Commercial maize farmers' adaptations to climate change in Sannieshof, North West Province, South Africa

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Declaration

I Benjamin Graham Dunn declare that this Research Report is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signature of candidate: 

Date: 15th of May 2024

Abstract

Commercial agriculture is a critical industry for South Africa, both from an economic and a social perspective. Maize forms a vital part of the diet of millions of people across the country and the continent of Africa. It is also an important commercial export crop. It is, therefore, imperative that the industry can adapt to both climate and socioeconomic changes. This study aims to investigate the specific challenges faced by commercial maize farmers in the Sannieshof region, North West Province, South Africa, in relation to climate change and socioeconomic factors. This study undertook questionnaires with 21 commercial maize farmers in the region, followed up by field observations and photographs from one large commercial maize farm. Several socioeconomic factors were identified by participants as having negative impacts on farming operations, including government policies, crime, and load shedding. Climate change adaptation includes several dynamic management practices which vary between seasons, including adjustments in cultivar choice, sowing dates, sowing depth, and plant population density. Adopting conservation agriculture and precision agriculture techniques forms an important element used by the farmers to achieve long-term climate change adaptation. Going forward, farmers need to consider the impacts of both climate change and socioeconomic factors, both of which impact their agricultural operation and which can be conceptualised through a Water-Energy-Food nexus framework. Due to limited financial resources, farmers need to consider which drivers of change need to be prioritised in their decision-making, which ultimately may create differences in adaptation strategies adopted by different farmers.

Keywords: Commercial maize agriculture; Conservation agriculture; Precision agriculture; Climate change adaptation

Contents

List of Figures:

List of Tables:

1. Introduction

1.1. Background

Maize forms a significant part in the diets of millions of people across the world and is the leading global staple cereal, with an annual production of over 1 billion metric tons (García-Lara & Serna-Saldivar, 2019). Within the context of South Africa, maize is an essential part of the staple diet of the majority of low-income households and is considered the most important staple food and subsistence crop for maintaining food security (Diko & Jun, 2020; Bradshaw *et al.*, 2022). Global trends in the production of maize yields have shown steadily increasing production since 1961 and this is expected to continue into the future as food demands increase (Shiferaw *et al*., 2011). Maize is a multi-purpose crop, with a variety of applications beyond just the production for human consumption, as it is also used for the production of animal feed and biofuel (Erenstein *et al*., 2022). In developed countries, maize is predominately used for animal feed and as countries begin to make progress with regard to economic development, there is a simultaneous increase in the demand for animal-sourced products. This places a greater demand for maize production to support these markets, an example of which is the increase in demand for animal feed throughout Asia (Erenstein *et al.*, 2022). The variety of applications for maize highlights its importance within the global agri-food system and in the goal of achieving food security (Shiferaw *et al*., 2011; Erenstein *et al*., 2022). In South Africa, maize is the staple crop produced, and commercial maize farmers are responsible for almost all the maize produced, with subsistence maize farmers accounting for less than 1% of total annual maize production (Meyer *et al*., 2019).

During the year 2020, South Africa was the 9th largest maize-producing country in the world, with three major commercial maize-producing provinces accounting for approximately 84% of the total maize produced during the 2020/2021 season, being the Free State, Mpumalanga, and North West Province (The Southern Africa Grain Laboratory NPC, 2022; Bradshaw *et al*., 2022). This region of commercial maize production is commonly referred to as the 'maize belt' of South Africa. While maize is produced throughout South Africa, it is concentrated across the Free State, Mpumalanga and North West, largely due to favourable climatic conditions as well as historical developments of the industry (Greyling *et al*., 2018). The discovery of gold and diamonds towards the end of the 19th century created favourable markets to produce maize in this maize belt, where a large proportion of mining operations were located (Greyling *et al*., 2018). Towards the middle of the 20^{th} century, the political economy of South Africa heavily favoured the commercial maize industry, supporting the development on the sector across the maize belt through public investment and policy implementation (Greyling & Pardey, 2019). During this period, commercial maize farmers were limited in their ability to market their yields due to the strong state regulation of the maize market, however they benefited from the economic stability associated with this market regulation (Brits, 1969). During the 1980s, the South African government began to reduce its influence on the commercial agriculture sector and dismantled its commodity marketing scheme (Greyling & Pardey, 2019). This state involvement within the industry protected the sector and allowed for its development. In the current political climate, there is substantially less government involvement within the industry and subsequently the sector bears the brunt of socioeconomic and climate impacts (Greyling & Pardey, 2019).

Commercial maize agriculture is impacted by a diverse range of climate and socioeconomic elements. Changes in either can result in disruptions throughout crop production season as well as the broader circular economy of maize. For example, socioeconomic and climate factors which the agricultural sector faces can be seen through flooding which occurred as a result of excessive rainfall between November 2021 and January 2022, in the western Free State and parts of the North West. This caused significant loss of maize in these regions (Coleman, 2022). It is expected that the frequency of climate extremes will increase as temperatures continue to rise and rainfall patterns become more varied (Mangani *et al.*, 2019; Nhemachena *et al.*, 2020). These climatic changes will place traditional maize agricultural cropping systems under greater pressure to maintain yields, placing a greater emphasis on the need for adaptation (Bradshaw *et al.*, 2022). Furthermore, socioeconomic factors such as the impacts of power cuts in the form of load shedding have placed the industry under more financial pressure. This forces farmers to either pump irrigation water using generators or to pump water during peak times at an increased utility price (Hlomendlini, 2023; Majola, 2023; Sihlobo, 2023). The operating cost for use of heavy machinery such as tractors and combine harvesters which are used in commercial maize agriculture has become significantly more expensive through increased fuel prices (Ayo & Odhiambo, 2021). The market stability for agricultural inputs such as fertilisers and agrochemicals are also factors which can negatively impact crop production.

1.2. Problem Statement

Commercial maize production forms a critical part of South Africa's economy and aids significantly in the country's efforts to maintain food security, both locally and regionally. During the year 2020, almost all the maize imported by Namibia and Botswana was produced in South Africa (Bradshaw *et al*., 2022). Commercial maize agriculture is influenced heavily by climate conditions as well as socioeconomic factors, such as increases in fuel, utility, fertiliser costs, as well as global trade networks and political decisions. Severe drought due to El Niño weather patterns during the 2015/2016 growing season resulted in substantial yield reductions of maize crops across southern Africa. In South Africa this resulted in national yield decreases of 16% decrease in 2015 and a 38% decrease in 2016 (Ainembabazi *et al*., 2018; The Southern Africa Grain Laboratory NPC, 2022). As highlighted by Ainembabazi *et al*. (2018) yield reductions heavily influence the price of maize which increased across the region between 2015 and 2018, placing pressure on consumers. The price of maize increased by 22% in South Africa during the year of 2016 when compared to a five-year average. As highlighted by Bradshaw *et al*. (2022) maize is one of the most important crops in the country and it is imperative that environmental and socioeconomic resilience is achieved in order to protect the industry. The rising production costs continues, to place farmers under strain with the economic viability of production becoming more challenging particularly as climatic conditions continue to change (Smith *et al.*, 2021). The selection of the Sannieshof region for this study is due to its rural and relatively isolated position when compared to larger agricultural towns in the region. The region of Sannieshof has been overlooked in previous research efforts in favour of more prominent agricultural regions such as Ottosdal and Lichtenburg. This study seeks to contribute to the understanding of the specific challenges faced by commercial maize farmers in Sannieshof region, North West Province, South Africa, and how management practices are being developed at the farm level in response to changing climates and socioeconomic pressures. These challenges may include maintaining crop and soil quality in drier conditions; managing agricultural inputs such as fuel, fertiliser, and agrochemicals with unstable markets; and maintaining profitable crop yields. The varied adaptation strategies undertaken by farmers are important to understand in order to help maintain food security both locally and regionally, as well as recognising the importance of commercial maize production in supporting local economies through employment.

