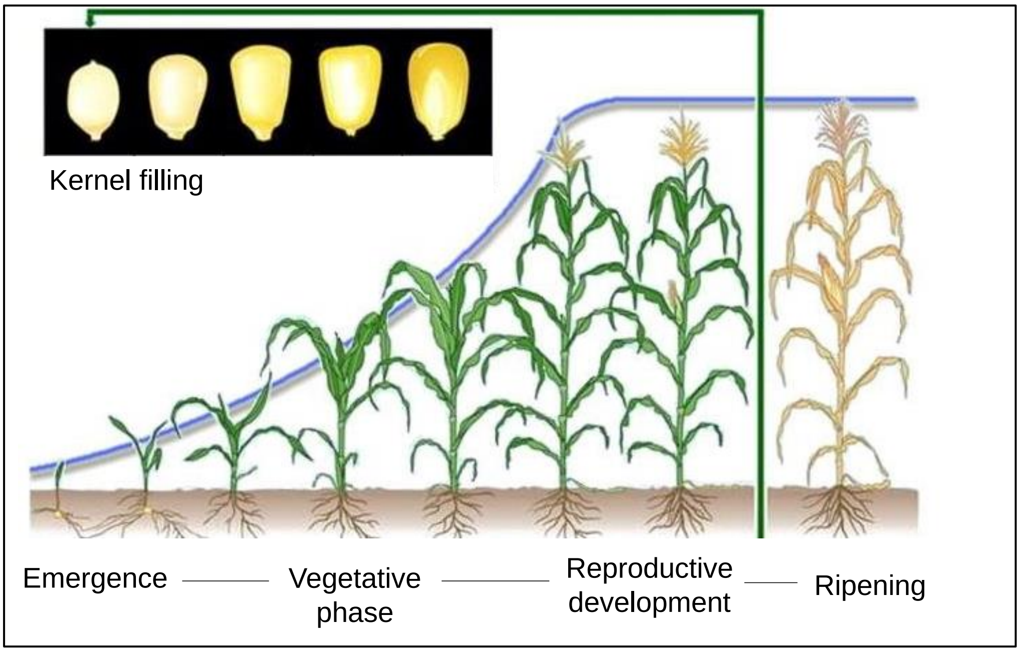

Figure 2.6: Growth cycle of the maize plant from emergence through to ripening (adapted from Dlamini (2015))

2.5 Factors affecting maize production

Many factors play a role in the production of maize (Moeletsi, 2010; Tadross *et al.*, 2009). Environmental factors include geographical features, climate conditions and soil health (Adamgbe & Ujoh, 2013; Moeletsi, 2010; Tadross *et al.*, 2009). In addition, biotic factors including pests and diseases as well as weeds influence the production of maize (Adamgbe & Ujoh, 2013; Cairns *et al.,* 2012). Furthermore, economic factors, population growth and human capital impact maize production (Akhtar *et al.,* 2018; Boakye, 2023; Nyamekye, Fianker & Ntoni, 2016; Shiferaw *et al.,* 2011).

2.5.1 Geographical features

Geographical features, such as altitude indirectly affect the growth of maize in that it influences climatic conditions and soil characteristics (Xue-jun *et al.,* 2013). Evidence suggests that maize was originally grown at altitudes above 1 300 m but has since been grown successfully in a variety of conditions ranging from 0 – 3 800 m above sea level (Ramirez-Cabral, Kumar & Shabani, 2017). Altitudes higher than this result in unfavourable climatic conditions for optimal maize production (Chen *et al.,* 2009).

2.5.2 Climatic conditions

As early as 1914 long humid summers with intermittent rains and plenty of sunshine were identified as ideal climatic conditions for maize production (Burtt-Davy, 1914). Optimum day time temperatures are considered to be between 28°C and 32°C (Zampieri *et al.,* 2019). Maize can be produced under rainfall levels of 200 – 2000 mm (Ramirez-Cabral, Kumar & Shabani, 2017). In South Africa, maize requires a seasonal rainfall of 450 – 650 mm depending on the specific environment (Moeletsi, Walker & Landman, 2011). Sunny conditions produce photosynthetically active radiation which is vital for maize growth (Ghosh *et al.,* 2017).

Maize was originally thought to be sensitive to climatic variations however, studies have shown that maize is able to tolerate many of these variations to a degree (Akpalu, Hassan & Ringler, 2008). Maize is sensitive to warmer day time temperatures during the flowering stage which results in reduced pollen germination (Zampieri *et al.,* 2019). However, maize in the final period of the cropping season, is able to tolerate slightly higher day time temperatures (Zampieri *et al.,* 2019). Lower temperatures are not ideal for maize production, and it is particularly vulnerable to frost, especially during day 120 – 140 of production (Du Plessis, 2003; Moeletsi, 2010).

The timing and duration of rainfall plays an essential role in determining maize planting dates and the growth cycle of the maize plant (Moeletsi, 2010; Tadross *et al.,* 2009). In South Africa, the first rains after the last frost are an indication of the start of planting season (Moeletsi, Walker & Landman, 2011). Early cessation of rainfall results in a shorter maize growing period while rain cessation later in the season favours crop production (Moeletsi, Walker & Landman, 2011). Heavy rainfall or flooding can lead to waterlogged fields which is a major contributor to maize yield reduction, this is especially so before and during pollination (Dar *et al.,* 2019; Mano & Omori, 2007).

Maize is generally considered a drought-resistant plant (Burtt-Davey, 1914; Dar *et al.,* 2019). However, a considerable amount of water is required at certain stages of growth (Zhao, Liu, & Zhang, 2010). Drought early in the cropping season (at flowering and the latter stages of grain filling) negatively affect grain yields (Huang, Birch & George, 2006; Zampieri *et al.,* 2019). If the availability of soil moisture decreases, the effects of heat stress are worsened (Zampieri *et al.,* 2019).

Hail can cause major damage to maize plants, especially later in the cropping season (Miya, 2015). A relatively small maize plant (not in tassel) is able to adapt and can recover from hail damage by producing new leaves for photosynthesis to take place (Bălaş-Baconschi *et al.,* 2019). Although maize parts below the ground are generally not affect by hail, hail damage to larger plants often results in the main stem breaking, preventing the formation of new leaves and plant recovery (Miya, 2015). Hail damaged plants are also more susceptible to bacterial and fungal infections (Robertson *et al.,* 2011).

Sunshine, a precursor of solar radiation, is crucial for photosynthesis (Yang *et al.,* 2021). A mature maize plant uses the amount of energy equivalent to 8 293 15 W electric globes in an hour (Du Plessis, 2003). Cloudy and partly cloudy conditions reduce photosynthetically active radiation by 10 – 30% (Carrié *et al*., 2023). A decline in solar radiation at any stage of the maize plant effects its production (Yang *et al.,* 2019; Yang *et al.,* 2021). A greater effect is seen in maize plants experiencing shady conditions during or after the silking stage, resulting in decreased yields (Yang *et al.,* 2019).

In addition to temperature, rainfall and sunshine, wind is also an influential climatic phenomenon on maize production (Iderawumi & Friday, 2018). Maize stems are fairly robust and have the ability to support its own weight, especially mature maize plants (Mulungu, 2017; Xue *et al.,* 2020). However, wind erosion has potential to damage immature crops and degrade soils (Vos *et al.,* 2022; Xue *et al.,* 2020). Extreme winds result in stalk and root lodging of maize plants which reduces yield and grain quality (Bian *et al.,* 2016; Wen *et al.,* 2019). Windy conditions also result in the removal of topsoil and nutrients (Vos *et al.,* 2022).

2.5.3 Soil health

Soil is a medium for growth and home to ecosystems that are essential for all plant processes (Ahmad, Mustafa & Didams, 2020; Alemu, Selassie & Yitaferu, 2022). Therefore, it is crucial to maintain soil health (Norris *et al.,* 2020). Soil health is defined by Lehmann *et al.* (2020:2) as "the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans". This functionality depends on physical, chemical and biological processes in the soil (Fonteyne *et al.,* 2021).

Physical processes in soil

Maize is often grown on a variety of soil types however, maize production is influenced by soil texture, aggregate stability, porosity, aeration and water holding capacity (Alemu, Selassie & Yitaferu, 2022). The type of texture (sand, silt, clay) determines how, and how much, water penetrates the ground and how it is filtered and stored (Magdoff & Van Es, 2021; Strauss *et al.,* 2021). Figure 2.7 illustrates the different soil textual classes according to the percentages of sand, silt and clay (Magdoff & Van Es, 2021).

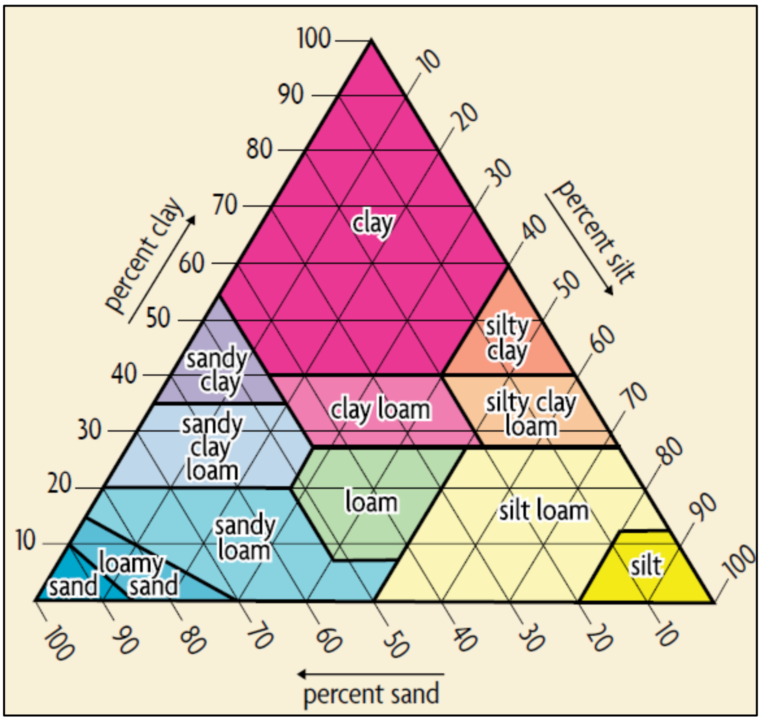

Figure 2.7: Soil textual classes according to the percentages of sand, silt and clay (Magdoff & Van Es, 2021)

Soil aggregation, which is how well soil particles are connected, determines the aeration, porosity and water holding capacity of the soil (Hoffland *et al.,* 2020). Soil aggregates encapsulate organic material (Lehmann, Leifheit & Rillig, 2017). Organic matter, defined as “accumulated, decaying debris, mainly of plant origin”, is considered the foundation for healthy and productive soils (Hoffland *et al.,* 2020:1). Although only occurring in small percentages (1 – 6%), organic matter is important because it directly influences all soil properties (Magdoff & Van Es, 2021). As the organic matter in soils decrease, so the probability of problems increase, therefore by maintaining sufficient organic matter, soil automatically gains health (Magdoff & Van Es, 2021).

Physical properties of soil can be eroded either by natural phenomena or human interactions (Ahmad, Mustafa & Didams, 2020). Erosion not only results in soil organic matter and nutrients being depleted but also reduces the moisture availability and rooting depth (Muoni *et al.,* 2020). Soil erosion can be limited through minimum tillage, contour ploughing, inclusion of shrubs/ trees and the use of cover crops (Muoni *et al.,* 2020).

Chemical processes in soil

The chemical components of soil include pH, nutrients and water (Sassenrath *et al.,* 2018). Maize production is most efficient in soil with pH levels of 5,50 – 6,50 (Opala, Odendo & Muyekho, 2018). The pH influences many important processes as the entire rooting system of plants is found in the soil (Hinsinger *et al.,* 2009; Morgan, Beinding & White, 2005). These processes include availability of plant essential nutrients, chemical solubility, organic matter decomposition and pesticide performance (Dar *et al.,* 2019; Mc Cauley, Jones & Jacobsen, 2009).

Essential nutrients required in soil include nitrogen (N), phosphorous (P) and potassium (K) (Magdoff & Van Es, 2021). N is fundamental for a healthy ecosystem and can either be in inorganic or organic form (Girkin & Cooper, 2023; Hood-Nowotny *et al.,* 2010). Inorganic N is usually in the form of ammonium (NH_4-N) and nitrate (NO_3-N) which is the N available to the plant (Fernandez & Kaiser, 2021). P is important for root development and nutrient uptake (Mitran *et al.,* 2018) likewise, K is essential for plant growth and stress adaption (Johnson *et al.,* 2022). Other soil nutrients include the macronutrients sulphur (S), calcium (Ca) and magnesium (Mg). The Ca: Mg ratio is important for soil aggregation with more Ca than Mg required for sufficient drainage resulting in better microbial life and aerobic breakdown of organic matter (Davidson, Savage & Finzi, 2014; Soto *et al.,* 2023). Micronutrients, namely, iron (Fe), zinc (Zn), manganese (Mn), copper (Cu) are often called trace elements as they are required in small amounts for photosynthesis and other plant growing processes (Kaur *et al.,* 2023).

Soil pH is mostly corrected through the application of lime (Mosharrof *et al.,* 2021; Opala, Odendo & Muyekho, 2018), while the nutrient requirement of soil for maize production is satisfied by the application of the right form of fertilizer containing the right combination of the elements needed at the right time (Iken & Amusa, 2004; Jaidka, Bathla & Kaur, 2019; Van Zyl, 2016). Fertilizer can be organic in the form of natural materials such as manure or inorganic in the form of synthetic, man-made chemicals (Jjagwe *et al.,* 2020; Roba, 2018). It is estimated that one ton of maize will remove about 15,00 kg of N, 3,00 kg of P, 400 kg K, 0,50 kg Ca, 0,50 kg Mg and 4,50 kg S (Botha, 2019). To establish how much fertilizer is required these figures can be multiplied by the specific target yield per hectare (Botha, 2019).

Biological processes in soil

Soil biology refers to living organisms (microorganisms) in the soil that contribute to the nutritional requirements of plants (Abbott & Murphy, 2003). These microorganisms include bacteria, archaea and eukarya, with bacteria being the most abundant (Umar, Kassim & Chiet, 2016). In addition to converting organic matter into nutrients to be used by plants, microorganisms also fix atmospheric nitrogen (Bhattacharjee, Singh & Mukhopadhyay, 2008), decompose organic matter (Strauss *et al.,* 2021), increase phosphorous availability (Hallama *et al.,* 2021), degrade pesticides (Lo, 2010), control pathogens (Singh, 2014) and improve soil structure (Bronick & Lal, 2005).

2.5.4 Pests and diseases

Pests and diseases negatively affect maize production and yield by either destroying the host plant, using up the plant's food and/ or interfering with photosynthesis (Sibiya *et al.,* 2013). Kumar *et al.* (2018) stated that in the early 1900s over 160 pests affecting maize production had been identified and by 1987 more than 250 pests were associated with maize production and processing. Maize diseases are primarily caused by fungi, bacteria and viruses, which can affect different parts of the plant, from the roots to the cobs (Shiferaw *et al.,* 2011).

In Africa an estimated 20% of attainable yield is lost annually to insects and animals (Shiferaw *et al.,* 2011). Insect pests commonly associated with maize damage in South Africa are stalk borers, cutworms, and black maize beetle (Figure 2.8a-c) (Bell, 2016). Maize stalk borers are widespread and ranked high among maize pests accounting for 10% of annual yield losses (Abate, 2011; Boa, Chernoh & Jackson, 2015). Cutworms can cause severe damage by cutting stems at ground level (normally at night), causing the plant to die (Erasmus, Van Rensburg & Van Den Berg, 2010). Black maize beetles favour sandy soils where they attack the root and subterranean part of young maize plants (De Klerk, 2015). More recently the fall armyworm (Figure 2.8d) has been observed in South Africa, with the first outbreak being in 2017 (Maluleke, 2020). In some cases, fall armyworm can destroy entire crops in only a few weeks as they attack all development stages of maize and feed on maize leaves, tassels and ears (Maluleke, 2020; Van Den Berg *et al.,* 2021).

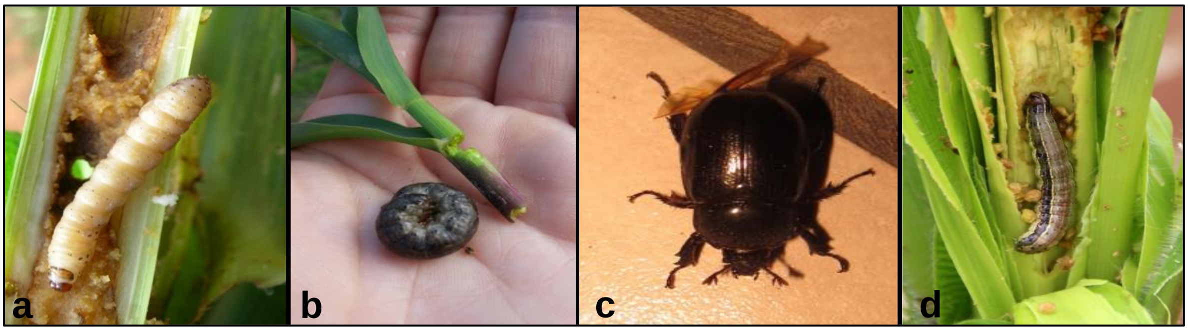

Figure 2.8: Common insects associated with a decrease in maize production and yield a) stalk borer (African Farming, 2022), b) cutworm (Strawser, 2014), c) black maize beetle (Magda, 2016) and d) the more recent fall army worm (Agencies, 2019)

Nematodes are microscopic worms that cause damage to maize crops (Figure 2.9), especially during crop development (Coyne *et al.,* 2018). The amount of damage caused by nematodes depends on their lifecycle and the ability to keep nematode populations below the damage threshold level (Mc Donald, De Waele & Fourie, 2017). Infestation is not often seen on maize parts above the ground however, maize growth is poor and stunted, normally as a result of root knot nematodes and lesion nematodes (Coyne *et al.,* 2018; Mc Donald & Nicol, 2005).

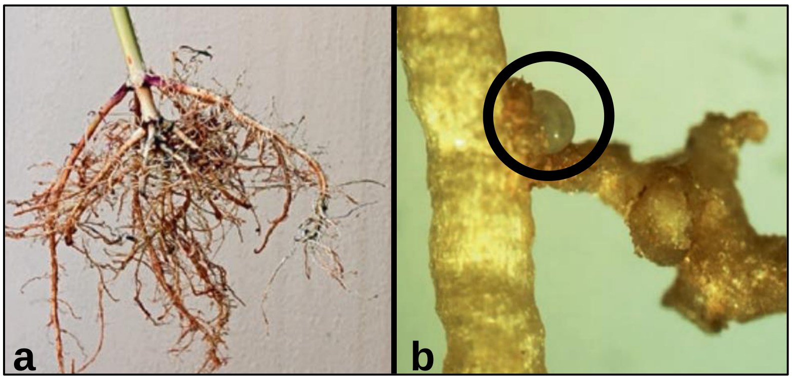

Figure 2.9: a) Root knot nematodes damage can be seen on the roots of maize plants b) under a microscope root knot nematodes are visible in the root tissue of swollen infected root tips (adapted from Mc Donald, De Waele and Fourie (2017))

Rodents and locusts are also considered maize pests (Bosque-Pèrez, 1995; Mulungu, 2017). Rodents damage maize crops through direct consumption and spoilage (Mulungu, 2017). Rodents commonly dig up planted seeds and seedlings but, although not often, cause the most damage when they attack maize cobs (Mulungu, 2017). Locusts spread in swarms feeding on the leaves of maize plants, and in extreme cases they can cause plant death (Bosque-Pèrez, 1995).

In addition to pests, diseases influence the maize yield potential (Shiferaw *et al.,* 2011). Diseases can be caused by fungi, bacteria or viruses (Shiferaw *et al.,* 2011). Common leaf diseases caused by fungi include: Grey leaf spot, northern corn leaf blight and common rust (Figure 2.10a-c). The fungi infested maize plants usually have rectangular lesions (grey leaf spot) on leaves, cigar-shaped (corn leaf blight) lesions on leaves, or yellowish-brown round to elongated spore-like lesions (common rust) on both leaf surfaces (Dey *et al.,* 2015; Ward *et al.,* 1999; Welz & Greiger, 2000). Other fungi related diseases are caused by *Aspergillus* species which produce a yellow-green mould on maize ears and also causes mycotoxin contamination, making grain unsafe for food and animal feed (Boa, Chernoh & Jackson, 2015; Shiferaw *et al.,* 2011). Bacterial leaf streak (Figure 2.10d) is caused by a bacterium that results in long, irregular streaks of dead cells and dark yellow to brown lesions (Plazas *et al.,* 2018). In addition, maize lethal necrosis disease (MLND) is a new viral disease causing concern in Africa as plants are killed with little or no grain being produced (Boa, Chernoh & Jackson, 2015).

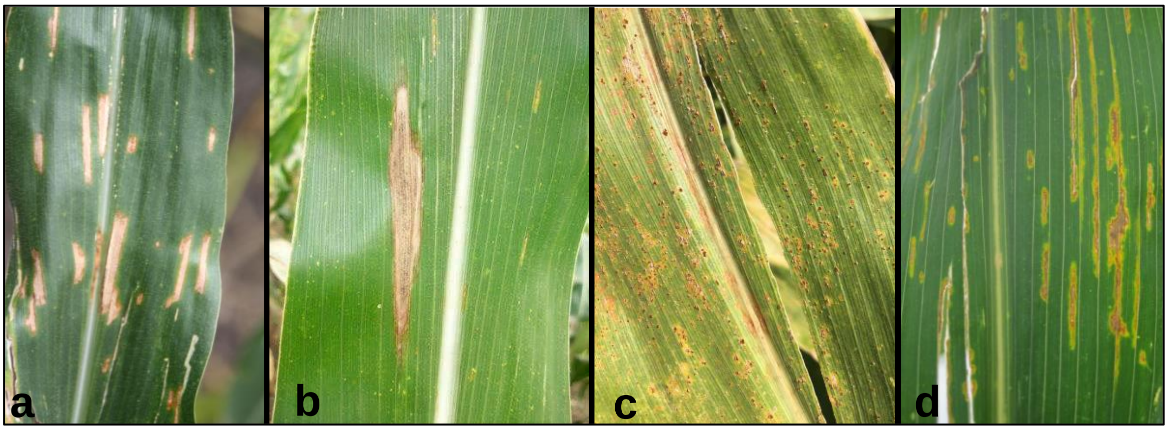

Figure 2.10: Common maize leaf diseases caused by fungi include a) grey leaf spot (Mueller, 2018), b) northern corn leaf blight (Mideros, 2022) and c) common rust (Plantix, 2022). d) Bacterial leaf streak (Gullickson, 2016)

Pests and diseases are mainly controlled by the use of chemicals. Although chemicals are effective, they are generally expensive and have many side effects including disease resistance, environmental pollution and health threats (Anderson *et al.,* 2019; Iken & Amusa, 2004). Chemicals should therefore be used sparingly and carefully and rather be included in an integrated pest management (IPM) plan (Bosque-Pèrez, 1995). IPM integrates biological, physical and cultural alternatives with chemicals to control pests with minimal human and environmental risks (Anderson *et al.,* 2019; Jaidka, Bathla & Kaur, 2019). These alternatives include deep summer ploughing, inter-cropping, use of good quality planting material, destroying infected plants and using traps (Jaidka, Bathla & Kaur, 2019).

2.5.5 Weeds

Weeds, which are often ever-present and robust with speedy growth and extensive rooting, are a major contributor to maize yield losses (Rajcan & Swanton, 2001; Sharma & Rayamajhi, 2022). Weeds compete for water, nutrients and light which are all important resources for optimal maize yield and growth (Tesfay, Amin & Mulugeta, 2014). Furthermore, the presence of weeds during maize harvest slows down the process, transmits odours and lowers grain grade (Du Plessis, 2003). Maize weeds can be characterised as either sedges, grass weeds or broadleaf weeds (Rai *et al.,* 2018). Common names include nutsedge, blackjack, witchweed, pigweed and crab grass. (South African Herbicide Resistance Initiative [SAHRI], 2022).

There is a critical time for weed control, which for maize is usually between one and eight weeks after the crop has emerged (Dar *et al.,* 2019; Rajcan & Swanton, 2001). This is due to maize yield being more effected by weeds that emerge at the same time as maize in comparison to weed growth occurring later in the maize growth cycle (Rajcan & Swanton, 2001). Mechanical means of weed management include hand weeding which is effective to a degree but time and labour intensive (Tesfay, Amin & Mulugeta, 2014). Herbicides were introduced as a means of weed management in the 1940's (Rajcan & Swanton, 2001). However, some weeds have become herbicide resistant and there are growing concerns over the effects of herbicides on the environment and human health (Rajcan & Swanton, 2001).

2.5.6 Economic factors

Economic factors affecting maize production include high fixed and input costs, high interest rates and unreliable output prices (Akhtar *et al.,* 2018; Jordaan & Grovè, 2007; Mokone, 2018). Fixed costs need to be paid regardless of production, these include electricity, levies and taxes while input costs involve costs for seeds, fertilizer, chemicals, fuel, equipment, maintenance and repairs, and labour (Meyo & Egoh, 2020; Van Der Westhuizen & Otterman, 2021). The recent inflation of some of these inputs are illustrated in Figure 2.11. The sharp increase, specifically for fertilizer, can be due to high raw material costs, limited supply and high demand, Covid-19 related slowdown of production and logistical constraints (Van Der Westhuizen & Otterman, 2021). South Africa's dependence on imports and the weaker Rand puts even more pressure on these input prices (Van Der Westhuizen & Otterman, 2021).

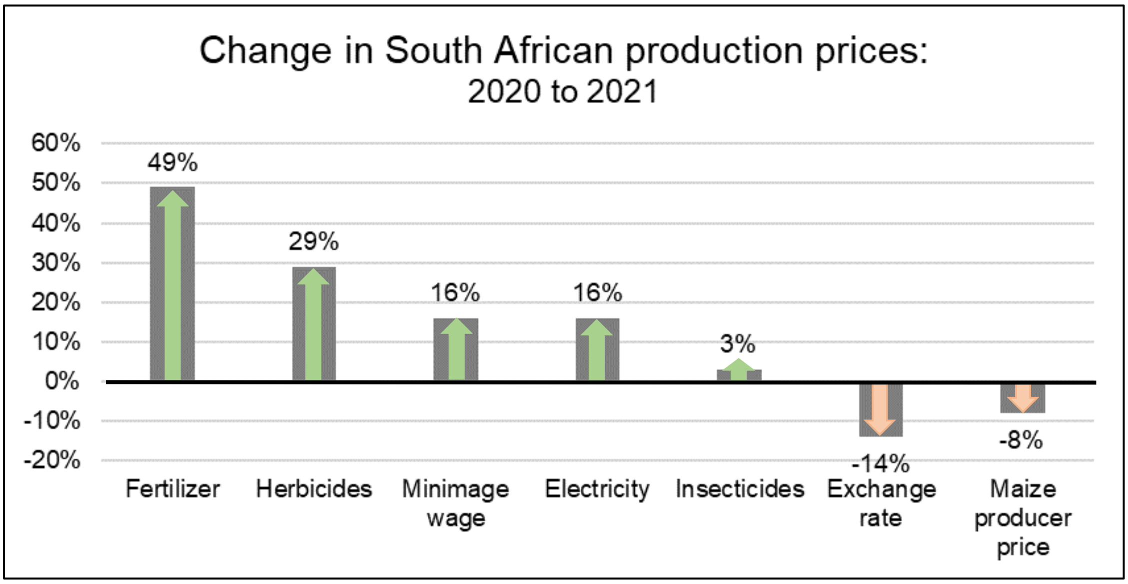

Figure 2.11: Percentage change in agricultural input costs and producer price from 2020 to 2021 (adapted from Van Der Westhuizen & Otterman (2021) and Knoema (2022b))

The biggest challenge for farmers is the imbalance in input costs and output prices (Figure 2.11), squashing production margins (Akhtar *et al.,* 2018; Van Der Westhuizen & Otterman, 2021). South Africa's agricultural market was deregulated in 1997, which put a stop to fixed seasonal prices, making the market volatile (Jordaan & Grovè, 2007; Sayed & Auret, 2020). Maize prices are now determined by both domestic and international market forces (supply and demand) (DALRRD, 2021). The private sector has put price risk management tools in place which include cash (spot) and forward contract markets (physical product markets), as well as the derivatives market (futures and options trading) which does not usually involve physical delivery of maize (Brown, Ortmann & Darroch, 2000). The derivative market involves the trading of maize through South African Futures Exchange (SAFEX) (Brown, Ortmann & Darroch, 2000).

2.5.7 Population growth

According to the FAO (2009), world population is growing at a rate of 160 persons per minute and 70% more food needs to be produced for an additional 2,3 billion people by 2050 (Prashar & Shah, 2016). This population growth puts enormous pressure on food security (Wu & Guclu, 2013). A total of 821 million people experienced hunger or malnutrition in 2017 (Santpoort, 2020). Maize production directly influences food security as maize is a major source of food, and indirectly due to its diverse uses and market demand (Shiferaw *et al.,* 2011). A shortage of maize could put entire populations at risk of starvation (Shiferaw *et al.,* 2011).

2.5.8 Human capital

The concept of human capital refers to "a conscious and continuous process of acquiring and increasing the number of people with requisite knowledge, education, skill and experience that are crucial for the economic and political development of a country" (Nyamekye, Fiankor & Ntoni, 2016:125-126). Research has linked farmer skills and experience to maize production (De la Fuente, 2011; Nyamekye et al., 2016). If a farmer lacks education and training, they not only struggle with basic literacy and numeracy skills but also have limited decision-making abilities (Nyamekye, Fiankor & Ntoni, 2016). Uneducated farmers generally refuse to adopt innovative practises or change their way of thinking (Khapayi & Celliers, 2015). With a compromised education level (Soudien, Reddy & Harvey, 2022) and unskilled Agricultural Extension and Advisory Services (Van Niekerk, Von Maltitz & Davis, 2022) in South Africa, the country risks not only affecting farmer livelihoods but also maize production and the economy as a whole.

2.6 Strategies for improved maize production

Improving maize production is vital for maintaining agricultural sustainability and improving food security (Kafle, 2010; Kutka, 2011). The primary means for farmers to increase their maize production is to expand the area of their cultivated lands (Ahmed *et al.,* 2017). This is not always viable as it is costly, impractical, and often insufficient (Asfaw *et al.,* 2012). Therefore, other interventions to increase maize production need to be considered and applied. One such intervention is the use of improved seed varieties (Sinyolo, 2020). Gebre *et al.* (2019) hypothesised that if all maize farmers adopted improved maize varieties (IMVs), maize yield could potentially double. Modernised agriculture has shown a direct relationship between technological adoption and yield increase (Boakye, 2023). Another intervention to improve maize production is conservation agriculture (CA) (Siziba *et al.,* 2019). CA is a holistic approach that aims at sustainable, reliable and climate-smart farming practices (Strauss *et al.,* 2021).

2.6.1 Improved seed varieties

IMVs are carefully breed through selection, which is the process of choosing individual plants with desirable traits (Latha, Lone & Ahmed, 2020). Maize yield can be increased by breeding IMVs based on crop conditions such as climate, length of growing season, moisture availability and soil fertility, aimed at meeting the needs of the grower and consumer (Jaidka, Bathla & Kaur, 2019; Kutka, 2011). IMVs include open pollinated varieties (OPVs), hybrids, and genetically modified (GM) varieties (Gebre *et al.,* 2019; Kafle, 2010).

OPVs are normally farm bred and yields are primarily used for seed (Kutka, 2011). The seed can potentially be recycled up to three years without losing yield potential (Gebre *et al.,* 2019). Conventional hybrids are formed when plants cross-pollinate, often aimed at ensuring desirable traits (disease resistance, size, yield and colour), resulting in what is known as 'hybrid vigour' (Morris, 2001; Muzhinji & Ntuli, 2021). Hybrids generally have a higher yield potential than OPVs but cannot be recycled (Gebre *et al.,* 2019).

GM varieties involve the incorporation of genetic engineering to improve crop productivity and reduce inputs such as fertilizer and pesticides (Muzhinji & Ntuli, 2021; Mwamahonje & Mrosso, 2016). Muzhinji and Ntuli (2021) noted that GM varieties resulted in a 37% reduction in chemical usage and a 68% increase in farmer profits between its introduction in 1996 and 2014. The most well-known GM maize varieties contain proteins that allow them to be herbicide-tolerant (Roundup ready) and insect resistant (*Bacillus thuringiensis* (Bt)) (Mwamahonje & Mrosso, 2016). These traits are either bred individually, as a single gene or combined, as stacked genes (Douglas & Halpin, 2009). Stacked GM crops, which combine two or more traits, have multiple benefits, and satisfy the need for planting diversity (Liu *et al.,* 2021). In South Africa, GMO adoption in maize for insect resistance, herbicide resistance and insect/ drought resistance have been given environmental commercial release (Muzhinji & Ntuli, 2021). Although introduced in 1998, the first Bt white maize was planted in 2001, the first herbicide-resistant maize in 2003 and the first stack-gene hybrids (Bt + herbicide tolerance) in 2007 (Coleman, 2012; Fischer, 2022).

The advancement in breeding biotechnology has resulted in the development and release of novel traits aimed at improved maize production (Mwamahonje & Mrosso, 2016). Genetic research has gone into breeding disease resistant maize (Hossain *et al.,* 2022), drought resistant maize (Lunduka *et al.,* 2019; Setimela *et al.,* 2017), heat tolerant maize (Tesfaye *et al.,* 2018), water-logging tolerance maize (Mano & Omori, 2007) and low nitrogen tolerant maize (Setimela *et al.,* 2017). In addition, characteristics associated with higher planting density are also a breeding focus (Hossain *et al.,* 2022). The appropriate genomic regions, known as quantitative trait loci (QTLs), are identified on chromosomes, and bred accordingly (Balint-Kurti & Johal, 2009; Hossain *et al.,* 2022). Figure 2.12 illustrates how these QTLs are mapped on maize chromosomes.

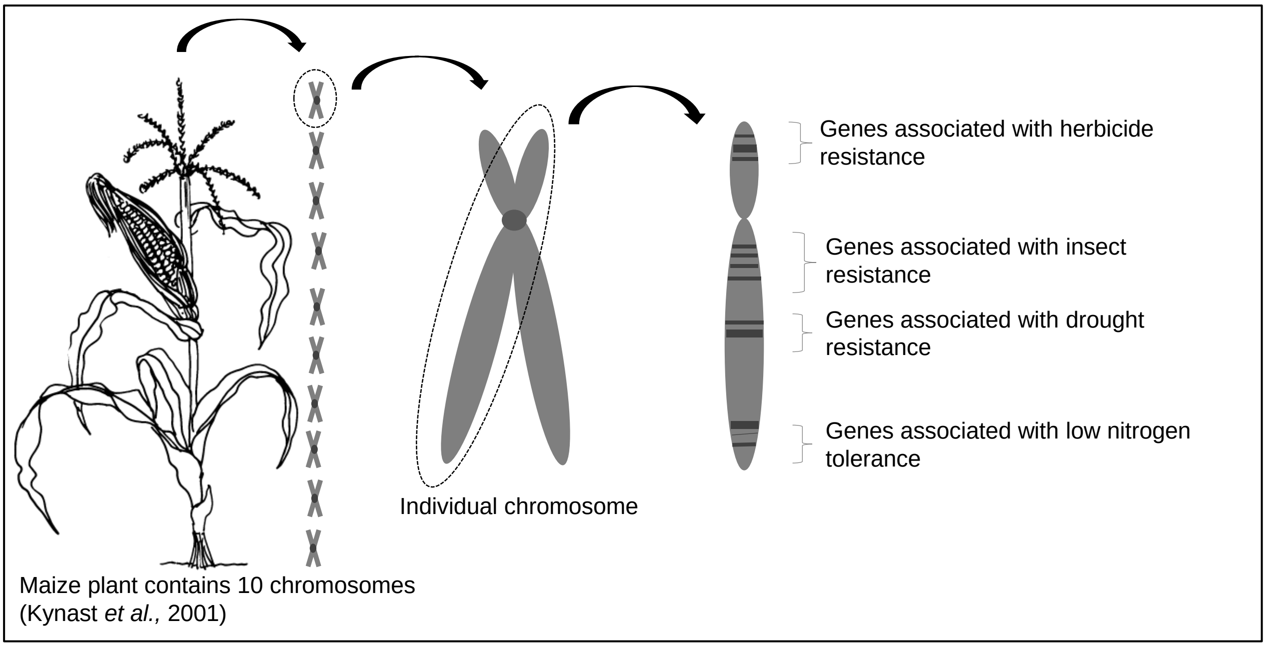

Figure 2.12: QTLs located on a maize chromosome (for illustration purposes only) (illustration by M de Bruyn)

2.6.2 Modernised agriculture

Modern technology including new technologies and digital infrastructures are enabling smart farming with high productivity levels across the world (Boakye, 2023). Precision farming is one such example which is often supported by Geographic Information Systems (GIS) (Raj, Appadurai & Athiappan, 2022). This process involves the usage of drones, sensors and satellites to make decisions based on detailed real-time data collected through the monitoring of environmental and physical parameters (Raj, Appadurai & Athiappan, 2022; Boakye, 2023). Inputs can then be utilised in precise amounts to increase crop yields (Raj, Appadurai & Athiappan, 2022).