1.3. Aim and Objectives

Aim

The aim of this study is to understand the specific challenges relating to climate change and socioeconomic factors faced by commercial maize farmers in Sannieshof region, North West Province, South Africa.

Objectives

The objectives of the study are to:

1. Critically examine what the management practices of commercial maize farmers in Sannieshof region are and how and why these have developed.
2. Assess to what extent socioeconomic and climatic factors influence farmers' decision-making related to climate change adaptation, in relation to maize cultivation, resource management and seasonal planning in the Sannieshof region.
3. Assess the perceptions of farmers towards conservation and precision agriculture, as well as how these practices are manifested at the farm level.

2. Literature Review

2.1. Introduction

A wide range of studies have focused on the impacts of climate change on agricultural systems in sub-Saharan Africa (Fischer *et al.*, 2005; Benhin, 2006; Ainembabazi *et al*., 2018; Diko & Jun, 2020; Bradshaw *et al.*, 2022). These studies have often looked at the potential adaptations of agriculture to climate change, as well as the socioeconomic factors which may influence the decisions relating to adaptation strategies undertaken by different types of farmers in different situations (e.g. Benhin, 2006; Ainembabazi *et al*., 2018; Diko & Jun, 2020; Bradshaw *et al.*, 2022). However, a large portion of these studies have focused on smallholder and subsistence farmers, with commercial agricultural systems often receiving less attention (Stuch *et al.*, 2021; Thinda *et al.*, 2021; Bogale & Bekele, 2023). This literature review concentrates on commercial grain agriculture, with a focus specifically on maize. The purpose of the literature review is to gain an understanding of the broader context of previous research surrounding commercial maize agriculture, in order to provide a basis for understanding the challenges that commercial maize farmers in North West Province currently face.

2.2. Brief historical overview of maize agriculture in South Africa

Maize production has been a part of South African farming since the 19th century when it was originally cultivated by small-scale subsistence farmers (Greyling & Pardey, 2019). The discovery of diamonds and gold towards the end of the 19th century created the first shift in the production of maize, pushing it away from cultivation for subsistence to commercial farming, as a result of markets created by the mining industry (Greyling & Pardey, 2019). During the early 20th century, the cultivated area of maize continually increased in South Africa and this rapidly accelerated from around the mid-1930s due to the adoption of tractors and agricultural machinery, which inevitably led to the development of the conventional maize faming system predominately utilised in South Africa today (Meyer *et al.*, 2018; Greyling & Pardey, 2019). In the wider region surrounding Sannieshof, it was noted that few farmers made use of combine harvesters in 1966 and the adoption of this technology became more prevalent from 1970 onwards (De Klerk, 1983). The export of maize added significantly to the South African economy up until 1981 when a combination of drought and macro-economic variables significantly reduced the profitability of commercial maize agriculture (Van Zyl & Nel, 1988). The export of maize remains a cornerstone for the commercial maize industry with neighbouring states continuing to remain heavily dependent on South African maize production to maintain food security (The Southern African Grain Laboratory NPC, 2022; Bradshaw *et al*., 2022). Recent changes in the commercial price of maize have given South African maize exporters an edge over global competition and this was followed up by a record-breaking export for the South Africa market to China, with a total of 108 104 tonnes of yellow feed maize shipped in May 2023 (Banya, 2023). While this amount may not be significant within the broader context of South African maize exports, which average at around 3 million tonnes per annum, there is optimism surrounding the potential development of a continued trade agreement into the world's largest maize market (Banya, 2023). The development of this continued trade agreement may significantly benefit commercial maize farmers through the continued opportunity to export their crops.

The combination of climate and socioeconomic factors has been a recurring theme which has negatively impacted the yield outputs and financial stability of the commercial maize industry throughout South Africa's history (Brits, 1969; Van Zyl & Nel, 1988; Ainembabazi *et al*., 2018; Greyling & Pardey, 2019). While rainfall trends remain variable, there is evidence to suggest that increased duration of dry spells in the future will impact South Africa, with fewer days of rain set to be received, as well as higher intensity of rainfall events (Smith *et al.*, 2021). As highlighted by Engelbrecht *et al.* (2015), it can be expected that South Africa will experience a greater frequency of heatwaves, impacts of El Niño events as well an increased frequency of droughts which will significantly impact dryland agriculture across South Africa. Furthermore, the continued rise of input and overhead costs is placing greater economic pressure on the viability of current crop producers' agricultural practices across South Africa (Smith *et al.,* 2021). The pressure for commercial maize farmers to implement agricultural adaptations in order to build resilience against climate and socioeconomic changes is mounting, with the key challenge being maintaining profitable production while developing adaptation techniques relevant to their requirements. Adaptation can be understood as adjustments in ecological-social-economic systems, in response to current or anticipated changes in environmental conditions, whereby resilience to drivers of change can be achieved (Smit *et al.*, 1999; Raaijmakers & Swanepoel, 2020; Dimitrova & Mokhele, 2022). Resilience is a critical component in the process of developing a successful approach to adaptation. Resilience can be understood as the ability for a socio-ecological system to absorb impacts and continue to operate rather than returning to its previous state (Smit *et al.*, 1999; Raaijmakers & Swanepoel, 2020; Dimitrova & Mokhele, 2022). Successful adaptation of agricultural systems may take many forms but can be understood as implemented changes to farm management practices to increase operational resilience; in order to absorb environmental, social and/or economic changes in a way that agricultural output remains sustainable, both economically and environmentally (Smit *et al.,* 1999; Raaijmakers & Swanepoel, 2020). Adaptation may be applied following events which are experienced, such as droughts, floods, or heat waves, with a key example being seen in the drought in Western Cape from 2015-2018, which resulted in farmers adapting their operations towards conservation agriculture systems in order to avoid future impacts or conditions (Raaijmakers & Swanepoel, 2020). Furthermore, adaptations may be applied based on predications of future impacts. Adaptation requires significant and long term changes to operations rather than short-term responses such as the actions taken as coping measures, with long-term planning being critical component of adaptation (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020). A key part of successful adaption is the adaptive capacity shown by a farm/farmer. This may relate to factors such as social, natural, human, financial assets, and institutional arrangements, which can influence the adopted actions (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020).

Global trends in maize production have been rising since 1961 and the industry surrounding the production of maize has been rapidly developing (Erenstein *et al*., 2022). Globalisation of the industry relating to research and development, specifically with regards to mechanisation of production, as well as the development of genetically modified maize variants, will benefit maize production in the Global South (Erenstein *et al*., 2022). Genetically modified maize variants may give greater resistance to drought and diseases increasing the crop resilience to heat stress. This aids farmers in maintaining and in some cases improving crop yields under drier conditions. Developments pertaining to these aspects have been highlighted as critical pathways for climate change adaption and obtaining environmental sustainability (Fisher *et al.,* 2015; Erenstein *et al*., 2022). The combination of agricultural technologies and farm management practices is critical for maintaining economically and environmentally sustainable maize farms.

2.3. Commercial Maize Farming

It is estimated that commercial maize farming contributes around R9.4 billion per annum to the South African economy (Adisa *et al.,* 2018). Commercial maize farming in South Africa usually takes place between October and December, however planting dates may vary due to climate conditions and selected cultivars. Maize requires between 450 mm and 600 mm of rainfall per season (Du Plessis, 2003). The majority of commercial maize agriculture in South Africa takes place under dryland conditions. This type of agriculture relies on soil moisture content and rainfall for cultivation. This can be highlighted by grain production figures from the 2020/2021 season, which saw a total area of dryland rainfed maize cultivation of 2 529 200 ha for white and yellow maize variants combined (The Southern Africa Grain Laboratory NPC, 2022). Maize cultivation under irrigation during the 2020/2021 season amounted to a total area of 226 200 ha for white and yellow maize variants combined. This means that roughly only 8.21% of maize during the 2020/2021 season took place under irrigation (The Southern Africa Grain Laboratory NPC, 2022). Dryland maize cultivation places a greater emphasis on sustainable agricultural management practices such as soil maintenance and water management, as well as careful management of inputs such as fertilisers (Haarhoff *et al*., 2020). Approximately 60% of maize in South Africa is produced under dryland conditions in the Free State and North West provinces (Adisa *et al*., 2018). Commercial maize agriculture can take place in a continuous cycle or by a maize-fallow cycle, however both systems place a requirement for good land management practices during the pre-planting, growth, harvesting and post-harvest stages (Haarhoff *et al*., 2020). Good land management practices relate to maintenance of healthy soils specifically taking into consideration the soil nutrient and pH levels, as well as the overall structure of the soil, protecting against compaction and or crusting while protecting against soil erosion (Haarhoff *et al*., 2020). Furthermore, good land management practices during the pre-planting and planting phases need to consider plant population and density based on the environmental conditions in order to optimise the available land (Haarhoff *et al*., 2020). Continuous cycles of maize production take place from November through to July in the Western regions of the Highveld, including the Free State and North West, and September to June in the Eastern regions of South Africa, including Mpumalanga and KwaZulu-Natal provinces (Haarhoff *et al*., 2020). The maize-fallow system which is predominately used in the western Free State and North West provinces takes place between December and July, which is then followed by an 11- to 12-month fallow period when fields are kept uncultivated (Haarhoff *et al*., 2020). Maize production systems utilising a fallow period have been implemented across the western region of the Highveld and have shown increases in maize yields, particularly on the sandy soils found in this region (Bennie *et al.*, 1995).

Optimal conditions for maize growth during the planting phase are temperatures of between 20°C to 30°C, with a soil moisture content of around 60% and a soil pH range of around 5.0-

7.0, dependent on the cultivar of choice (Du Plessis, 2003; Sithole & Magwaza, 2019). Temperatures of 32°C and above are detrimental to maize crop production, due to the associated heat stress which can cause significant crop loss, especially under drought conditions (Du Plessis, 2003). Furthermore, maize crops need between 120-140 days of frost-free conditions for optimal growth, as frost can cause damage to the plant's leaves and stems, which causes yield reductions (Du Plessis, 2003).

2.3.1. Conventional maize practices within commercial farming

The development of commercial maize agriculture has largely been as a result of processes of intensification and extensification, meaning that a combination of increased agricultural inputs and an increase in land cultivation has provided higher maize yields globally (Matson *et al.,* 1998; De Wit *et al*., 2015; Erenstein *et al*., 2022). The commercial maize farming sector in South Africa has developed through a variety of intensification techniques such as mechanisation, monoculture, high yielding crop varieties and increased inputs in order to achieve increased production output. The process of implementing these intensification techniques resulted in what can now be understood as the conventional farming systems and practices which have been commonly adopted by commercial maize farmers in South Africa. This approach towards an agricultural production system can be understood as being largely dependent on a variety of external inputs in order to achieve and maintain high crop yields (Matson *et al.*, 1998; Hole *et al.*, 2005; Mondelaers *et al*., 2009; Meyer *et al.*, 2018; Cammarano *et al*., 2020). This includes capital investment towards the use of production and management technologies, high labour demands, single crops grown continuously making use of hybrid seed varieties, as well as substantial use of pesticides and fertilisers (Mondelaers *et al.*, 2009; Meyer *et al.*, 2018; Sumberg & Giller, 2022). This agricultural system is energy intensive both from the use of electricity and fuel while also requiring high labour efficiency. The process of conventional maize farming practices within the commercial context is closely tied to the agribusiness sector and often has a dependency on the inputs from a variety of agronomists. These inputs may include advice relating to soil management; crop protection in relation to pests and weeds; as well as plant nutrition (Bruwer & Khwidzhili, 2022). The improved decision-making as a result of contributions from agronomists has shown increased yields by over 40% within the last decade, alongside improved efficiency from machinery (Bruwer & Khwidzhili, 2022). The conventional farming practices predominantly utilised by commercial maize farmers in South Africa have been identified as having negative effects on the environment due to the connections between agronomic inputs and environmental degradation

(Meyer *et al.,* 2018). There are concerns relating to the soil and water quality due to chemical leaching from agrochemical inputs such as fertilisers, pesticides, and herbicides (Meyer *et al.,* 2018). Furthermore, there are concerns surrounding the sustainability of the conventional farming practices implemented by commercial maize farmers, both environmentally and economically (Smith *et al.,* 2021). Conventional farming practices are dependent on large inputs of inorganic fertilisers to achieve high yields, these fertilisers which often contain nitrogen, phosphorus, and potassium (Meyer *et al.,* 2018). The dependence on these inorganic fertilisers is largely due to the lack of availability of these elements within soil or from the depletion of nutrients within the soil due to the removal of harvested crops (Meyer *et al.,* 2018; Pellissier & Swanepoel, 2021). Excessive use of inorganic fertilisers has been linked to several environmental issues, including groundwater and river contamination through leaching of these elements through the soil as well as through soil erosion (Mondelaers *et al.,* 2009; Meyer *et al*., 2018; Smith *et al.,* 2021). Long-term water quality monitoring of the 20 largest primary river catchments in South Africa, conducted between the 1970s and 2005, has demonstrated that nutrient fluxes associated with agriculture runoff are present across the country (De Villiers & Thiart, 2007). Although the nutrient enrichment of water sources in South Africa is often closely connected to failures in sewage works or human settlements, diffuse nutrient sources are connected to seasonal fluctuations of nutrient inputs rather constant input throughout the year (De Villiers & Thiart, 2007). The data show that all catchments with greater than 20% agricultural land-use have higher fluxes of nitrogen and phosphorus present which suggests diffuse agricultural sources (De Villiers & Thiart, 2007). Examples of this are highlighted by the Oilfants and Phongola rivers (De Villiers & Thiart, 2007). Furthermore, in the Western Cape, agricultural development has been connected to a decreased in water quality due to fertiliser runoff, as well as the degradation of endangered natural Renosterveld vegetation due to agricultural expansion (Jacklin *et al.,* 2019). Fertilisers rich with nitrogen and phosphorus have been shown to contribute to surface water eutrophication. Water quality degradation may also be linked to the use of herbicides which can also contribute to water contamination (Jacklin *et al.,* 2019). This aspect highlights a key aspects in input management for maize farmers, due to the large amounts of fertilisers utilised, it is important to make sure that inputs are optimised.