2.6.3 Conservation agriculture

The FAO has proposed CA, as one means towards the transformation of efficient, reliable and sustainable food production systems (Strauss *et al.,* 2021). The FAO (2022a) defines CA as the following:

> “CA is a farming system that can prevent losses of arable land while regenerating degraded lands. It promotes maintenance of a permanent soil cover, minimum soil disturbance, and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground

> surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production."

The holistic approach of CA includes three main principles: Permanent soil cover, minimal soil disturbance and crop diversification (Hobbs, Sayre & Gupta, 2008; Mutuku *et al.,* 2020). The ultimate goal of CA is to farm sustainably (Jug *et al.,* 2018). Sustainable agriculture aims at sufficient, high-quality production while preserving natural resources as well as being economically and socially viable (Gomiero, Pimental & Paoletti, 2011; Reganold, Papendick & Parr, 1990). Therefore, three main goals are integrated into sustainable agriculture, namely environmental health, economic profitability and social equity (Brodt *et al.,* 2011).

2.6.3.1 Permanent soil cover

Permanent soil cover can either be residue from a harvested crop, a specifically grown cover crop, or organic material (FAO, 2022b; Jug *et al.,* 2018). Bare soils are especially susceptible to compaction and crusting (Indoria *et al.,* 2017), while soil cover has shown to influence crop production by influencing the soil's physical, chemical and biological functions as well as water and soil quality (Kumar & Goh, 1999). Soil cover protects soil from erosion, releases chemicals during decomposition, moderates soil temperature, prevents weeds and enhances water infiltration, all improving the soils' long-term productivity (Hobbs, Sayre & Gupta, 2008; Indoria *et al.,* 2017).

2.6.3.2 Minimal soil disturbance

Soil disturbance is mainly caused by tillage, a process of loosening soil (normally mechanically) which allows seeds to be planted at suitable depths, helps release soil nutrients and prevents soil compaction (Hobbs, Sayre & Gupta, 2008; Indoria *et al.,* 2017). However, the benefits of tillage come at a cost to the farmer and the environment, as it results in high production costs, inconsistent yields and soil degradation (Haarhoff, Kotzè & Swanepoel, 2020; Hobbs, Sayre & Gupta, 2008). Reduced tillage systems save time and labour, use less fossil fuel, reduce run-off and erosion of soils (FAO, 2022a; Hobbs, Sayre & Gupta, 2008). No-till (NT) in combination with soil cover has the potential to further reduce soil crusting, increase water infiltration and result in higher yields compared to tilled soils (Thierfelder *et al.,* 2022).

2.6.3.3 Crop diversification

Crop diversification refers to the addition of more crops to an existing cropping system (Feliciano, 2019). The diversification lowers risk in that different crops respond differently to different stress and provides dietary variation (Lakhran, Kumar & Bajiya, 2017; Renwick *et al.,* 2021). Crop diversification is generally in the form of intercropping, where crops are grown simultaneously in the same field and/ or crop rotation, where selected crops are grown in succession each season (Beillouin *et al.,* 2021).

Intercropping

Intercropping has been associated with higher land and nutrient efficiency, better economic returns and lower pest and disease incidence (Huang *et al.,* 2019). Cash crops are often included in intercropping systems, some examples include: Maize-soybean (Gao *et al.,* 2010), wheat-maize/watermelon (Huang *et al.,* 2015) and maize-chili pepper (Ouyang *et al.,* 2017). Common constraints accompanying intercropping is the complicated planting and harvesting process, as well as finding the correct combination of crops (Gebru, 2015; Huang *et al.,* 2015; Lithourgidis *et al.,* 2011).

Crop rotation

Crop rotational systems, normally made up of shallow and deep-rooted crops alternating with leguminous crops, improve soil structure, organic matter and water infiltration (Acevedo-Siaca & Goldsmith, 2020; Indoria *et al.,* 2017). Using crops with different root depths (tap roots vs adventitious roots) allow nutrients to be extracted from different levels of the soil, maintaining continuous, uniform nutrient availability (Tanveer, Ikram & Ali, 2019). Restoration crops, such as legumes (soybean, groundnuts, chickpeas), are able to provide an income but also put nutrients back into the soil, making it more fertile for the proceeding crop (Acevedo-Siaca & Goldsmith, 2020; Tanveer, Ikram & Ali, 2019). Successful crop rotational systems for maize production include maize-soybean (Hailemariam *et al.,* 2021), maize-millet-peanut (Zhang *et al.,* 2023), wheat-maize-sunflower (Zhao *et al.,* 2024) and maize-rye grass (Wang *et al.,* 2023) rotations. Crop rotational systems like these, together with minimal soil disturbance, helps water to infiltrate deeper and decrease pests and diseases by increasing microbial diversity (Hobbs, Sayre & Gupta, 2008).

The success of crop rotational systems relies heavily on the site and season (Al-Kaisi *et al.,* 2015; Alhameid *et al.,* 2017; Arriaga, Guzman & Lowery, 2017). Soil conditions such as drainage, texture, organic matter content and water-holding capacity together with weather conditions such as rain and temperature influence the success rate of specific crop rotational systems (Al-Kaisi *et al.,* 2015). Furthermore, management practices and crop demand also influence crop rotational systems (Tanveer, Ikram & Ali, 2019). Although rotational systems should involve at least three different crops, it is important to establish crop rotational system that ensures farm profitability while continually improving soil quality for long-term productivity (Jug *et al.,* 2018; Tanveer, Ikram & Ali, 2019).

Chapter 3

Sample collection and methodology

3.1 Introduction

An interdisciplinary approach of social and natural science was taken to achieve the aim of this study. Social science methodology was used to determine the perception of North-Western Free State farmers on crop diversification. This was a once-off process. A seasonal process of natural science methods were used to measure the sustainability aspects (environmental, social and economic) of crop rotation in the North-Western Free State.

3.2 Site description

The study was conducted in the North-Western Free State, South Africa. This area forms part of South Africa's maize quadrangle (Figure 3.1). Figure 3.2 shows the general climate conditions of the North-Western Free State with hot summers, mild winters and an annual rainfall of approximately 500 mm per year (Meteoblue, 2024; Nortjè & Laker, 2021). A common characteristic of the maize quadrangle is the non-oscillating patterns of low rainfall seasons, followed by high rainfall seasons (Laker, 2008).

Figure 3.1: Map of South Africa showing the location of sample collection in relation to the maize quadrangle (illustration by M de Bruyn)

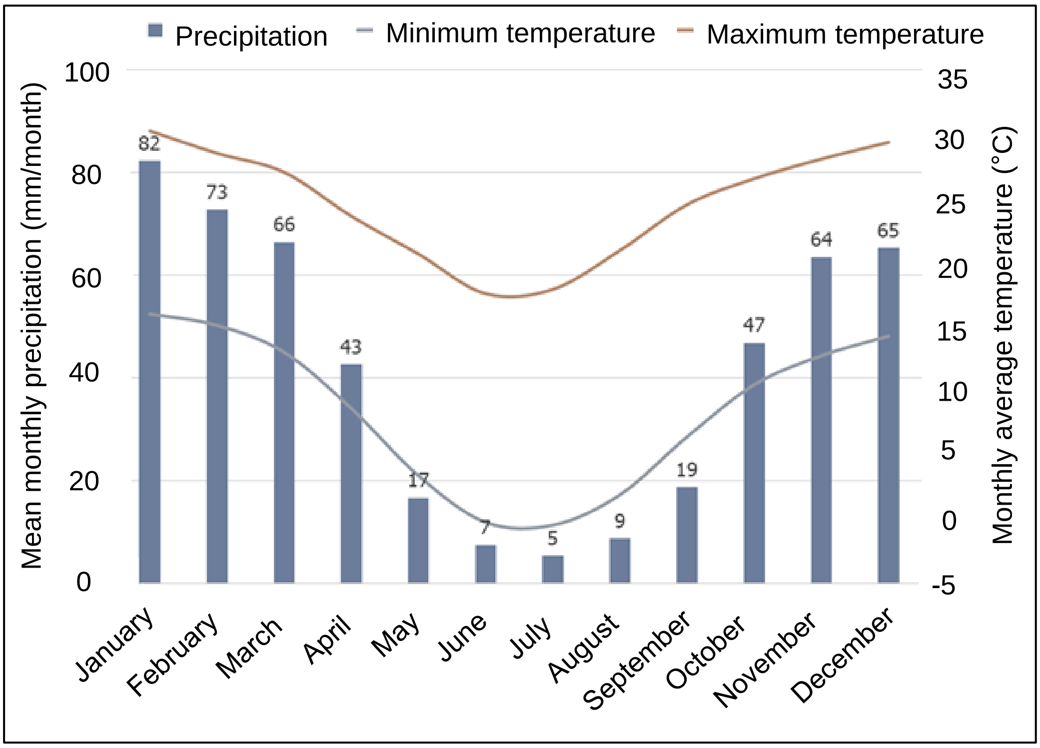

Figure 3.2: Mean monthly temperature and long-term mean precipitation for North-Western Free State (adapted from Meteoblue (2024))

The North-Western Free State is also known for its sandy soils which contains very little organic material, silt and clay (Beukes *et al.,* 2019; Strauss *et al.,* 2021). These soils fall in the extreme corner of the textual classes, as indicated in Figure 3.3. Only about 1 – 2% of the soil is made up of silt while the clay content in the A-horizon is normally less than 10%, and less than 15% in the B-horizon (Nortjè & Laker, 2021). These sandy soils are vulnerable to wind erosion (especially during August and September when westerly winds are strong), susceptible to soil compaction and are normally infertile (Nortjè & Laker, 2021; Strauss *et al.,* 2021). In addition, the soil has a relatively high rate of water filtration however, the layer of clay at a depth of 1,50 – 2,00 m prevents water drainage, often forming a temporary water table (Beukes *et al.,* 2019).

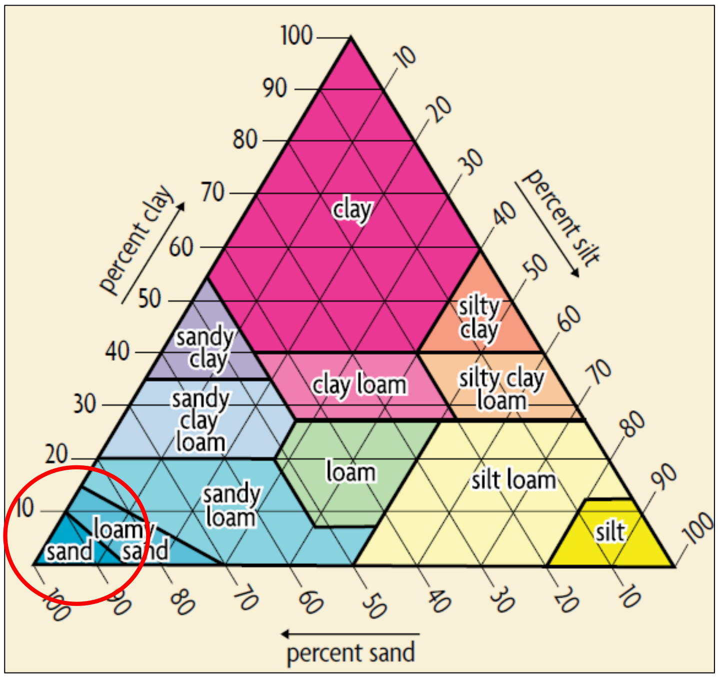

Figure 3.3: Sandy soils of the North-Western Free State in relation to the soil textual classes (modified from Magdoff & Van Es (2021))

The ability of the North-Western Free State soils to effectively capture and store rainwater through the temporary water table, is a major contributing factor to the high maize production in the area (Nel & Loubser, 2004). Field trials were conducted on the farm Christinasrus near the agricultural towns of Bothaville and Wesselsbron in the Lejweleputswa district. An array of samples were collected from the field trials to determine the sustainability of different rotational systems on maize production.

3.3 Target population and trial layout

A total of 60 North-Western Free State farmers took part in the social aspect of the study. A questionnaire was uniquely developed to determine the views and perspectives of North-Western Free State farmers on crop diversification. Human ethical clearance was received from the University of the Free State (UFS) in April 2022 (UFS-HSD2022/0242).

A trial comparing different crop rotational systems (maize-cover crop-soybean (MCS), maize-soybean-maize (MS) and maize-maize-soybean (MMS)) with monoculture maize (MM) as a control were established on the farm Christinasrus (Environmental ethical clearance was granted by the UFS in June 2022, UFS-ESD2022/0118.) The MMS system was further identified as MMS1 and MMS2 to distinguish between the first (MMS1) and second (MMS2) season of maize. A randomised complete block design with three replicates was used for the trial layout (Table 3.1). Plots were 80,00 x 24,40 m in size. Rotational systems were assigned to plots and each crop within each system, representing a different stage, was assigned to a plot in each season to be able to distinguish between seasonal and rotational effects. Table 3.2 illustrates the diversified rotational system for three seasons (2020/2021, 2021/2022 and 2022/2023).

Table 3.1: Randomised complete block design with three replicates on the farm Christinasrus

Replicate 1	**Plot 1** MMS	**Plot 2** MS	**Plot 3** MM	**Plot 4** MCS	**Plot 5** MCS	**Plot 6** MMS	**Plot 7** MS	**Plot 8** MCS	**Plot 9** MMS
Replicate 2	**Plot 10** MCS	**Plot 11** MS	**Plot 12** MCS	**Plot 13** MMS	**Plot 14** MCS	**Plot 15** MM	**Plot 16** MMS	**Plot 17** MS	**Plot 18** MMS
Replicate 3	**Plot 19** MM	**Plot 20** MMS	**Plot 21** MCS	**Plot 22** MS	**Plot 23** MMS	**Plot 24** MMS	**Plot 25** MS	**Plot 26** MCS	**Plot 27** MCS

Table 3.2: Rotational system plan for three seasons (2020/2021, 2021/2022 and 2022/2023)

Plot number	Rotational system	2020/2021	2021/2022	2022/2023
Plot 1	MMS	Maize	Maize	Soybean
Plot 2	MS	Maize	Soybean	Maize
Plot 3	MM	Maize	Maize	Maize
Plot 4	MCS	Maize	Cover crop	Soybean
Plot 5	MCS	Cover crop	Soybean	Maize
Plot 6	MMS	Soybean	Maize	Maize
Plot 7	MS	Soybean	Maize	Soybean
Plot 8	MCS	Soybean	Cover crop	Maize
Plot 9	MMS	Maize	Soybean	Maize
Plot 10	MCS	Maize	Cover crop	Soybean
Plot 11	MS	Soybean	Maize	Soybean
Plot 12	MCS	Cover crop	Soybean	Maize
Plot 13	MMS	Maize	Maize	Soybean
Plot 14	MCS	Soybean	Maize	Cover crop
Plot 15	MM	Maize	Maize	Maize
Plot 16	MMS	Maize	Soybean	Maize
Plot 17	MS	Maize	Soybean	Maize
Plot 18	MMS	Soybean	Maize	Maize
Plot 19	MM	Maize	Maize	Maize
Plot 20	MMS	Soybean	Maize	Maize
Plot 21	MCS	Maize	Cover crop	Soybean
Plot 22	MS	Soybean	Maize	Soybean
Plot 23	MMS	Maize	Maize	Soybean

Plot number	Rotational system	2020/2021	2021/2022	2022/2023
Plot 24	MMS	Maize	Soybean	Maize
Plot 25	MS	Maize	Soybean	Maize
Plot 26	MCS	Cover crop	Soybean	Maize
Plot 27	MCS	Soybean	Maize	Cover crop

3.4 Planting of trials

Season 1: 2020/2021

Soybean (P64T39R at ± 300 000 seeds ha^{-1}) and maize (DKC75-65R at 22 700 seeds ha^{-1}) were planted on 11 December 2020 and 14 December 2020, respectively. Maize was planted in 1,01 m spaced rows, while soybean were planted in 0,87 m rows, both in a rip-on-row system at a depth of 0,75 m. A cover crop mixture was planted on 11 December 2020 using a 14-row planter of which eight rows planted grass seeds and six rows planted legumes (0,87 m spaced rows). Grass seeds included forage sorghum (Honeymax and Agflash cultivars) and pearl millet (Okashana cultivar). The legumes consisted of dolichos (Rongai cultivar) and cowpeas (Glenda cultivar).

Season 2: 2021/2022

The soil was cultivated with a tandem ripper at a depth of 0,75 m on 21 September 2021. Maize (DKC75-65BR at 25 000 seeds ha^{-1}) and rhizobium inoculated soybean (PAN1644 at ± 300 000 seeds ha^{-1}) were planted on 9 December 2021 and 10 December 2021, respectively. Maize was planted in 1,01 m spaced rows, while soybean were planted in 0,87 m rows. A cover crop mixture was planted on 10 December 2021. Grass seeds included forage sorghum (Honeymax and Agflash cultivars) and pearl millet (Okashana cultivar). The legumes consisted of dolichos (Rongai cultivar) and cowpeas (Glenda cultivar). The legumes and grasses were planted in alternate 0,87 m spaced rows.

Season 3: 2022/2023

The soil was cultivated with a tandem ripper at a depth of 0,75 m prior to planting. Rhizobium inoculated soybean (PAN1644 at ± 300 000 seeds ha^{-1}) were planted on 23 November 2022, followed by maize (DKC76-77BR at 30 000 seed ha^{-1}) on 1 December 2022 and cover crop on 23 December 2022. The cover crop mixture consisted of grasses: Sorghum x sadangras (Multicut) and babala (Okashsana and

Supasweet) as well as and legumes: dolichos (Rongai cultivar) and cowpeas (Glenda cultivar). A 14-row planter was used to plant the cover crop, with eight rows planting grass seeds and six rows planting legumes (0,87 m spaced rows).

3.5 Fertilization and spraying of trials

Season 1: 2020/2021

Fertilization was applied with a 6,50 and 2,80 ton ha^{-1} maize and soybean target yield respectively. Preplant fertilization for maize, soybean and cover crop were done placing 140 kg ha^{-1} urea during the ripping action, at a depth of 0,30 m. Maize was additionally fertilized with 300 kg ha^{-1} 11:5:2 (18) at planting and top dressed with 175 kg ha^{-1} 3:0:1 (29) (Table 3.3). Soybean and cover crop received no additional fertilizer. Maize and soybean plots were sprayed with Round-up (glyphosate) for the control of weeds. (Cover crop is not Round-up ready).

Season 2: 2021/2022

Fertilization was applied with a 6,50 and 2,80 ton ha^{-1} maize and soybean target yield respectively. Preplant fertilization for maize, soybean and cover crop were done placing 140 kg urea ha^{-1} urea during the ripping action, at a depth of 0,30 m. Maize was additionally fertilized with 240 kg 11:5:2 (18) at planting and top dressed with 100 kg Greensulph (26% N) on 1 February 2022 (Table 3.3). Soybean and cover crop received no additional fertilizer however, 140 kg ha^{-1} urea was applied to the cover crop on 1 February 2022. Soybean were treated against nematodes with velum according to dosage instructions. Maize and soybean plots were sprayed with Round-up (glyphosate) for the control of weeds.

Season 3: 2022/2023

Fertilization was applied with a 6,50 and 2,80 ton ha^{-1} maize and soybean target yield respectively. Preplant fertilization for maize, soybean and cover crop were done placing 100 kg urea ha^{-1} during the ripping action, at a depth of 0,30 m. Maize and soybean were additionally fertilized with 320 kg 11:5:2 (18) at planting, and maize was top dressed with 175 kg ha^{-1} 3:0:1 (29) (Table 3.3). Soybeans were treated against nematodes with velum, while maize was treated with terbufos, both according to dosage requirements. Maize and soybean plots were sprayed with Round-up (glyphosate) for the control of weeds.

Table 3.3: Total N, P and K fertilization applied on maize plots each season (including pre-plant, with planting and top dress)

	Nitrogen (N)	**Phosphorous (P)**	**Potassium (K)**
Season 1 (2020/2021)	135 kg ha^{-1}	15 kg ha^{-1}	19 kg ha^{-1}
Season 2 (2021/2022)	116 kg ha^{-1}	12 kg ha^{-1}	5 kg ha^{-1}
Season 3 (2022/2023)	119 kg ha^{-1}	16 kg ha^{-1}	19 kg ha^{-1}

3.6 Seasonal rainfall

Season 1: 2020/2021

A favourable rainfall season was experienced during the 2020/2021 season. Figure 3.4 shows that a total of 689 mm was measured on Christinasrus from September 2020 and May 2021, with most rainfall falling between December and February (477 mm). Heavy rainfall in December resulted in some damage to crops due to waterlogged lands. Plot 9, 17, 18, 26 and 27 (highlighted in Table 3.4) were waterlogged, with most water building up on plots 26 and 27.

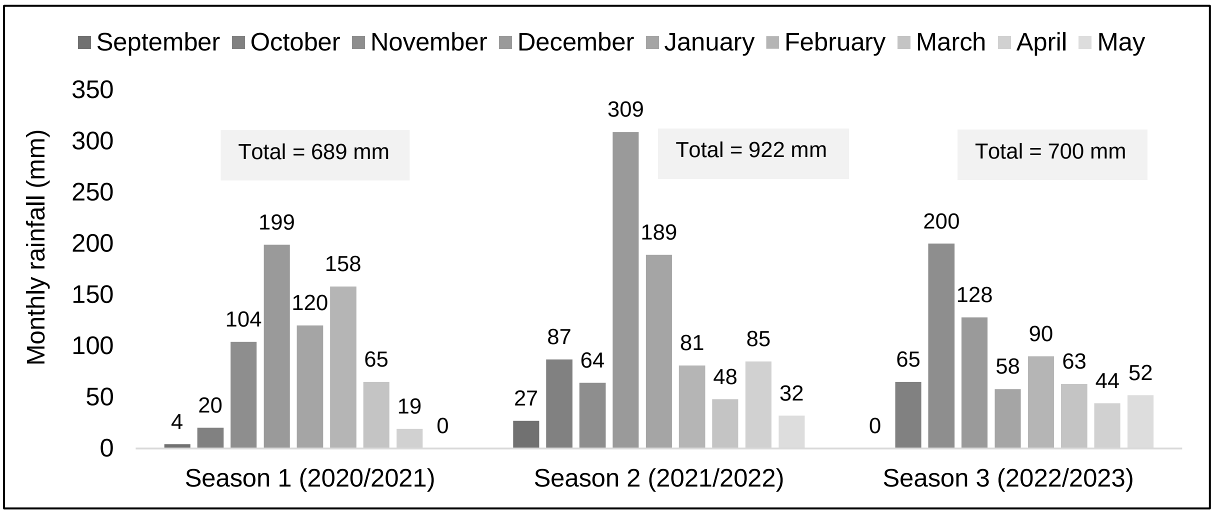

Figure 3.4: Rainfall distribution over Christinasrus for the months September to May during season 1 (2020/2021), season 2 (2021/2022) and season 3 (2022/2023) respectively (illustration by M de Bruyn)

Table 3.4: Plots waterlogged during the 2020/2021 season

Plot 1 **MMS** Maize 1	**Plot 2** **MS** Maize	**Plot 3** **MM** Maize	**Plot 4** **MCS** Maize	**Plot 5** **MCS** Cover crop	**Plot 6** **MMS** Soybean	**Plot 7** **MS** Soybean	**Plot 8** **MCS** Soybean	**Plot 9** **MMS** Maize 2
Plot 10 **MCS** Maize	**Plot 11** **MS** Soybean	**Plot 12** **MCS** Cover crop	**Plot 13** **MMS** Maize 1	**Plot 14** **MCS** Soybean	**Plot 15** **MM** Maize	**Plot 16** **MMS** Maize 2	**Plot 17** **MS** Maize	**Plot 18** **MMS** Soybean
Plot 19 **MM** Maize	**Plot 20** **MMS** Soybean	**Plot 21** **MCS** Maize	**Plot 22** **MS** Soybean	**Plot 23** **MMS** Maize 1	**Plot 24** **MMS** Maize 2	**Plot 25** **MS** Maize	**Plot 26** **MCS** Cover crop	**Plot 27** **MCS** Soybean

Season 2: 2021/2022

The 2021/2022 season had a very wet start compared to the previous season. A total of 922 mm was measured on Christianasrus between September 2021 and May 2022, with 309 mm of rain being measured in December 2021 alone (Figure 3.4). Unusually high rainfall caused serious waterlogging, especially on the plots already affected by the previous years' downpour. This waterlogging prevented the sprayer from getting into those sections of the field, affecting weed management (Figure 3.5).

Figure 3.5: Waterlogged plot 18 (maize) on 08/02/2022 (photograph by M de Bruyn)

Season 3: 2022/2023

Figure 3.6: Lush growth of crops (plot 6 and 7) on 16/01/2023 (photograph by M de Bruyn)

The third season saw a more wide-spread rainfall season (Figure 3.4). A total of 700 mm of rain was measured between September 2022 and January 2023 (24% less than in 2021/2022). This was welcomed after the high and heavy rainfall experienced the previous season. Figure 3.6 shows the lush growth of the crops.

Chapter 4

Views and perspectives of North-Western Free State farmers on crop diversification

4.1 Introduction

Sustainable agriculture through crop rotation falls under one of the FAO's (2022a) principles of conservation agriculture which states: "[practice of] species diversification through varied crop sequences and associations involving at least three different crops" (Nortjè & Laker, 2021:6). Studies suggest that by diversifying crops farmers prevent nutrient losses and have the potential to maintain high production levels with less fertilizer (Nevens & Reheul, 2001; Rovers & Kroonen, 1999; Smit, Strauss & Swanepoel, 2021). These benefits improve soil structure and moisture holding capacity which in turn improves root growth and root vigour, resulting in a healthy, high yielding plant (Nickel, Crookston & Russelle, 1995; Weisskopf *et al.,* 1995).

Sustainable systems differ according to climate and soil conditions, what works for one area does not necessarily work in another (Nortjè & Laker, 2021; Smit, Strauss & Swanepoel, 2021). Often farming systems proven successful in developed countries are attempted elsewhere with disappointing results, especially in developing countries (Nortjè & Laker, 2021). The challenge is to find sustainable systems that involve suitable and profitable crops ideal for a certain environment (Strauss *et al.,* 2021).

For many decades maize in the North-Western Free State has been grown in monoculture (Nel & Loubser, 2004; Nortjè & Laker, 2021). This was due to a generally high and stable maize price, the use of mineral fertilizers and pesticides as well as the unique climate and soil conditions (Nel & Loubser, 2004; Nevens & Reheul, 2001; Nortjè & Laker, 2021). Although mineral fertilizers replenish soil nutrients and pesticides control diseases and pests, prolonged use of these chemicals has shown to have undesirable effects on the environment (Prashar & Shah, 2016). In addition, the unique climate and soil conditions of the North-Western Free State limits the crop options available for rotation (Nortjè & Laker, 2021). Understanding the perceptions of local farmers on crop diversification and identifying the factors influencing farmers decisions on crop rotation will be fundamental in determining guidelines for successful crop diversification (with a focus on crop rotation) in the North-Western Free State (Kemausuor *et al.,* 2011).

4.2 Materials and methods

A mixed method research approach was taken whereby quantitative and qualitative data were collected through the admission of a questionnaire. The questionnaire was uniquely designed to determine the views and perspectives of North-Western Free state farmers on crop diversification based on crop rotation. The questionnaire was prepared in English but translated into Afrikaans, as this was the language spoken by most farmers in the area. There were three sections to the questionnaire: Demographic characteristics, farm information and crop diversification.

Convenience sampling was conducted whereby farmers were approached personally at farmer gatherings and/ or visitations during 2022. Inclusion criteria was based on occupation and farming area. Only farmers in the North-Western Free State were included in the study. Data were successfully collected from 60 North-Western Free State farmers who gave consent to participate in the study.

The questionnaire was pre-tested and reviewed by selected respondents. Face validity ensured that the questionnaire linguistically and analytically measured the views and perspectives of North-Western Free State farmers. Questionnaire reliability was determined by measuring the internal consistency to ensure stable and consistent results. For overall reliability Cronbach's alpha = 0,60, this was slightly below the general threshold value of 0,70, but according to Van Griethuijsen *et al.* (2015) can still be regarded acceptable.

4.3 Data analysis

Demographic and farm information

Completed questionnaires were captured and analysed using the Statistical Package for the Social Sciences (SPSS) version 28. Descriptive statistical analysis included frequency tables for categorical data (demographic characteristics) and measures of central tendency and dispersion for continuous data (farm information). Data were represented as mean ± standard deviation unless stated otherwise. General data were rounded off to two decimals, percentages and hectarage were rounded off to the nearest whole number. Qualitative data were manually analysed by creating themes and coded accordingly. Visual interpretation of data included tables and graphs.

Perception of crop diversity

Farmer's perception on crop diversity was measured using descriptive statistics. All participating farmers ($n = 60$) were asked to rate the relevance of crop diversification on a scale of 0 – 5 (0 = no relevance, 5 = very relevant). Five aspects of crop diversity were included namely: Yield increase, increased farm profit, improved soil health, better grain quality/ grading and lower financial risk. The mean of each aspect was measured individually, as well as the mean of all the aspects collectively to give an overall crop diversity relevance.

Further knowledge and understanding on how farmers in North-Western Free State apply crop rotation was gained by collecting additional data from farmers who indicated that they rotate their crops. Additional data included which crops were rotated and in what sort of system, as well the results seen in practice. Furthermore, data relating to the aspects influencing crop rotation application and sources of information used to gain technical information and guidance regarding crops and crop rotation were collected.

Crop diversity index (CDI)

Crop diversity was measured using the Herfindahl Index (HI). HI is defined as the sum of squares of n proportions (Malik & Singh, 2002). Participants were asked to indicate the percentage of land under each cultivated crop. Crops included were maize, sunflowers, soybean and wheat, as these were common commodities in North-Western Free State (Strauss *et al.,* 2021). Percentages were converted to proportions and used to calculate each farmer's HI. HI is directly related to CDI, in that CDI = 1 – HI (Malik & Singh, 2002). This calculation was used to determine each farmers CDI. CDI can range from zero to one with zero being an indication of complete specialisation while one indicates perfect diversification (Malik & Singh, 2002).

Inferential analysis

Inferential statistics were used to assess the relationship between demographic variables and the relevance of crop diversity as well as between demographic variables and CDI respectively. In addition, the association between the relevance of crop diversity and CDI was investigated. Statistical significance was accepted at $p \leq 0{,}05$.

Average relevance of crop diversification was cross tabulated by demographic response categories and a one-way analysis of variance (ANOVA) was run to explore the differences between demographic categories and the relevance of crop diversity. Assumption testing included testing for outliers, normal distribution and homogeneity of variances. Similarly, a one-way ANOVA was run to explore differences between demographic response categories and CDI. Again, assumption testing included testing for outliers, normal distribution and homogeneity of variances.

The association between the relevance of crop diversity and CDI was investigated by running a simple linear regression. Assumption testing included testing for outliers, normal distribution and homoscedasticity. A prediction equation was determined based on the regression results.

4.4 Results

Demographic and farm information

The descriptive statistics of the demographic characteristics are shown in Table 4.1. All 60 participants were male farmers. Most farmers were in the age range of 51 – 60 years (30%) and many were married (85%). Two-thirds of the farmers had at least a diploma/ degree and more than half of them had been farming for more than 15 years. Furthermore, 85% of the participants belonged to a farmer’s study group.

Table 4.1: Demographic characteristics of participating farmers

Variable	**Categories**	**Frequency**	
		Number	**Percentage**
Gender	Male	60	100%
Age	21 – 30 years	8	13%
	31 – 40 years	15	25%
	41 – 50 years	15	25%
	51 – 60 years	18	30%
	More than 60 years	4	7%
Marital status	Single	7	12%
	Married	51	85%
	Divorced	2	3%
Highest level of education	Grade 12	15	25%
	Diploma/ Degree	20	33%
	Postgraduate degree	20	33%

Variable	Categories	Frequency	
		Number	Percentage
Duration of farming	Less than 5 years	6	10%
	5 – 10 years	8	13%
	11 – 15 years	6	10%
	More than 15 years	35	58%
Belong to a farmer's study group		51	85%

Measures of central tendency and dispersion relating to farm information are shown in Table 4.2. The mean number of people employed on the farms were 22,35 ± 23,15 with a minimum of 4,00 and a maximum of 120,00. The mode indicated that the majority of the farmers employed 10 employees. The mean farm size was 3 256 ± 3 108 ha with a mean of 2 528 ± 2 625 ha being cultivated. Most of the farmers had 2 000 ha land, of which 1 400 ha was cultivated.

Table 4.2: Measures of central tendency and dispersion relating to farm information of participating farmers

Statistics	Number of employees	Farm size (ha)	Cultivated land (ha)
Mean	22,35	3 256	2 528
Median	15,00	2 000	1 800
Mode	10,00	2 000	1 400
Standard deviation	23,15	3 108	2 625
Minimum	4,00	700	250
Maximum	120,00	15 000	12 000
Range	116,00	14 300	11 750
Interquartile range (IQR)	13,00	1 900	1 600

Perception of crop diversity

Farmers in the study area had a positive perception of crop diversity. The farmers rated all aspects of crop diversity relatively high (Figure 4.1). Yield increase had the highest relevance rating (4,26 ± 0,77) followed closely by improved soil health (4,25 ± 0,93). Better grain quality/ grading had the lowest relevance rating but still scored relevant (3,96 ± 1,01).

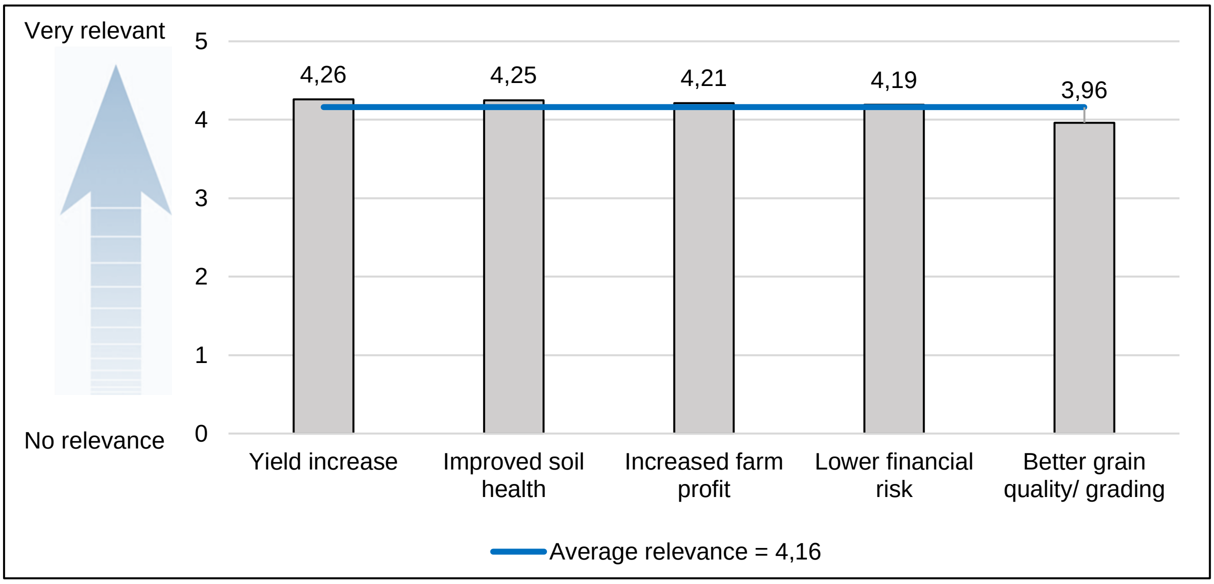

Figure 4.1: Farmer perception of the relevance of crop diversification in terms of yield increase, improved soil health, increased farm profit, lower financial risk and better grain quality

Almost all farmers in the study cultivated maize (93%) with 87% of the farmers rotating their crops (n = 52). Figure 4.2 shows the main crops used in rotational systems by farmers rotating their crops. The majority of these farmers rotated maize with soybean, sunflowers and/ or wheat. Other crops included dry beans, peanuts, potatoes, cover crops and other grasses. Those who did not rotate crops (n = 8) mentioned that it came down to the practicality of it, mainly due to the lack of equipment but also an issue of time management.

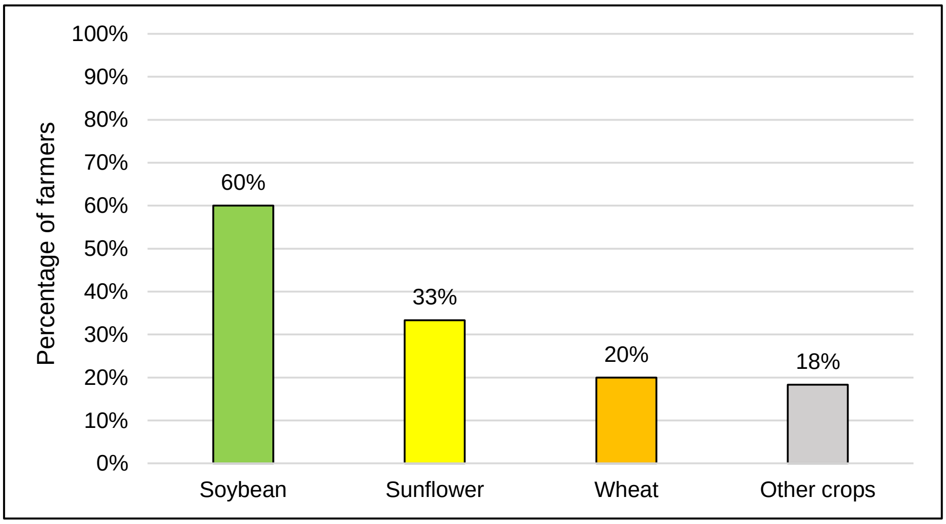

Figure 4.2: Percentage of farmers rotating maize with soybean, sunflower, wheat and other crops in the North-Western Free State

The results experienced by farmers rotating their crops are illustrated in Figure 4.3. Most farmers who rotated their crops experienced an increase in crop yield (90%). Many of these farmers also experienced an increase in farm profit and soil health (80% and 77% respectively). Half of the participants (50%) experienced an increase in financial risk, while 32% experienced a decrease in financial risk.