There are impacts relating to the use of fertilisers which contain an ammonium base, which are commonly used to deliver nitrogen to soils. This process can contribute to soils becoming more acidic which can cause damage to the root development of crops in some cases (Schroder *et al.,* 2011; Meyer *et al.,* 2018; Pellissier & Swanepoel, 2021). Intensive agriculture as seen under conventional farming systems utilised by commercial maize farmers can lead to the acidification of soil, even with reduced amounts of fertiliser inputs, due to the disruption of natural nutrient cycles. It is estimated that roughly 60% of the commercially utilised cropland within South Africa experiences moderately to severely acidic topsoil conditions (De Wit *et al.,* 2015). Monocrop systems can lead to the depletion of specific plant nutrients such as calcium, magnesium, and potassium, which can contribute to soil acidification if not managed correctly over an extended period of time (Pellissier & Swanepoel, 2021). The pH level of soil plays a significant role in the ability for crops to regulate nutrition uptake, which can lead to farmers over-fertilising crops. This can happen due to crops not showing signs of nutrient deficiencies, even when sufficient nutrients are available within the soil however the nutrient uptake is limited due to a lower pH level of the soil (Obour *et al.*, 2017; Pellissier & Swanepoel, 2021). Over-fertilising can contribute to nutrient leaching and eutrophication of water sources as well as contributing to increased cost of cultivation.

Under conventional maize farming practices, maize cultivation requires soil to be tilled before seeds can be planted. Within commercial agriculture this takes place through the use of large machinery to plough fields in order to create soil conditions favourable for sowing (Meyer *et al.,* 2018). Mouldboard, chisel or disc ploughs as well as rippers may be utilised during this process depending on field conditions (Du Plessis, 2003). The process of soil tillage may vary, dependent on the type of soils on a specific farm and challenges which may be presented due to changes in conditions over time. For example, in the western cropping areas of the Highveld, notably the northwestern Free State, the dominate soil type is aeolian sandy soils which have high infiltration rates as well as high water storage capacity provided that they are deep enough with a layer of impermeable deeper clay layer (Smith *et al.,* 2021). These soils are, however, susceptible to wind erosion and subsurface compaction making deep tillage practices such as rip-on-row commonly adopted in order to break up compaction (Smith *et al.,* 2021). The process of soil tillage can have long term negative effects on the soil structure and health, with decreased amounts of organic matter being present within soils that are consistently ploughed (Mondelaers *et al*., 2009; Smith *et al.,* 2021). Consistent ploughing of fields can cause the soil’s natural structure and porosity, which can lead to soil compaction. This can result in slower water infiltration, increase soil moisture loss, higher amounts of runoff, and increased wind erosion (Meyer *et al.,* 2018).

Commercial maize farmers under conventional farming systems are reliant on chemical inputs in the forms of insecticides, herbicides, and fungicides to effectively manage the impacts of organisms such as insects, bacteria and weeds which can reduce maize crop yields (Meyer *et al.,* 2018). The use of pesticides can increase crop yields and protect against crop failure; however, there may be potential negative environmental impacts associated with the use of these products. South Africa is the largest agrochemical consumer in sub-Saharan Africa and due to this extensive use, there are several environmental and health legacies attached (Horak *et al.,* 2021). Now-banned pesticides such as endosulfan and dichlorodiphenyltrichloroethane, commonly known as DDT, have residues which remain within South African watercourses as well as within wildlife (Horak *et al.,* 2021). A variety of current-use pesticide chemicals have also been detected within watercourses and wildlife (Horak *et al.*, 2021). These chemicals may harm non-target organisms, particularly through prolonged exposure to these chemicals which may cause biological changes due to altering hormone levels (Horak *et al.,* 2021). The use of these products may decrease biodiversity and reduce soil quality through contamination. Pesticides residues have been found in both rain and groundwater, increasing the environmental risks associated with these products (Meyer *et al*., 2018; Horak *et al.*, 2021).

Commercial maize agriculture in South Africa, which takes place under conventional farming practices and systems, is largely unsustainable from an environmental perspective, with changes in climatic conditions and climate variability often being met with increased agronomic inputs in order to maintain crop yields (Meyer *et al.*, 2018; Smith *et al.*, 2021). Through a combination of climate change and socioeconomic impacts, commercial maize farmers in South Africa are becoming increasingly vulnerable to potential crop failure and a loss of profitability (Meyer *et al.,* 2018). As a result of this, a variety of potential adaptations have been identified to build resilience against climate change as well as the various socioeconomic challenges faced within the sector. These adaptions range from a change in the overall farming systems implemented, such as moving away from conventional farming systems, towards systems such as conservation agriculture (Gilder & Swanepoel, 2018). Alternative adaptations which have been identified including adjustments in farming operations/crop management, such as delaying planting dates, utilising crop varieties with characteristics such as high-water use efficiency and high heat stress resistance, as well as increased use of irrigation (Benhin, 2006; Wilk *et al.,* 2013; Nhemachena *et al.,* 2020; Cammarano *et al.,* 2020). Furthermore, farmers have also implemented increased chemical applications such as fertilisers and lime to maintain correct soil pH levels (Benhin, 2006;

Sithole & Magwaza, 2019; Pellissier & Swanepoel, 2021). Commercial farms have also opted for insurance against loss of income from climate and environmental factors which may reduce yields (Benhin, 2006).

2.3.2. Adaptations to maize farming systems

There is agreement throughout the literature that successful adaptation to climate change for commercial maize farmers will require engagement involving a wide range of stakeholders, using a co-designed adaption strategy which is locally relevant (Gilder & Swanepoel, 2018; Cammarano *et al*., 2020; Smith *et al.,* 2021; Coleman, 2023a). This process requires farmers to be involved proactively in order to position themselves for long-term sustainable agriculture as well as mitigation against potential losses, while simultaneously contributing to decision-making relating to climate change on a national level (Coleman, 2023a). While the long-term goal for adaption should be focused towards addressing aspects of sustainability within agriculture while maintaining maize yields, immediate adaptation requirements towards climate variability cannot be overlooked.

While the adjustment of planting dates and the use of heat/drought resistant seeds is common practice, a shift towards sustainable agriculture has been be suggested as a long-term adaptation for commercial maize farmers in South Africa, with the goal of creating more resilient and sustainable crop production systems (Wilk *et al.,* 2013; De Wit *et al*., 2015; Gilder & Swanepoel, 2018; Findlater *et al.,* 2019; Raaijmakers & Swanepoel, 2020). Throughout the literature surrounding field crops and sustainable agriculture, the term 'Conservation Agriculture' becomes prevalent as the model of application towards achieving sustainable long-term crop agriculture. The conservation agricultural system offers a set of management principles which aim to improve sustainability and profitability as well as improve drought resilience (Raaijmakers & Swanepoel, 2020). This method of agricultural production has been heavily promoted by the Food and Agriculture Organization (FAO) of the United Nations, with research in South Africa suggesting the approach may be a suitable path for long-term adaptation (De Wit *et al*., 2015; Gilder & Swanepoel, 2018; Findlater *et al.*, 2019; Strauss *et al.,* 2021a). Conservation agriculture is dependent on the implementation of three key principles which are: minimum soil disturbance to improve soil structure, infiltration, and water retention; year around organic soil cover to preserve soil moisture; and advanced crop rotations (De Wit *et al*., 2015; Findlater *et al.,* 2019; Strauss *et al.,* 2021a). In order for an agricultural system to be considered as a 'Conservation Agricultural' system; these three principles need to be applied simultaneously (De Wit *et al*., 2015). The implementation of a conservation agriculture system can be understood through a series of steps which allows for the gradual shift from conventional agriculture towards the most sustainable form of agriculture which is organic conservation agriculture (De Wit *et al.,* 2015). This gradual shift includes production elements such as level of tillage and external inputs can lead farmers gradually reducing the cost associated with cultivation due to reduced agronomic inputs as well as reduced fuel consumption, which may contribute towards building socioeconomic resilience for commercial maize farms.