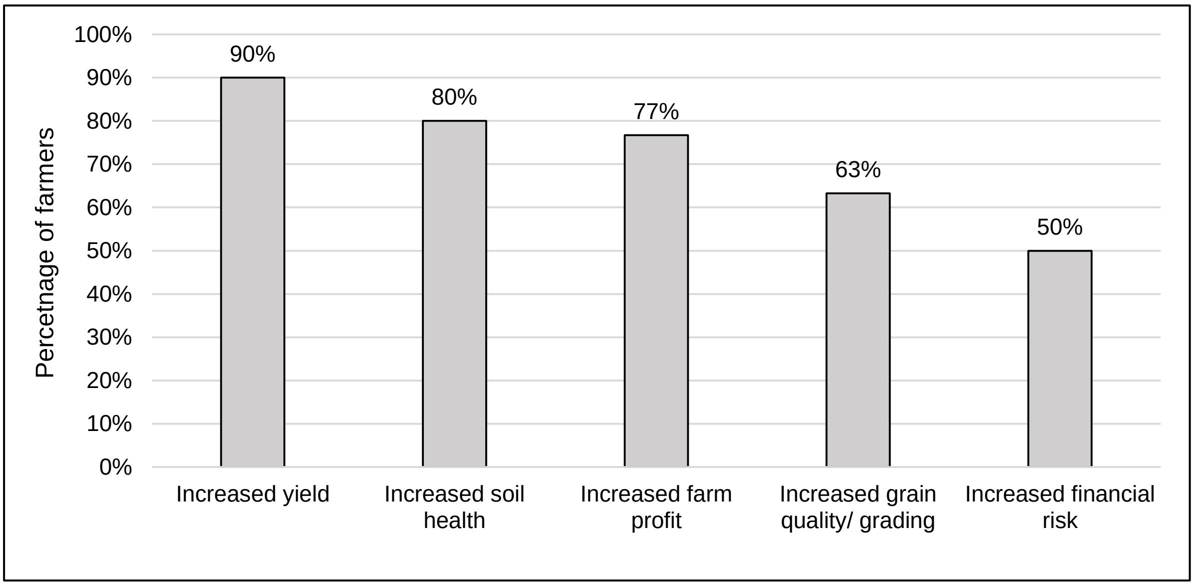

Figure 4.3: Crop rotation results experienced by farmers regarding crop yield, soil health, farm profit, grain quality and financial risk

Figure 4.4 shows how certain aspects influenced the application of crop rotation. Many farmers who rotated their crops did not consider following a fixed rotational system as very important but instead adjusted their rotational system according to the weather (rainfall) predications. Soil health and sustainability was also rated an important aspect when applying rotational systems.

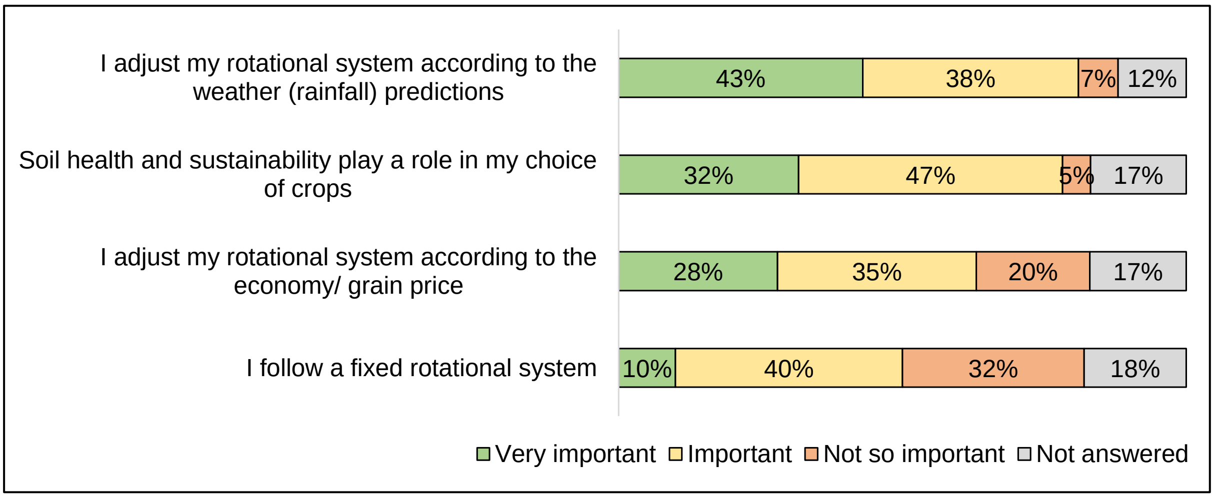

Figure 4.4: Farmers perceived importance of aspects influencing the application of crop rotation

The results in Figure 4.5 show that technical information or guidance regarding crops and crop rotation from fellow farmers (mentor farmers) was considered most important by farmers rotating their crops. Farmer days as a source of crop rotation information was also rated very important. Technical information or guidance from magazines was less likely to influence farmers perception on crop rotation.

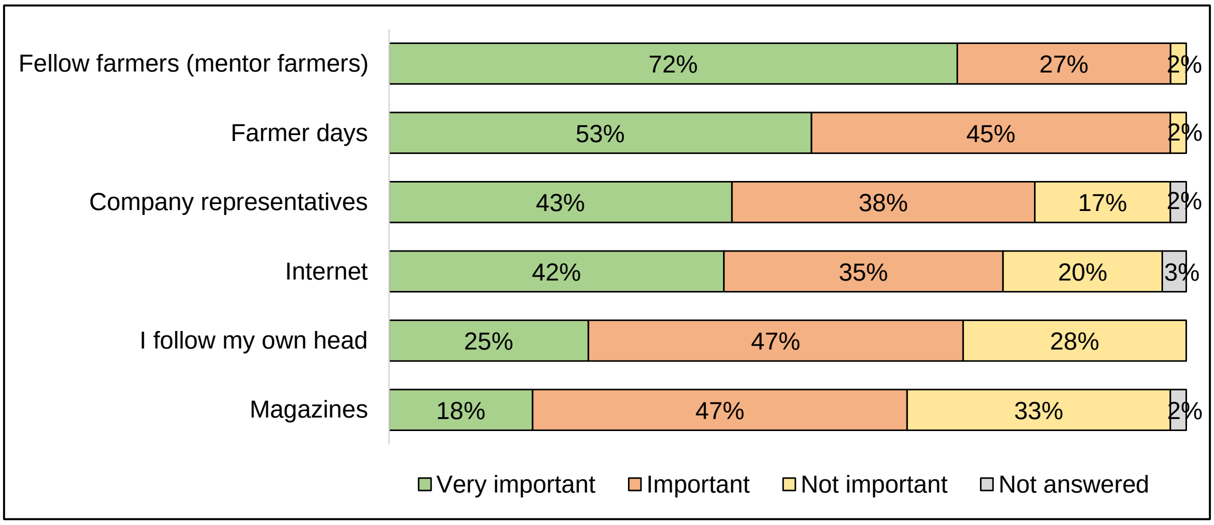

Figure 4.5: Farmers perceived importance regarding the sources of crop rotation technical information

Crop diversity index (CDI)

The mean CDI was 0,42 ± 0,23 with a minimum of 0,00 and a maximum of 0,73. The distribution of farmer's CDI is shown in Figure 4.6 (CDI could not be measured for four participants due to missing data). Some farmers had a low CDI showing a high degree of specialisation, with 13% of farmers having complete specialisation (CDI = 0,00). On the contrary, more than half of the farmers had a CDI of 0,50 or higher, showing movement towards diversification.

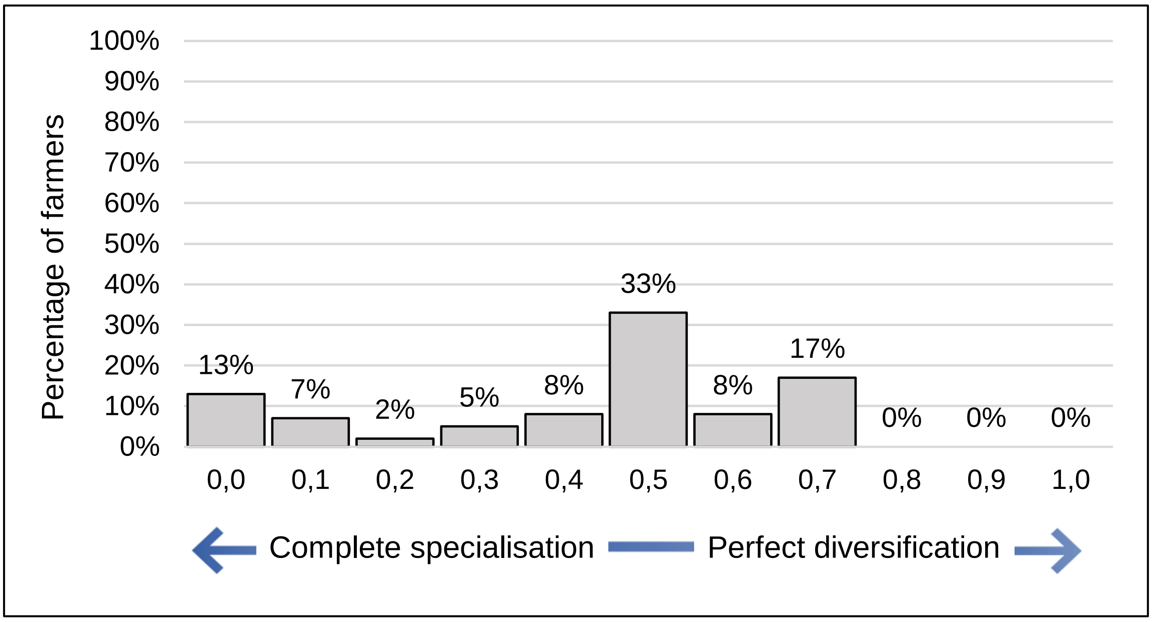

Figure 4.6: Distribution of farmer's CDI ranging from complete specialisation to perfect diversification

Inferential analysis

Table 4.3 shows the ANOVA results of the average relevance of crop diversification per demographic variable after assumption testing found no violations. There were no statistically significant relationships between any demographic variable and the relevance of crop diversification, all *p*-values > 0,05. As a result of no statistically significant differences, no post-hoc tests were required.

Table 4.3: ANOVA results for average relevance of crop diversification per demographic variable

Demographic variable	**Categories**	**Average relevance of crop diversification**	**ANOVA results**	
			***F*-statistic**	***p*-value**
Marital status	Single	4,20	0,81	0,63
	Married	4,10		
	Divorced	4,30		
Age group	21-30 years	3,90	1,17	0,33
	31-40 years	4,10		
	41-50 years	4,20		
	51-60 years	4,10		
	60 years and older	4,50		
Level of education	Grade 12	4,50	1,62	0,13
	Diploma/ degree	4,00		
	Post graduate degree	4,10		

Demographic variable	**Categories**	**Average relevance of crop diversification**	**ANOVA results** ***F*-statistic**	 ***p*-value**
Farming duration	Less than 5 years	4,20	1,22	0,31
	5-10 years	3,80		
	11-15 years	4,30		
	More than 15 years	4,30		
Belong to farmers study group	Yes	4,30	0,59	0,82
	No	4,70		

Table 4.4 shows the ANOVA results of the average CDI per demographic variable after assumption testing found no violations. There were no statistically significant relationships between any demographic variable and CDI, all *p*-values > 0,05. As a result of no statistically significant differences, no post-hoc tests were required.

Table 4.4: ANOVA results for average CDI per demographic variable

Demographic variable	**Categories**	**Average CDI**	**ANOVA results** ***F*-statistic**	 ***p*-value**
Marital status	Single	0,50	1,42	0,20
	Married	0,40		
	Divorced	0,70		
Age group	21-30 years	0,30	0,56	0,94
	31-40 years	0,40		
	41-50 years	0,50		
	51-60 years	0,40		
	60 years and older	0,50		
Level of education	Grade 12	0,40	1,10	0,42
	Diploma/ degree	0,40		
	Post graduate degree	0,40		
Farming duration	Less than 5 years	0,50	0,49	0,96
	5-10 years	0,40		
	11-15 years	0,30		
	More than 15 years	0,40		
Belong to farmers study group	Yes	0,40	0,99	0,52
	No	0,30		

A linear regression established that average crop diversity relevance could statistically significantly predict CDI, $F(1,49) = 9,71$, $p = 0,003$. Average crop diversity relevance accounted for 17% of the explained variability in CDI. The crop diversity relevance was associated with a 0,13 unit increase in CDI, indicating a positive association between crop diversity relevance and CDI with a regression equation of: CDI = -0,10 + (0,13 x (crop diversity relevance)). This regression is shown in Figure 4.7.

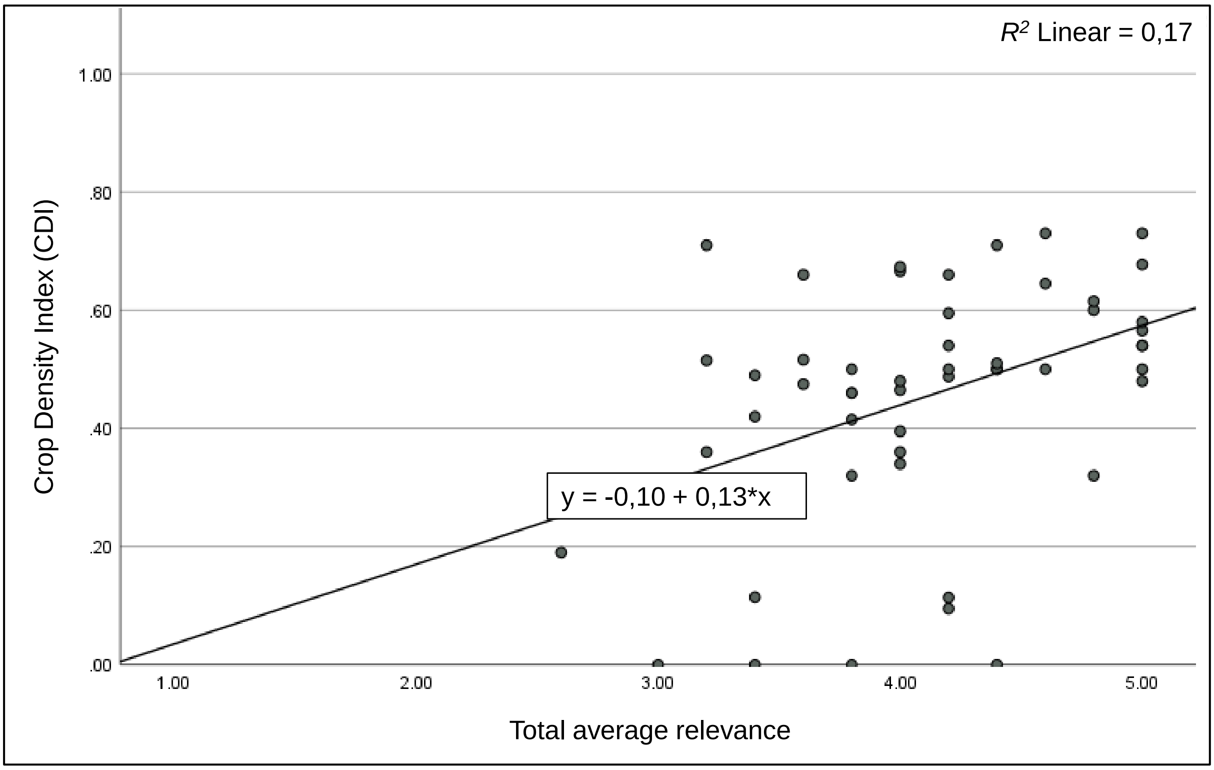

Figure 4.7: Scatter plot illustrating the linear association between average crop diversity relevance and CDI

4.5 Discussion and conclusion

North-Western Free State agriculture is dominated by male farmers, very few, if any, women are directly involved in commercial maize production. This could be attributed to the more traditional, conservative nature of the older population. More conservative communities tend to favour married living arrangements and the men are normally more hands on in the fields while women are inclined to be responsible for family and house chores. Similar observations were made in a research study done by Mazibuko and Antwi (2019) in the North West province of South Africa.

North-Western Free State farmers are making a shift towards crop diversification. It has been noted that the area was previously dominated by monoculture maize (Nel & Loubser, 2004; Nortjè & Laker, 2021). Similarly, in this study maize was the major crop cultivated in the area with some farmers still specialising in monoculture maize. However, most farmers recognised the relevance of crop diversification, especially with regards to yield increase, improved soil health and increased farm profit. It is likely that this positive perception of crop diversity contributed to the fact that so many farmers in the area did in fact rotate their crops.

Rotation systems in the North-Western Free State were similar to those mentioned in Strauss *et al.* (2021) which comprised mainly of rotating maize with soybean, sunflower and/ or wheat. Soybean was the most popular choice to rotate with maize, which corresponds to the current surge in soybean production. The area planted under soybean in South Africa has increased by 64% since 2016/2017 with the North-Western Free State being a major contributor (Coleman, 2021; DALRRD, 2020). Few farmers in the area rotated maize with cover crop, which is a cash crop substitute that should be considered to improve rotational system's productivity (Smit, Strauss & Swanepoel, 2021). By introducing cover crops, with the already included soybean in rotation with maize, soil nutrients could be replenished naturally, decreasing the amount of costly fertilizer required (Nortjè & Laker, 2021). This, together with the lower input costs associated with cover crop and soybean production (Coleman, 2021), could steer farmers into crop diversification resulting in more farmers experiencing the decrease in financial risks thought to be involved in crop rotation.

North-Western Free State farmer's perception on crop diversity, and practise thereof, was not influenced by demographic characteristics. This could be attributed to the fact that many farmers often followed their own head when it came to making crop diversification decisions. However, similar to findings from a study tour by United States Agency for International Development (USAID) (2007) and research conducted by Sinyolo and Mudhara (2018), the importance of farmer organisations as a means of spreading knowledge and influencing decision making was evident in this study. Most North-Western Farmers belonged to some form of farmer group or association and also rated fellow farmers (mentor farmers) as the most important means of gaining technical information or guidance regarding crops and crop rotation. The transfer and spread of information and knowledge regarding crop diversification are pivotal, as was confirmed by the positive association between farmers who were more aware of, and rated, the relevance of crop diversification high and a higher CDI.

In conclusion, by acknowledging the benefits of crop diversity and moving away from crop specialisation towards crop diversification, North-Western Free State farmers are affirming to the crop diversification principle of conservation agriculture, ultimately ensuring sustainable agriculture in the area.

The results reported in this chapter have been published in de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2022). Views and perspectives of local farmers on crop diversification in the North-Western Free State, South Africa, *African Journal of Agricultural Research*, vol. 18, no. 11, pp. 1006-1012. A slightly modified version was also published in the September 2022 issue of SA Grain.

Chapter 5

The effect of crop rotation on soil health in the North-Western Free State

5.1 Introduction

The concept of soil health emerged in the 1990s but has regained interest with the recent emphasis on sustainable agriculture (Lehmann *et al.,* 2020; Magdoff & Van Es, 2021). It's definition of "the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals, and humans" stresses its importance in our life support system (Lehmann *et al.,* 2020:2). Soil is considered healthy when good yields are consistently produced without having a negative effect on the environment (Magdoff & Van Es, 2021).

Soil health is promoted when all three of its components (physical, chemical and biological) are optimal (Magdoff & Van Es, 2021). Soil is physically healthy when sufficient volumetric aggregate stability allows water infiltration, limits surface runoff and provides adequate aeration (Cardoso *et al.,* 2013). The volumetric aggregate stability, which encapsulates organic matter, should be more than 45% (Sundermeier, Shedekar & Lijun, 2023), while there should be 3% organic matter in soil (Ward Laboratories, 2019).

Soil must be able to sufficiently absorb, release and transform essential nutrients including N, P and K (Magdoff & Van Es, 2021). These macronutrient measurements should ideally be as shown in Table 5.1 to optimally perform specific roles. In order to obtain ideal nutrient measurements, the pH of the soil should be slightly acidic (5,50 – 6,50), with the optimum for grain crops being 5,50 – 7,50. (Hinsinger *et al.,* 2009; Morgan, Beinding & White, 2005; Opala, Odendo & Muyekho, 2018).

Table 5.1: Ideal measurements for soil macronutrients and their role in crop production

Macronutrient	**Ideal soil measurement (mg kg^{-1})**	**Role in crop production**
Nitrogen (N)	40 (Cowen, 2023)	Fundamental for a healthy ecosystem (Girkin & Cooper, 2023)
Phosphorous (P)	16 – 20 (Mallarino & Sawyer, 2013)	Root growth and nutrient uptake (Mitran *et al.,* 2018)
Potassium (K)	120 – 200 (Mallarino & Sawyer, 2013)	Growth and stress adaption (Johnson *et al.,* 2022)

Furthermore, if the soil is healthy, biodiversity is increased and beneficial organisms are active which stimulates plant growth (Magdoff & Van Es, 2021). The more microbial respiration CO_2-C soils produce, the more microbial life can thrive in that environment (Ward Laboratories, 2019). Soil respiration can range between 0 and 1000 mg kg^{-1} of CO_2-C, most agricultural soils do not exceed 200 mg kg^{-1}, with an ideal measurement considered to be > 50 mg kg^{-1} (Ward Laboratories, 2019). Microbially active carbon (C) should be > 20% for a good fertility balance to support biomass (Ward Laboratories, 2019). In addition, the C:N ratio is important to keep microbes thriving (Ward Laboratories, 2019). An ideal ratio of 10:1 – 12:1 means that there is a good balance of available energy and nitrogen for microbes (Ward Laboratories, 2019).

Generally, the sandy soils of the Northern Free State have very little organic material and are vulnerable to wind erosion (Beukes *et al.,* 2019; Strauss *et al.,* 2021). Erosion, which mostly occurs during the windy months of August and September, removes a lot of nutrients from the soil (Strauss *et al.,* 2021). Soil degradation is further influenced by heavy machinery causing compaction, tillage which break soil aggregates and the addition of artificial fertilizers (Magdoff & Van Es, 2021; Nortjè & Laker, 2021). Therefore, these soils are not always able to provide sufficient water and nutrients for crops. There is a need to adopt practices that will improve the health of the North-Western Free State soils.

Different management practises often result in differences in biological, chemical and physical soil properties which in return results in changes in functional quality of the soil (Islam & Weil, 2000). Magdoff and Van Es (2021) mentioned that following practices that build and maintain organic matter may be the key to healthy soils. One such practice is that of crop rotation (Raphael *et al.,* 2016). Crop rotations play an integral role in maintaining organic matter, promoting healthy soil and encouraging sustainable agriculture as a whole (Deiss *et al.,* 2021; Raphael *et al.,* 2016).

The North-Western Free State is dominated by maize production, which is normally grown in monoculture (Loubser & Nel, 2004; Nortjè & Laker, 2021). However, the combination of maize with leguminous crops creates a more efficient environment in which soil fertility is protected and results in higher yields (Acevedo-Siaca & Goldsmith, 2020). Soybean (*Glycine max*), a leguminous crop, has been recognised for its commercial potential because of its use in food, livestock feed and as an industrial raw material (Acevedo-Siaca & Goldsmith, 2020). Soybean plants in symbiosis with *Rhizobium* bacteria are able to fix atmospheric N, the underground residue left behind after harvest improves soil N content and organic matter (Acevedo-Siaca & Goldsmith, 2020; Coskan & Dogan, 2011). This decreases the need for chemical fertilizer as N is produced naturally (Acevedo-Siaca & Goldsmith, 2020). In addition, soybean in rotational systems can increase total microbial communities and bacterial diversity (Fu *et al.,* 2020; Gil *et al.,* 2011).

The inclusion of a third crop in rotational systems is encouraged (Jug *et al.,* 2018; Tanveer, Ikram & Ali, 2019). Including a third crop in crop rotational systems has potential to further enhance soil health, resulting in better crop production (Jug *et al.,* 2018; Tanveer, Ikram & Ali, 2019). It has been suggested that including a cover crop mixture as a third crop improves the rotational system's productivity (Magdoff & Van Es, 2021; Smit, Strauss & Swanepoel, 2021). Cover crop is a cash crop substitute and usually refers to plants that are grown but not harvested (Magdoff & Van Es, 2021; Smit, Strauss & Swanepoel, 2021). There are many benefits associated with growing a cover crop (Figure 5.1).

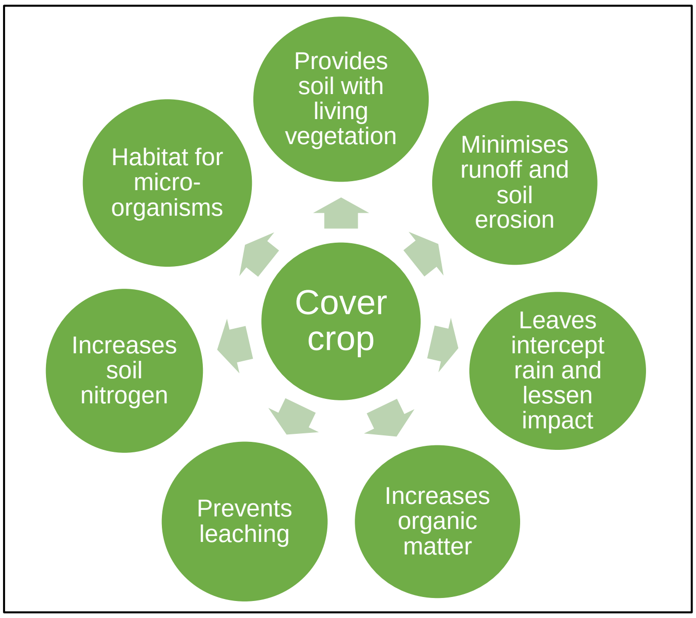

Figure 5.1: Benefits associated with including a cover crop in rotational systems (adapted from Magdoff & Van Es (2021))

Research has shown that agricultural sustainability can be achieved through improvement of soil health by means of crop rotational systems (Deiss *et al.,* 2021; Raphael *et al.,* 2016). The key is finding crop rotational systems ideal for the North-Western Free State. As part of identifying ideal crop rotational systems, it is important to closely monitor soil health.

5.1.1 Haney soil health test (HSHT)

A crucial initial step in evaluating soil health is properly assessing the condition of the soil (Haney *et al.,* 2018). Unlike traditional methods, Haney takes a different approach of evaluating soil health by focusing on soil as a dynamic living system, rather than just physical or chemical processes. (Haney *et al.,* 2018). Haney *et al.* (2018) highlights the importance of including the biological aspect into soil health score. Soil microbes colonise plant roots inducing mechanisms that increase plant growth (Miransari, 2011). Therefore, the HSHT not only estimates plant available N, P and K but also provides an indication of soil health with respect to nutrient and C cycling (Haney *et al.,* 2018).

The HSHT uses a H3A (Haney, Haney, Hossner and Arnold) extractant to measure plant available nutrients including N (NH_4-N and NO_3-N), P and K (Chu *et al.,* 2019; Singh *et al.,* 2020). This extractant is made up of organic acids (citric acid, oxalic acid and acetic acid), which mimic plant root exudates better than other extractants (Haney *et al.,* 2018; Singh *et al.,* 2020). Since the majority of nutrient cycling is due to a natural drying- rewetting effect (rainfall and irrigation), water extracts are also investigated to better represent the natural environment (Haney *et al.,* 2018). The water extractable organic N (WEON) is the active organic soil N (Haney *et al.,* 2018). The water extractable C (WEOC) reflects the quality of soil organic C as it provides the energy source for soil microbial activity, therefore similar to WEON, WEOC estimates the active pool of soil C (Haney *et al.,* 2018). This approach considers the WEOC/ WEON ratio a more sensitive indicator of microbial activity than the traditional total C:N ratio (Chu *et al.,* 2019).

An important factor in the HSHT is the microbial respiration CO_2-C (Chu *et al.,* 2019). The CO_2-C released by soil microbes in 24 hours after the soil has been dried and rewetted is an indicator of soil respiration, and consequently microbial activity (Haney *et al.,* 2018; Singh *et al.,* 2020). The properties measured by the HSHT are integrated using Haney's formula to obtain an overall soil health score as related to nutrient and C cycling. (Haney *et al.,* 2018; Ward Laboratories, 2019). The resulting score can range between 0 and 50, with a higher score meaning better soil health (Ward Laboratories, 2019). Most soils do not score more than 30, while scores below seven are regarded low (Ward Laboratories, 2019).

5.2 Materials and methods

5.2.1 Sample collection and testing

Soil samples were collected from all maize plots in the Christinasrus trial during each season (Table 5.2, Table 5.3, Table 5.4). The samples were taken at maize maturity, approximately 100 days after planting (23/03/2021, 23/03/2022 and 24/03/2023 respectively) and collected at a depth of 0 – 0,15 m (Figure 5.2). Samples were taken randomly within each plot 0,20 m from the plant row and combined to form a composite sample. Environmental ethical clearance was received from the UFS (UFS-ESD2022/0118) and samples were sent to Soil Health Solutions for further analysis. (No biomass was removed nor utilised by any farm animals.)

Figure 5.2: Soil sample collection on 23/03/2022 (photograph by M de Bruyn)

Table 5.2: Plots from which soil samples were taken for soil health analysis during the 2020/2021 season (highlighted in green)

Plot 1 **MMS** Maize 1	**Plot 2** **MS** Maize	**Plot 3** **MM** Maize	**Plot 4** **MCS** Maize	**Plot 5** **MCS** Cover crop	**Plot 6** **MMS** Soybean	**Plot 7** **MS** Soybean	**Plot 8** **MCS** Soybean	**Plot 9** **MMS** Maize 2
Plot 10 **MCS** Maize	**Plot 11** **MS** Soybean	**Plot 12** **MCS** Cover crop	**Plot 13** **MMS** Maize 1	**Plot 14** **MCS** Soybean	**Plot 15** **MM** Maize	**Plot 16** **MMS** Maize 2	**Plot 17** **MS** Maize	**Plot 18** **MMS** Soybean
Plot 19 **MM** Maize	**Plot 20** **MMS** Soybean	**Plot 21** **MCS** Maize	**Plot 22** **MS** Soybean	**Plot 23** **MMS** Maize 1	**Plot 24** **MMS** Maize 2	**Plot 25** **MS** Maize	**Plot 26** **MCS** Cover crop	**Plot 27** **MCS** Soybean

Table 5.3: Plots from which soil samples were taken for soil health analysis during the 2021/2022 season (highlighted in green)

Plot 1 **MMS** Maize 2	**Plot 2** **MS** Soybean	**Plot 3** **MM** Maize	**Plot 4** **MCS** Cover crop	**Plot 5** **MCS** Soybean	**Plot 6** **MMS** Maize 1	**Plot 7** **MS** Maize	**Plot 8** **MCS** Maize	**Plot 9** **MMS** Soybean
Plot 10 **MCS** Cover crop	**Plot 11** **MS** Maize	**Plot 12** **MCS** Soybean	**Plot 13** **MMS** Maize 2	**Plot 14** **MCS** Maize	**Plot 15** **MM** Maize	**Plot 16** **MMS** Soybean	**Plot 17** **MS** Soybean	**Plot 18** **MMS** Maize 1
Plot 19 **MM** Maize	**Plot 20** **MMS** Maize 1	**Plot 21** **MCS** Cover crop	**Plot 22** **MS** Maize	**Plot 23** **MMS** Maize 2	**Plot 24** **MMS** Soybean	**Plot 25** **MS** Soybean	**Plot 26** **MSC** Soybean	**Plot 27** **MCS** Maize

Table 5.4: Plots from which soil samples were taken for soil health analysis during the 2022/2023 season (highlighted in green)

Plot 1 MMS Soybean	**Plot 2 MS** Maize	**Plot 3 MM** Maize	Plot 4 MCS Soybean	**Plot 5 MCS** Maize	**Plot 6 MMS** Maize 2	Plot 7 MS Soybean	Plot 8 MCS Cover crop	**Plot 9 MMS** Maize 1
Plot 10 MCS Soybean	Plot 11 MS Soybean	**Plot 12 MCS** Maize	Plot 13 MMS Soybean	Plot 14 MCS Cover crop	**Plot 15 MM** Maize	**Plot 16 MMS** Maize 1	**Plot 17 MS** Maize	**Plot 18 MMS** Maize 2
Plot 19 MM Maize	**Plot 20 MMS** Maize 2	Plot 21 MCS Soybean	Plot 22 MS Soybean	Plot 23 MMS Soybean	**Plot 24 MMS** Maize 1	**Plot 25 MS** Maize	**Plot 26 MCS** Maize	Plot 27 MCS Cover crop

Soil pH was measured in a water (H_2O) suspension (Soil Health Solutions, 2021). Physical properties which included volumetric stability and organic matter were measured in the laboratory (Soil Health Solutions, 2021). Chemical and biological properties, as described in Table 5.5 were measured and calculated using the HSHT. The subsequent overall soil health score was determined using the calculation described by Haney (Haney *et al.,* 2018; Soil Health Solutions, 2021).

Table 5.5: Chemical and biological soil properties measured and calculated in the HSHT (Haney *et al.,* 2018)

Chemical properties	Total water extractable N (WEN)
	Inorganic N (NO_3-N and NH_4-N)
	Organic N (WEON)
	Total P
	Total K
Biological properties	Soil respiration CO_2-C
	Water extractable organic C (WEOC)

5.2.2 Data analysis

Data received from Soil Health Solutions contained the results of the soil properties and HSHT. Data were cleaned and prepared for SPSS, where it was further analysed using descriptive and inferential statistics. Descriptive statistics were represented in text as mean ± standard deviation, unless stated otherwise. General data were rounded off to two decimals, percentages were rounded off to the nearest whole number. Inferential statistics included two-way ANOVAs, which were run to determine if there was a statistically significant interaction effect of rotational system and season on soil properties and overall soil health. Assumption testing included testing for outliers, normal distribution and homogeneity of variances. Assumptions of normal distribution and homogeneity were violated in some cases however, because of the small sample size and the fact that ANOVAs are considered robust to deviations all results were interpreted (Jaccard, 1998; Maxwell, Delany & Kelley, 2017). Post-hoc Least Significant Difference (LSD) tests were run for statistically significant ANOVA results. Statistical significance was accepted at $p \leq 0{,}05$.

5.3 Results

5.3.1 Soil pH

Figure 5.3 shows the mean soil pH (H_2O) over the study period. The two-way ANOVA (Table 5.6) showed that soil pH was affected by season ($F(2) = 91{,}96$, $p < 0{,}001$) but not the rotational system ($F(4) = 0{,}57$, $p = 0{,}69$), with no interaction between these variables, $F(8) = 0{,}80$, $p = 0{,}61$. There was an upward trend in soil pH with regards to the seasons. Soil pH in the first season (2020/2021) was within the ideal range of 5,50 - 6,50 (Soil Health Solutions, 2021) for all systems. The proceeding two seasons saw an increase in soil pH exceeding the ideal range, with movement towards a more neutral state (pH = 7,15 and 7,62) in the second season (2021/2022) and third season (2022/2023), respectively. In addition, LSD results in Table 5.7 showed the mean difference to be statistically significant between all seasons, with season one (2020/2021) having the lowest average pH (6,07 ± 0,18) and season three (2022/2023) having a 25% higher pH of 7,62 ± 0,26.

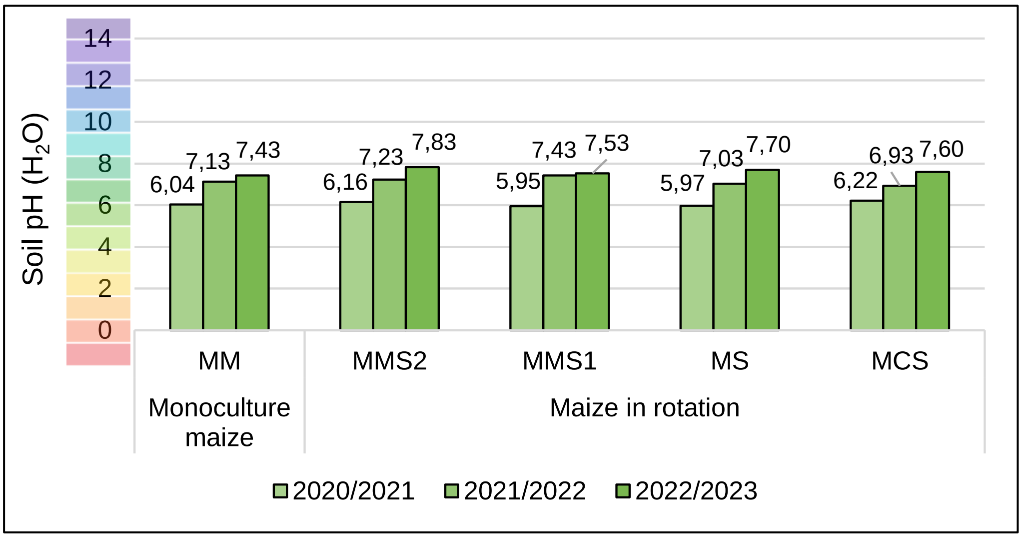

Figure 5.3: Mean soil pH (H_2O) of maize plots in different rotational systems for three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 5.6: Results of the two-way ANOVA for rotational system and season with soil pH

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Rotational system	0,24	4	0,06	0,57	0,69
Season	19,04	2	9,52	91,96	**<0,001**
Interaction	0,66	8	0,08	0,80	0,61
Error	3,12	30	0,10		
Corrected total	23,04	44			

Statistical significance indicated in bold text

Table 5.7: Post-hoc test: LSD results for statistically significant difference in soil pH between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	-1,09	**<0,001**
	2022/2023	-1,55	**<0,001**
2021/2022	2020/2021	1,09	**<0,001**
	2022/2023	-0,47	**<0,001**
2022/2023	2020/2021	1,55	**<0,001**
	2021/2022	0,47	**<0,001**

Statistical significance indicated in bold text

5.3.2 Physical soil properties

The sandy soils had a very low volumetric aggregate stability percentage. All maize plots had a volumetric aggregate stability percentage of 2% for all seasons. This percentage is well below the ideal of more than 45% (Soil Health Solutions, 2021).

5.3.2.1 Organic matter

Similar to the volumetric aggregate stability percentage, the organic matter percentages were below the ideal value of 3% (Soil Health Solutions, 2021). Table 5.8 shows that organic matter varied from 0,27% (MCS in 2021/2022) to 0,50% (MM in 2020/2021). The two-way ANOVA (Table 5.9) showed that organic matter was affected by season ($F(2) = 6{,}36$, $p = 0{,}01$) but not the rotational system ($F(4) = 0{,}63$, $p = 0{,}65$), with no interaction between these variables, $F(8) = 0{,}67$, $p = 0{,}72$. In addition, LSD results in Table 5.10 showed the mean difference in organic matter to be statistically significant from the first season (2020/2021), with the proceeding two seasons having a lower mean organic matter percentage.

Table 5.8: Mean organic matter percentage for rotational systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Rotational system		**Organic matter (%)**			
		2020/2021	**2021/2022**	**2022/2023**	**Mean**
MM		0,50	0,37	0,37	**0,41**
MMS2		0,47	0,37	0,40	**0,41**
MMS1		0,43	0,40	0,33	**0,39**
MS		0,40	0,30	0,37	**0,36**
MCS		0,47	0,27	0,40	**0,38**
	Mean	**0,45**	**0,34**	**0,37**	

Results in the table are represented as means only

Table 5.9: Results of the two-way ANOVA for rotational system and season with organic matter percentage

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Rotational system	0,02	4	0,01	0,63	0,65
Season	0,10	2	0,05	6,36	**0,01**
Interaction	0,04	8	0,01	0,67	0,72
Error	0,35	30	0,01		
Corrected total	0,40	44			

Statistical significance indicated in bold text

Table 5.10: Post-hoc test: LSD results for statistically significant difference in organic matter percentage between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	0,11	**0,002**
	2022/2023	0,08	**0,02**
2021/2022	2020/2021	-0,11	**0,002**
	2022/2023	-0,03	0,32
2022/2023	2020/2021	-0,08	**0,02**
	2021/2022	0,03	0,32

Statistical significance indicated in bold text

5.3.3 Chemical and biological soil properties

The mean measurements of three seasons, and ANOVA results of chemical and biological properties measured during the HSHT for each rotational system are shown in Table 11a-c. The chemical properties WEN, inorganic N and total K were similar between rotational systems and seasons, with no interaction between the two variables (p-values > 0,05). However, season had a statistically significant effect on the chemical properties WEON ($F(2) = 22{,}63$, $p < 0{,}001$) and total P ($F(2) = 4{,}60$, $p = 0{,}02$) as well as the biological properties WEOC ($F(2) = 31{,}79$, $p < 0{,}001$) and CO_2-C ($F(2) = 77{,}99$, $p < 0{,}001$). WEON and WEOC were both the highest in the first season (2020/2021), declined in the second season (2021/2022) and increased again in the third season (2022/2023). WEON decreased by 41% and then increased by 30% while WEOC decreased by 39% and increased by 36%.

Similar to WEON and WEOC, total P and CO_2-C had their highest measurements in the first season (2020/2021) with a decline in the second season (2021/2022). However, contrary to WEON and WEOC, total P and CO_2-C had a further decline in the third season (2022/2023). Total P decreased 19% from season one (2020/2021) to season three (2022/2023), while CO_2-C decreased 45%.

Table 5.11a: Mean measurements of three seasons and ANOVA results of N soil properties measured during the HSHT for each rotational system

HSHT soil properties		**Rotational system**		**Season 1 (2020/2021)**	**Season 2 (2021/2022)**	**Season 3 (2022/2023)**		**ANOVA results**					
								Rotational system		**Season**		**Interaction**	
								***F*-statistic**	***p*-value**	***F*-statistic**	***p*-value**	***F*-statistic**	***p*-value**
							Mean						
Chemical properties	WEN (mg kg^{-1})	MM		11,83	10,80	10,53	**11,06**	0,73	0,58	0,75	0,48	0,84	0,58
		MMS2		11,80	10,37	13,87	**12,01**						
		MMS1		12,70	11,80	9,63	**11,38**						
		MS		10,23	9,97	10,80	**10,33**						
		MCS		11,87	10,67	13,17	**11,90**						
			Mean	**11,69**	**10,72**	**11,60**							
	Inorganic N (mg kg^{-1})	MM		5,83	5,26	3,43	**4,84**	0,57	0,69	1,51	0,24	1,15	0,36
		MMS2		4,63	5,77	5,90	**5,43**						
		MMS1		5,57	5,96	4,10	**5,21**						
		MS		4,60	5,38	3,37	**4,45**						
		MCS		5,47	4,27	5,50	**5,08**						
			Mean	**5,22**	**5,33**	**4,46**							
	WEON (mg kg^{-1})	MM		8,23	5,43	7,10	**6,92**	0,83	0,52	22,63	**<0,001**	0,94	0,50
		MMS2		8,60	4,57	8,10	**7,09**						
		MMS1		9,70	5,80	6,07	**7,19**						
		MS		7,37	4,03	7,23	**6,21**						
		MCS		8,77	5,50	7,63	**7,30**						
			Mean	**8,53**	**5,07**	**7,23**							

Results in the table are represented as means only
Statistical significance indicated in bold text

Table 5.11b: Mean measurements of three seasons and ANOVA results of total P and K measured during the HSHT for each rotational system

HSHT soil properties		**Rotational system**		**Season 1 (2020/2021)**	**Season 2 (2021/2022)**	**Season 3 (2022/2023)**		**ANOVA results**					
								Rotational system		**Season**		**Interaction**	
								***F*-statistic**	***p*-value**	***F*-statistic**	***p*-value**	***F*-statistic**	***p*-value**
							Mean						
Chemical properties	Total P (mg kg^{-1})	MM		32,00	35,37	24,00	**30,46**	0,26	0,90	4,60	**0,02**	1,69	0,14
		MMS2		35,33	33,71	23,67	**30,90**						
		MMS1		42,00	31,52	25,00	**32,84**						
		MS		31,33	31,00	31,00	**31,11**						
		MCS		28,33	29,89	32,00	**30,07**						
			Mean	**33,80**	**32,30**	**27,13**							
	Total K (mg kg^{-1})	MM		93,00	80,71	104,00	**92,57**	1,14	0,36	1,36	0,27	0,88	0,55
		MMS2		82,67	83,37	102,67	**89,57**						
		MMS1		83,67	75,24	71,33	**76,75**						
		MS		62,00	87,69	81,67	**77,12**						
		MCS		85,00	61,28	90,33	**78,87**						
			Mean	**81,27**	**77,66**	**90,00**							

Results in the table are represented as means only
Statistical significance indicated in bold text

Table 5.11c: Mean measurements of three seasons and ANOVA results of biological properties measured during the HSHT for each rotational system

HSHT soil properties		**Rotational system**		**Season 1 (2020/2021)**	**Season 2 (2021/2022)**	**Season 3 (2022/2023)**		**ANOVA results**					
								Rotational system		**Season**		**Interaction**	
								***F*-statistic**	***p*-value**	***F*-statistic**	***p*-value**	***F*-statistic**	***p*-value**
							Mean						
Biological properties	WEOC (mg kg^{-1})	MM		84,33	56,00	87,00	**75,78**	0,03	0,99	31,79	**<0,001**	1,26	0,30
		MMS2		86,33	50,00	89,33	**75,11**						
		MMS1		98,33	58,33	68,67	**75,22**						
		MS		80,33	56,00	87,00	**74,44**						
		MCS		89,33	46,33	86,00	**73,89**						
			Mean	**87,73**	**53,33**	**83,60**							
	Soil respiration CO$_2$-C (mg kg^{-1} C)	MM		21,26	16,67	11,33	**16,42**	0,45	0,77	77,99	**<0,001**	1,30	0,28
		MMS2		19,63	13,67	13,00	**15,43**						
		MMS1		21,37	13,33	10,67	**15,12**						
		MS		21,28	14,33	11,00	**15,54**						
		MCS		22,24	12,00	12,33	**15,52**						
			Mean	**21,16**	**14,00**	**11,67**							

Results in the table are represented as means only
Statistical significance indicated in bold text

5.3.4 Overall soil health

The overall soil health score obtained from the integrated chemical and biological measurements are shown in Figure 5.4. All soil health scores were below the ideal value of 7,00, varying from 2,70 (MCS in 2021/2022) to 5,07 (MMS1 in 2020/2021) (Ward Laboratories, 2019). The mean, maximum and minimum soil health score for each season can be seen in Table 5.12.

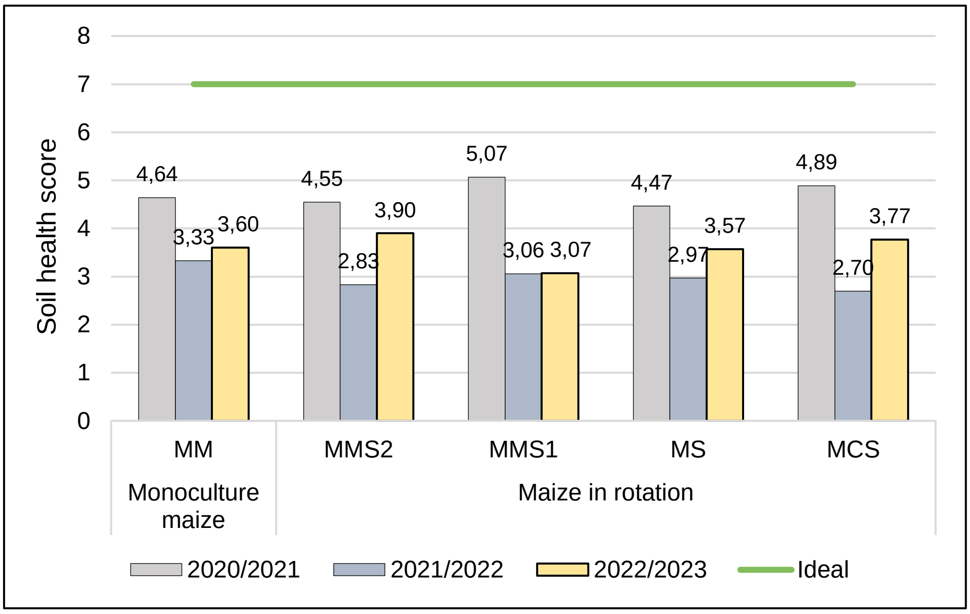

Figure 5.4: Mean soil health score of maize plots in different rotational systems for three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 5.12: Mean, maximum and minimum soil health score for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Season	Mean soil health	Maximum soil health	Minimum soil health
2020/2021	4,72 ± 0,65	MMS1 (5,07 ± 0,93)	MS (4,47 ± 0,46)
2021/2022	2,98 ± 0,34	MM (3,33 ± 0,49)	MCS (2,70 ± 0,00)
2022/2023	3,58 ± 0,42	MMS2 (3,90 ± 0,26)	MMS1 (3,07 ± 0,26)

The two-way ANOVA (Table 5.13) showed that soil health was affected by season ($F(2) = 48{,}13$, $p < 0{,}001$) but not the rotational system ($F(4) = 0{,}17$, $p = 0{,}95$), with no interaction between these variables, $F(8) = 1{,}27$, $p = 0{,}30$. In addition, LSD results in Table 5.14 showed the mean difference in soil health to be statistically significant between all seasons, with season one (2020/2021) having the highest average soil health score (4,72 ± 0,65) and season two (2021/2022) the lowest (2,98 ± 0,34). The average soil health dropped 37% in the second season (2021/2022) and improved again by 17% in the third season (2022/2023).

Table 5.13: Results of the two-way ANOVA for rotational system and season with soil health score

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Rotational system	0,17	4	0,04	0,17	0,95
Season	23,54	2	11,77	48,13	**<0,001**
Interaction	2,48	8	0,31	1,27	0,30
Error	7,34	30	0,24		
Corrected total	33,53	44			

Statistical significance indicated in bold text

Table 5.14: Post-hoc test: LSD results for statistically significant difference in soil health score between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	1,74	**<0,001**
	2022/2023	1,14	**<0,001**
2021/2022	2020/2021	-1,74	**<0,001**
	2022/2023	-0,60	**0,002**
2022/2023	2020/2021	-1,14	**<0,001**
	2021/2022	0,06	**0,002**

Statistical significance indicated in bold text

5.4 Discussion and conclusion

The overall soil health of the maize plots in the rotational systems trial was low. This can be attributed to the semi-arid climate and low clay and organic matter content leading to low physical, chemical and biological properties observed in the soil. Although common for the North-Western Free State, the soils had very low volumetric aggregate stability and organic matter percentages, which in turn results in inadequate chemical properties and restricted biological processes (Horneck *et al.,* 2011; Lal, 2016).

In contrast to what was expected, this study showed no effect of crop rotational systems on individual soil properties, nor overall soil health. This could be due to the fact that the benefits of soil health only reach full potential when the organic matter is above 1,5 – 2% (Lal, 2016). However, this was not an isolated case as studies by Bavougian *et al.* (2019) and Roper *et al.* (2017) showed similar results where soil health scores were not sensitive to management changes, including crop rotations. Nevertheless, the fact that the monoculture maize received more fertilizer over time than maize rotated with soybean and cover crops, without significantly effecting soil health, could be an indication that by incorporating these crops chemical levels can be maintained naturally. Soybean is able to fix atmospheric N in symbiosis with *Rhizobium* bacteria (Acevedo-Siaca & Goldsmith, 2020; Coskan & Dogan, 2011). Similarly, the legumes in the cover crop are also able to act as a source of nitrogen (Fageria, Baligar & Bailey, 2005).

The role that season variation (mainly rainfall) plays on soil and its health was evident throughout the study. This co-insides with the findings of numerous studies that continually show the seasonal effect on soil health (Babur & Dindaroglu, 2020; Mitchell *et al.,* 2017; Sharma, Singh & Singh, 2020; Sherbine *et al.,* 2023). Three different significant seasonal trends were identified in this study. The first was an increase in measured values over the duration of the study. This was seen with soil pH (H_2O) and could be as a result of the application of lime before the onset of the trial which is one of the most common practises to reduce soil acidity (Li *et al.,* 2019) as well as salts in the topsoil being diluted due to the wet conditions (Rengel, 2011).

The second trend identified was a decrease in measured values over the duration of the study. This was the case for total P and CO_2-C. This could be linked to pH as a higher pH is associated with constraints in P (Rengel, 2011). The variation in P is related to the magnitude of soil respiration and could have been further suppressed by the anaerobic conditions caused by the heavy rainfall of the second season (2021/2022) (Cusack *et al.,* 2019; Magdoff & Van Es 2021; Parent *et al.,* 2008). The kinetic energy of raindrops causes surface sealing and crust formation that reduces soil infiltration (Vaezi, Ahmadi & Cerdà, 2017).

The third, and most common, trend was a significant decrease in measured values from season one (2020/2021) to season two (2021/2022), with an increased value in the third season (2022/2023). The measured organic matter was one such value which is generally low in sandy soil but was further degraded by the anaerobic conditions caused by the rain intensity and duration of season two (2021/2022) (Horneck *et al.,* 2011). Sitthaphanit *et al.* (2009) further explains that when rainfall intensity is high decomposition occurs too quickly, causing organic matter and nutrients to be lost through leaching, rather than being released slowly into the soil, resulting in a lower WEON and WEOC which are key determinants of the overall soil health score. The more wide-spread rainfall in the third season (2022/2023) allowed some physical, chemical and biological properties to recover due to their ability to withstand short-term fluctuations (Turner *et al.,* 2015) and because the surface sealing and crust formation was less severe (Vaezi, Ahmadi & Cerdà, 2017).

In conclusion, soybean and the legumes incorporated in cover crops are able to naturally maintain similar soil health as artificially fertilized monoculture maize therefore minimising the need for fertilizer application. This is a promising sign for the incorporation of crop rotational systems as a means of sustainable agriculture in this area. In addition, with the prediction of more extreme weather in the future, it is important to note that recovery rates of different soil properties vary after intense, high rainfall, yet the overall soil health is generally weakened by such events. Seasonal variation (especially rainfall intensity and duration) in combination with inherent soil properties are important attributes of soil health the region.

The results reported in this chapter have been published in de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). The effect of crop rotation on soil health in the north-western Free State region, *South Africa, South African Journal of Plant and Soil*, vol. 40, no. 4-5, pp. 1-8.

Chapter 6

Nutritional benefits of maize-soybean rotational systems in the North-Western Free State

6.1 Introduction

Maize is a common food source for both animals and humans (Nuss & Tanumihardjo, 2010). Figure 6.1 illustrates the various products and by-products derived from maize (DALRRD, 2021). The maize plant and its by-products are used as feed for animals, either directly in fields or after processing (Adeniyi & Ariwoola, 2019; Dei, 2017). Although maize is generally used more for animal feed, in Africa maize (specifically white maize) is produced mostly for human consumption (Dei, 2017; Okoruwa & Kling, 1996; Shew *et al.,* 2021). In South Africa 38% of the maize produced is for human consumption (Jordaan, 2022). In 2020/2021, 60% of white maize products in South Africa consisted of maize meal (SAGL, 2021). Maize kernels can also be dried, boiled, fried, roasted, ground and fermented for use in breads, porridges, cereals, cakes and alcoholic beverages (Nuss & Tanumihardjo, 2010).

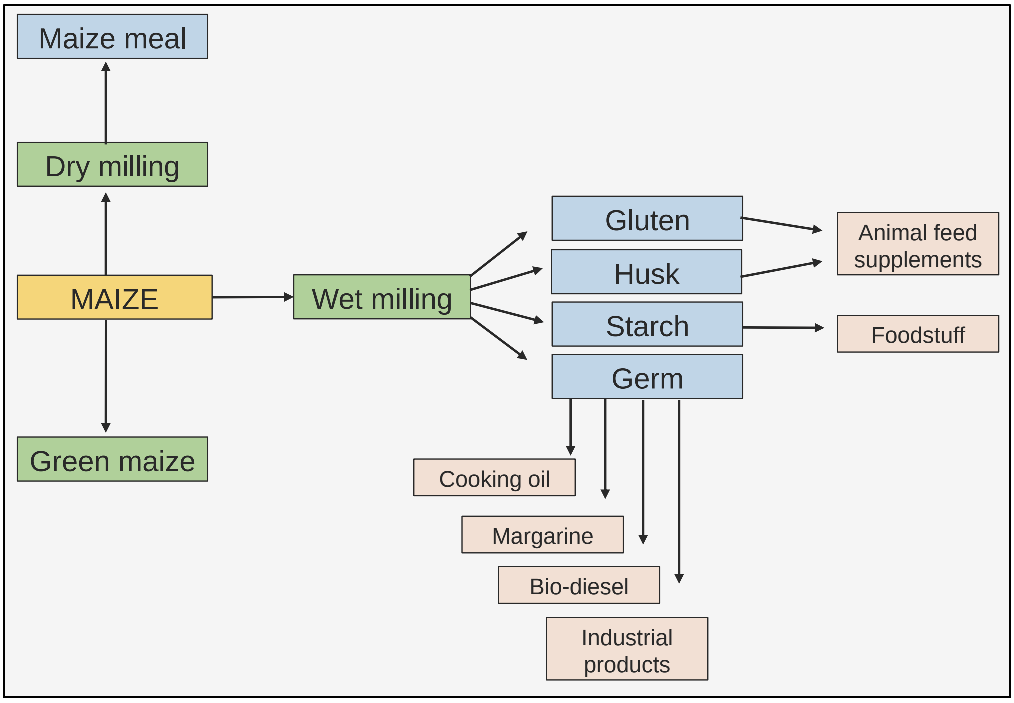

Figure 6.1: The maize value chain diagram (adapted from DALRRD (2021))

6.1.1 Maize kernels

Maize kernels are storage organs that contain the components essential for plant growth and reproduction, they are also the edible part of the plant used for processing and consumption (Nuss & Tanumihardjo, 2010; Shah, Prasad & Kumar, 2016). Moisture content of maize kernels is important to the maize processor and consumer (Adeniyi & Ariwoola, 2019). Sufficiently ripened and dried maize kernels have a moisture content of 10 – 14% (Dei, 2017). The higher the moisture content of maize, the more likely it is to deteriorate in quality (Adeniyi & Ariwoola, 2019).

Figure 6.2 illustrates the constituents of a typical maize kernel. The outermost layer, the pericarp (seed coat) is made up of the fibres: Hemicellulose, cellulose and lignin (Nuss & Tanumihardjo, 2010). Crude fibre, which is a measure traditionally associated with animal nutrition, is indigestible and remains as a food residue after digestion (Muinos, 2022). Crude fibre is also found in the endosperm and embryo (germ) but in much lower quantities (Nuss & Tanumihardjo, 2010). The total dietary fibre, which is more commonly used in relation to human nutrition, is similar to crude fibre in that it is not digested but rather passes through the body intact to help food move through the digestive tract and assist in nutrient absorption (Muinos, 2022). Sufficient intake of dietary fibre improves health and reduces the risk of heart disease, type 2 diabetes and colon cancer (Muinos, 2022).

The endosperm is the largest section of the maize kernel and mostly made up of starch which is the primary carbohydrate constituent of a kernel (Nuss & Tanumihardjo, 2010). Other carbohydrates include small amounts of sugars such as glucose, sucrose and fructose (FAO, 1992). Digestion of carbohydrates together with fats provide a source of energy. (Okoruwa & Kling, 1996; Poole, Donovan & Erenstein, 2021). Energy can be stored in fats and used when calorie intake is insufficient to meet demand (Okoruwa & Kling, 1996).

The endosperm also has the majority of the crude protein, which includes the N content (Nuss & Tanumihardjo, 2010; Rasby & Martin, 2023). Protein is found in the embryo (germ) in higher concentrations than the endosperm but of less quantity (Nuss & Tanumihardjo, 2010). Generally maize has a low protein content (about 8%) which limits it nutritional value (Dei, 2017; SAGL, 2021). The low protein content is due to the lack of essential amino acids, lysine and tryptophan, which are essential for building and maintaining the body (Dei, 2017). These amino acids contribute to the production of enzymes and antibodies which are vital for normal body functions (Adeniyi & Ariwoola, 2019).

The embryo, which gives rise to the future plant, has the highest ash content compared to the pericarp and endosperm (Nuss & Tanumihardjo, 2010). The ash content of maize (1 – 3%) is an indication of the total minerals present and normally includes Ca, Mg, Na and K (Adeniyi & Ariwoola, 2019; Precisa, 2023; Qamar *et al.,* 2017). A lower ash content is an indication that less processing has occurred, normally natural foods have a lower ash content than processed foods (Precisa, 2023).

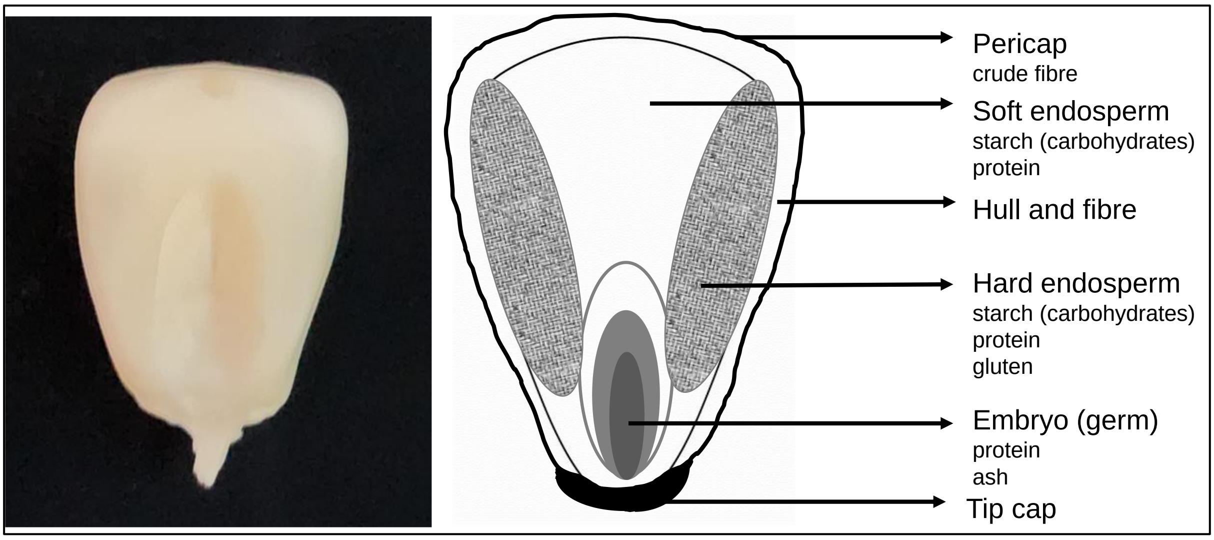

Figure 6.2: Constituents of a maize kernel (illustration by M de Bruyn)

Total digestible nutritional (TDN) value is a composition score of nutritional properties. The TDN is a calculated value which takes moisture, fibre, carbohydrates, fat, protein and ash contents into account (SAGL, 2020b). The TDN is proportional to the energy available, therefore a higher TDN is an indication of more energy available (Albin, 2021).

The energy made available by maize, together with its nutrients make it an affordable, healthy food option and is recommended by Shah, Prasad and Kumar (2016) to be part of our daily diet. This is promising as malnutrition caused due to consumption of unbalanced diet has emerged as one of the major health concerns particularly in the developing and under-developed world (Hossain *et al.,* 2022). The composition of maize kernels is influenced by many factors, including genetic background, seed variety, environmental conditions, plant age and geographic location (Galani, Orfila & Gong, 2022). In this study we looked at the influence of crop rotation on the nutritional value of maize.

6.2 Materials and methods

6.2.1 Sample collection and testing

Maize kernels (grain) were collected after maturity for nutritional analysis from all maize plots in the Christinasrus trial during each season (Table 6.1, Table 6.2, Table 6.3). The maize kernels were collected by hand before harvesting on 01/05/2021, 16/05/2022 and 23/05/2023 respectively (Figure 6.3). Two samples were randomly taken per maize plot. Samples from the same rotational system were combined to give a composite sample per rotational system. Environmental ethical clearance was received from the UFS (UFS-ESD2022/0118) and samples were sent to the SAGL for nutritional analysis.

Figure 6.3: Maize kernel collection on 16/05/2022 (photograph by J de Bruyn)

Table 6.1: Plots from which maize kernels were taken for nutritional analysis during the 2020/2021 season (highlighted in green)

Plot 1 **MMS** Maize 1	**Plot 2** **MS** Maize	**Plot 3** **MM** Maize	**Plot 4** **MCS** Maize	**Plot 5** **MCS** Cover crop	**Plot 6** **MMS** Soybean	**Plot 7** **MS** Soybean	**Plot 8** **MCS** Soybean	**Plot 9** **MMS** Maize 2
Plot 10 **MCS** Maize	**Plot 11** **MS** Soybean	**Plot 12** **MCS** Cover crop	**Plot 13** **MMS** Maize 1	**Plot 14** **MCS** Soybean	**Plot 15** **MM** Maize	**Plot 16** **MMS** Maize 2	**Plot 17** **MS** Maize	**Plot 18** **MMS** Soybean
Plot 19 **MM** Maize	**Plot 20** **MMS** Soybean	**Plot 21** **MCS** Maize	**Plot 22** **MS** Soybean	**Plot 23** **MMS** Maize 1	**Plot 24** **MMS** Maize 2	**Plot 25** **MS** Maize	**Plot 26** **MCS** Cover crop	**Plot 27** **MCS** Soybean

Table 6.2: Plots from which maize kernels were taken for nutritional analysis during the 2021/2022 season (highlighted in green)

Plot 1 **MMS** Maize 2	**Plot 2** **MS** Soybean	**Plot 3** **MM** Maize	**Plot 4** **MCS** Cover crop	**Plot 5** **MCS** Soybean	**Plot 6** **MMS** Maize 1	**Plot 7** **MS** Maize	**Plot 8** **MCS** Maize	**Plot 9** **MMS** Soybean
Plot 10 **MCS** Cover crop	**Plot 11** **MS** Maize	**Plot 12** **MCS** Soybean	**Plot 13** **MMS** Maize 2	**Plot 14** **MCS** Maize	**Plot 15** **MM** Maize	**Plot 16** **MMS** Soybean	**Plot 17** **MS** Soybean	**Plot 18** **MMS** Maize 1
Plot 19 **MM** Maize	**Plot 20** **MMS** Maize 1	**Plot 21** **MCS** Cover crop	**Plot 22** **MS** Maize	**Plot 23** **MMS** Maize 2	**Plot 24** **MMS** Soybean	**Plot 25** **MS** Soybean	**Plot 26** **MSC** Soybean	**Plot 27** **MCS** Maize

Table 6.3: Plots from which maize kernels were taken for nutritional analysis during the 2022/2023 season (highlighted in green)

Plot 1 MMS Soybean	**Plot 2** **MS** Maize	**Plot 3** **MM** Maize	Plot 4 MCS Soybean	**Plot 5** **MCS** Maize	**Plot 6** **MMS** Maize 2	Plot 7 MS Soybean	Plot 8 MCS Cover crop	**Plot 9** **MMS** Maize 1
Plot 10 MCS Soybean	Plot 11 MS Soybean	**Plot 12** **MCS** Maize	Plot 13 MMS Soybean	Plot 14 MCS Cover crop	**Plot 15** **MM** Maize	**Plot 16** **MMS** Maize 1	**Plot 17** **MS** Maize	**Plot 18** **MMS** Maize 2
Plot 19 **MM** Maize	**Plot 20** **MMS** Maize 2	Plot 21 MCS Soybean	Plot 22 MS Soybean	Plot 23 MMS Soybean	**Plot 24** **MMS** Maize 1	**Plot 25** **MS** Maize	**Plot 26** **MCS** Maize	Plot 27 MCS Cover crop

Nutritional analysis included measuring moisture, crude fibre, total dietary fibre, crude fat, crude protein, ash, total carbohydrates, energy and TDN value. Analysis was conducted using South African National Accreditation System (SANAS) accredited methods, as shown in Table 6.4 (SAGL, 2020b). Values were calculated using standard operating procedures (SOP) (SAGL, 2020b).

Table 6.4: Methods used by SAGL to measure nutritional aspects of collected maize kernels in each season (2020/2021, 2021/2022 and 2022/2023)

Analysis	Method
Moisture	AACCI 44-15.02, latest edition (130°C for 60 min)
Crude fibre	In-house method 031
Total dietary fibre	In-house method 012
Crude fat	In house method 024 (petroleum ether extraction)
Crude protein	AACCI 46-30.01, latest edition
Ash	In-house method 011 (700°C for 45 min)
Total carbohydrates	Calculated value (SOP MC023: Includes moisture, fat, protein, ash and fibre)
Energy value	Calculated value (SOP MC023: Includes moisture, fat, protein, ash, carbohydrates and fibre)
TDN value	Calculated value (SOP MC023: Includes moisture, fat, protein, ash, carbohydrates and fibre)

6.2.2 Data analysis

Data received from SAGL contained the results of the nutritional analysis. Data were cleaned and prepared for SPSS where it was further analysed using descriptive and inferential statistics. The rotational system variable was transformed into a dichotomous cropping system variable to compare the nutritional values in maize after maize and in maize after soybean (Table 6.5).

Table 6.5: Rotational systems allocated to each category of the dichotomous cropping system variable

Cropping system	Rotational system
Maize after maize	MM, MMS2
Maize after soybean	MMS1, MS, MCS

Descriptive statistics were represented in text as mean ± standard deviation, unless stated otherwise. General data were rounded off to two decimals, percentages were rounded off to the nearest whole number. Inferential statistics included two-way ANOVAs, which were run to determine if there was a statistically significant interaction effect of cropping system and season on crude fibre, total dietary fibre, crude fat, crude protein, total carbohydrates, energy and TDN value respectively. Assumption testing included testing for outliers, normal distribution and homogeneity of variances. The assumptions of normal distribution and homogeneity of variances were violated, however, because of the small sample size and the fact that ANOVAs are considered robust to deviations all results were interpreted (Jaccard, 1998; Maxwell, Delany & Kelley, 2017). Post-hoc LSD tests were run for statistically significant ANOVA results. Statistical significance was accepted at $p \leq 0,05$.

6.3 Results

6.3.1 Moisture content

Moisture content of the maize kernels ranged from 12 – 15%. All maize kernel samples were therefore sufficiently ripened and dried (Dei, 2017). The moisture content was similar between cropping systems as well as between seasons.

6.3.2 Crude fibre and total dietary fibre content

Figure 6.4 shows the crude fibre and dietary fibre content of the cropping systems. Crude fibre varied between 1,50 and 2,07 g 100 g^{-1} grain, while dietary fibre varied between 8,00 and 9,83 g 100 g^{-1} grain. The two-way ANOVA results in Table 6.6 show that crude fibre and dietary fibre were affected by both cropping system and season (p values < 0,05), with no interaction between these variables, $F(2) = 1,49$, $p = 0,24$ and $F(2) = 0,33$, $p = 0,72$ respectively. Maize after soybean had higher crude fibre and dietary fibre than maize after maize in all three seasons. The mean crude fibre of the maize after soybean was 1,82 ± 0,23 g 100 g^{-1} grain which is 8% higher than the crude fibre of maize after maize. Similarly, the dietary fibre of maize after soybean was 9,05 ± 0,69 g 100 g^{-1} grain which is 4% higher than the dietary fibre of maize after maize. In addition, the LSD results in Table 6.7 show the mean difference in crude fibre and dietary fibre to be statistically significant between all seasons. Season three (2022/2023) recorded the highest mean crude fibre (1,99 ± 0,11 g 100 g^{-1} grain) and dietary fibre (9,72 ± 0,17 g 100 g^{-1} grain).

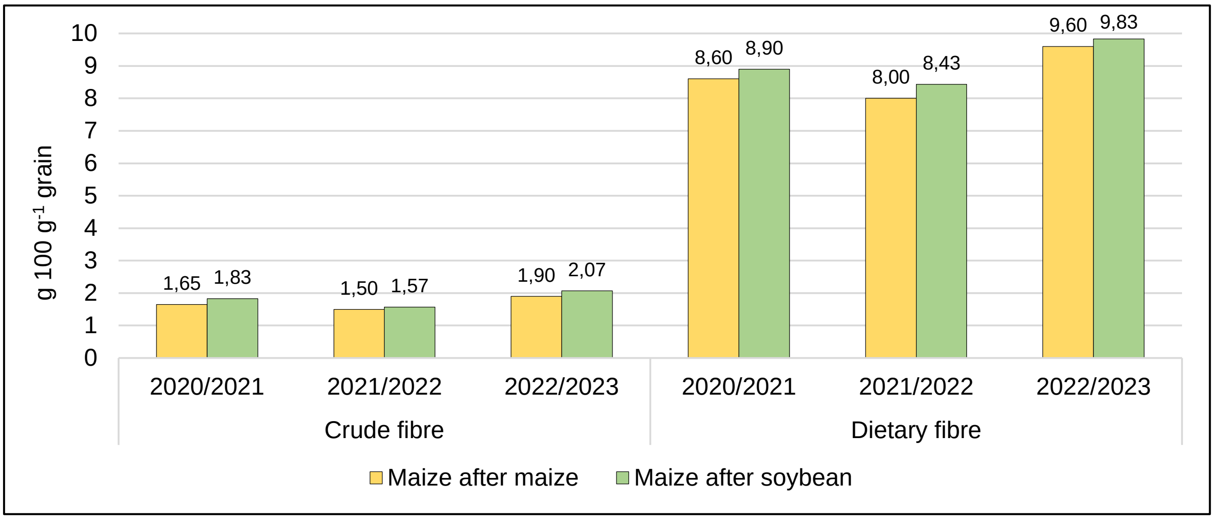

Figure 6.4: Crude fibre and dietary fibre in cropping systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 6.6: Results of the two-way ANOVA for cropping system and season with crude fibre and dietary fibre

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Crude fibre:					
Cropping system	0,21	1	0,21	21,67	**<0,001**
Season	1,46	2	0,73	75,96	**<0,001**
Interaction	0,03	2	0,01	1,49	0,24
Error	0,38	39	0,01		
Corrected total	2,20	44			
Dietary fibre:					
Cropping system	1,12	1	1,12	9,76	**0,003**
Season	16,65	2	8,33	72,48	**<0,001**
Interaction	0,08	2	0,04	0,33	0,72
Error	4,48	39	0,16		
Corrected total	22,59	44			

Statistical significance indicated in bold text

Table 6.7: Post-hoc test: LSD results for statistically significant difference in crude fibre and dietary fibre between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
Crude fibre:			
2020/2021	2021/2022	0,22	**<0,001**
	2022/2023	-0,24	**<0,001**
2021/2022	2020/2021	-0,22	**<0,001**
	2022/2023	-0,46	**<0,001**
2022/2023	2020/2021	0,24	**<0,001**
	2021/2022	0,46	**<0,001**
Dietary fibre:			
2020/2021	2021/2022	0,52	**<0,001**
	2022/2023	-0,96	**<0,001**
2021/2022	2020/2021	-0,52	**<0,001**
	2022/2023	-1,48	**<0,001**
2022/2023	2020/2021	0,96	**<0,001**
	2021/2022	1,48	**<0,001**

Statistical significance indicated in bold text

6.3.3 Crude fat content

Crude fat content of the maize is illustrated in Figure 6.5. The crude fat ranged from 3,10 to 3,45 g 100 g^{-1} grain with little difference between cropping systems. The two-way ANOVA results in Table 6.8 show that crude fat was affected by season ($F(2) = 126{,}34$, $p < 0{,}001$) but not cropping system ($F(1) = 1{,}89$, $p = 0{,}18$), with no interaction between these variables, $F(2) = 2{,}96$, $p = 0{,}06$. Similar to the fibre results, LSD results show the mean difference in crude fat to be statistically significant between all seasons (Table 6.9), with season three (2022/2023) recording the highest mean crude fat (3,43 ± 0,04 g 100 g^{-1} grain), 3% more than the first season (2020/2021) and 9% more than the second season (2021/2022).