2.3.3. Conservation Agriculture and its potential for adaption in South Africa

Following the dustbowls which severely impacted large parts of the mid-west of the United States of America during the 1930s, tillage as a form of soil management was called into question (Kassam *et al.,* 2019; Strauss *et al.,* 2021b). This prompted the development of new farm management practices which were specifically aimed at reducing soil erosion and was followed in the 1940s by the development of specialised equipment which allowed for no-till seeding to take place (Kassam *et al.,* 2019). Globally there has been a steady increase in the adoption of conservation agriculture and this is illustrated through the global increase in cropland under conservation agriculture, which has been increasing at a rate of 10 million ha per annum since 2008/2009 (Kasam *et al*., 2022). Within a South African context, the extreme dust storms experienced in the western Free State during the 1960s, which were closely connected to drought conditions, prompted the early idea of shifting towards reducing tillage to what is now recognised as conservation tillage (Strauss *et al.,* 2021b).

As previously mentioned, conservation agricultural is characterised through the presence of three key principles which need to be applied simultaneously (Derpsch *et al.,* 2014; De Wit *et al*., 2015; Findlater *et al.,* 2019; Strauss *et al.,* 2021a; Van Antwerpen *et al.,* 2021; Kassam *et al.,* 2022). This can be implemented through the introduction of no-till seeding, utilising specialised equipment to limit soil disturbance. Furthermore, soil disturbance should be limited from any other forms of farm traffic such as the delivery methods of fertilisers and harvesting equipment (Derpsch *et al.,* 2014; Kassam *et al.,* 2019; Van Antwerpen *et al.,* 2021). Secondly, there is the requirement of year around organic cover in order to assist in the preservation of soil moisture content, with at least 30% of the field being covered. This can be achieved through retaining crop biomass, plant roots and stubble as well as the introduction of cover crops (Derpsch *et al.,* 2014; Kassam *et al.,* 2019; Strauss *et al.,* 2021b; Van Antwerpen *et al.,* 2021).

Thirdly, conservation agriculture requires advanced crop rotations, meaning that fields should be rotated with a variety of crops to avoid the same field being cultivated with a single crop for many seasons in sequence. Advanced crop rotations assist in maintaining soil quality by changing the nutrient demands placed on the fields, each set of crops have different nutrient requirements, this process helps maintain soil fertility (Shah *et al.,* 2021). Furthermore, this process can assist in disrupting weed and pathogen cycles which can develop when a monoculture method is implemented (Shah *et al.,* 2021). Critically, conservation agriculture systems are less vulnerable to the effects of drought, floods, and erosion, due to the maintenance of soil structures while simultaneously reducing the impacts of soil temperature extremes (Kassam *et al.,* 2009; Strauss *et al.,* 2021b).

Research surrounding conservation agriculture in South Africa has been scattered across the country and generally has been connected to a few established research sites with links to universities or research institutes (Swanepoel *et al.*, 2018). These research sites have focused on experimental trials relating to the viability of conservation agricultural systems for both commercial and small-scale farms; as well as community-based projects with a focus on small-scale and subsistence agriculture (Swanepoel *et al.,* 2018). However, as highlighted by Swanepoel *et al.* (2018) through an extensive review of literature output relating conservation agriculture in South Africa, the majority of research attention is placed on small-scale farmers in Limpopo, Eastern Cape and KwaZulu-Natal, with a focus on larger communal areas. These studies aimed to develop awareness and skills for the implementation of conservation agriculture system for these participating communities in order to build resilient agriculture production systems (Swanepoel *et al.,* 2018). Research relating to conservation agriculture in a South African context can be traced back to the 1980s, however there has only been a significant increase in research output from around 2010 (Swanepoel *et al.,* 2018; Strauss *et al.,* 2021b). From 2010, conservation agriculture research has received support and funding from the grain industry; primarily from the Maize Trust and Winter Cereal Trust. This led to the creation of the Conservation Agriculture Farmer Innovation Programme in 2013/2014 (Swanepoel *et al.,* 2018; Strauss *et al.,* 2021b). This programme was implemented by Grain SA between 2013 until 2020, where the programme was handed over to Asset Research to continue building upon previous studies (Strauss *et al.,* 2021b). The purpose of the Conservation Agriculture Farmer Innovation Programme is to strengthen, coordinate as well as facilitate conservation agriculture research for commercial, semi-commercial and smallholder grain farmers within the summer rainfall zone of South Africa (Swanepoel *et al.,* 2018; Strauss *et al.,* 2021b). There is a variety of ongoing trials under the umbrella of the Conservation Agriculture Farmer Innovation Programme with a focus on comparing yields between conservation and conventional systems, crop rotation, crop density and cover crops with livestock integration.

A central part of the Conservation Agriculture Farmer Innovation Programme is to work alongside farmers on the ground in order to support and strengthen the on-farm management practices, irrespective of their progress in implementing conservation agricultural practices. This is done by providing consultation relating to management practices as well as education on new developments and techniques. The programme also aims to reach out to as many grain farmers as possible in order to involve them within the programme (Strauss *et al,* 2021b). Farmers are more likely to adopt new techniques or systems when they are adapted to their local area and tested on experimental plots. This allows for farmers to develop an understanding of the new technique and make an informed decision on whether they want to implement the change (Wilk *et al.*, 2013).

The objectives of the Conservation Agricultural Farmer Innovation Programme are closely tied to the idea of generating a co-designed adaption strategy which is locally relevant, involving a wide range of stakeholders (Gilder & Swanepoel, 2018; Cammarano *et al*., 2020; Coleman, 2023a). This has included engaging with commercial farmer groups in the Free State, Mpumalanga, and North West. The groups engaged with in the North West are the Ottosdal No-Till Club and the North West Conservation Agriculture Farmer Forum (Strauss *et al.,* 2021b). Through the programme, different on-farm field trials have been conducted in order assess a variety of crop management practices, changes in soil properties, agronomic aspects including yield and productivity, and the impacts of weed on crops. These aspects of research are all associated with the implementation of a conservation agriculture system (Swanepoel *et al.,* 2018). On-farm trials conducted in the North West Province have suggested that higher maize yield increases can be expected through the implementation of higher plant density (specifically relating to narrower row width and higher plant population) through the utilisation of Conservation Agriculture systems (Strauss *et al.,* 2021a). Similarly, a three year on-farm trial conducted in Reitz, eastern Free State, found that increasing maize plant population resulted in increased maize yields and improved water utilisation by maize crops under a conservation agriculture system (Haarhoff & Swanepoel, 2020). Higher plant population and the associated increased maize-leaf canopy cover allowed for benefits of increased soil moisture associated with the conservation system to be fully utilised. Conservation agriculture systems are associated with increased soil water content, which therefore supports the increased plant population when compared to a conventional system. On-farm trials in the Ottosdal region, North West Province, found that conservation agricultural systems out-performed their comparative conventional agriculture systems in relation to yield, due to increased water infiltration associated with conservation system (Strauss *et al.,* 2021a). Furthermore, studies have also focused on modelling the long-term economic impacts which may be associated with a change in agricultural systems, which have suggested that long-term profitability may be increased and climate change risks may be decreased with a change of system (De Wit *et al.,* 2015; Swanepoel *et al.,* 2018; Smith *et al.,* 2021). These early finding from Conservation Agricultural Farmer Innovation Programme, highlight the potential which conservation agriculture has as an adaptive measure to climate change and climate resilience.