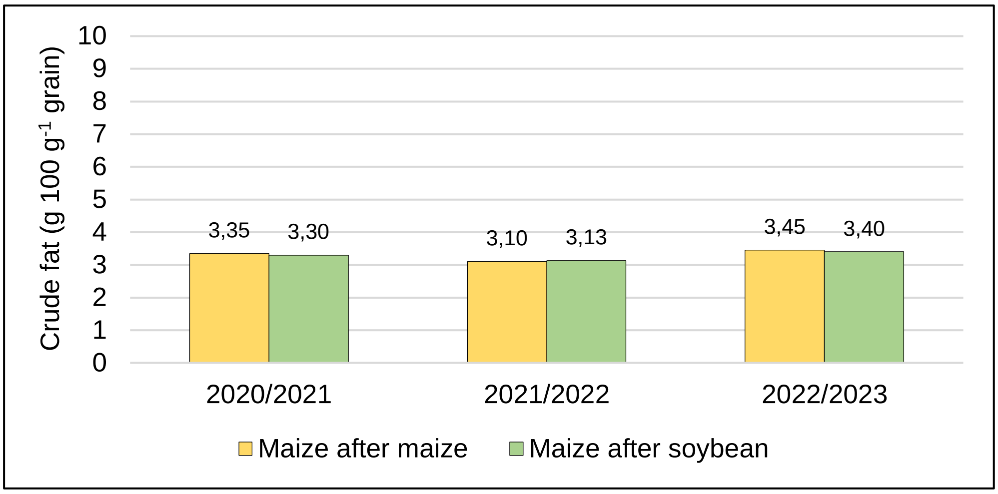

Figure 6.5: Crude fat content in cropping systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 6.8: Results of the two-way ANOVA for cropping system and season with crude fat content

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Cropping system	0,01	1	0,01	1,89	0,18
Season	0,71	2	0,36	126,34	**< 0,001**
Interaction	0,17	2	0,01	2,96	0,06
Error	0,11	39	0,003		
Corrected total	0,83	44			

Statistical significance indicated in bold text

Table 6.9: Post-hoc test: LSD results for statistically significant difference in crude fat content between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	0,20	**<0,001**
	2022/2023	-0,10	**<0,001**
2021/2022	2020/2021	-0,20	**<0,001**
	2022/2023	-0,30	**<0,001**
2022/2023	2020/2021	0,10	**<0,001**
	2021/2022	0,30	**<0,001**

Statistical significance indicated in bold text

6.3.4 Crude protein content

Crude protein ranged between 5,98 and 6,85 g 100 g^{-1} (Figure 6.6). The two-way ANOVA results in Table 6.10 show that crude protein was affected by season (*F*(2) = 17,26, *p* < 0,001) but not cropping system (*F*(1) = 0,96, *p* = 0,33), with no interaction between these variables, *F*(2) = 0,50, *p* = 0,61. In addition, LSD results (Table 6.11) show that the mean crude protein content difference was statistically significant between all seasons, with the second season (2021/2022) having the highest mean crude protein (6,73 ± 0,27 g 100 g^{-1}).

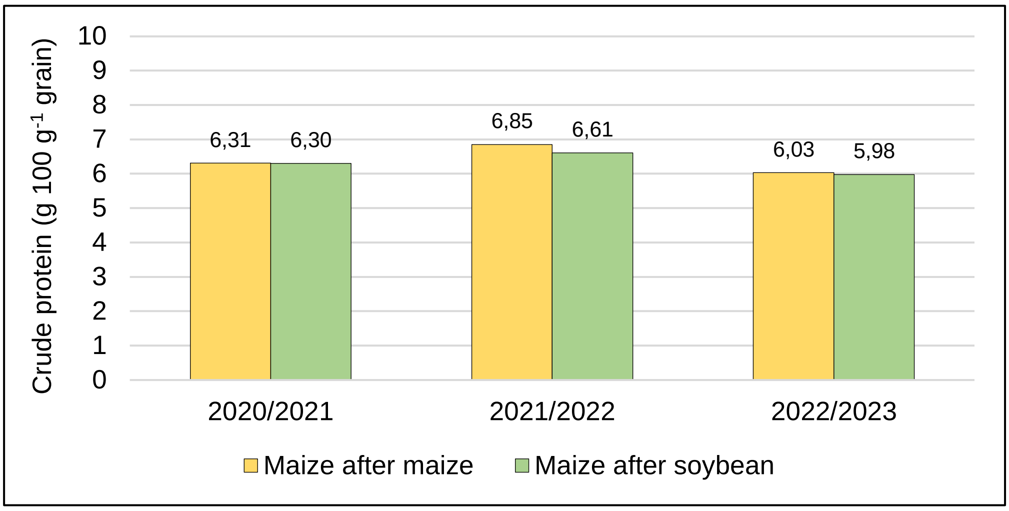

Figure 6.6: Crude protein content in cropping systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 6.10: Results of the two-way ANOVA for cropping system and season with crude protein content

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Cropping system	0,10	1	0,10	0,96	0,33
Season	3,77	2	1,87	17,26	**< 0,001**
Interaction	0,11	2	0,06	0,50	0,61
Error	4,26	39	0,11		
Corrected total	8,19	44			

Statistical significance indicated in bold text

Table 6.11: Post-hoc test: LSD results for statistically significant difference in crude protein content between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	-0,40	**0,002**
	2022/2023	0,31	**0,02**
2021/2022	2020/2021	0,40	**0,002**
	2022/2023	0,70	**< 0,001**
2022/2023	2020/2021	-0,31	**0,02**
	2021/2022	-0,70	**<0,001**

Statistical significance indicated in bold text

6.3.5 Ash content

Similar to the FAO guidelines, the ash content of all maize kernels was 1% (FAO, 1992). All cropping systems in all three seasons had an ash content of 1%. Therefore, the mineral content of maize was similar between cropping systems and seasons.

6.3.6 Total carbohydrates

Figure 6.7 shows the total carbohydrates between cropping systems in each season (2020/2021, 2021/2022 and 2022/2023). Total carbohydrates were similar within seasons varying from 66,10 to 68,07 g 100 g^{-1} grain. The two-way ANOVA results in Table 6.12 show that total carbohydrates was affected by season ($F(2) = 3{,}82$, $p = 0{,}03$) but not cropping system ($F(1) = 0{,}84$, $p = 0{,}37$), with no interaction between these variables, $F(2) = 1{,}03$, $p = 0{,}37$. In addition, LSD results (Table 6.13) showed that the mean total carbohydrates difference was statistically significant from the second season (2021/2022), with grain from this season having 2% more total carbohydrates than season one (2020/2021) and season three (2022/2023) respectively.

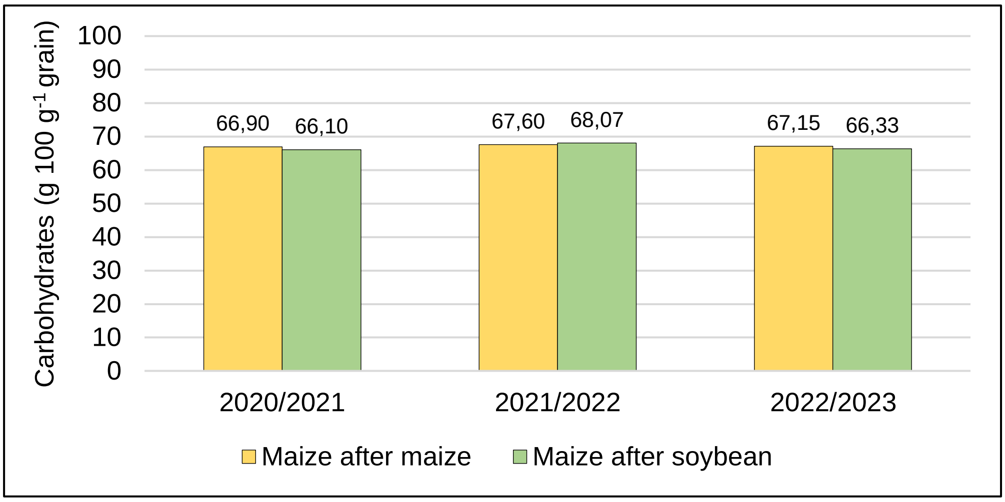

Figure 6.7: Total carbohydrates in cropping systems for all three seasons (2020/2021, 2021/22 and 2022/23)

Table 6.12: Results of the two-way ANOVA for cropping system and season with total carbohydrates

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Cropping system	1,59	1	1,59	0,84	0,37
Season	14,53	2	7,27	3,82	**0,03**
Interaction	3,90	2	1,95	1,03	0,37
Error	74,16	39	1,90		
Corrected total	98,03	44			

Statistical significance indicated in bold text

Table 6.13: Post-hoc test: LSD results for statistically significant difference in total carbohydrates between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	-1,46	**0,01**
	2022/2023	-0,24	0,64
2021/2022	2020/2021	1,46	**0,01**
	2022/2023	1,22	**0,02**
2022/2023	2020/2021	0,24	0,64
	2021/2022	-1,22	**0,02**

Statistical significance indicated in bold text

6.3.7 Energy value

The energy values are shown in Figure 6.8. Energy values varied from 1289,00 to 1318,00 kJ 100 g^{-1} grain. The two-way ANOVA results in Table 6.14 show that energy values were affected by season ($F(2) = 14,55$ $p < 0,001$) but not cropping system ($F(1) = 0,53$, $p = 0,47$), with an interaction between these variables, $F(2) = 10,31$, $p < 0,001$. Maize after soybean had a 1% higher energy value than maize after maize in season one (2020/2021) and two (2021/2022) respectively, while the opposite was seen in the third season (2022/2023), where maize after maize had a 1% higher energy value than maize after soybean. In addition, LSD results (Table 6.15) showed that the mean energy value difference was statistically significant from the third season (2022/2023), with grain from this season having a 1 – 2% lower energy value than season one (2020/2021) and season two (2021/2022).

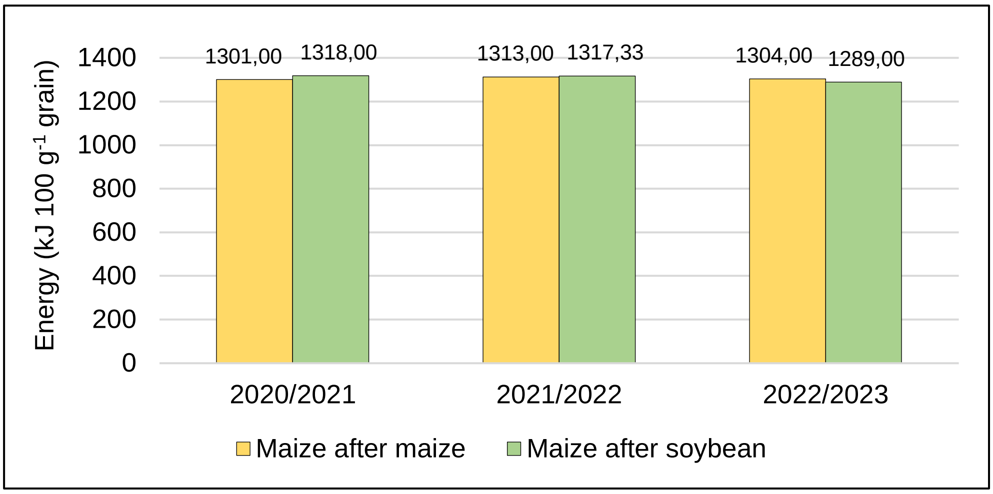

Figure 6.8: Energy value in cropping systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 6.14: Results of the two-way ANOVA for cropping system and season with energy value

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Cropping system	48,13	1	48,13	0,53	0,47
Season	2637,87	2	1318,93	14,55	**<0,001**
Interaction	1869,87	2	934,93	10,31	**<0,001**
Error	3536,00	39	90,67		
Corrected total	8987,80	44			

Statistical significance indicated in bold text

Table 6.15: Post-hoc test: LSD results for statistically significant difference in energy value between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	-4,40	0,21
	2022/2023	16,20	**<0,001**
2021/2022	2020/2021	4,40	0,21
	2022/2023	20,60	**<0,001**
2022/2023	2020/2021	-16,20	**<0,001**
	2021/2022	-20,60	**<0,001**

Statistical significance indicated in bold text

6.3.8 Total digestible nutritional value

The TDN values are shown in Figure 6.9 and varied from 89 to 91%. The two-way ANOVA results in Table 6.16 show that TDN was not affected by season (*F*(2) = 0,70, *p* = 0,51) nor cropping system (*F*(1) = 3,81, *p* = 0,06), but there was an interaction affect between these variables, *F*(2) = 6,67, *p* = 0,003. Similar to the energy value, maize after soybean had a 1 – 2% higher TDN than maize after maize in season one (2020/2021) and two (2021/2022) respectively, while the opposite was seen in the third season (2022/2023), where maize after maize had a 1% higher TDN than maize after soybean.

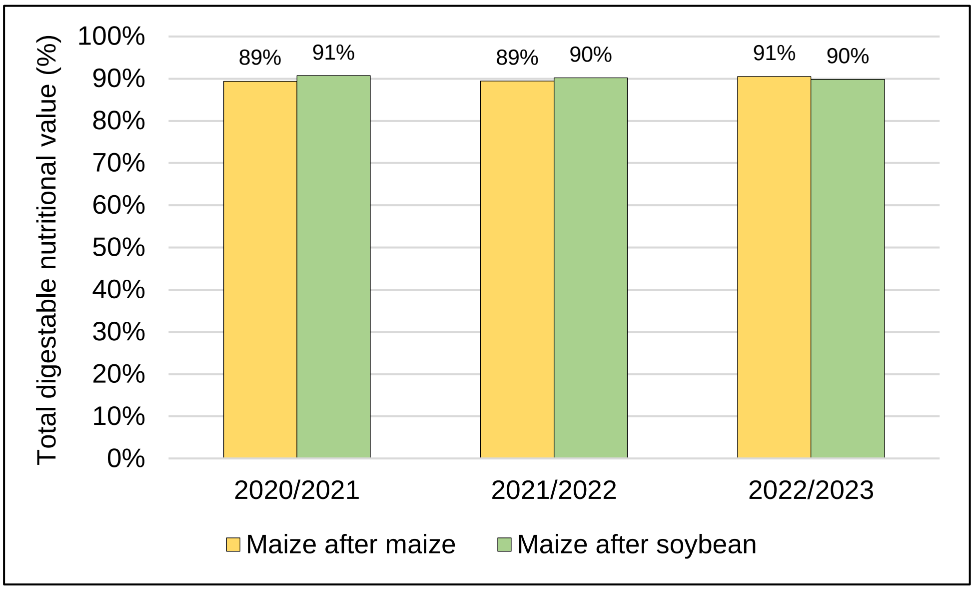

Figure 6.9: TDN value in cropping systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 6.16: Results of the two-way ANOVA for cropping system and season with TDN

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Cropping system	2,19	1	2,19	3,81	0,06
Season	0,80	2	0,40	0,70	0,51
Interaction	7,69	2	3,84	6,69	**0,003**
Error	22,40	39	0,57		
Corrected total	32,87	44			

Statistical significance indicated in bold text

6.4 Discussion and conclusion

Nutritional factors of maize are often neglected because there is no premium provided by markets for maize with superior nutritional value (Okoruwa & Kling, 1996). The nutritional analysis of maize kernels in this study showed the importance of maize as an essential food crop. Maize contained valuable amounts of fibre, fat, carbohydrates, minerals and energy. The lower amount of protein observed is a common characteristic of maize (Ekpa *et al.,* 2018), but could have been worsened by the sandy soil, as well as its poor soil health (Gaikwad *et al.,* 2020). A study by Spoljar *et al.* (2009) found that maize grown in physically and chemically unfavourable soil resulted in an inferior protein content in maize.

The composition of maize kernels was influenced by season and has been highlighted in many publications (Chemura *et al.,* 2022; Cowieson, 2005; Galani, Orfila & Gong, 2022). The most common seasonal trend was a decrease in measured values from season one (2020/2021) to season two (2021/2022), with increased values in the third season (2022/2023). The wet conditions of the second season caused maize to undergo abiotic stress, weakening its metabolic processes which reduced nutrient assimilation (Chemura *et al.,* 2022). However, despite the decline in nutritional parameters, the TDN of maize after soybean was higher than maize after maize in the wetter seasons, this could be due to the interactive affect observed between season and cropping system.

The inclusion of soybean into cropping systems with maize resulted in higher amounts of crude and dietary fibre. Costa *et al.* (2021) found similar results in their study where legume-modified rotations improved nutritional output of cereals. A higher fibre content could assist in the fight against malnutrition as it improves overall health (Muinos, 2022). Despite the protein content of maize not being influenced by the inclusion of soybean, actual protein intake can be increased by introducing soybean directly into a daily diet. Soybean contain 35 – 40% protein and nine essential amino acids, resulting in a more nutritious balanced diet when combined with maize (Hussain *et al.,* 2021; Wei *et al.,* 2023).

In conclusion, the production of maize grown in cropping systems with soybean should be promoted as a sustainable practise to fight malnutrition. Although consuming maize as a staple food provides sufficient energy, it tends to lack in protein and remains unbalanced (Dei, 2017; Galani, Orfila & Gong, 2022). There has been advancement in the development of quality protein maize as well as fortification by adding vitamins and minerals (Dei, 2017; Nuss & Tanumihardjo, 2010). However, results from this study suggest maize in cropping systems with soybean improves TDN (in wetter conditions) and fibre content of maize while the soybean in the system act as a protein-rich companion, providing a more nutritious, balanced diet for human consumption.

The results reported in this chapter have been published in de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). The nutritional benefits of maize-soybean rotational systems in the North-Western Free State, South Africa, *Agriculture and Food Security*, vol. 13, no. 12, pp. 1-7.

Chapter 7

Production and profitability of maize and soybean grown in rotation in the North-Western Free State

7.1 Introduction

Crop production and profitability is important as agricultural outputs affect a significant part of any population, either directly or indirectly (Machek & Špička, 2014). The two concepts typically go hand in hand, as shown in Figure 7.1. Productivity is a measurement of physical units and generally defined as the aggregate output versus the aggregate input (Machek & Špička, 2014; O'Donnell, 2010). Increased productivity improves agricultural and non-agricultural resources ultimately maintaining the environment and improving standard of living, which is key to economic development (O'Donnell, 2010; Xaba & Masuku, 2013). Maximum profitability (a monetary value calculated by deducted costs from revenue) is achieved by maximising the output from a given resource, or minimising the resources required for a given output (Machek & Špička, 2014; O'Donnell, 2010; Olujenyo, 2008). The more financial stable a farmer becomes, the more likely they are to invest in new technology, equipment and resources which in return again sustains production levels (Atube *et al.,* 2021).

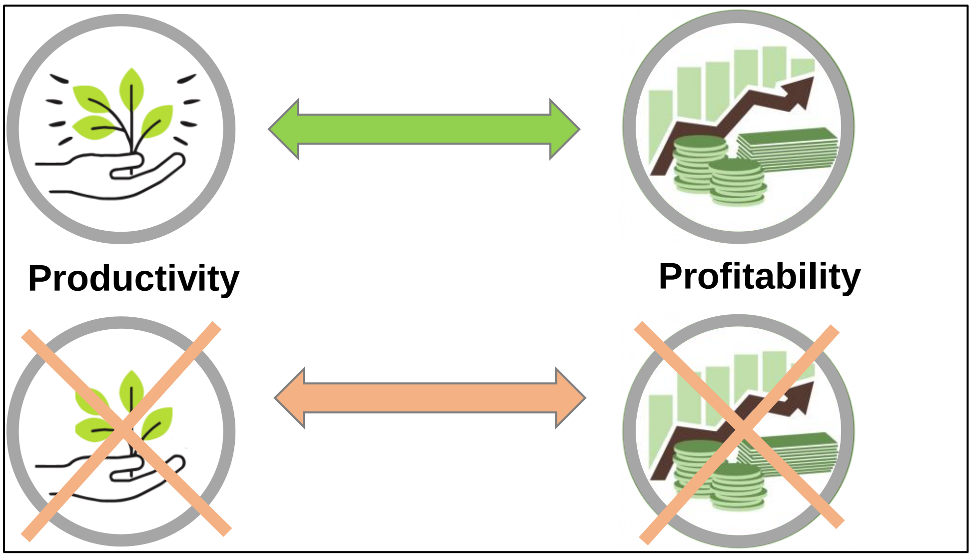

Figure 7.1: The relationship between crop productivity and profitability (illustration by M de Bruyn)

Crop production and profitability is highly dependent on crop management (Feng *et al.,* 2021). Crop rotation is an on-farm strategy that has potential to decrease production risks and increase profitability by suppressing pest outbreaks and buffering the effects of extreme climate conditions (Nel & Loubser, 2004; Meena *et al.,* 2018). Maize-soybean rotations are ideal in that they require simple management, similar equipment, sufficient seed availability and they have relatively high market prices (Feng *et al.,* 2021). This study looks at the production and profitability of different rotational systems in the North-Western Free State, with a focus on maize and soybean.

7.2 Materials and methods

7.2.1 Sample collection

Environmental ethical clearance was received from the UFS (UFS-ESD2022/0118). Maize and soybean were combine-harvested using commercial farm equipment in June of each season respectively. The maize and soybean weights were determined electronically. Yield results and industry data were used for further enterprise analysis. The cover crop yield was measured by cutting aboveground plant material over a randomly selected two rows 2,00 m length (Table 7.1). Plant material was placed in a plastic bag and weighed. Sub samples were taken and the moisture content determined to calculate dry biomass.

Table 7.1 Date and plots from which cover crop material were collected to determine biomass during each season

Season	Date samples collected	Plots
Season 1 (2020/2021)	23 March 2021	Plots 5, 12, 26
Season 2 (2021/2022)	23 March 2022	Plots 4, 10, 21
Season 3 (2022/2023)	24 March 2023	Plots 8, 14, 27

7.2.2 Enterprise analysis

Enterprise analysis was conducted for maize and soybean production by a service provider (Agribusinessconsult). The seasonal commodity price for maize and soybean together with the yield data were used to determine the gross production value for each crop in each rotational system. Input costs were calculated from total specified costs and deducted from gross production values to obtain a gross margin for each crop in each rotational system.

7.2.3 Data analysis

Yield data were cleaned and prepared for SPSS where it was further analysed using descriptive and inferential statistics. Descriptive statistics were represented in text as mean ± standard deviation, unless stated otherwise. General data were rounded off to two decimals, percentages were rounded off to the nearest whole number. Inferential statistics included one-way and two-way ANOVAs, which were run to determine if there was a statistically significant interaction effect of rotational system and season on yield. Assumption testing included testing for outliers, normal distribution and homogeneity of variances. Post-hoc LSD tests were run for statistically significant ANOVA results. Statistical significance was accepted at $p \leq 0,05$.

7.3 Results

7.3.1 Yield

7.3.1.1 Maize yield

Maize yield is shown in Figure 7.2 and varies from 1,69 to 8,49 ton ha^{-1}. The two-way ANOVA results in Table 7.2 show that the maize yield was affected by rotational system ($F(4) = 4,17$, $p = 0,01$) and season ($F(2) = 61,78$, $p < 0,001$). There was also a statistically significant interaction between these variables, $F(8) = 2,61$ $p = 0,03$.

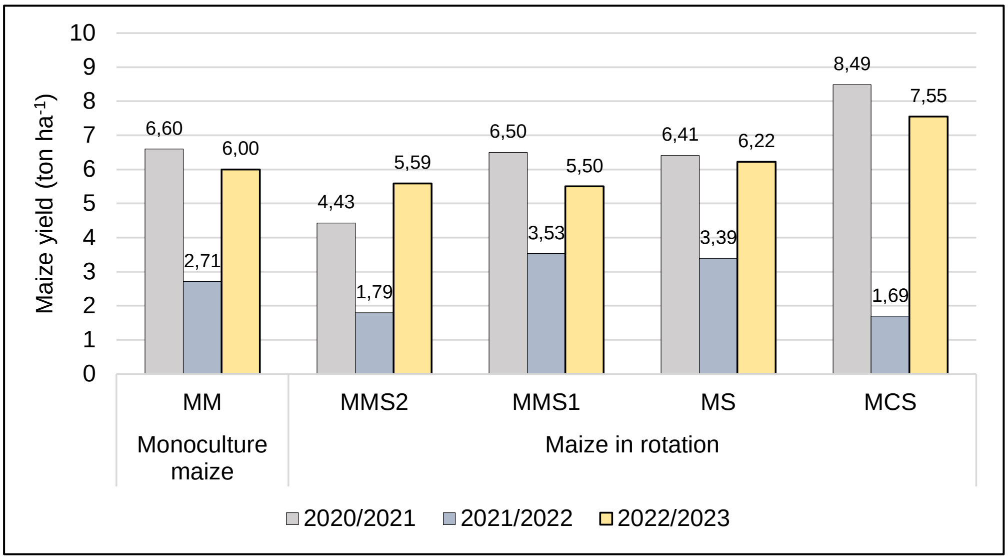

Figure 7.2: Mean maize yield in different rotational systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Calculated across all seasons, maize in the MCS rotational system had the highest mean yield (5,91 ton ha^{-1}), 14% higher than the mean yield for monoculture maize. Maize in the MMS2 system had the lowest mean yield and was statistically significantly lower than all other systems (Table 7.3). Additional analysis showed that maize yields after soybean were 18% higher than maize yields after maize, this difference was statistically significant ($F(1) = 6{,}08$, $p = 0{,}02$). LSD results (Table 7.4) showed that the mean maize yield was statistically significantly different from the second season (2021/2022), with maize yield from this season being 58 – 60% lower than season one (2020/2021) and season three (2022/2023).

Table 7.2: Results of the two-way ANOVA for rotational system and season with maize yield

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Rotational system	18,65	4	4,66	4,17	**0,01**
Season	138,08	2	69,04	61,78	**<0,001**
Interaction	23,32	8	2,91	2,61	**0,03**
Error	33,53	30	1,12		
Corrected total	213,57	44			

Statistical significance indicated in bold text

Table 7.3: Post-hoc test: LSD results for statistically significant difference in maize yield between rotational systems

Rotational system (a)	**Rotational system (b)**	**Mean difference (a-b)**	***p*-value**
MM	MMS1	-0,07	0,88
	MMS2	1,17	**0,03**
	MS	-0,24	0,64
	MCS	-0,80	0,12
MMS1	MM	0,07	0,88
	MMS2	1,24	**0,02**
	MS	-0,16	0,75
	MCS	-0,73	0,15
MMS2	MM	-1,17	**0,03**
	MMS1	-1,24	**0,02**
	MS	-1,40	**0,01**
	MCS	-1,97	**<0,001**
MS	MM	0,24	0,64
	MMS1	0,16	0,75
	MMS2	1,40	**0,01**
	MCS	-0,57	0,26
MCS	MM	0,80	0,12
	MMS1	0,73	0,15
	MMS2	1,97	**<0,001**
	MS	0,57	0,26

Statistical significance indicated in bold text

Table 7.4: Post-hoc test: LSD results for statistically significant difference in maize yield between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	3,86	**<0,001**
	2022/2023	0,31	0,42
2021/2022	2020/2021	-3,86	**<0,001**
	2022/2023	-3,55	**<0,001**
2022/2023	2020/2021	-0,31	0,42
	2021/2022	3,55	**<0,001**

Statistical significance indicated in bold text

7.3.1.2 Soybean yield

The soybean yield ranged from 0,76 to 3,97 ton ha^{-1} and showed an overall improvement from the first season (2020/2021) to the third season (2022/2023) (Figure 7.3). The MCS rotational system had the greatest improvement of 40%. The two-way ANOVA results in Table 7.5 show that soybean yield was not affected by rotational system but was affected by season ($F(2) = 140,60$, $p = 0,03$). LSD results in Table 7.6 show that all season's soybean yield differed significantly (p values < 0,05). There was also a statistically significant interaction affect between rotational system and season, $F(4) = 3,32$, $p = 0,03$. The MMS rotational system was the rotational system with the highest soybean yield in the first season (2020/2021), 9% more than MS and 33% more than MCS. In the wetter second (2021/2022) and following third season (2022/2023) soybean in the MS rotational system performed up to 42% better than the MMS rotational system.

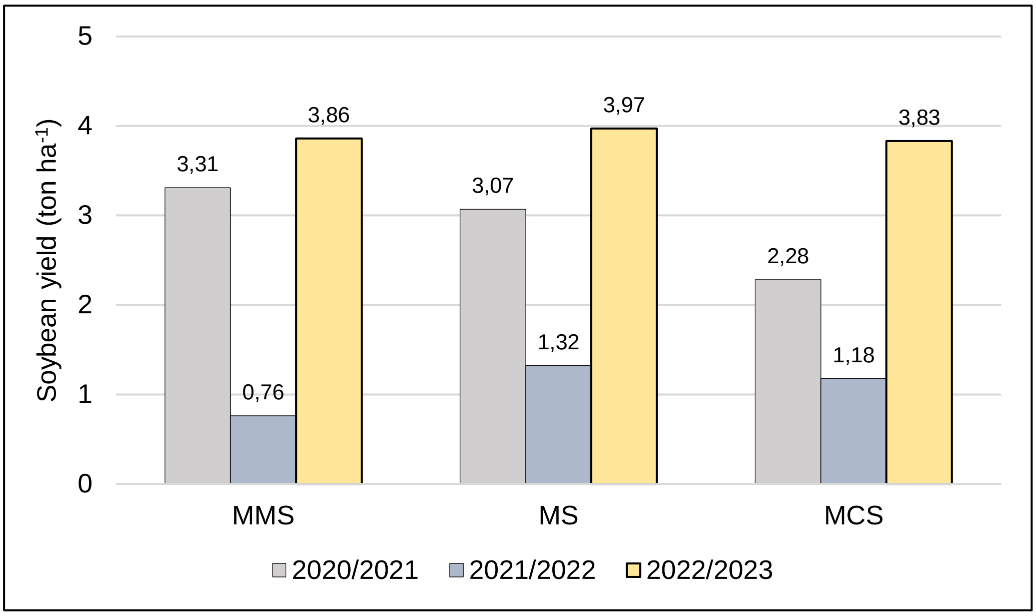

Figure 7.3: Mean soybean yield in different rotational systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 7.5: Results of the two-way ANOVA for rotational system and season with soybean yield

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Rotational system	0,58	2	0,29	2,25	0,14
Season	36,20	2	18,10	140,60	**<0,001**
Interaction	1,71	4	0,43	3,32	**0,03**
Error	2,32	18	0,13		
Corrected total	40,80	26			

Statistical significance indicated in bold text

Table 7.6: Post-hoc test: LSD results for statistically significant difference in soybean yield between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	1,80	**<0,001**
	2022/2023	-1,00	**<0,001**
2021/2022	2020/2021	-1,80	**<0,001**
	2022/2023	-2,80	**<0,001**
2022/2023	2020/2021	1,00	**<0,001**
	2021/2022	2,80	**<0,001**

Statistical significance indicated in bold text

7.3.1.3 Cover crop biomass

The mean cover crop biomass ranged from 2,64 to 11,37 ton ha^{-1} (Figure 7.4). ANOVA and LSD results in Table 7.7 and Table 7.8 show that the cover crop biomass was statistically significantly different between seasons ($p \leq 0,05$). The highest cover crop biomass was in season one (2020/2021), 35% higher than season two (2021/2022) and 78% higher than season three (2022/2023). The third season's cover crop biomass was well below the expectation of at least 7 ton ha^{-1}, and was therefore regarded as a failure.

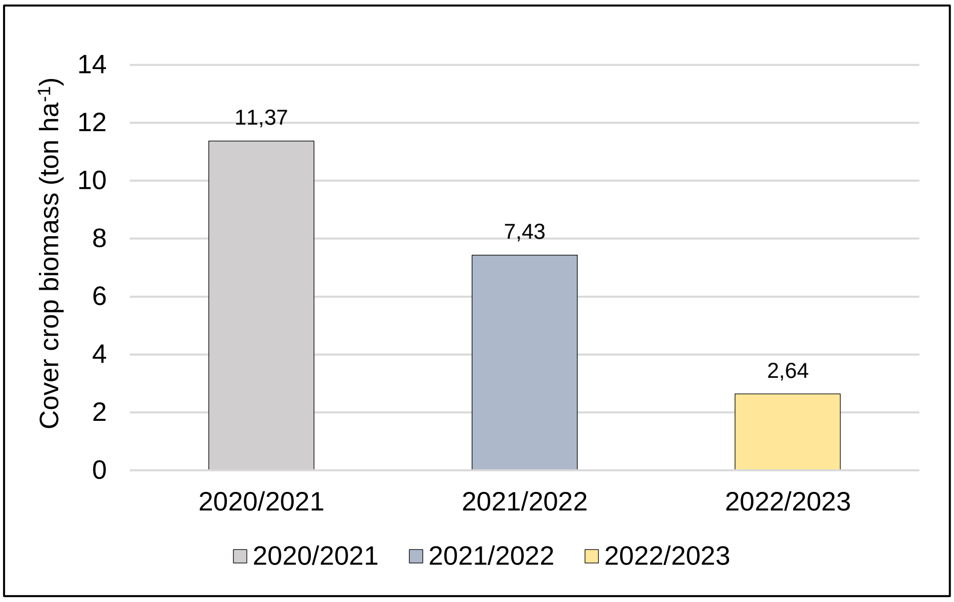

Figure 7.4: Mean cover crop biomass in different rotational systems for all three seasons (2020/2021, 2021/2022 and 2022/2023)

Table 7.7: Results of the one-way ANOVA for season with cover crop biomass

Source	**Sum of squares**	**df**	**Mean square**	***F*-statistic**	***p*-value**
Season	114,60	2	57,30	14,36	**0,005**
Error	23,94	6	3,99		
Corrected total	138,53	8			

Statistical significance indicated in bold text

Table 7.8: Post-hoc test: LSD results for statistically significant difference in cover crop biomass between seasons

Season (a)	**Season (b)**	**Mean difference (a-b)**	***p*-value**
2020/2021	2021/2022	3,94	**0,05**
	2022/2023	8,73	**0,002**
2021/2022	2020/2021	-3,94	**0,05**
	2022/2023	4,79	**0,03**
2022/2023	2020/2021	-8,73	**0,002**
	2021/2022	-4,79	**0,03**

Statistical significance indicated in bold text

7.3.2 Enterprise analysis

The results for the enterprise analysis for maize and soybean production are shown in Table 7.9. The gross margin of both maize and soybean varied from season to season. The highest gross margin for maize production was seen in the MCS rotational system in 2020/2021 (R16 604,50 ha^{-1}) and 2022/2023 (R15 949,96 ha^{-1}), 32-33% more than the gross margin for maize production of monoculture maize in the respective seasons. In the unfavourable second season (2021/2022), the MMS1 rotational system had the highest gross margin (R2 960,65 ha^{-1}), 95% more than the gross margin for maize production of monoculture maize (R136,66 ha^{-1}). Soybean production in the MMS rotational system had the highest gross margin in the first season (2020/2021), while soybean production in the MS rotational system did better in the second and third season (2021/2022 and 2022/2023), resulting in an overall 14% higher gross margin for soybean production in the MS rotational system compared to the MCS and MMS rotational systems. Estimating the gross margin of the cover crop, the mean gross margin of the rotational systems were: MS (R11 153,87) > MCS (R9 755,00) > MMS (R8 064,92) > MM (R7 349,66).