A survey conducted Findlater *et al.* (2019) aimed to assess the adoption rate of conservation agriculture among commercial grain farmers in South Africa. Adoption of conservation agriculture by commercial grain farmers has been slower than expected, with research suggesting that only 14.2% of grain farmers in South Africa have adopted the principles of conservation agriculture comprehensively, with estimates placing the adoption of this approach specifically in the North-West Province being around 20% in 2015 (De Wit *et al.,* 2015; Findlater *et al.,* 2019). More recent studies have suggested that the adoption rate of conservation agriculture may be as high as 37% in the North-West Province as of 2021 (Smith *et al.,* 2021).

Critically, the adoption rate of conservation agriculture is not spread across the country equally, with estimates places the adoption of the system being by far the greatest at around 83% within the Western Cape; due to its previous experiences with drought (Strauss *et al.,* 2021b). It is however highlighted that there remain variations in the forms and the extent to which conservation agriculture has been applied and adhered to by farmers, as there is a degree to which farmers may choose to implement only certain aspects of conservation agriculture (Raaijmakers & Swanepoel, 2020). Through the research conducted by Findlater *et al.* (2019) it is clear that, complete adoption of the conservation agriculture system across South Africa is significantly lower than the perceived adoption by farmers, with farmers' self-assessments suggesting that between 40% and 80% of farmers have adopted the system. This is largely due to the understanding that farmers have pertaining to what constitutes conservation agriculture, or that they have only adopted some elements of the system, which differs from the definition set out by the FAO (Findlater *et al.,* 2019). Farmers may implement certain aspects of conservation agriculture, such as the permanent organic soil cover and minimal soil disturbance but may not use advanced crop rotations (Findlater *et al.,* 2019). Van Antwerpen *et al.* (2021) has suggested that farmers tend to only adopt practices if they deem them to be relevant and suitable for their specific conditions. This suggests that farmers may only opt to utilise specific aspects of conservation agriculture in order to address site specific challenges which they experience, rather than comprehensively overhauling their own agricultural systems. This can be seen by commercial farmers in the Winterton and Bergville area of KwaZulu-Natal who have identified elements of conservation agriculture for adaptive measures, most notably highlighting a shift towards a no-till system (Wilk *et al.,* 2013).

It is important to understand which elements of adoption and adaptation are implemented by maize farmers across South Africa, as the implementation of climate change adaptation for commercial farmers is geographically specific, and understanding where commercial farmers are within their process of adaptation is critical (Strauss *et al.*, 2021b). Agriculture adaptation cannot follow a one-size-fits-all approach, with the challenge of successful adaptation remaining around formulating an effective response for specific regions and individual cropping systems.

2.3.4. Precision Agriculture

'Precision Agriculture' can be understood as a management strategy which allows for farmers to gain greater control over their farm management practices. This takes places through the use of electronic information and technologies in order to gather, process and analyse spatial and temporal data pertaining to their agricultural operations (Jacobs *et al*., 2018; Lowenberg-DeBoer & Erickson, 2019). This may include information on soils and yield mapping which can help identify areas which require inputs, allowing for farmers to vary input applications such as fertiliser, pesticides, herbicides, and irrigation, targeting specific zones rather than the whole field (Jacobs *et al*., 2018; Lowenberg-DeBoer & Erickson, 2019; Bwambale *et al*., 2022). The overall goal of precision agriculture is to improve farm management practices through guiding farmers towards improved resource optimisation and efficiency in order to maximise productivity, while reducing input losses and production costs. Successful implementation of precision agriculture techniques can have a profound impact of effectively utilising available resources and can aid in reducing environmental degradation which is associated with commercial agriculture (Nyaga *et al*., 2021). Critically, precision agriculture is not a singular piece of technology, but should rather be understood as a range of tools and technologies, from which individual farmers can select in order to create a farm specific toolkit which best suits their agricultural operations or agricultural system, whether that is a conventional or conservation system (Lowenberg-DeBoer & Erickson, 2019).

Crop establishment is the first and most important part of an agricultural season and is critical for successful crop productivity. There are three sub-phases to crop establishment, which are sowing to seed germination, seed germination to seedling emergence, and seedling to emergence of initial competition among young plants (Lamichhane & Solanti, 2020). Precision agriculture may also include the use of agricultural machinery such as planting or seeding equipment which are imperative for commercial farmers in order to cultivate maize crops with maximum yield potential, through consistent plant spacing in order to achieve the greatest possible crop establishment success rate (Lamichhane & Solanti, 2020). This not only includes the spacing between the rows of crops and the distance between seeds, but also consistent sowing depth (Lamichhane & Solanti, 2020). A key piece of technology related to this, are planters which that allows for variable-rate seeding. When combined with greater data inputs, such as historical performances of cultivars in a specific field, utilising data such as yield maps or aerial imagery from Unmanned Aerial Vehicles (UAVs) which many include timelapse photos to assess plant emergence, as well as data relating to soil properties such as patterns of soil moisture (Lamichhane & Solanti, 2020; Munghemezulu *et al*., 2023). The benefits to utilising UAVs are the relative affordability, immediate access to data and the precision which the machinery offers, allowing for informed decisions to be made on a much faster timescale, as well as reducing the amount of machinery which is required to drive over fields, reducing compaction risks (Munghemezulu *et al*., 2023). Areas of high and low productivity can be identified, allowing greater seed optimisation to be achieved while also minimizing costs (Lamichhane & Solanti, 2020).

The use of precision agriculture also includes farm management practices such as controlled traffic. There are applications for precision agricultural machinery which allow for the optimisation of planting and nutrient delivery, making sure there is no overlap of planting or spraying, while reducing soil compaction (Van Antwerpen *et al.*, 2021). The use of GPS and self-steering tractors allows for farmers to control the traffic and routes which machinery takes when driving through their fields. The implementation of specified lanes allows for same paths are followed for various tasks such as planting, harvesting, or spraying (Van Antwerpen *et al.,* 2021). Precision agricultural machinery may also contribute significantly during harvesting by reducing losses through technology such as optimised header control systems which allow for maize to be harvested more accurately reducing the amount of yield left on the field, as well as supplying a wide range of data relating to yield mapping which can contribute to future seasonal planning.

A study in Schweizer-Reneke, North West Province, focused on the perceptions of crop farmers on the implementation of precision agriculture techniques (Jacobs *et al.,* 2018). The study found that the majority of farmers utilised precision agriculture techniques in order to apply varying rates of chemical amendments to their soil including lime, nitrogen, phosphorus and potassium, which is in line with historical applications of precision chemical applications (Maine *et al.,* 2007; Jacobs *et al.,* 2018). This method of application has a wide range of economic benefits for farmers and allows for inputs to be adjusted throughout the season (Jacobs *et al.,* 2018). Only 17% of farmers opted to utilise variable rates of application for herbicides and pesticides due to the associated costs, which means they believe there is no economic benefit to investing in this technology (Jacobs *et al.,* 2018). Almost half of the farmers in this study stated that they did not need to invest in new harvesters or tractors but were rather able to upgrade their existing equipment with the appropriate computer systems and software packages (Jacobs *et al.,* 2018). All the farmers in this study stated that the adoption of precision agriculture techniques was financially beneficial to their operations and the associated costs were recompensed within one to two years. The cost of adaptive technology implementation appears to be the determining factor in farmers’ choices, which was also highlighted by farmers in the Western Cape (Maine *et al.,* 2010; Jacobs *et al.,* 2018; Raaijmakers & Swanepoel, 2020). The adoption of precision agriculture requires careful consideration relating to the potential environmental and economic benefits, while also considering the risks associated with large capital investments (Maine *et al.,* 2010). Although the study conducted in North West Province had only small sample size of 36 farmers, it provides insight into the consideration of precision agriculture as an adaptive measure for agricultural operations (Jacobs *et al.,* 2018). Historical on-farm trials in the Bothaville District, Free State, found that the implementation of precision techniques such variable rate applications of phosphorus and nitrogen had positive economic benefits for maize farmers, however the profitability was largely determined by the size of the farm (Maine *et al.,* 2007, 2010). This aspect was also highlighted by Jacobs *et al.* (2018) who stated that farms with less than 500 ha under cultivation did not practice precision agriculture. Commercial farmers in the Winterton and Bergville area of KwaZulu-Natal have also identified more efficient resource management as a key adaptation to both climate and socioeconomic stresses (Wilk *et al.,* 2013). It is also highlighted by Wilk *et al.* (2013) that commercial farmers plan extensively for their investment in new technology, suggesting that elements of precision agriculture may be more commonly adopted.

2.4. Climate change vulnerability of maize agriculture

The assessment of crop vulnerability to climate change has been a central element in research surrounding crop agriculture (Fischer *et al.,* 2005; Walker & Schulze, 2008; Lobell *et al.,* 2011; Serdeczny *et al.,* 2015; Mangani *et al.,* 2018). Climate change projections have shown that a wide range of impacts in South Africa can be expected, these impacts include increased temperatures, changes in rainfall patterns and an increase in climate extremes (Mangani *et al.,* 2019; Nhemachena *et al.*, 2020). Climate extremes such as heat waves, droughts, and cold snaps can negatively affect cropping systems by reducing yields and the quality of harvest (Mangani *et al.,* 2018; Nhemachena *et al.*, 2020). For example, drought and heat stress negatively affect photosynthesis and transpiration processes which can cause plants to die (Mangani *et al.,* 2018). Globally, research has focused on climate and crop models which are able to predicyt the potential impacts of climate change on cropping systems (Fischer *et al.,* 2005; Walker & Schulze, 2008; Lobell *et al.,* 2011; Serdeczny *et al.,* 2015). Using these models, there is agreement that maize is particularly vulnerable due to its sensitivity to environmental stresses such as increased temperature and drought (Fischer *et al.,* 2005; Walker & Schulze, 2008; Lobell *et al.,* 2011; Serdeczny *et al.,* 2015).

According to Lobell *et al.* (2011), each day maize crops are exposed to temperatures above 30°C, under optimal rainfed conditions, the final yield is reduced by 1%. Given drought conditions, maize yields are estimated to be reduced by 1.7%. The use of crop and climate modelling which has focused on Africa has indicated with a high degree of certainty that maize production will be negatively impacted under all climate change scenarios, although there is an indication that areas that have cooler climates may potentially benefit from increased maize production in future (Lobell *et al.,* 2011; Li *et al.,* 2022). However, the regions which may experience the potential benefits of increased maize production will not compensate for the overall loss of yields across the continent (Lobell *et al.,* 2011; Li *et al.,* 2022). Sub-Saharan Africa has been highlighted as one of the regions which may be impacted most significantly due to its maize cropping system's dependence on rainfed agriculture, supplemented by irrigation in some areas (Walker & Schulze, 2008; Lobell *et al.*, 2011; Serdeczny *et al.*, 2015). In South Africa, the western parts of the Highveld, including the North West Province, have been flagged as particularly sensitive to climate variability under present conditions (Walker & Schulze, 2008). However, with various crop and climate modelling applications, there is consensus that this region will experience increased vulnerability if agricultural management practices remain the same (Walker & Schulze, 2008; Mangani *et al.,* 2018). There have been considerable advances in the technology and software utilised in order to make climate change impact projections. Historically, projection software was able to model climate change impacts on crops with limited ability to consider factors relating to extreme weather events, which can lead to underestimated impacts being reported (Mangani *et al.,* 2018, 2019). Mangani *et al.* (2019) aimed to evaluate the impact of climate change on maize yield production while taking into consideration the potential impacts of extreme climate events, through comparing two models with different climate variables. The models were run for three locations across South Africa which were Bloemfontein, Free State; Lichtenburg, North West and Nelspruit, Mpumalanga (Mangani *et al.,* 2019). The projections from both models displayed decreasing yield trends for all three locations particularly from 2051 onwards (Mangani *et al.,* 2019). Projected yield decreases for Bloemfontein were between 27.6% to 30%, 24.3% to 25.9% for Lichtenburg, and 18.3% to 18.7% for Nelspruit (Mangani *et al.*, 2019). Under all three scenarios, yield losses are attributed to increased temperatures and the projected increase of days exceeding 30°C, which has been highlighted as detrimental for maize crops alongside reduced moisture availability (Lobell *et al.*, 2011; Mangani *et al.,* 2019). Furthermore, efforts have been made to include economic aspects within crop models, as demonstrated by Cammarano *et al.* (2020). A projected decrease in maize yields from commercial maize farms in the Bethlehem District, Free State, was in the range of 10% to 16% under all five projected climate scenarios, with economic impacts being highlighted by a modelled decrease in net returns per hectare (Cammarano *et al.,* 2020). Olabanji *et al*. (2021) highlighted expected yield decreases in the range of 15% to 65% for maize agriculture within the Olifants catchment of South Africa depending on climate scenarios and adaption measures such as the implementation of irrigation.

Although each model has its own strengths and weaknesses, there is consensus that climate change will negatively impact future maize agriculture if suitable adaptations are not implemented. Benefits associated with crop and climate modelling include the ability to highlight potential regions of severe climate impact (Lobell *et al.*, 2011). Using historical crop trial and daily weather data, areas that may be at risk under climate change scenarios can be highlighted based on historical crop responses to similar climate scenarios (Lobell *et al.*, 2011). These simulation techniques can demonstrate how maize responds under historical climate and therefore offer a prediction as to how maize would respond based on projected climate scenarios. The impacts of climate change will be felt across the agriculture sector in South Africa, and sustainable adaption to future climate projections is required in order to maintain food security (Nhemachena *et al.*, 2020). South Africa as recently as 2015-2018 experienced severe drought across the country which had significant impacts on the agriculture industry and the broader economy, with future projections suggesting that such events will increase in frequency and intensity (Serdeczny *et al.*, 2015; Ainembabazi *et al.*, 2018; Mangani *et al.*, 2019; Raaijmakers & Swanepoel, 2020; The Southern Africa Grain Laboratory NPC, 2022). Projection data can assist in developing more resilient agricultural systems in order to reduce future impacts. This is a valuable approach in developing countries where there are often limited resources available as well as a lack of monitoring data for mitigation and adaptive capacity. This allows agricultural associations, governments, and farmers to make informed decisions pertaining to resource allocation as well as potential adaptations to their operations (Lobell *et al.*, 2011; Mangani *et al.*, 2018; Cammarano *et al.*, 2020).