Table 7.9: Enterprise analysis for the study period

Season	**Crop**	**Commodity price**	**Rotational system**	**Average yield**	**Gross production value**	**Input costs**	**Gross margin**	**Break-even yield**
2020/2021	Maize	R2850,00 ton^{-1}	MM	6,60 ton ha^{-1}	R18 810,00	R7 520,00 ha^{-1}	R11 290,00 ha^{-1}	2,64 ton ha^{-1}
			MMS2	4,43 ton ha^{-1}	R12 625,50	R7 457,00 ha^{-1}	R5 168,50 ha^{-1}	2,62 ton ha^{-1}
			MMS1	6,50 ton ha^{-1}	R18 525,00	R7 417,00 ha^{-1}	R11 108,00 ha^{-1}	2,60 ton ha^{-1}
			MS	6,41 ton ha^{-1}	R18 268,50	R7 513,00 ha^{-1}	R10 755,50 ha^{-1}	2,64 ton ha^{-1}
			MCS	8,49 ton ha^{-1}	R24 196,50	R7 592,00 ha^{-1}	R16 604,50 ha^{-1}	2,66 ton ha^{-1}
	Soybean	R7300,00 ton^{-1}	MMS	3,31 ton ha^{-1}	R24 163,00	R6 441,00 ha^{-1}	R17 722,00 ha^{-1}	0,88 ton ha^{-1}
			MS	3,07 ton ha^{-1}	R22 411,00	R6 432,00 ha^{-1}	R15 979,00 ha^{-1}	0,88 ton ha^{-1}
			MCS	2,28 ton ha^{-1}	R16 640,00	R6 411,00 ha^{-1}	R10 229,00 ha^{-1}	0,88 ton ha^{-1}
2021/2022	Maize	R3500,00 ton^{-1}	MM	2,71 ton ha^{-1}	R9 495,66	R9 358,00 ha^{-1}	R137,66 ha^{-1}	2,67 ton ha^{-1}
			MMS2	1,79 ton ha^{-1}	R6 268,73	R9 310,00 ha^{-1}	-R3 041,27 ha^{-1}	2,66 ton ha^{-1}
			MMS1	3,53 ton ha^{-1}	R12 361,65	R9 401,00 ha^{-1}	R2 960,65 ha^{-1}	2,69 ton ha^{-1}
			MS	3,39 ton ha^{-1}	R11 875,36	R9 394,00 ha^{-1}	R2 481,36 ha^{-1}	2,68 ton ha^{-1}
			MCS	1,69 ton ha^{-1}	R5 912,14	R9 305,00 ha^{-1}	-R3 392.86 ha^{-1}	2,66 ton ha^{-1}
	Soybean	R8490,00 ton^{-1}	MMS	0,76 ton ha^{-1}	R6 411,45	R7 281,00 ha^{-1}	-R869,55 ha^{-1}	0,86 ton ha^{-1}
			MS	1,32 ton ha^{-1}	R10 016,42	R7 311,00 ha^{-1}	R3 916,06 ha^{-1}	0,86 ton ha^{-1}
			MCS	1,18 ton ha^{-1}	R11 227,06	R7 303,00 ha^{-1}	R2 713,41 ha^{-1}	0,86 ton ha^{-1}
2022/2023	Maize	R3500,00 ton^{-1}	MM	6,00 ton ha^{-1}	R21 003,62	R10 383,00 ha^{-1}	R10 620,61 ha^{-1}	2,97 ton ha^{-1}
			MMS2	5,59 ton ha^{-1}	R19 578,23	R10 362,00 ha^{-1}	R9 216,23 ha^{-1}	2,96 ton ha^{-1}
			MMS1	5,50 ton ha^{-1}	R19 250,69	R10 357,00 ha^{-1}	R8 893,68 ha^{-1}	2,96 ton ha^{-1}
			MS	6,22 ton ha^{-1}	R21 784,04	R10 390,33 ha^{-1}	R11 393,70 ha^{-1}	2,97 ton ha^{-1}
			MCS	7,55 ton ha^{-1}	R26 413,96	R10 464,00 ha^{-1}	R15 949,96 ha^{-1}	2,99 ton ha^{-1}
	Soybean	R8200,00 ton^{-1}	MMS	3,89 ton ha^{-1}	R31 643,01	R10 098,00 ha^{-1}	R21 545,01 ha^{-1}	1,23 ton ha^{-1}
			MS	3,97 ton ha^{-1}	R32 516,72	R10 103,00 ha^{-1}	R22 413,72 ha^{-1}	1,23 ton ha^{-1}
			MCS	3,83 ton ha^{-1}	R31 385,94	R10 096,00 ha^{-1}	R21 289,94 ha^{-1}	1,23 ton ha^{-1}

7.4 Discussion and conclusion

The production of maize and soybean were in line with that produced nationally in South Africa. The average maize production of 5,10 ton ha^{-1} was above the average national maize production of 3,60 ton ha^{-1} during the study period (Boakye, 2023). Similarly, the average soybean production was 2,62 ton ha^{-1}, 0,32 ton ha^{-1} above the national soybean production over the study period (Van Der Linde, 2023).

The production results were proportional to profitability results with similar trends being identified between the two for maize and soybean. Maize production was affected by rotational systems with maize in the MCS rotational system performing the best over the study period. In general, maize yields after soybean were significantly higher than maize yields after maize. This is in agreement with a number of studies that have shown that maize grown after soybean gives higher yield than maize after maize (Crookston *et al.,* 1991; Meese *et al.,* 1991; Porter *et al.,* 1997; Stanger, Lauer & Chavas, 2008). The soybean production was not influenced by rotational systems, however it did show an overall improvement from season one (2020/2021) to season three (2022/2023) with the MCS rotational system showing the greatest improvement. This is in conjunction with Acevedo-Siaca and Goldsmith (2020) who mentioned that the incorporation of soybean in maize-rotation not only has a benefit for the maize crop but also improves soybean yield.

Season influenced both maize and soybean production. Both crops were negatively affected by the unfavourable second season (2021/2022), with significantly less production and profit generated. Magdoff and Van Es (2021) stated that the excess of water is one of the most significant overall yield-limiting factors to crop production. However, it appears that soybean tolerated waterlogging conditions better than maize. This could be due to soybean's ability to form secondary aerenchyma, which is different to primary aerenchyma formed by maize in that it is more adaptable and flexible (Takahashi *et al.,* 2014). Aerenchyma is a type of tissue that enhances aeration and transports oxygen to roots (Boru *et al.,* 2003; Takahashi *et al.,* 2014). Furthermore, soybean also have the ability to form a barrier that prevents oxygen leakage and enhances oxygen diffusion to root tips (Langan *et al.,* 2022).

The effect of the rotational systems was dependent on the season, the yield ranking order varied, with the maize in the MCS performing better in the more favourable first (2020/2021) and third season (2022/2023), while MMS1 performed better in the wetter second season (2021/2022). The waterlogged MCS plots caused excessive damage that negatively affected the maize yield in the second season (2021/2022). In addition, the cover crop consisted of sorghums, which are known to produce sorgoleone

(Sarr *et al.,* 2020). Sorgoleone has allelopathic properties which can suppress the growth and yield of the proceeding crops in certain seasons, especially on sandy soil (Bansal, 2020; Sarr *et al.,* 2020). *Trichoderma viride* and *Aspergillus sp* are some organisms that are responsible for the loss of sorgoleone (Bansal, 2020) and could have been inhibited during the second season (2021/2022). This together with the possibility that excessive water prevented cover crops binding with soil particles to prevent soil erosion (Magdoff & Van Es, 2021), resulted in a poorer performance of maize and soybean in the MCS rotational system. Although no single rotational system dominated over seasons, it can be noted that monoculture maize never had the top-ranking position, while maize after soybean (MCS and MMS1) always performed better, with MS having the highest mean gross margin over the study period.

In conclusion, farmers are encouraged to introduce crop rotations as a strategy to improve their production and profitability. In the North-Western Free State maize in rotation with soybean has potential to increase the production and profitability of each crop respectively. In addition, the incorporation of a cover crop in the rotational system during a season with a favourable predicted climate, has potential to further increase production and profitability, resulting in a more sustainable agricultural system.

The results reported in this chapter have been published in de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). Production and profitability of maize and soybean grown in rotation in the North-Western Free State, South Africa, *African Journal of Agricultural Research*, vol. 20, no. 2, pp. 155-162.

Chapter 8

Association between soil health, nutritional value and maize production in different rotational systems in the North-Western Free State

8.1 Introduction

The soil health, grain nutritional value and crop yield in different rotational systems have been discussed in depth in Chapter 5, 6 and 7. Individually, these factors align with the three pillars of sustainable agriculture: Environmental, social and economic (Lampridi, Sørenson & Bochtis, 2019). These sustainability pillars are known to be interdependent (Khwidzhili & Worth, 2016). Figure 8.1 shows that when the environmental and social pillars intercept a bearable condition is formed, when the social and economic pillar intercept an equitable condition is formed and when the environmental and economic pillars intercept a viable condition is created (Mulligan, 2014). Ultimately, when all three pillars intercept sustainability is achieved (Mulligan, 2014). Understanding how these concepts associate with each other under rotational systems will allow for better prediction and future decisions on maize production in the North-Western Free State with its unique inherent soil characteristics.

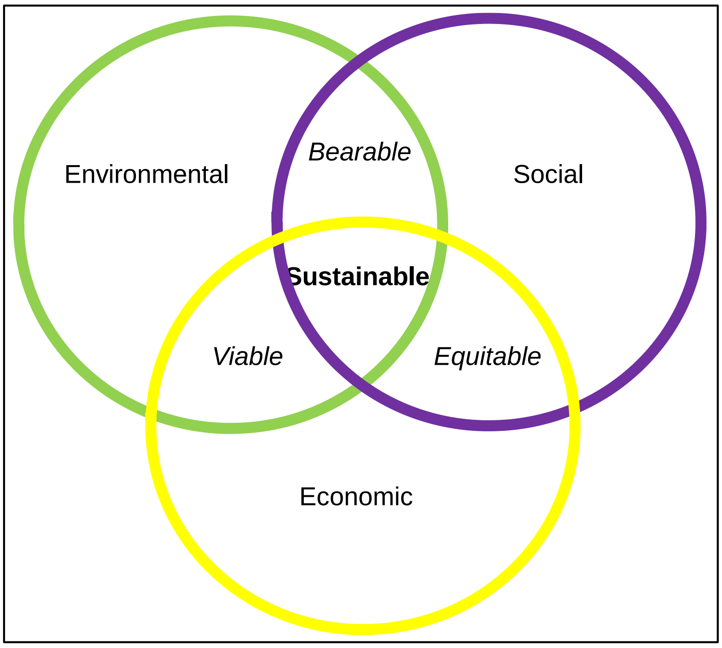

Figure 8.1: Pillars of sustainability and their interaction with each other (adapted from Mulligan (2014) and Purvis, Mao and Robinson (2019))

8.2 Methodology

8.2.1 Data analysis

Results from the previous chapters (chapter 5, chapter 6 and chapter 7) were used to determine the association between soil health, nutritional value and maize production in different rotational systems. Linear regressions were run to determine these associations. Assumption testing included testing for outliers, normal distribution and homoscedasticity. A prediction equation was determined based on the regression results. Statistical significance was accepted at $p \leq 0,05$.

8.3 Results

The main results from chapter 5, chapter 6 and chapter 7 are summarised in Table 8.1. The highest soil health score was found in the MM rotational system however, the highest maize yield was seen in the MCS rotational system, 14% higher than the maize yield in the MM rotational system. The TDN were similar among rotational systems.

Table 8.1: Mean soil health, TDN and maize yield for each rotational system for 2020/2021, 2021/2022 and 2022/2023

Rotational system	Soil health	TDN	Yield
MM	3,86	89%	5,10
MMS2	3,76	90%	3,94
MMS1	3,74	90%	5,18
MS	3,67	90%	5,34
MCS	3,78	90%	5,91

No relationship was found between TDN and soil health, nor between TDN and maize yield. However, there was a statistically significant association between soil health and maize yield, with 40% of the variation in maize yield explained by the regression model, $F(1,43) = 30,46$, $p < 0,001$. Soil health added statistically significantly to the prediction of maize yield with a one unit increase in soil health resulting in a 1,62 ton ha^{-1} maize yield. Therefore, a positive association was determined between soil health and maize yield (Figure 8.2), with a regression equation of: Maize yield = -1,02 + (1,62 x (soil health)).

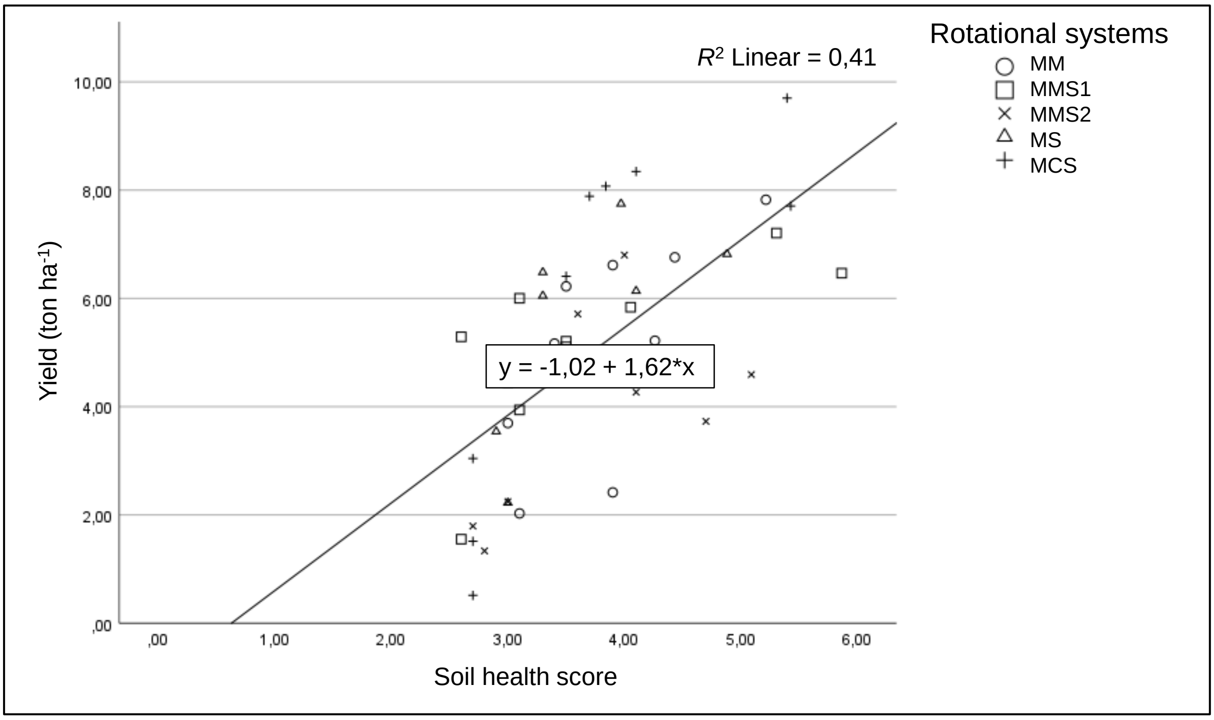

Figure 8.2 Scatter plot illustrating the linear association between soil health score and maize yield

8.4 Discussion and conclusion

There was not a clear interdependence relationship between soil health, TDN and maize production in this study. However, despite soil health not directly influencing TDN, the influence of soil health on maize yield enhanced nutritional value in terms of quantity albeit it not in quality (Farre *et al.,* 2010). The increase in soil health resulting in an increased maize yield is often the case, as described by Batool (2023) and Awoonor, Dogbey and Quansah (2023). These results link the environmental and economic pillars of sustainability, which according to the sustainability model make the conditions viable, where environmental practices are able to maintain economic stability (Mulligan, 2014; Purvis, Mao & Robinson, 2019). If the indirect association between soil health and TDN were included, the social pillar of sustainability could be incorporated resulting in sustainability.

Although a higher soil health was associated with higher maize yield, the highest yield in this study did not come from the healthiest soil. All maize after soybean rotational systems (MMS1, MS and MCS) had higher yields than monoculture maize albeit lower soil health scores. The MCS system had a 14% higher maize production than monoculture maize despite a 2% lower soil health. This suggests a rotational effect not captured in the soil health score. The proposed rotational effect is that the soil of maize after soybean and/ or cover crop is replenished more naturally compared to monoculture maize which received more inorganic fertilizer, allowing for a slower release of nutrients over a longer period of time, resulting in a higher maize yield (Hernandez *et al*., 2021). Studies by Mtambanengwe and Mapfumo (2006), and Mamuye *et al.* (2021) showed that a combination of organic and inorganic nutrients result in better yields. In addition, soybean can significantly reduce the prevalence of Striga (*Striga hermonthica*), a parasitic weed also known as witchweed, by inducing suicidal germination which decreases its presence and reduces weed pressure in subsequent maize rotations (Acevedo-Siaca & Goldsmith, 2020). Furthermore, rotational systems disrupt pathogen cycles resulting in a breakdown of diseases and boost in productivity (Shah *et al.,* 2021).

In conclusion, rotational systems focusing on maize production in the North-Western Free State are viable, with potential for agricultural sustainability in the area. According to Lampridi, Sørenson and Bochtis (2019) the sustainability assessment of such practices can be difficult due to case-specific variables that need to be taken into consideration. Therefore, considering the extremely sandy soils of the North-Western Free state (with a critically low organic matter content) maize rotational systems incorporating soybean and cover crops are recommended.

The results reported in this chapter have been published in de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). The effect of crop rotation on agricultural sustainable in the North-Western Free State, South Africa, *African Journal of Sustainable Agricultural Development*, vol. 5, no. 2, pp. 32-45.

Chapter 9

Conclusion

9.1 Introduction

The objective of this study was to determine the perception of North-Western Free State farmers on crop diversification as well as to determine the sustainability of different rotational systems in the area. The social science aspect of the study revealed that North-Western Free State farmers recognised the potential benefits of crop diversification and were moving away from crop specialisation. Most farmers in the area rotated maize with soybean and had seen an increase in yield. The natural science findings of this study further revealed that maize-soybean rotational systems maintained soil health, provided nutritional benefits and improved crop production and productivity. These results link the environmental, social and economic pillars of agricultural sustainability as shown in Figure 9.1.

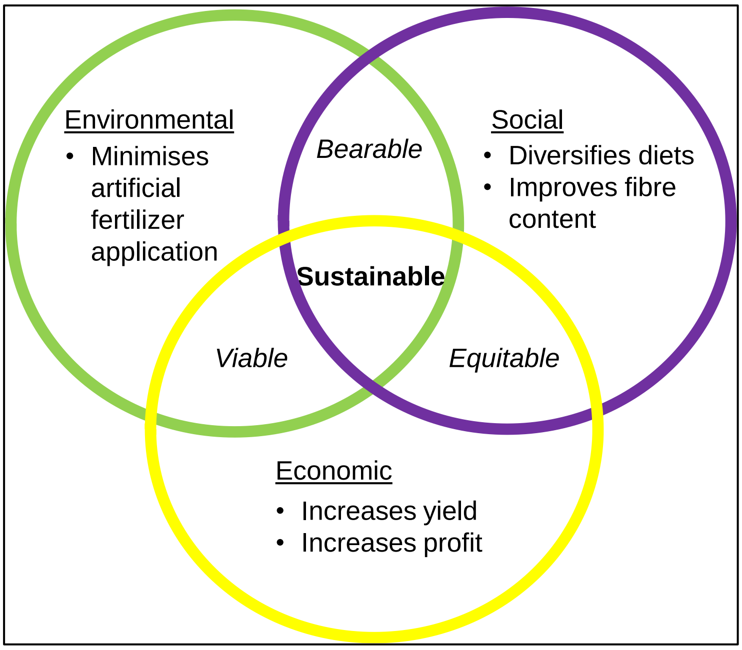

Figure 9.1: Environmental, social and economic effects of crop rotation in the North-Western Free State (illustration by M de Bruyn)

Although well documented in literature, an important observation in this study was the role that season variation (mainly rainfall) played on soil health, nutrition and crop production. Aspects such as organic matter, nutrient availability and crop production were negatively affected by above normal rainfall conditions whereas other aspects were better able to withstand these conditions. It is important to take note of and monitor these observations as farmers in the area indicated that they adjust their rotational system according to the weather predictions. With the prediction of more extreme weather in the future knowledge and insight into these processes could be key to success.

9.2 Guidelines for sustainable rotational systems in the North-Western Free State

It is recommended that farmers in the North-Western Free State implement crop rotation as an on-farm practise. The simplest form of crop rotation that provides noticeable benefits includes the incorporation of soybean into rotational systems with maize (Figure 9.2). This rotational system maintains soil health naturally and has potential to increase gross margins by 34% compared to monoculture maize.

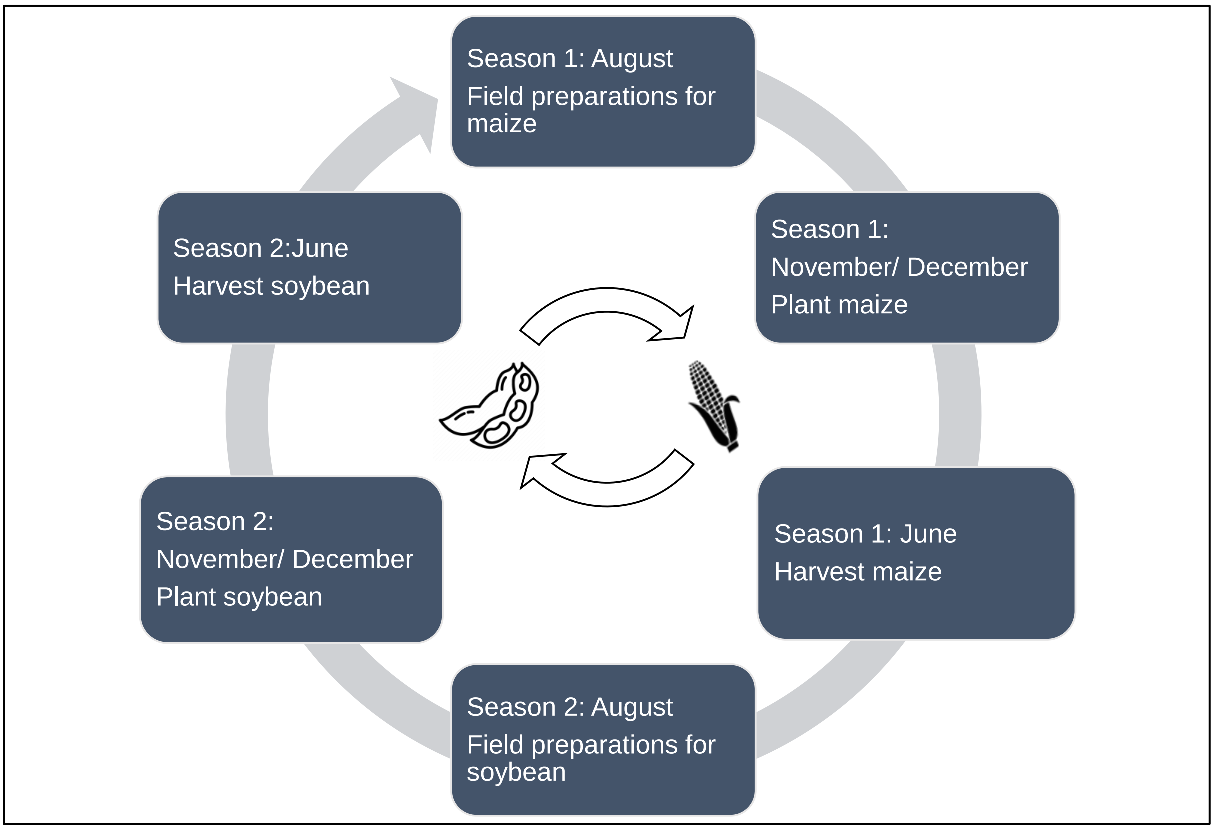

Figure 9.2: Guidelines for a maize-soybean crop rotational system in the North-Western Free State (illustration by M de Bruyn)

Figure 9.3 shows how the maize-soybean rotational system can be further diversified to include a cover crop. Although this system requires a livestock component to reach its full potential, the relatively high estimated gross margins validate further exploration. Incorporation of a cover crop can increase maize production by 5% compared to monoculture maize and soybean production can increase up to 40%. It is also important to note here that the MCS systems performs better than the MS system in seasons with favourable rainfall while the MS system outperforms MCS in seasons with higher rainfall.

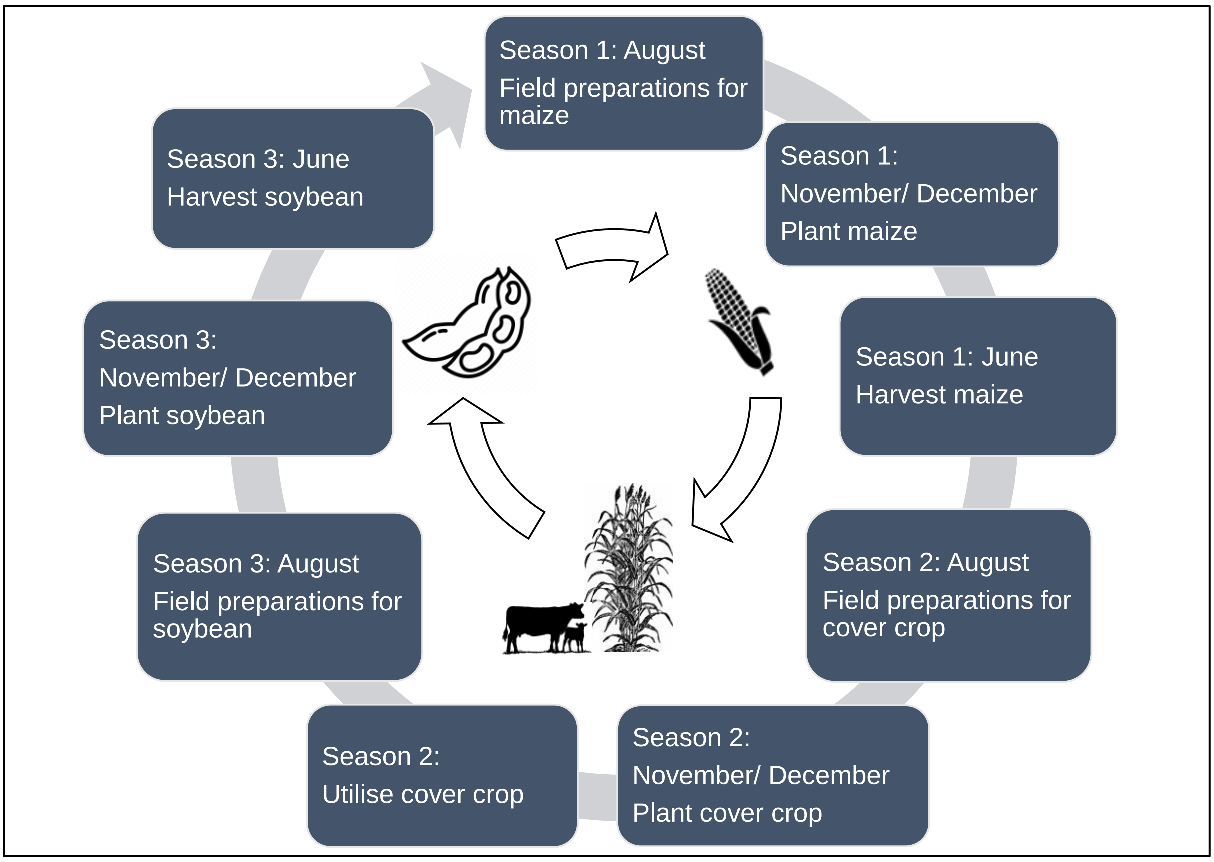

Figure 9.3: Guidelines for a maize-cover crop-soybean rotational system in the North-Western Free State (illustration by M de Bruyn)

In addition, it is recommended that these findings and guidelines be disseminated to farmer groups and associations in the area. Farmers in the area indicated that these groups and associations were their highest ranked decision influencer. Since farmers in the area had a positive attitude towards crop rotation the dissemination of these results could enhance sustainability in the area.

In conclusion, this study provided in-depth insight into the effects of crop rotation specific to the North-Western Free State. The results provided evidence that crop rotation is a sustainable practice to ensure sufficient and nutritious food for an ever-increasing population, while conserving and improving the soil and environment. Ongoing research into this concept is necessary to ensure long-term sustainability.

References

Abate, T. (2011). ‘Maize stalk borers of Ethiopia: Quantitative data on ecology and management’, in M Worku, S Twumasi-Afriyie, L Wolde, B Tedesse, G Demisie, G Bogale, D Wegnary, B Prasanna (eds.), *Meeting the challenges of global climate change and food security through innovative maize research*, CIMMYT, Ethiopia, pp. 174-184.

Abbott, L.K., & Murphy, D.V. (2003). *Soil biological fertility: A key to sustainable land use in agriculture*, Kluwer, Dordrecht.

Acevedo-Siaca, L., & Goldsmith, P.D. (2020). Soy-maize crop rotations in sub-Saharan Africa: A literature review, *International Journal of Agronomy*, pp. 1-14.

Adamgbe, E.M., & Ujoh, F. (2013). Effect of variability in rainfall characteristics on maize yield in Gboko, Nigeria, *Journal of Environmental Protection,* vol. 4, no. 9, pp. 881-887.

Adeniyi, O.O., & Ariwoola, O.S. (2019). Comparative proximate composition of maize (*Zea mays* L.) varieties grown in south-western Nigeria, *International Annals of Science*, vol. 7, no. 1, pp. 1-5.

Adu, G.B., Abdulai, M.S., Alidu, H., Nustugah, S.K., Buah, S.S., Kombiok, J.M., Obeng-Antwi, K., Abudulai, M.P.M.E., & Etwire, P.M. (2014). *Recommended production practices for maize in Ghana*, AGRA/CSIR, Ghana.

African Farming. (2022). Stalk borers pile more woes on maize farmers, viewed 25 July 2022, https://www.africanfarming.com/news/stalk-borers-maize-farmers/

Agencies. (2019). Fall armyworms: Eating their way around the world, *Eagle online*, viewed 25 July 2022, https://eagle.co.ug/2019/07/02/fall-armyworms-eating-their-way-around-the-world/

Ahmad, N.S.B.N., Mustafa, F.B., & Didams, G. (2020). A systematic review of soil erosion control practices on the agricultural land in Asia, *International Soil and Water Conservation Research,* vol. 8, no. 2, pp. 103-115.

Ahmed, M.H., Geleta, K.M., Tazeze, A., & Andualem, E. (2017). The impact of improved maize varieties on farm productivity and wellbeing: Evidence from the east Hararghe zone of Ethiopia, *Development Studies Research*, vol. 4, no. 1, pp. 9-21.

Akhtar, S., Li, G.C., Ullah, R., Nazir, A., Iqbal, M.A., Raza, M.H., Iqbal, N., & Faisal, M. (2018). Factors influencing hybrid maize farmers' risk attitudes and their perceptions in Punjab Province, Pakistan, *Journal of Integrative Agriculture,* vol. 17, no. 6, pp. 1454-1462.

Akpalu, W., Hassan, R.M., & Ringler, C. (2008). Climate variability and maize yield in South Africa: Results from GME and MELE Methods, IFPRI Discussion Paper No. 843, Washington, USA.

Al-Kaisi, M.M., Archontoulis, S.V., Kwaw-Mensah, D., & Miguez, F. (2015). Tillage and crop rotation effects on corn agronomic response and economic return at seven Iowa locations, *Agronomy Journal*, vol. 107, no. 4, pp. 1411-1424.

Alarcón, M.V., Lloret, P.G., & Salguero, J. (2014). 'The development of the maize root system: Role of auxin and ethylene', in A Morte, A Varma (eds.), *Root Engineering*, Springer, Berlin, pp. 75-103.

Albin, D. (2021). Total digestible nutrients (TDN): How useful is it? *Insta-pro*, viewed 29 June 2023, https://www.insta-pro.com/en/blog/nutritionandtechnologies/tdn-how-useful-is-it/

Alemu, E., Selassie, Y.G., & Yitaferu, B. (2022). Effect of lime on selected soil chemical properties, maize (*Zea mays L*.) yield and determination of rate and method of its application in Northwestern Ethiopia, *Heliyon*, vol. 8, no. 1, pp. 1-8.

Alhameid, A., Tobin, C., Maiga, A., Kumar, S., Osborne, S., & Schumacher, T. (2017). 'Intensified agroecosystems and changes in soil carbon dynamics', in M Al-Kaisi, B Cowery (eds.), *Soil Health and Intensification of Agroecosytems*, Academic Press, USA, pp. 195-214.

Anderson, J.A., Ellsworth, P.C., Faria, J.C., Head, G.P., Owen, M.D., Pilcher, C.D., Shelton, A.M., & Meissle, M. (2019). Genetically engineered crops: Importance of diversified integrated pest management for agricultural sustainability, *Frontiers in Bioengineering and Biotechnology*, vol. 7, p. 24.

Arriaga, F.J., Guzman, J., & Lowery, B. (2017). ‘Conventional agricultural production systems and soil functions’, in M Al-Kaisi, B Cowery (eds.), *Soil health and intensification of agroecosytems*, Academic Press, USA, pp. 109-125.

Asfaw, S., Shiferaw, B., Simtowe, F., & Lipper, L. (2012). Impact of modern agricultural technologies on smallholder welfare: Evidence from Tanzania and Ethiopia, *Food Policy*, vol. 37, no. 3, pp. 283-295.

Atube, F., Malinga, G., Nyeko, M., Okello, D., Alarakol, S., & Okello-Uma, I. (2021). Determinants of smallholder farmers’ adaptation strategies to the effects of climate change: Evidence from northern Uganda, *Agriculture and Food Security*, vol. 10, no. 1, pp. 1-14.

Awoonor, J.K., Dogbey, B.F., & Quansah, G.W. (2023). Soil suitability assessment for sustainable intensification of maize production in the humid savannah of Ghana, *Frontiers in Sustainable Food Systems,* vol. 7, n.p.

Babur, E., & Dindaroglu, T. (2020). Seasonal changes of soil organic carbon and microbial biomass carbon in different forest ecosystem, *Environmental Factors Affecting Human Health*, vol. 1, pp. 1-21.

Bălaş-Baconschi, C.G., Pamfil, D., Savati, M., Tinca, E., Călugăr, R., & Haș, V. (2019). Effect of simulating hail and late spring frost on certain parental forms of registered maize hybrids in the North-West of Transylvania, *Romanian Agricultural Research,* vol. 36, pp. 273-282.

Balint-Kurti, P.J., & Johal, G.S. (2009). ‘Maize disease resistance’, in J Bennetzen, S Hake (eds.), *Handbook of maize: Its biology*, Springer, New York, pp. 229-250.

Bansal, M. (2020). Wheat (*Triticum aestivum*) growth and yield response to previous summer crop, sorghum (*Sorghum bicolor*) allelochemicals and pre-plant nitrogen fertilization, doctoral thesis, North Carolina State University, North Carolina.

Batool, M. (2023). ‘Nutrient management of maize’, in P Kaushik (ed.), *New prospects of maize*, IntechOpen, London, n.p.

Bavougian, C.M., Shapiro, C.A., Stewart, Z.P., & Eskridge, K.M. (2019). Comparing biological and conventional chemical soil tests in long-term tillage, rotation, N rate field study, *Soil Science Society of America Journal,* vol. 83, pp. 419-428.

Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V., & Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services, *Global Change Biology*, vol. 27, no. 19, pp. 4697-4710.

Bell, R.A. (2016). Insect pests of maize in KwaZulu-Natal*, Department Agriculture and Rural Development*, viewed 23 June 2022, https://www.kzndard.gov.za/insect-pests-of-maize-in-kwazulu-natal

Beukes, D.J., Nel, A.A., Trytsman, G., Steenkamp, S., Rhode, O.H.J., Abrahams, A.M., van Staden, P., Marx, F., & van Zyl, B. (2019). *SOK Annual Progress Report: Investigating the impacts of conservation agriculture practices on soil health as key to sustainable dry land maize production systems on semi-arid sandy soils with water tables in the North Western Free State*, Potchefstroom, South Africa.

Bhattacharjee, R.B., Singh, A., & Mukhopadhyay, S.N. (2008). Use of nitrogen-fixing bacteria as biofertiliser for non-legumes: Prospects and challenges, *Applied Microbiology and Biotechnology*, vol. 80, no. 2, pp. 199-209.

Bian, D., Jia, G., Cai, L., Ma, Z., Eneji, A.E., & Cui, Y. (2016). Effects of tillage practices on root characteristics and root lodging resistance of maize, *Field Crops Research*, vol. 185, pp. 89-96.

Boa, E., Chernoh, E., & Jackson, G. (2015). *Pest and disease manual*, Africa Soil Health Consortium, Nairobi.

Boakye, A. (2023). Estimating agriculture technologies' impact on maize yield in rural South Africa, *SN Business and Economics*, vol. 3, no. 8, pp. 149-166.

Bobojonov, I., Lamers, J.P., Djanibekov, N., Ibragimov, N., Begdullaeva, T., Ergashev, A.K., Kienzler, K., Eshchanov, R., Rakhimov, A., Ruzimov, J., & Martius, C. (2012). 'Crop diversification in support of sustainable agriculture in Khorezm', in C Martius, I Rudenko, J Lamers, P Vlek (eds.), *Cotton, Water, Salts and Soums: Economic and Ecological Restructuring in Khorezm Uzbekistan,* Springer, Dordrecht, pp. 219-233.

Boru, G., Vantoai, T., Alves, J., Hua, D., & Knee, M. (2003). Responses of soybean to oxygen deficiency and elevated root-zone carbon dioxide concentration, *Annals of Botany*, vol. 91, no. 4, pp. 447-453.

Bosque-Pèrez, N.A. (1995). *Major insect pests of maize in Africa: Biology and control*, IITA Research guide, Nigeria.

Botha, P. (2019). Fertiliser requirements for optimal maize production*, Grain SA,* viewed 1 August 2022, https://www.grainsa.co.za/fertiliser-requirements-for-optimal-maize-production

Brodt, S., Six, J., Feenstra, G., Ingels, C., & Campbell, D. (2011). Sustainable agriculture, *Nature Education Knowledge*, vol. 3, no. 10, pp.1-8.

Bronick, C.J., & Lal, R. (2005). Soil structure and management: A review, *Geoderma,* vol. 124, no. 1-2, pp. 3-22.

Brown, A., Ortmann, G.F., & Darroch, M.A.G. (2000). Factors affecting the use of price risk management tools by large commercial maize producers in South Africa, *South African Journal of Economic and Management Sciences*, vol. 3, no. 1, pp. 75-96.

Burtt-Davy, J. (1914). *Maize: Its history, cultivation, handling, and use,* Longmans, Green and Company, London.

Cairns, J.E., Sonder, K., Zaidi, P.H., Verhulst, N., Mahuku, G., Babu, R., Nair, S.K., Das, B., Govaerts, B., Vinayan, M.T., & Rashid, Z. (2012). Maize production in a changing climate: Impacts, adaptation, and mitigation strategy, *Advances in Agronomy,* vol. 114, pp. 1-58.

Cardoso, E., Vasconcellos, R., Bini, D., Miyauchi, M., Santos, C., Alves, P., Paula, A., Nakatani, A., Pereira, J.M., & Nogueira, M. (2013). Soil health: Looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? *Scientia Agricola,* vol. 70, pp. 274-289.

Carrié, E., Grechi, I., Boudon, F., Frak, E., Combes, D., & Normand, F. (2023) Modeling functional relationships between morphogenetically active radiation and photosynthetic photon flux density in mango tree crown, *Frontiers in Ecology and Evolution*, vol. 11, n.p.

Chambers, K. (2020). From farm to fork: Crop diversification initiatives show promising future for sustainable agriculture, *NASW*, viewed 24 August 2020, https://www.nasw.org/article/farm-fork-crop-diversification-initiatives-show-promising-future-sustainable-agriculture

Chemura, A., Nangombe, S.S., Gleixner, S., Chinyoka, S., & Gornott, C. (2022). Changes in climate extremes and their effect on maize (*Zea mays* L.) suitability over Southern Africa, *Frontiers in Climate,* vol. 4, pp. 1-14.

Chen, X., Cao, G., Jia, Y., Wu, D., Chen, J., Yu, Y., Li, W., & Li, J. (2009). Influence of elevation on growth duration of maize (*Zea mays L.*), *Chinese Journal of Eco-Agriculture,* vol. 17, no. 3, pp. 527-532.

Chu, M., Singh, S., Walker, F.R., Eash, N.S., Buschermohle, M.J., Duncan, L.A., & Jagadamma, S. (2019). Soil health and soil fertility assessment by the Haney soil health test in an agricultural soil in west Tennessee, *Communications in Soil Science and Plant Analysis,* vol. 50, pp. 1123-1131.

Coleman, A. (2012). World-class maize seed, *Farmer's weekly*, viewed 15 September 2022, https://www.farmersweekly.co.za/crops/field-crops/world-class-maize-seed/

Coleman, A. (2021). SA on track to harvest record soya bean crop, *Farmer's weekly*, viewed 3 August 2022, https://www.farmersweekly.co.za/agri-news/south-africa/sa-on-track-to-harvest-record-soya-bean-crop/

Coskan, A., & Dogan, K. (2011). Symbiotic nitrogen fixation in soybean, *Soybean Physiology and Biochemistry*, vol. 307, pp. 167–182.

Costa, M.P., Reckling, M., Chadwick, D., Rees, R.M., Saget, S., Williams, M., & Styles, D. (2021). Legume-modified rotations deliver nutrition with lower environmental impact, *Frontiers in Sustainable Food Systems,* vol. 5, pp. 113-129.

Cowen, J. (2023). How to add nitrogen to soil: Fix nitrogen deficiency, *The yard and garden*, viewed 31 May 2023, https://theyardandgarden.com/how-to-add-nitrogen-to-soil/

Cowieson, A.J. (2005). Factors that affect the nutritional value of maize for broilers, *Animal Feed Science and Technology*, vol. 119, no. 3-4, pp. 293-305.

Coyne, D.L., Cortada, L., Dalzell, J.J., Claudius-Cole, A.O., Haukeland, S., Luambano, N., & Talwana, H. (2018). Plant-parasitic nematodes and food security in Sub-Saharan Africa, *Annual Review of Phytopathology*, vol. 56, pp. 381-403.

Crookston, R., Kurle, J., Copeland, P., Ford, J., & Leuschen, W. (1991). Rotational cropping sequence affects yield of corn and soybean, *Agronomy Journal,* vol. 83, pp. 108-113.

CropLife. (2014). Economic development boosted by plant science, viewed 3 September 2020, https://croplife.org/news/economic-development-boosted-by-plant-science/

Cusack, D.F., Ashdown, D., Dietterich, L.H., Neupane, A., Ciochina, M., & Turner, B.L. (2019). Seasonal changes in soil respiration linked to soil moisture and phosphorus availability along a tropical rainfall gradient, *Biogeochemistry*, vol. 145, pp. 235–254.

Dar, Z.A., Lone, A.A., Habib, M., & Naseer, S. (2019). *Temperate maize cultivation,* Bhumi Publishing, Maharashtra.

Davidson, E.A., Savage, K.E., & Finzi, A.C. (2014). A big-microsite framework for soil carbon modelling, *Global Change Biology,* vol. 20, no. 12, pp. 3610-3620.

De Klerk, N. (2015). Early warning system for the black maize beetle (*Heteronychus arator* Fabricius) in a major maize producing region of South Africa, masters thesis, University of the Free State, Bloemfontein.

De la Fuente, A. (2011). Human capital and productivity, *Nordic Economic Policy Review*, vol. 2, no. 2, pp. 103-132.

Dei, H.K. (2017). Assessment of maize (*Zea mays*) as feed resource for poultry, *Poultry Science*, vol. 1, pp. 1-32.

Deiss, L., Sall, A., Demyan, M.S., & Culman, S.W. (2021). Does crop rotation affect soil organic matter stratification in tillage systems? *Soil and Tillage Research,* vol. 209, pp. 1-14.

Department of Agriculture, Land Reform and Rural Development (DALRRD). (2019). *Annual Report 2018/2019*.

Department of Agriculture, Land Reform and Rural Development (DALRRD). (2020). A profile of the South African soyabean market value chain, viewed 11 October 2023, https://www.dalrrd.gov.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Soyabean%20Market%20Value%20Chain%20Profile%202020.pdf

Department of Agriculture, Land Reform and Rural Development (DALRRD). (2021). A profile of the South African maize market value chain, viewed 15 September 2022, http://webapps1.daff.gov.za/AmisAdmin/upload/Maize%20profile%202021.pdf

Dey, U., Harlapur, S.I., Dhutraj, D.N., Suryawanshi, P., & Bhattacharjee, R. (2015). Integrated disease management strategy of common rust of maize incited by *Puccinia sorghi Schw*, *African Journal of Microbiology Research,* vol. 9, no. 20, pp. 345-1351.

Diamond, J. (2002). Evolution, consequences and future of plant and animal domestication, *Nature*, vol. 418, no. 6898, pp. 700-707.

Dlamini, J.E. (2015). Maize growth and yield as affected by different soil fertility regimes in a long term trial, doctoral thesis, University of Pretoria, Pretoria.

Doran, J.W., & Zeiss, M.R. (2000). Soil health and sustainability: Managing the biotic component of soil quality, *Applied Soil Ecology,* vol. 15, no. 1, pp. 3-11.

Douglas, E., & Halpin, C. (2009). ‘Gene stacking’, in S Jain, D Brar (eds.), *Molecular techniques in crop improvement*, 2nd edn, Springer, Dordrecht, pp. 613-629.

Du Plessis, J. (2003). *Maize production*, Department of Agriculture in cooperation with ARC-Grain Crops Institute.

Ekpa, O., Palacios-Rojas, N., Kruseman, G., Fogliano, V., & Linnemann, A.R. (2018). Sub-Saharan African maize-based foods: Technological perspectives to increase the food and nutrition security impacts of maize breeding programmes, *Global Food Security,* vol. 17, pp. 48-56.

Erasmus, A., Van Rensburg, J.B.J., & Van Den Berg, J. (2010). Effects of Bt maize on *Agrotis segetum* (Lepidoptera: Noctuidae): A pest of maize seedlings, *Environmental Entomology,* vol. 39, no. 2, pp. 702-706.

Fageria, N.K., Baligar, V.C., & Bailey, B.A. (2005). Role of cover crops in improving soil and row crop productivity, *Communications in Soil Science and Plant Analysis*, vol. 36, pp. 2733-2757.

Farre, G., Ramessar, K., Twyman, R.M., Capell, T., & Christou, P. (2010). The humanitarian impact of plant biotechnology: Recent breakthroughs vs bottlenecks for adoption, *Current Opinion in Plant Biology*, vol. 13, no. 2, pp. 219-225.

Feldman, L. (1994). ‘The maize root’, in M Freeling, V Walbot (eds.), *The Maize Handbook*, Springer, New York, pp. 29-37.

Feliciano, D. (2019). A review on the contribution of crop diversification to Sustainable Development Goal 1 “No poverty” in different world regions, *Sustainable Development,* vol. 27, no. 4, pp. 795-808.

Feng, H., Wang, T., Osborne, S., & Kumar, S. (2021). Yield and economic performance of crop rotation systems in South Dakota, *Agrosystems, Geosciences and Environment*, vol. 4, no. 3, pp. 1-10.

Fernandez, F.G., & Kaiser, D.D. (2021). Understanding nitrogen in soils, *University of Minnesota Extension*, viewed 1 February 2024, https://extension.umn.edu/nitrogen/understanding-nitrogen-soils#why-understand-n--760360

Fischer, K. (2022). Why Africa’s new green revolution is failing – maize as a commodity and anti-commodity in South Africa, *Geoforum*, vol. 130, pp. 96-104.

Fonteyne, S., Burgueño, J., Contreras, B.A., Enríquez, E., Villasenor, L., Velázquez, F., Cruz, H., Balbuena, J., Solorio, A., Meza, P., & Galindo, F. (2021). Effects of conservation agriculture on physicochemical soil health in 20 maize-based trials in different agro-ecological regions across Mexico, *Land Degradation & Development*, vol. 32, no. 6, pp. 2242-2256.

Food and Agricultural Organisation of the United Nations (FAO). (1992). Maize in human nutrition: Gross chemical composition, viewed 23 June 2023, https://www.fao.org/3/t0395e/T0395E03.htm

Food and Agricultural Organisation of the United Nations (FAO). (2009). Global agriculture towards 2050, viewed 8 September 2022, https://www.fao.org/fileadmin/templates/wsfs/docs/Issues_papers/HLEF2050_Global_Agriculture.pdf

Food and Agricultural Organisation of the United Nations (FAO). (2022a). Conservation agriculture: What is conservation agriculture? viewed 24 August 2022, https://www.fao.org/conservation-agriculture/overview/what-is-conservation-agriculture/en/

Food and Agricultural Organisation of the United Nations (FAO). (2022b). Conservation agriculture: Soil organic cover, viewed 24 August 2022, https://www.fao.org/conservation-agriculture/in-practice/soil-organic-cover/en/

Fu, X., Zhang, Y., Du, X., She, R., An, C., Fang, Y., Xu, W., & Zhang, N. (2020). Effect of annual nitrogen application rate on nitrogen use efficiency and yield of summer soybean in winter wheat-summer soybean rotation system, *Journal of Plant Nutrition and Fertilizers*, vol. 26, no. 3, pp. 453-460.

Gaikwad, K.B., Rani, S., Kumar, M., Gupta, V., Babu, P.H., Bainsla, N.K., & Yadav, R. (2020). Enhancing the nutritional quality of major food crops through conventional and genomics-assisted breeding, *Frontiers in Nutrition*, vol. 7, pp. 1-30.

Galani, Y.J.H., Orfila, C., & Gong, Y.Y. (2022). A review of micronutrient deficiencies and analysis of maize contribution to nutrient requirements of women and children in Eastern and Southern Africa, *Critical Reviews in Food Science and Nutrition,* vol. 62, no. 6, pp. 1568-1591.

Gao, Y., Duan, A., Qiu, X., Sun, J., Zhang, J., Liu, H., & Wang, H. (2010). Distribution and use efficiency of photosynthetically active radiation in strip intercropping of maize and soybean, *Agronomy Journal*, vol. 102, no. 4, pp. 1149-1157.

Gebre, G.G., Isoda, H., Amekawa, Y., & Nomura, H. (2019). Gender differences in the adoption of agricultural technology: The case of improved maize varieties in southern Ethiopia, *Women's Studies International Forum*, vol. 76, pp. 1-11.

Gebru, H. (2015). A review on the comparative advantages of intercropping to mono-cropping system, *Journal of Biology, Agriculture and Healthcare,* vol. 5, no. 9, pp. 1-13.

Ghosh, A.P., Dass, A., Krishnan, P., Kaur, R., & Rana, K.S. (2017). Assessment of photosynthetically active radiation, photosynthetic rate, biomass and yield of two maize varieties under varied planting dates and nitrogen application, *Journal of Environmental Biology,* vol. 38, no. 4, pp. 683-688.

Gil, S.V., Meriles, J., Conforto, C., Basanta, M., Radl, V., Hagn, A., Schloter, M., & March, G.J. (2011). Response of soil microbial communities to different management practices in surface soils of a soybean agroecosystem in Argentina, *European Journal of Soil Biology*, vol. 47, no. 1, pp. 55-60.

Girkin, N.T., & Cooper, H.A. (2023). ‘Nitrogen and ammonia in soils’, in M Goss, M Oliver (eds.), *Encyclopedia of soils in the environment*, Academic Press, USA, pp. 142-151.

Gomiero, T., Pimentel, D., & Paoletti, M.G. (2011). Environmental impact of different agricultural management practices: Conventional vs. organic agriculture, *Critical Reviews in Plant Sciences,* vol. 30, no. 1-2, pp. 95-124.

Gullickson, G. (2016). Bacterial leaf streak is a new corn disease, *Successful farming*, viewed 15 July 2022, https://www.agriculture.com/crops/bacterial-leaf-streak-is-a-new-corn-disease

Gurr, G.M., Lu, Z., Zheng, X., Xu, H., Zhu, P., Chen, G., Yao, X., Cheng, J., Zhu, Z., Catindig, J.L., & Villareal, S. (2016). Multi-country evidence that crop diversification promotes ecological intensification of agriculture, *Nature Plants*, vol. 2, no. 3, pp. 1-4.

Haarhoff, S.J., Kotzé, T.N., & Swanepoel, P.A. (2020). A prospectus for sustainability of rainfed maize production systems in South Africa, *Crop Science*, vol. 60, no. 1, pp. 14-28.

Hailemariam, M., Sileshi, Y., Asfaw, E., Tesfaye, A., & Assen, M. (2021). Demonstration of maize-soybean (Glycine max (L) Merrill) rotations in promotion for sustainable cropping system in Southwest Ethiopia, *Journal of Genetic and Environment Conservation*, vol. 9, no. 2, pp. 96-101.

Hallama, M., Pekrun, C., Pilz, S., Jarosch, K.A., Frąc, M., Uksa, M., Marhan, S., & Kandeler, E. (2021). Interactions between cover crops and soil microorganisms increase phosphorus availability in conservation agriculture, *Plant and Soil,* vol. 463, no. 1, pp. 307-328.

Haney, R.L., Haney, E.B., Smith, D.R., Harmel, R.D., & White, M.J. (2018). The soil health tool – Theory and initial broad-scale application, *Applied Soil Ecology*, vol. 125, pp. 162-168.

Hernandez, D.J., David, A.S., Menges, E.S, Searcy, C.A., & Afkhami, M.E. (2021). Environmental stress destabilizes microbial networks, *The ISME Journal*, vol. 15, no. 6, pp. 1722-1734.

Hinsinger, P., Bengough, A.G., Vetterlein, D., & Young, I.M. (2009). Rhizopshere: Biophysics, biogeochemistry and ecological relevance, *Plant Soil,* vol. 321, pp. 117-152.

Hobbs, P.R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture, *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 363, no. 1491, pp. 543-555.

Hochholdinger, F. (2009). 'The maize root system: Morphology, anatomy, and genetics', in L Bennetzen, S Hake (eds.), *Handbook of maize: Its biology*, Springer, New York, pp. 145-160.

Hoffland, E., Kuyper, T.W., Comans, R.N., & Creamer, R.E. (2020). Eco-functionality of organic matter in soils, *Plant and Soil,* vol. 455, pp. 1-22.

Hood-Nowotny, R., Umana, N.H.N., Inselbacher, E., Oswald-Lachouani, P., & Wanek, W. (2010). Alternative methods for measuring inorganic, organic, and total dissolved nitrogen in soil, *Soil Science Society of America Journal,* vol. 74, no. 3, pp. 1018-1027.

Horneck, D.A., Sullivan, D.M., Owen, J.S., & Hart, J.M. (2011). *Soil test interpretation guide*. Oregon State University, Corvallis.

Hossain, F., Muthusamy, V., Bhat, J.S., Zunjare, R.U., Kumar, S., Prakash, N.R., & Mehta, B.K. (2022). ‘Maize Breeding’, in H Dikshit, G Mishra, S Tripathi (eds.), *Fundamentals of Field Crop Breeding*, Springer, Singapore, pp. 221-258.

Huang, C., Liu, Q., Heerink, N., Stomph, T., Li, B., Liu, R., Zhang, H., Wang, C., Li, X., Zhang, C., & Van Der Werf, W. (2015). Economic performance and sustainability of a novel intercropping system on the North China Plain, *PloS One,* vol. 10, no. 8, pp. 1-16.

Huang, C.D., Liu, Q.Q., Li, X.L., & Zhang, C.C. (2019). Effect of intercropping on maize grain yield and yield components, *Journal of Integrative Agriculture,* vol. 18, no. 8, pp. 1690-1700.

Huang, R., Birch, C.J., & George, D.L. (2006). Water use efficiency in maize production-the challenge and improvement strategies, *Proceeding of 6th Triennial Conference*, 21-23 February, Australia.

Hussain, S., Shafiq, I., Skalicky, M., Brestic, M., Rastogi, A., Mumtaz, M., Hussain, M., Iqbal, N., Raza, M.A., Manzoor, S., & Liu, W. (2021). Titanium application increases phosphorus uptake through changes in auxin content and root architecture in soybean (*Glycine Max* L.), *Frontiers in Plant Science*, vol. 12, pp. 1-18.

Iderawumi, A.M., & Friday, C.E. (2018). Characteristics effects of weed on growth performance and yield of maize (*Zea Mays*), *Biomedical Journal of Scientific & Technical Research,* vol. 7, no. 3, pp. 1-4.

Iken, J.E., & Amusa, N.A. (2004). Maize research and production in Nigeria, *African Journal of Biotechnology*, vol. 3, no. 6, pp. 302-307.

Indoria, A.K., Rao, C.S., Sharma, K.L., & Reddy, K.S. (2017). Conservation agriculture - a panacea to improve soil physical health, *Current Science,* pp. 52-61.

International Atomic Energy Agency (IAEA). (2020). Crop nutrition, viewed 7 September 2020, https://www.iaea.org/topics/crop-nutrition

Islam, K.R., & Weil, R.R. (2000). Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management, *Journal of Soil and Water Conservation,* vol. 55, pp. 69-78.

Jaccard, J. (1998). *Interaction effects in factorial analysis of variance*, Sage, Washington.

Jaidka, M., Bathla, S., & Kaur, R. (2019). 'Improved technologies for higher maize production', in A Hossain (ed.), *Maize-production and use*, IntechOpen, London, n.p.

Jjagwe, J., Chelimo, K., Karungi, J., Komakech, A.J., & Lederer, J. (2020). Comparative performance of organic fertilizers in maize (*Zea mays L.*) growth, yield, and economic results, A*gronomy,* vol. 10, no. 1, pp. 69-84.

Johnson, R., Vishwakarma, K., Hossen, M.S., Kumar, V., Shackira, A.M., Puthur, J.T., Abdi, G., Sarraf, M., & Hasanuzzaman, M. (2022). Potassium in plants: Growth regulation, signalling, and environmental stress tolerance, *Plant Physiology and Biochemistry,* vol. 172, pp. 56-69.

Jordaan, H., & Grové, B. (2007). Factors affecting maize producers adoption of forward pricing in price risk management: The case of Vaalharts, *Agrekon*, vol. 46, no. 4, pp. 548-565.

Jordaan, K. (2022). Market overview: Maize meal production in South Africa, *ROFF*, viewed 4 July 2023, https://www.roff.co.za/blogs/blog/case-study-maize-meal-production-in-south-africa

Jug, D., Jug, I., Brozović, B., Vukadinović, V., Stipešević, B., & Đurđević, B. (2018). The role of conservation agriculture in mitigation and adaptation to climate change, *Poljoprivreda*, vol. 2, no. 1, pp. 35-44.

Kafle, B. (2010). Determinants of adoption of improved maize varieties in developing countries: A review, *International Research Journal of Applied and Basic Sciences,* vol. 1, no. 1, pp. 1-7.

Kaur, H., Kaur, H., Kaur, H., & Srivastava, S. (2023). The beneficial roles of trace and ultratrace elements in plants, *Plant Growth Regulation,* vol. 100, no. 2, pp. 219-236.

Kemausuor, F., Dwamena, E., Bart-Plange, A., & Kyei-Baffour, N. (2011). Farmers' perception of climate change in the Ejura-Sekyedumase district of Ghana, *ARPN Journal of Agricultural and Biological Science,* vol. 6, no. 10, pp. 26-37.

Khapayi, M., & Celliers, P.R. (2015). Issues and constraints for emerging farmers in the Eastern Cape Province, South Africa, *African Journal of Agricultural Research*, vol. 10, no. 41, pp. 3860-3869.

Khwidzhili, R.H., & Worth, S.H. (2016). The sustainable agriculture imperative: Implications for South African agricultural extension, *South African Journal of Agricultural Extension*, vol. 44, no. 2, pp. 19-29.

Kibblewhite, M.G., Ritz, K., & Swift, M.J. (2008). Soil health in agricultural systems, *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 363, no. 1492, pp. 685-701.

Knoema. (2022a). World maize production 1961-2021, viewed 23 August 2022, https://knoema.com/atlas/World/topics/Agriculture/Crops-Production-Quantity-tonnes/Maize-production

Knoema. (2022b). Market price – production – maize, viewed 15 September 2022, https://knoema.com/data/marker-price+agriculture-inidcators-production+maize

Kumar, K., & Goh, K.M. (1999). Crop residues and management practices: Effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery, *Advances in Agronomy,* vol. 68, pp. 197-319.

Kumar, P., Kaur, J., Suby, S.B., Sekhar, J.C., & Lakshmi, S.P. (2018). Pests of maize, *Pests and Their Management,* pp. 51-79.

Kutka, F. (2011). Open-pollinated vs. hybrid maize cultivars, *Sustainability*, vol. 3, no. 9, pp. 1531-1554.

Kynast, R.G., Riera-Lizarazu, O., Vales, M.I., Okagaki, R.J., Maquieira, S.B., Chen, G., Ananiev, E.V., Odland, W.E., Russell, C.D., Stec, A.O., & Livingston, S.M. (2001). A complete set of maize individual chromosome additions to the oat genome, *Plant Physiology*, vol. 125, no. 3, pp. 1216-1227.

Laker, M.C. (2008). 'Challenges to soil fertility management in the "Third Major Soil Region of the World", with special reference to South Africa', in S Haneklause, C Hera, R Rietz, E Schnug (eds.), *Fertilizers* *and fertilization for sustainability in agriculture: The First World meets the Third World – challenges for the future,* CIEC, Pretoria, pp. 309-350.

Lakhran, H., Kumar, S., & Bajiya, R. (2017). Crop diversification: An option for climate change resilience, *Trends Bioscience*, vol. 10, no. 2, pp. 516-518.

Lal, R. (2016). Soil health and carbon management, *Food and Energy Security*, vol. 5, no. 4, pp. 212-222.

Lampridi, M.G., Sørensen, C.G., & Bochtis, D. (2019). Agricultural sustainability: A review of concepts and methods, *Sustainability,* vol. 11, no. 18, pp. 1-27.

Langan, P., Bernád, V., Walsh, J., Henchy, J., Khodaeiaminjan, M., Mangina, E., & Negrão, S. (2022). Phenotyping for waterlogging tolerance in crops: Current trends and future prospects, *Journal of Experimental Botany,* vol. 73, no. 15, pp. 5149-5169.

Latha, V.A., Lone, A., & Ahmed, Z. (2020). *Maize breeding manual: Manual Serial/DR/SKUAST-K/2020/3*, AICRP-Maize, India.

Lehmann, A., Leifheit, E.F., & Rillig, M.C. (2017). 'Mycorrhizas and soil aggregation', in N Johnson, C Gehring, J Jansa (eds.), *Mycorrhizal mediation of soil: Fertility structure and carbon storage,* Elsevier, Netherlands, pp. 241-262.

Lehmann, J., Bossio, D.A., Kögel-Knabner, I., & Rillig, M.C. (2020). The concept and future prospects of soil health, *Nature Reviews Earth and Environment,* vol. 1, pp. 544-553.

Li, Y., Cui, S., Chang, S.X., & Zhang, Q. (2019). Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: A global meta-analysis, *Journal of Soils and Sediments,* vol. 19, pp. 1393-1406.

Lin, B.B. (2011). Resilience in agriculture through crop diversification: Adaptive management for environmental change, *BioScience*, vol. 6, no. 3, pp. 183-193.

Lithourgidis, A.S., Dordas, C.A., Damalas, C.A., & Vlachostergios, D. (2011). Annual intercrops: An alternative pathway for sustainable agriculture, *Australian Journal of Crop Science,* vol. 5, no. 4, pp. 396-410.

Liu, W., Zhao, H., Miao, C., & Jin, W. (2021). Integrated proteomics and metabolomics analysis of transgenic and gene-stacked maize line seeds, *GM Crops and Food*, vol. 12, no. 1, pp. 361-375.

Lo, C.C. (2010). Effect of pesticides on soil microbial community, *Journal of Environmental Science and Health,* vol. 45, no. 5, pp. 348-359.

Loubser, H.L., & Nel, A.A. (2004). Productivity and stability of grain yield in maize and sorghum as affected by rotational cropping systems in the North Western Free State, *South African Journal of Plant and Soil,* vol. 21, pp. 80-84.

Lunduka, R.W., Mateva, K.I., Magorokosho, C., & Manjeru, P. (2019). Impact of adoption of drought-tolerant maize varieties on total maize production in South Eastern Zimbabwe, *Climate and Development*, vol. 11, no. 1, pp. 35-46.

Machek, O., & Špička, J. (2014). Productivity and profitability of the Czech agricultural sector after the economic crisis, *WSEAS Transactions on Business and Economics,* vol. 11, pp. 700-706.

Magda. (2016). Black maize beetle came to the light, *iSpot share nature*, viewed 25 July 2022, https://www.ispotnature.org/communities/southern-africa/view/observation/639490/black-maize-beetle-came-to-the-light-

Magdoff, F., & Van Es, H. (2021). *Building soils for better crops: Ecological management for healthy soils,* Sustainable Agriculture Network, Beltsville.

Majía, D. (2003). Maize: Post harvest operation, *Food and Agricultural Organisation of the United Nations*, viewed 10 June 2022, https://www.fao.org/fileadmin/user_upload/inpho/docs/Post_Harvest_Compendium_-_MAIZE.pdf

Makate, C., Wang, R., Makate, M., & Mango, N. (2016). Crop diversification and livelihoods of smallholder farmers in Zimbabwe: Adaptive management for environmental change, *SpringerPlus*, vol. 5, no. 1, pp. 1-18.

Malik, D.P., & Singh, I.J. (2002). Crop diversification – An economic analysis, *Indian Journal of Agricultural Research*, vol. 36, no. 1, pp. 61-64.

Mallarino, A.P., & Sawyer, J.E. (2013). Interpretation of soil test results, *Iowa State University*, viewed 31 May 2021, http://lib.dr.iastate.edu/extension_pubs

Maluleke, W. (2020). The African scare of fall armyworm: Are South African farmers immune? *International Journal of Social Sciences and Humanity Studies,* vol. 1, no. 1, pp. 192-206.

Mamuye, M., Nebiyu, A., Elias, E., & Berecha, G. (2021). Combined use of organic and inorganic nutrient sources improved maize productivity and soil fertility in southwestern Ethiopia, Int*ernational Journal of Plant Production,* vol. 15, pp. 407-418.

Mano, Y., & Omori, F. (2007). Breeding for flooding tolerant maize using "teosinte" as a germplasm resource, *Plant Root,* vol. 1, pp. 17-21.

Mashabela, T. (2017). Agriculture sector: Cultivating jobs is aim, *Cape Argus*, 14, September 17, p. 13.

Mashingaidze, K. (2006). 'Maize research and development', in M Rukuni, P Tawonezvi, C Eicher (eds.), *Zimbabwe's agricultural revolution revisited*, University of Zimbabwe Publications, Harare, pp. 363-378.

Maxwell, S.E., Delaney, H.D., & Kelley, K. (2017). *Designing experiments and analyzing data: A model comparison perspective*, Routledge, UK.

Mazibuko, N.V.E., & Antwi, M.A. (2019). Socio-economic factors influencing smallholder farmers agricultural infrastructure availability, accessibility and satisfaction: A case on North West province in South Africa, *OIDA International Journal of Sustainable Development*, vol. 12, no. 5, pp. 11-26.

Mc Cauley, A., Jones, C., & Jacobsen, J. (2009). Soil pH and organic matter, *Nutrient Management Module*, vol. 8, no. 2, pp. 1-12.

Mc Donald, A.H., & Nicol, J. (2005). 'Nematode parasites of cereals', in M Luc, R Sikora, J Bridge (eds.), *Plant parasitic nematodes in subtropical and tropical agriculture*, 2nd edn, CAB International, Wallingford, pp. 131-191.

Mc Donald, A.H., De Waele, D., & Fourie, H. (2017). Nematode pests of maize and other cereal crops, *Nematology in South Africa: A view from the 21st century*, pp. 183-199.

Meena, B., Shirale, A., Biswas, A., Lakaria, B., Jha, P., Gurav, P., Wanjari, R., & Patra, A. (2018). Diversified agriculture for higher productivity and profitability-A review, *Agricultural Reviews,* vol. 39, no. 2, pp. 104-112.

Meese, B., Carter, P., Oplinger, E., & Pendleton, J. (1991). Corn/ soybean rotation effect as influenced by tillage, nitrogen, and hybrid/ cultivar, *Journal of Production Agriculture,* vol. 4, no. 1, pp. 74-80.

Mejía, D. (2003). *Maize: Post-Harvest Operation*, Food and Agriculture Organization of the United Nations (FAO), Columbia.

Meteoblue. (2024). Simulated historical climate and weather data for Wesselsbron, viewed 12 February 2024, https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/wesselsbron_south-africa_940424

Meyo, E.S.M., & Egoh, I.M. (2020). Assessing the impacts of variable input costs on maize production in Cameroon, *Agricultural Sciences*, vol. 11, pp. 1095-1108.

Mideros, S. (2022). Northern corn leaf blight genes identified, *Lancaster Farming*, viewed 25 July 2022, https://www.lancasterfarming.com/farming-news/field-crops/northern-corn-leaf-blight-genes-identified/article_e14571ba-c638-5c50-a8dd-df4a71a86ea7.htm

Miransari, M. (2011). Soil microbes and plant fertilization, *Applied Microbiology and Biotechnology*, vol. 92, pp. 875-885.

Mitchell, J.P., Shrestha, A., Mathesius, K., Scow, K.M., Southard, R.J., Haney, R.L., Schmidt, R., Munk, D.S., & Horwath, W.R. (2017). Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California’s San Joaquin Valley, USA, *Soil and Tillage Research,* vol. 165, pp. 325-335.

Mitran, T., Meena, R.S., Lal, R., Layek, J., Kumar, S., & Datta, R. (2018). Role of soil phosphorus on legume production, *Legumes for Soil Health and Sustainable Management,* pp. 487-510.

Miya, S.P. (2015). Maize (*Zea mays L.*) seed quality in response to simulated hail damage, masters thesis, University of Kwa-Zulu Natal, Pietermaritzburg.

Moeletsi, M.E. (2010). Agroclimatological risk assessment of rainfed maize production for the Free State province of South Africa, doctoral thesis, University of the Free State, Bloemfontein.

Moeletsi, M.E., Walker, S., & Landman, W.A. (2011). ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa, *Physics and Chemistry of the Earth*, vol. 36, no. 14-15, pp. 715-726.

Mokone, M. (2018). Key factors that influence local maize prices, *GrainSA*, viewed 1 August 2022, https://www.grainsa.co.za/key-factors-that-influence-local-maize-prices

Montgomery, S. (2014). *Field crop manual: Maize a guide to upland production in Cambodia*, NSW Department of Primary Industries, New South Wales.

Morgan, J.A.W., Beinding, G.D., & White, P.J. (2005). Biological costs and benefits to plant-microbe interactions in the rhizosphere, *Journal of Experimental Botany*, vol. 56, pp. 1729-1739.

Morris, M. (2001). *Assessing the benefits of international maize breeding research: An overview of the global maize impacts study*, CIMMYT, Mexico.

Mosharrof, M., Uddin, M., Sulaiman, M.F., Mia, S., Shamsuzzaman, S.M., & Haque, A.N.A. (2021). Combined application of biochar and lime increases maize yield and accelerates carbon loss from an acidic soil, *Agronomy*, vol. 11, no. 7, pp. 1313-1333.

Mueller, D. (2018). Gray leaf spot, *Forestry images*, viewed 25 July 2022, https://www.forestryimages.org/browse/detail.cfm?imgnum=5465612

Muinos, L. (2022). What's the difference between crude and dietary fiber? *Livestrong*, viewed 28 June 2023, https://www.livestrong.com/article/480986-differences-of-crude-and-dietary-fiber/

Mulligan, M. (2014). *An introduction to sustainability: Environmental, social and personal perspectives*. London: Routledge.

Mulungu, L.S. (2017). Control of rodent pests in maize cultivation: The case of Africa, *Achieving Sustainable Maize Cultivation,* vol. 2, pp. 318-337.

Muoni, T., Koomson, E., Öborn, I., Marohn, C., Watson, C.A., Bergkvist, G., Barnes, A., Cadisch, G., & Duncan, A. (2020). Reducing soil erosion in smallholder farming systems in east Africa through the introduction of different crop types, *Experimental Agriculture,* vol. 56, no. 2, pp. 183-195.

Muroyiwa, B., & Mushunje, A. (2017). Price discovery in the South African white and yellow maize futures market, *International Journal of Sciences and Research,* vol. 73, no. 8, pp. 121-133.

Mutuku, E.A., Roobroeck, D., Vanlauwe, B., Boeckx, P., & Cornelis, W.M. (2020). Maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya, *Field Crops Research,* vol. 254, pp. 1-15.

Muzhinji, N., & Ntuli, V. (2021). Genetically modified organisms and food security in Southern Africa: Conundrum and discourse, *GM Crops and Food*, vol. 12, no. 1, pp. 25-35.

Mtambanengwe, F., & Mapfumo, P. (2006). Effects of organic resource quality on soil profile N dynamics and maize yields on sandy soils in Zimbabwe, *Plant and Soil,* vol. 281, pp. 173-191.

Mwamahonje, A., & Mrosso, L. (2016). Prospects of genetic modified maize crop in Africa, *African Journal of Biotechnology,* vol. 15, no. 15, pp. 571-579.

Nel, A.A., & Loubser, H.L. (2004). The impact of crop rotation on profitability and production risk in the Eastern and North Western Free State, *Agrekon*, vol. 43, no. 1, pp. 101-111.

Nevens, F., & Reheul, D. (2001). Crop rotation versus monoculture: Yield, N yield and ear fraction of silage maize at different levels of mineral N fertilization, *NJAS: Wageningen Journal of Life Sciences*, vol. 49, no. 4, pp. 405-425.

Nickel, S.E., Crookston, R.K., & Russelle, M.P. (1995). Root growth and distribution are affected by corn-soybean cropping sequence, *Agronomy Journal,* vol. 87, no. 5, pp. 95-902.

Norris, C.E., Bean, G.M., Cappellazzi, S.B., Cope, M., Greub, K.L., Liptzin, D., Rieke, E.L., Tracy, P.W., Morgan, C.L., & Honeycutt, C.W. (2020). Introducing the North American project to evaluate soil health measurements, *Agronomy Journal,* vol. 112, no. 4, pp. 3195-3215.

Nortjè, G.P., & Laker, M.C. (2021). Soil fertility trends and management in conservation agriculture: A South African perspective, *South African Journal of Plant and Soil,* vol. 38, no. 3, pp. 247-257.

Nuss, E.T., & Tanumihardjo, S.A. (2010). Maize: A paramount staple crop in the context of global nutrition, *Comprehensive Reviews in Food Science and Food Safety,* vol. 9, no. 4, pp. 417-436.

Nyamekye, I., Fiankor, D., & Ntoni, J.O. (2016). Effect of human capital on maize productivity in Ghana: A quantile regression approach, *International Journal of Food and Agricultural Economics*, vol. 4, no. 2, pp.125-135.

O'Donnell, C. (2010). Measuring and decomposing agricultural productivity and profitability change, *Australian Journal of Agricultural and Resource Economics,* vol. 54, no. 4, pp. 527-560.

Okoruwa, A.E., & Kling, J.G. (1996). *Nutrition and quality of maize*, IITA, Croydon.

Olujenyo, F. (2008). The determinants of agricultural production and profitability in Akoko Land, Ondo-State, Nigeria, *Journal of Social Sciences,* vol. 4, no. 1, pp. 37-41.

Opala, P.A., Odendo, M., & Muyekho, F.N. (2018). Effects of lime and fertilizer on soil properties and maize yields in acid soils of Western Kenya, *African Journal of Agricultural Research,* vol. 13, no. 13, pp. 657-663.

Ouyang, C., Wu, K., An, T., He, J., Zi, S., Yang, Y., & Wu, B. (2017). Productivity, economic, and environmental benefits in intercropping of maize with chili and grass, *Agronomy Journal,* vol. 109, no. 5, pp. 2407-2414.

Parent, C., Capelli, N., Berger, A., Crèvecoeur, M., & Dat, J.F. (2008). An overview of plant responses to soil waterlogging, *Plant Stress,* vol. 2, pp. 20-27.

Plantix. (2022). Common rust of maize, viewed 25 July 2022, https://plantix.net/en/library/plant-diseases/100082/common-rust-of-maize/

Plazas, M.C., de Rossi, R.L., Brücher, E., Guerra, F.A., Vilaro, M.L., Guerra, G.D., Wu, G., Ortiz-Castro, M.C., & Broders, K. (2018). First report of *Xanthomonas vasicola pv. vasculorum* causing bacteria leaf streak of maize (*Zea mays*) in Argentina, *Plant Disease*, vol. 102, no. 5, n.p.

Poole, N., Donovan, J., & Erenstein, O. (2021). Agri-nutrition research: Revisiting the contribution of maize and wheat to human nutrition and health, *Food Policy*, vol. 100, pp. 1-13.

Porter, P., Lauer, J., Lueschen, W., Ford, J., Hoverstad, T., Oplinger, E., & Crookston, K. (1997). Environment affects the corn and soybean rotation effect, *Agronomy Journal,* vol. 89, pp. 441-448.

Prashar, P., & Shah, S. (2016). Impact of fertilizers and pesticides on soil microflora in agriculture, *Sustainable Agriculture Reviews*, vol. 19, pp. 331-361.

Precisa. (2023). Ash content analysis in food, viewed on 29 June 2023, https://www.precisa.com/blog/ash-content-in-food-analysis/

Purugganan, M.D. (2019). Evolutionary insights into the nature of plant domestication, *Current Biology*, vol. 29, no. 14, pp. 705-714.

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: In search of conceptual origins, *Sustainability Science,* vol. 14, pp. 681-695.

Qamar, S., Aslam, M., Huyop, F., & Javed, M.A. (2017). Comparative study for the determination of nutritional composition in commercial and noncommercial maize flours, *Pakistan Journal of Botany*, vol. 49, no. 2, pp. 519-523.

Rai, A., Mahata, D., Lepcha, E., Nandi, K., & Mukherjee, P.K. (2018). A review on management of weeds in maize (*Zea mays* L.), *International Journal of Current Microbiology and Applied Sciences,* vol. 7, no. 8, pp. 2906-2922.

Raj, E., Appadurai, M., & Athiappan, K. (2022). ‘Precision farming in modern agriculture’, in A Choudhury, A Biswas, T Singh, S Ghosh (eds.), *Smart agriculture automation using advanced technologies: Data analytics and machine learning, cloud architecture, automation and IoT,* Springer, Singapore, pp. 61-87.

Rajcan, I., & Swanton, C.J. (2001). Understanding maize–weed competition: Resource competition, light quality and the whole plant, *Field Crops Research,* vol. 71, no. 2, pp. 139-150.

Ramirez-Cabral, N.Y., Kumar, L., & Shabani, F. (2017). Global alterations in areas of suitability for maize production from climate change and using a mechanistic species distribution model (CLIMEX), *Scientific Reports,* vol. 7, no. 1, pp. 1-13.

Ranum, P., Peña-Rosas, J.P., & Garcia-Casal, M.N. (2014). Global maize production, utilization, and consumption, *Annals of the New York Academy of Sciences*, vol. 1312, no. 1, pp. 105-112.

Raphael, J.P., Calonego, J.C., Milori, D.M.B., & Rosolem, C.A. (2016). Soil organic matter in crop rotations under no-till, *Soil and Tillage Research,* vol. 155, pp. 45-53.

Rasby, R., & Martin, J. (2023). Understanding feed analysis, *University of Nebraska-Lincoln*, viewed 29 June 2023, https://beef.unl.edu/learning/feedanalysis.shtml

Reganold, J.P., Papendick, R.I., & Parr, J.F. (1990). Sustainable agriculture, *Scientific American,* vol. 262, no. 6, pp. 112-121.

Reneau, J.W., Khangura, R.S., Stager, A., Erndwein, L., Weldekidan, T., Cook, D.D., Dilkes, B.P., & Sparks, E.E. (2020). Maize brace roots provide stalk anchorage, *Plant Direct,* vol. 4, no. 11, pp. 284-306.

Rengel, Z. (2011). ‘Soil pH, soil health and climate change’, in B Singh, A Cowie, K Chan (eds.), *Soil Health and Climate Change*, Springer, Berlin, pp. 69-85.

Renwick, L.L., Deen, W., Silva, L., Gilbert, M.E., Maxwell, T., Bowles, T.M., & Gaudin, A.C. (2021). Long-term crop rotation diversification enhances maize drought resistance through soil organic matter, *Environmental Research Letters,* vol. 16, no. 8, pp. 1-12.

Roba, T.B. (2018). Review on: The effect of mixing organic and inorganic fertilizer on productivity and soil fertility, *Open Access Library Journal,* vol. 5, no. 6, pp. 1-11.

Robertson, A.E., Munkvold, G.P., Hurburgh, C.R., & Ensley, S. (2011). Effects of natural hail damage on ear rots, mycotoxins and grain quality characteristics of corn, *Agronomy Journal,* vol. 103, no. 1, pp. 1193-1199.

Roper, W.R., Osmond, D.L., Heitman, J.L., Wagger, M.G., Reberg-Horton, S.C. (2017). Soil health indicators do not differentiate among agronomic management systems in North Carolina soils, *Soil Science Society of America Journal*, vol. 81, pp. 828-843.

Rovers, J.A.J.M., & Kroonen, B.M.A. (1999). Using crop rotation as a strategic weapon, *PAV Bulletin*, vol. 3, no. 3, pp. 22-26.

Santpoort, R. (2020). The drivers of maize area expansion in Sub-Saharan Africa: How policies to boost maize production overlook the interests of smallholder farmers, *Land,* vol. 9, no. 3, pp. 1-13.

Sarr, P., Ando, Y., Nakamura, S., Deshpande, S., & Subbarao, G. (2020). Sorgoleone release from sorghum roots shapes the composition of nitrifying populations, total bacteria, and archaea and determines the level of nitrification, *Biology and Fertility of Soils*, vol. 56, pp. 145-166.

Sassenrath, G.F., Davis, K., Sassenrath-Cole, A., & Riding, N. (2018). Exploring the physical, chemical and biological components of soil: Improving soil health for better productive capacity, *Kansas Agricultural Experiment Station Research Reports,* vol. 4, no. 3, pp. 16-24.

Sayed, A., & Auret, C. (2020). Volatility transmission in the South African white maize futures market, *Eurasian Economic Review*, vol. 10, no. 1, pp. 71-88.

Setimela, P.S., Magorokosho, C., Lunduka, R., Gasura, E., Makumbi, D., Tarekegne, A., Cairns, J.E., Ndhlela, T., Erenstein, O., & Mwangi, W. (2017). On-farm yield gains with stress-tolerant maize in Eastern and Southern Africa, *Agronomy Journal,* vol. 109, no. 2, pp. 406-417.

Shah, K.K., Modi, B., Pandey, H.P., Subedi, A., Aryal, G., Pandey, M., & Shrestha, J. (2021). Diversified crop rotation: An approach for sustainable agriculture production, *Advances in Agriculture,* pp. 1-9.

Shah, T., Prasad, K., & Kumar, P. (2016). Maize - A potential source of human nutrition and health: A review, *Cogent Food & Agriculture*, vol. 2, no. 1, pp. 1-9.

Sharma, N., & Rayamajhi, M. (2022). Different aspects of weed management in maize (*Zea mays* L.): A brief review, *Advances in Agriculture,* pp. 1-10.

Sharma, R., Singh, N.S., & Singh, D.K. (2020). Impact of heavy metal contamination and seasonal variations on enzyme's activity of Yamuna river soil in Delhi and NCR, *Applied Water Science,* vol. 10, pp. 1-8.

Sherbine, K., Frankl, A., Fernandez, F., Pease, L., & Cates, A.M. (2023). Haney soil health test changes with season, not subsurface drainage, *Agricultural and Environmental Letters*, vol. 8, pp. 1-7.

Shew, A.M., Tack, J.B., Nalley, L.L., Chaminuka, P., & Maali, S. (2021). Yield gains larger in GM maize for human consumption than livestock feed in South Africa, *Nature Food,* vol. 2, no. 2, pp. 104-109.

Shiferaw, B., Prasanna, B.M., Hellin, J., & Bänziger, M. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security, *Food Security,* vol. 3, pp. 307-327.

Sibiya, J., Tongoona, P., Derera, J., & Makanda, I. (2013). Smallholder farmers' perceptions of maize diseases, pests, and other production constraints, their implications for maize breeding and evaluation of local maize cultivars in KwaZulu-Natal, South Africa, *African Journal of Agricultural Research*, vol. 8, no. 17, pp. 1790-1798.

Sihlobo, W. (2018). A brief history of South Africa's maize production, *Agricultural Economics Today,* viewed 31 August 2020, https://wandilesihlobo.com/2018/12/01/a-brief-history-of-south-africas-maize-production/

Singh, H.B. (2014). Management of plant pathogens with microorganisms, *Proceedings of the Indian National Science Academy*, vol. 80, no. 2, pp. 443-454.

Singh, S., Jagadamma, S., Yoder, D., Yin, X., & Walker F. (2020). Agroecosystem management responses to Haney soil health test in the southeastern United States, *Soil Science Society of America Journal*, vol. 84, pp. 1705-1721.

Sinyolo, S. (2020). Technology adoption and household food security among rural households in South Africa: The role of improved maize varieties, *Technology in Society*, vol. 60, pp. 1-10.

Sinyolo, S., & Mudhara, M. (2018). Collective action and rural poverty reduction: Empirical evidence from KwaZulu-Natal, South Africa, *Agrekon,* vol. 57, no. 1, pp. 78-90.

Sitthaphanit, S., Limpinuntana, V., Toomsan, B., Panchaban, S., & Bell, R.W. (2009). Fertiliser strategies for improved nutrient use efficiency on sandy soils in high rainfall regimes, *Nutrient Cycling in Agroecosystems,* vol. 85, pp. 123-139.

Siziba, S., Nyikahadzoi, K., Makate, C., & Mango, N. (2019). Impact of conservation agriculture on maize yield and food security: Evidence from smallholder farmers in Zimbabwe, *African Journal of Agricultural and Resource Economics,* vol. 14, no. 2, pp. 89-105.

Smale, M., & Jayne, T.S. (2003). *Maize in Eastern and Southern Africa: "Seeds" of success in retrospect*, Environment and Production Technology Division (EPTD) discussion paper: 97, International Food Policy Research Institute, Washington.

Smit, E.H., Strauss, J.A., & Swanepoel, P.A. (2021). Utilisation of cover crops: Implications for conservation agriculture systems in a mediterranean climate region of South Africa, *Plant and Soil,* vol. 462, pp. 207-218.

Smith, H.J., Nel, A.A., & Trytsman, G. (2019). *Farmer innovations in Conservation Agriculture (CA) systems for sustainable crop intensification in semi-arid, sandy soil conditions, North West Province*, Progress report*,* Maize Trust, Pretoria.

Soil Health Solutions. (2021). Results of the Haney soil health test for Christinasrus.

Soto, A.L., Culman, S.W., Herms, C., Sprunger, C., & Doohan, D. (2023). Managing soil acidity vs. soil Ca: Mg ratio: What is more important for crop productivity? *Crop, Forage and Turfgrass Management*, pp. 1-10.

Soudien, C., Reddy, V. & Harvey, J. (2022). 'The impact of COVID-19 on a fragile education system: The case of South Africa', in F Reimers (ed.), *Primary and secondary education during COVID-19: Disruptions to educational opportunity during a pandemic*, Springer, Switzerland, pp. 303-325.

South African Grain Laboratories (SAGL). (2020a). *Quality report 2019/2020: South African maize crop,* SAGL, City of Tshwane.

South African Grain Laboratories (SAGL). (2020b). Results of the nutritional analysis for Christinasrus.

South African Grain Laboratory (SAGL). (2021). *Quality report 2020/2021: South African maize crop,* SAGL, City of Tshwane.

South African Herbicide Resistance Initiative (SAHRI). (2022). Important weeds in maize, *University of Pretoria*, viewed 25 July 2022, https://www.up.ac.za/sahri/article/1810372/important-weeds-in-maize

Spoljar, A., Kisic, I., Birkas, M., Kvaternjak, I., Marencic, D., & Orehovacki, V. (2009). Influence of tillage on soil properties, yield and protein content in maize and soybean grain, *Journal of Environmental Protection and Ecology,* vol. 10, no. 4, pp. 1013-1031.

Standard Bank. (2015). The agricultural sector in South Africa – opportunities, challenges and legislation, viewed 3 September 2020, https://bizconnect.standardbank.co.za/sector-news/agriculturearticles/reference-documents/the-agricultural-sector-in-south-africa-%E2%80%93-opportunities,-challenges-and-legislation.aspx

Stanger, T., Lauer, J., & Chavas, J. (2008). Long-term cropping systems: The profitability and risk of cropping systems featuring different rotations and nitrogen rates, *Agronomy Journal,* vol. 100, pp. 105-113.

Strauss, J.A., Swanepoel, P.A., Laker, M.C., & Smith, H.J. (2021). Conservation agriculture in rainfed annual crop production in South Africa, *South African Journal of Plant and Soil,* vol. 38, no. 3, pp. 217-230.

Strawser, P. (2014). Black cutworm damage, *The Ohio State University*, viewed 25 July 2022, https://u.osu.edu/wayneipm/2014/06/13/black-cutworm-damage/

Sundermeier, A., Shedekar V., & Lijun, C. (2023). Soil aggregate stability: A soil health physical indicator, *The Ohio State University*, viewed 31 May 2023, https://soilhealth.osu.edu/sites/soilhealth/files/imce/WhitePapers/Soil%20Aggregate%20Stability.pdf

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F., Kamdonyo, D., & Muchinda, M. (2009). Growing-season rainfall and scenarios of future change in southeast Africa: Implications for cultivating maize, *Climate Research,* vol. 40, no. 2-3, pp. 147-161.

Takahashi, H., Yamauchi, T., Colmer, T., & Nakazono, M. (2014). ‘Aerenchyma formation in plants’, in P Nick (ed.), *Plant Cell Monographs*, Springer, Germany, pp. 247-265.

Tanveer, A., Ikram, R.M., & Ali, H.H. (2019). ‘Crop rotation: Principles and practices’, in M Hasanuzzaman (ed.), *Agronomic Crops: Volume 2: Management Practices*, pp. 1-12.

Tenaillon, M.I., & Charcosset, A. (2011). A European perspective on maize history, *Comptes Rendus Biologies*, vol. 334, no. 3, pp. 221-228.

Tesfay, A., Amin, M., & Mulugeta, N. (2014). Management of weeds in maize (*Zea mays* L.) through various pre and post emergency herbicides, *Advances in Crop Science and Technology*, vol. 2, no. 5, pp. 1-5.

Tesfaye, K., Kruseman, G., Cairns, J.E., Zaman-Allah, M., Wegary, D., Zaidi, P.H., Boote, K.J., & Erenstein, O. (2018). Potential benefits of drought and heat tolerance for adapting maize to climate change in tropical environments, *Climate Risk Management,* vol. 19, pp. 106-119.

Thierfelder, C., Paterson, E., Mwafulirwa, L., Daniell, T.J., Cairns, J.E., Mhlanga, B., & Baggs, E.M. (2022). Toward greater sustainability: How investing in soil health may enhance maize productivity in Southern Africa, *Renewable Agriculture and Food Systems,* vol. 37, no. 2, pp. 166-177.

Turner, B.L., Yavitt, J.B., Harms, K.E., Garcia, M.N., & Wright, S.J. (2015). Seasonal changes in soil organic matter after a decade of nutrient addition in a lowland tropical forest, *Biogeochemistry*, vol. 123, pp. 221-235.

Umar, M., Kassim, K.A., & Chiet, K.T.P. (2016). Biological process of soil improvement in civil engineering: A review, *Journal of Rock Mechanics and Geotechnical Engineering,* vol. 8, no. 5, pp. 767-774.

United Nations (UN). (2020). Sustainable development goals, viewed 3 September 2020, https://www.un.org/sustainabledevelopment/

United States Agency International Development (USAID). (2007*). The organization and development of farmer groups for agroenterprise: Conclusions from a CRS & RII-CIAT Study Tour in Asia, Africa and Latin America,* CRS Internal Working Paper, Balitmore.

Vaezi, A.R., Ahmadi, M., & Cerdà, A. (2017). Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls, *Science of the Total Environment,* vol. 583, pp. 382-392.

Van Den Berg, J., Prasanna, B.M., Midega, C.A., Ronald, P.C., Carrière, Y., & Tabashnik, B.E. (2021). Managing fall armyworm in Africa: Can Bt maize sustainably improve control? *Journal of Economic Entomology,* vol. 114, no. 5, pp. 1934-1949.

Van Der Linde, K. (2023). Productivity growth in the South African soybean industry: 2001-2021, masters thesis, Stellenbosch University, Stellenbosch.

Van Der Westhuizen, D., & Otterman H. (2021). Rising agricultural input costs, a growing concern for crop producer, *Bureau for Food and Agricultural Policy,* viewed 15 September 2022, https://old.bfap.co.za/wp-content/uploads/2021/12/Rising-input-costs-2021.pdf

Van Griethuijsen, R.A., Van Eijck, M.W., Haste, H., Den Brok, P.J., Skinner, N.C., Mansour, N., Savran Gencer, A., & BouJaoude, S. (2015). Global patterns in students' views of science and interest in science, *Research in Science Education*, vol. 45, pp. 581-603.

Van Niekerk, J.A., Von Maltitz, L. & Davis, K. (2022). Investigating process skills and competency gaps in undergraduate agricultural extension curriculum in selected South African Universities, *South African Journal of Agricultural Extension*, vol. 50, no. 2, pp. 57-80.

Van Zyl, F.J. (2016). Quantifying root growth dynamics and nutrient uptake in apple trees, doctoral thesis, Stellenbosch, Stellenbosch University.

Vos, H.C., Karst, I.G., Eckardt, F.D., Fister, W., & Kuhn, N.J. (2022). Influence of crop and land management on wind erosion from sandy soils in dryland agriculture, *Agronomy,* vol. 12, no. 2, pp. 457-475.

Wang, G., Kang, M.S., & Moreno, O. (1999). Genetic analyses of grain-filling rate and duration in maize, *Field Crops Research*, vol. 61, no. 3, pp. 211-222.

Wang, P., Xie, W., Ding, L., Zhuo, Y., Gao, Y., Li, J., & Zhao, L. (2023). Effects of maize–crop rotation on soil physicochemical properties, enzyme activities, microbial biomass and microbial community structure in southwest China, *Microorganisms*, vol. 11, no. 11, pp. 2621-2640.

Ward Laboratories. (2019). Haney test interpretation guide v1.0, viewed 17 July 2021, https://www.wardlab.com/wp-content/uploads/2019/09/Haney-Rev-1.0-Interpretation-Guide.pdf

Ward, J.M., Stromberg, E.L., Nowell, D.C., & Nutter Jr, F.W. (1999). Gray leaf spot: A disease of global importance in maize production, *Plant Disease*, vol. 83, no. 10, pp. 884-895.

Wei, X., Long, Y., Yi, C., Pu, A., Hou, Q., Liu, C., Jiang, Y., Wu, S., & Wan, X. (2023). Bibliometric analysis of functional crops and nutritional quality: Identification of gene resources to improve nutritional quality through gene editing technology, *Nutrients*, vol. 15, pp. 373-397.

Weisskopf, P., Meister, E., Ammon, H.U., Mediavilla, M., Malitius, T., Anken, T., & Sidler, A. (1995). Maize-dominated crop rotation: Integrated and intensive managements, *Agroscope*, vol. 2, no. 6, pp. 240-243.

Welz, H.G., & Geiger, H.H. (2000). Genes for resistance to northern corn leaf blight in diverse maize populations, *Plant Breeding*, vol. 119, no. 1, pp. 1-14.

Wen, W., Gu, S., Xiao, B., Wang, C., Wang, J., Ma, L., Wang, Y., Lu, X., Yu, Z., Zhang, Y., & Du, J. (2019). In situ evaluation of stalk lodging resistance for different maize (*Zea mays L.*) cultivars using a mobile wind machine, *Plant Methods,* vol. 15, no. 1, pp. 1-16.

Wu, F., & Guclu, H. (2013). Global maize trade and food security: Implications from a social network model, *Risk Analysis*, vol. 33, no. 12, pp. 2168-2178.

Xaba, B., & Masuku, M. (2013). Factors affecting the productivity and profitability of vegetables production in Swaziland, *Journal of Agricultural Studies*, vol. 1, no. 2, pp. 37-52.

Xue, J., Ming, B., Xie, R., Wang, K., Hou, P., & Li, S. (2020). Evaluation of maize lodging resistance based on the critical wind speed of stalk breaking during the late growth stage, *Plant Methods,* vol. 16, no. 1, pp. 1-12.

Xue-jun, C., Guang-cai, C., Qun, S., Dong-bin, W., Jing, C., Ya-xiong, Y.U., Jie, L., & Wei, L. (2013). Altitude effects on maize growth period and quality traits, *Acta Ecologica Sinica,* vol. 33, no. 4, pp. 233-236.

Yang, Y.S., Guo, X.X., Liu, H.F., Liu, G.Z., Liu, W.M., Bo, M.I.N.G., Xie, R.Z., Wang, K.R., Peng, H.O.U., & Li, S.K. (2021). The effect of solar radiation change on the maize yield gap from the perspectives of dry matter accumulation and distribution, *Journal of Integrative Agriculture,* vol. 20, no. 2, pp. 482-493.

Yang, Y., Xu, W., Hou, P., Liu, G., Liu, W., Wang, Y., Zhao, R., Ming, B., Xie, R., Wang, K., & Li, S. (2019). Improving maize grain yield by matching maize growth and solar radiation, *Scientific Reports,* vol. 9, no. 1, pp. 1-11.

Zampieri, M., Ceglar, A., Dentener, F., Dosio, A., Naumann, G., Van Den Berg, M., & Toreti, A. (2019). When will current climate extremes affecting maize production become the norm? *Earth's Future,* vol. 7, no. 2, pp. 113-122.

Zhang, L., Zhu, J., Zhang, Y., Xia, K., Yang, Y., Wang, H., Li, Q., & Cui, J. (2024). Maize, peanut, and millet rotations improve crop yields by altering the microbial community and chemistry of sandy saline–alkaline soils, *Plants*, vol. 13, no. 15, pp. 2170-2191.

Zhao, N., Ma, J., Wu, L., Li, X., Xu, H., Zhang, J., Wang, X., Wang, Y., Bai, L., & Wang, Z. (2024). Effect of organic manure on crop yield, soil properties, and economic benefit in wheat-maize-sunflower rotation system, Hetao Irrigation District, *Plants*, vol. 13, no. 16, pp. 2250-2261.

Zhao, W., Liu, B., & Zhang, Z. (2010). Water requirements of maize in the middle Heihe River basin, China, *Agricultural Water Management,* vol. 97, no. 2, pp. 215-223.

Appendices

Appendix A:	Farmers questionnaire: Crop diversity for sustainable agriculture in the North-Western Free State
Appendix B:	Research outputs

Appendix A

UFS·UV
UNIVERSITY OF THE FREE STATE
UNIVERSITEIT VAN DIE VRYSTAAT
YUNIVESITHI YA FREISTATA

FACULTY OF NATURAL AND AGRICULTURAL SCIENCES (UFS)
FAKULTEIT NATUUR- EN LANDBOUWETENSKAPPE (UV)

SUSTAINABLE FOOD SYSTEMS AND DEVELOPMENT
VOLHOUBARE VOEDSELSTELSELS EN -ONTWIKKELING

Doctor of Philosophy majoring in Sustainable Agriculture

QUESTIONNAIRE
VRAELYS

CROP DIVERSITY FOR SUSTAINABLE AGRICULTURE IN THE NORTH-WESTERN FREE STATE

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INFORMATION LEAFLET / *INLIGTINGSBLAD*

I, Melanie de Bruyn (PhD candidate at the UFS), am the primary researcher involved in this project. This questionnaire forms part of a larger study that investigates crop diversity as a proposed method of sustainable agriculture. The purpose of the questionnaire is to determine the views and perspectives of North-Western Free State farmers on crop diversification. Farmers in the area will be approached personally by the researcher at farmer gatherings and/ or visitations.

There are three sections to the questionnaire:
Section A: Demographic information
Section B: Farm information
Section C: Crop diversification

- The questionnaire should not take you more than 10 minutes to complete
- Research Ethics Committee of UFS, Record number: UFS-HSD2022/0242
- Your participation is voluntary, you are under no obligation to consent to participation
  (You will not be able to withdraw the questionnaire once it has been submitted)
- Your responses will be treated with the highest level of confidentiality
- Your name will not be recorded
  (Questionnaires will be given fictitious codes)
- Data used for research outputs (published articles, conference proceedings etc) will remain anonymous
- Hard copies of your answers will be stored by the researcher for five years in a locked cupboard for future research or academic purposes; electronic information will be stored on a password protected computer
- You will not receive compensation for taking part in this study
- If you would like to be informed of the final research findings, please contact the researcher

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Ek, Melanie de Bruyn (PhD-kandidaat aan die UV), is die primêre navorser wat by hierdie projek betrokke is. Hierdie vraelys is deel van 'n groter studie wat wisselbou as 'n voorgestelde metode van volhoubare landbou ondersoek. Die doel van die vraelys is om die sienings en perspektiewe van Noord Wes Vrystaatse boere op wisselbou te bepaal. Boere in die omgewing sal persoonlik deur die navorser genader word by boerebyeenkomste en/ of besoeke.

Daar is drie afdelings aan die vraelys:
Afdeling A: Demografiese inligting
Afdeling B: Plaasinligting
Afdeling C: Wisselbou

- *Die vraelys behoort u nie langer as 10 minute te vat om te voltooi nie*
- *Navorsingsetiekkomitee van die UV, Rekord nommer: UFS-HSD2022/0242*
- *U deelname is vrywillig, u is onder geen verpligting om in te stem tot deelname nie*
  (Vraelyste wat ingedien is kan nie terug getrek word nie)
- *Inligting wat u verskaf, sal met die hoogste mate van vertroulikheid hanteer word*
- *U naam sal nie aangeteken word nie*
  (Vraelyste word kodes gegee)
- *Data wat gebruik word vir navorsingsuitsette (gepubliseerde artikels, konferensieverrigtinge ens.) sal anoniem bly*
- *Harde afskrifte van u antwoorde sal vir vyf jaar deur die navorser gestoor word in 'n geslote kas vir toekomstige navorsing of akademiese doeleindes; elektroniese inligting sal op 'n wagwoordbeskermde rekenaar gestoor word*
- *U sal geen vergoeding vir deelname aan hierdie studie ontvang nie*
- *As u in kennis gestel wil word van die finale navorsingsbevindinge, kontak asseblief die navorser*

I have read the information leaflet and agree to take part in the aforementioned study
Ek het die inligtingsblad gelees en stem in om aan die bogenoemde studie deel te neem

NB!!

Participant consent (signature):
Deelnemer toestemming (handtekening)…………………………………………………………………………

SECTION A: DEMOGRAPHIC INFORMATION

AFDELING A: DEMOGRAFIESE INLIGTING

Please answer the following questions by ticking the appropriate box or providing written responses were required

Beantwoord asseblief die volgende vrae deur die toepaslike blokkie te merk of (waar nodig) skriftelike antwoorde te verskaf

1. What is your gender?
   Wat is jou geslag?

Male *Manlik*		0
Female *Vroulik*		1

2. What is your marital status?
   Wat is jou huwelikstatus?

Single *Enkelloppend*		1
Married *Getroud*		2
Divorced *Geskei*		3
Widowed *Weduwee*		4

3. What is your current age?
   Wat is jou huidige ouderdom?

18-20 years *18-20 jaar*		1
21-30 years *21-30 jaar*		2
31-40 years *31-40 jaar*		3
41-50 years *41-50 jaar*		4
51-60 years *51-60 jaar*		5
Older than 60 years *Ouer as 60 jaar*		6

4. What is your highest level of education?
Wat is jou hoogste vlak van opvoeding?

Grade 12 *Graad 12*		1
Diploma/ Degree *Diploma/ Graad*		2
Post graduate degree *Nagraadse graad*		3

5. How long have you been farming?
Hoe lank boer jy?

Less than 5 years *Minder as 5 jaar*		1
5-10 years *5-10 jaar*		2
11-15 years *11-15 jaar*		3
More than 15 years *Meer as 15 jaar*		4

6. Are you part of a farmer’s study group?
Is jy ‘n lid van ‘n boere studiegroup?

Yes *Ja*		1
No *Nee*		2

SECTION B: FARM INFORMATION

AFDELING B: PLAASINLIGTING

Please answer the following questions by ticking the appropriate box or providing written responses were required

Beantwoord asseblief die volgende vrae deur die toepaslike blokkie te merk of (waar nodig) skriftelike antwoorde te verskaf

1. In what area do you farm?
In watter gebied boer jy?

North-Western Free State *Noordwes Vrystaat* (Bothaville, Bultfontein, Hoopstad, Wesselsbron)		1
Other (specify) *Ander (spesifiseer)*………………………………		2

2. Farm ownership:
Plaaseienaarskap:

I own AND rent the land I farm *Ek besit EN huur die grond wat ek bewerk*		1
I own the land I farm (don’t rent) *Ek besit die grond wat ek bewerk (huur nie)*		2
I rent the land I farm (don’t own) *Ek huur die grond wat ek bewerk (besit nie)*		3
I manage the farm *Ek bestuur die plaas*		4
Other (specify) *Ander (spesifiseer)*………………………………		5

3. How many people are employed on the farm?
Hoeveel mense werk op die plaas?

…………………………………employees/ *werknemers*

4. What is the size of the farm (ha)?
Wat is die grootte van die plaas (ha)?

…………………………..ha

5. How much of the land is cultivated (ha)?
Hoeveel van die grond word bewerk (ha)?

………………………..ha

6. Please indicate the percentage of each crop cultivated (please specify any crops not mentioned):
Dui asseblief die persentasie van elke gewas wat geplant word, aan (spesifiseer asseblief enige gewasse wat nie genoem word nie):

Crop ***Gewas***	**Example** ***Voorbeeld***	**Your response** ***Jou antwoord***
Maize/ *Mielies*	70%	
Sunflowers/ *Sonneblomme*	15%	
Soya beans/ *Sojabone*	5%	
Wheat/ *Koring*	10%	
Cover crop/ *Dekgewas*	-	
Other/ *Ander*………………………………………	-	
Other/ *Ander*……………………………………...	-	
Other/ *Ander*………………………………………	-	
Total/ *Totaal*	100%	100%

SECTION C: CROP DIVERSIFICATION

AFDELING C: WISSELBOU

Please answer the following questions by ticking the appropriate box or providing written responses were required

Beantwoord asseblief die volgende vrae deur die toepaslike blokkie te merk of (waar nodig) skriftelike antwoorde te verskaf

1. Please rate the **relevance** of crop diversification on a scale of 0-5 (0 = no relevance, 5 = very relevant) with regards to the table below:
   *Beoordeel asseblief die **toepaslikheid** van wisselbou op 'n skaal van 0-5 (0 = geen toepassing, 5 = baie toepassing) met betrekking tot die tabel hieronder:*

	Relevance/ *Toepassing*					
	No relevance---Very relevant *Geen toepassing-------------------------------------Baie toepassing*					
Yield increase *Opbrengsverhoging*	0	1	2	3	4	5
Increased farm profit *Verhoogde plaaswins*	0	1	2	3	4	5
Improved soil health *Verbeterde grondgesondheid*	0	1	2	3	4	5
Better grain quality/ grading *Beter graan kwaliteit / gradering*	0	1	2	3	4	5
Lower financial risk *Laer finansiële risiko*	0	1	2	3	4	5

2. Do you rotate your crops?
   Wissel jy jou gewasse?

Yes *Ja*		1
No *Nee*		2

2a. If you **do not** rotate your crops, please provide your reason:
*Indien jy **nie** jou gewasse wissel nie, gee asseblief jou rede:*

Because/ *want:*

2b. If you **do** rotate your crops:
*Indien jy **wel** jou gewasse wissel:*

i. Which crops do you rotate and in what sort of system?
Watter gewasse wissel jy en in watter soort stelsel?

Example/ *Voorbeeld*: Maize-Soya-Maize

ii. Which of the following applies to your farm?
Watter van die volgende is van toepassing op jou plaas?

	Importance/ *Belangrikheid*		
	Not so important *Nie so belangrik*	Important *Belangrik*	Very important *Baie belangrik*
I follow a fixed rotational system *Ek volg 'n vaste rotasiestelsel*	1	2	3
I adjust my rotational system according to the economy/ grain price *Ek pas die rotasiestelsel aan volgens die ekonomie/ graanprys*	1	2	3
Soil health and sustainability play a role in my choice of crops *Grondgesondheid en volhoubaarheid speel 'n rol in my keuse van gewasse*	1	2	3
I adjust my rotational system according to the weather (rainfall) predictions *Ek pas my rotasiestelsel aan volgens die weer (reënval) voorspellings*	1	2	3

iii. What results are you **experiencing** with regards to the table below?
*Watter resultate **ervaar** jy met betrekking tot die tabel hieronder?*

	What do you experience? *Wat ervaar jy?*			
	1	2	3	4
	Decrease *Verminder*	Increase *Verhoog*	Nothing *Niks*	Not sure *Nie seker*
Effect on yield *Effek op opbrengs*				
Effect on farm profit *Effek op plaaswins*				
Effect on soil health *Effek op grondgesondheid*				
Effect on grain quality / grading Effek op *graan kwaliteit / gradering*				
Effect on financial risk *Effek op finansiële risiko*				

iv. Where do you get your technical information or guidance regarding crops and crop rotation?
Waar kry jy jou tegniese inligting of voorleiding oor gewasse en wisselbou?

	Importance/ *Belangrikheid*		
	Not so important *Nie so belangrik*	Important *Belangrik*	Very important *Baie belangrik*
Company representatives *Maatskappy veteenwoordiger*	1	2	3
Magazines *Tydskrifte*	1	2	3
Internet *Internet*	1	2	3
Fellow farmers (mentor farmers) *Medeboere (leierboere)*	1	2	3
Farmer days *Boeredae*	1	2	3
I follow my own head *Ek volg my eie kop*	1	2	3

3. Any additional comment/s regarding your view on crop diversity:
Enige bykomende opmerking/s met betrekking tot jou siening oor wisselbou:

Thank you for you participation / ***Dankie vir u deelname***

Appendix B

Research outputs:

de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2022). Views and perspectives of local farmers on crop diversification in the North-Western Free State, South Africa, *African Journal of Agricultural Research*, vol. 18, no. 11, pp. 1006-1012. DOI: 10.5897/ajar2022.16150

de Bruyn, M., & Nel, A. (2022). A shift towards crop rotation is a positive sign, *SA Grain*, Sep 2022, 80-81. Available at https://sagrainmag.co.za/2022/09/06/shift-towards-crop-rotation-is-a-positive-sign/

de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). Production and profitability of maize and soybean grown in rotation in the Norh-Western Free State, South Africa, *African Journal of Agricultural Research*, vol. 20, no. 2, pp. 155-162. DOI: 10.5897/AJAR2023.16568

de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). The effect of crop rotation on agricultural sustainability in the North-Western Free State, South Africa, *African Journal of Sustainable Agricultural Development,* vol. 5, no. 2, pp. 32-45. ISSN: 2714-4402

de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). The effect of crop rotation on soil health in the north-western Free State region, South African, *South African Journal of Plant and Soil,* vol. 40, no. 4-5, pp. 1-8. DOI: 10.1080/02571862.2023.2282504

de Bruyn, M.A., Nel, A.A., & van Niekerk, J.A. (2024). The nutritional benefits of maize-soybean rotational systems in the North-Western Free State, South Africa, *Agriculture and Food Security*, vol. 13, no. 20, pp. 1-7. DOI: 10.1186/s40066-024-00473-5