2.5. Socioeconomic influences on commercial agriculture

Commercial agriculture is a highly complex system, wherein a combination of environmental, economic, political, and social factors interact with each other to determine production output (Cammarano *et al.*, 2020). Economic factors may include changes in fuel prices, input costs, commodity prices, national and international policies, and labour practices. A variety of fluctuations beyond the control of individual farmers can have significant knock-on effects on the production and profitability of crops. Fluctuations in input costs and grain market prices can change the outlook dramatically for commercial farmers between seasons, emphasizing the need to build resilient agricultural systems. Commercial maize agriculture is dependent on a wide range of inputs in order to maintain successful production, with inputs varying between seasons with respect to price and availability, and with different types of inputs needed to address certain issues as they arise (Matson *et al.*, 1998; Hole *et al.*, 2005; Mondelaers *et al.*, 2009; Meyer *et al.*, 2018; Cammarano *et al.*, 2020). Inputs may include fertilisers, fuel, electricity and agrochemicals, however changes in market conditions of these inputs can rapidly change production and significantly increase costs (Kriel, 2022). Furthermore, institutional arrangements have been highlighted by commercial farmers in the Western Cape and KwaZulu-Natal as both a strength and a challenge, in which a lack of governmental support can be a limiting factor (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020). Institutional arrangements refers to the position that farmers have in relation to government, agricultural organisations, local and international market access/engagement, weather forecasting data, and information relating to agricultural activities and development. Some of these in the Western Cape and KwaZulu-Natal relate to uncertainty about land reform policies, which has led commercial farmers to think more carefully about making large investments over fears of losing their land (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020). Government decisions relating to trade tariffs, trade subsidies and taxes can also negatively impact the operations of commercial farmers (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020). Theft from farms is a source of socioeconomic stress for commercial farmers in KwaZulu-Natal, however there is a lack of detail in relation to the specific resources impacted by theft (Wilk *et al.,* 2013). The extent to which crime impacts agriculture across South Africa was highlighted by Agri SA in 2018 with the National Agricultural Sector Crime Survey, with the direct cost of agricultural crime in 2017 totalled to R5.45 billion, with replacement costs amounted to R2.3 billion (Coleman, 2023b). Commercial maize farmers in the Free State had an estimated R234 million worth of maize stolen directly from fields during 2020 (Coleman, 2023b). In the Ditsobotla Local Municipality, which neighbours the Tswaing Local Municipality where the Sannieshof region is located, constraining factors in the adaptation to climate change for commercial farmers were lack of information and governmental support, and financial constraints relating to operational budgets of individual farms (Pienaar *et al.,* 2021).

Agricultural input prices have steadily been increasing due to a range of market factors (Nkunjana *et al.,* 2023). International fertiliser prices during the period 2017 to May 2023 have significantly increased (Nkunjana *et al.,* 2023). Price trends during this period for muriate of potash have increased by 174.9% (from R2966 to R8154/ton), ammonia has risen by 167.5% (from R4562 to R12 204/ton), urea by 127.6% (from R2394 to R5448/ton), and di-ammonium phosphate by 92.9% (from R4748 to R9157/ton) (Nkunjana *et al*., 2023). These prices are also influenced by exchange rates between Rands and US Dollar, in which the South Africa Rand’s purchasing power has reduced by 42.4% in this period (Nkunjana *et al.,* 2023). Local fertiliser prices from 2017 to May 2023 have increased, with potassium chloride increasing by 89.9% (R6206 to R11 764/ton), monoammonium phosphate by 84.8% (R8553 to R15 803/ton), ammonium nitrate by 83.5% (from R5131 to R9414/ton), and urea granules by 68.3% (R5750 to R9678/ton) (Nkunjana *et al.,* 2023). The overall price trends for both local and international fertiliser inputs have implications for commercial farmers who may depend on these inputs to maintain crop yields, which increases the cost of production per hectare. The COVID-19 pandemic, supply chain bottlenecks and the Russia-Ukraine conflict has also resulted in supply chain issues for fertiliser, causing record high prices (Nkunjana *et al.,* 2023). Russia was the world's top exporter of fertiliser in 2020 and as a result of the conflict, fertiliser prices increased by 80% in 2021 (Hassen & El Bilali, 2022; Shahini *et al.,* 2022). The supply shortage and price of fertiliser significantly increasing the cost of agricultural inputs in South Africa where approximately 80% of imported fertiliser comes from Russia (Kriel, 2022). Analysing the fertiliser price trends for local and international fertilisers for the period May 2022 to May 2023 shows decreases from the record highs, however the decrease in Rand value has limited the impact of these recent price decreases (Nkunjana *et al.,* 2023).

The commercial agriculture sector is energy intensive and is affected by increases in fuel prices and energy costs (Nazlioglu & Soytas, 2011; Aye & Odhiambo, 2021). The need for fuel has increased across the sector in South Africa due to the increased use of generators as a result of more frequent power outages (Hlomendlini, 2023). It is estimated that 60% of South Africa's fuel demands are met by imports which creates further vulnerability to market changes (Aye & Odhiambo, 2021). During the period 2017 and May 2023, diesel prices increased by 70.7% from R11.80 to R20.15/litre, with petrol prices increasing by 70.4% from R13.70 to R23.34/litre (Nkunjana *et al.,* 2023). These prices are connected to international crude oil markets and the Rand to US Dollar exchange rate (Nkunjana *et al.,* 2023). Alongside the issues of fuel prices, there have also been changes to national legislation in relation to diesel rebate with a difficulties arising through the interpretations of log books which poses a challenge in terms of fuel management (Grain SA, 2022).

Machinery used for commercial maize agriculture can range in size and efficiency based on the age of the equipment and size of the farm. Agricultural machinery is one of the most expensive investments for farmers and requires continuous financial inputs for maintenance, fuel and upgrades (Tieppo *et al.,* 2019). The impacts of currency exchange rates has resulted in increased prices of equipment which has contributed to a decline in agricultural machinery sales. Investment in new machinery faces competition from other investments such as for solar energy systems (Kriel, 2023).

Different machinery is used for tillage, crop sowing, harvesting and crop spraying. Factors influencing fuel consumption of agricultural machinery include the terrain of operation, the type of soil being tilled, moisture content of the crop being harvested, operating time and intensity (Tieppo *et al.,* 2019). Operating intensity refers to the load placed on the tractor during a given task, for example if a tractor is required to perform tillage practices such as rip-on-row which may require 80% of the maximum towing capacity of a tractor, this would result in higher operational intensity, when contrasted against a task such towing of a boom sprayer which may only require 25% of the towing capacity. The use of precision agriculture technologies such as GPS guidance and tractor auto-steering can assist in reducing fuel consumption by optimising the most efficient route, as well as reducing overlapping (Bora *et al.,* 2012). Land management practices can reduce fuel input costs through effective decision-making, for example a no-till system will significantly reduce fuel inputs due to reduced run time of tractors and intensity of operation as no ploughing takes place (Tieppo *et al.,* 2019). De Wit *et al.* (2015) highlighted the decrease in fuel consumption per hectare when changing from conventional to no-till systems, 79.3 litres per hectare under a conventional system to 41.2 litres per hectare under a no-till system. Decision-making such as the use of two smaller tractors, each matched with specific implements such as crop spraying equipment or seed sowing implements, rather than one large tractor operating multiple pieces of equipment, can reduce fuel consumption (Dyer & Desjardins, 2003).

2.6. Water-Energy-Food nexus and commercial agriculture adaptation

Large scale global challenges such as climate change, land degradation, migration, rapid urbanisation and increasing population growth require integrated approaches in order to sustainably manage resources to deal with these complex issues (Endo *et al.,* 2017; Albrecht *et al*., 2018; Nhamo *et al.,* 2020a). This requires a shift from the conventional 'silo' approach, whereby drivers of change are considered individually, in favour of an approach which is cross-cutting, recognising the impacts as well as feedbacks that exist between sectors (Nhamo *et al.,* 2020a). The concept of the Water-Energy-Food (WEF) nexus is an approach to understanding and dealing with the dynamic interlinkages that exist between water, energy and food systems (Endo *et al.,* 2017; Albrecht *et al.,* 2018; Nhamo *et al.,* 2020a). The WEF nexus has been developed as a new perspective towards structuring of large-scale investments with a goal of optimising developmental plans and resource allocation, as opposed to creating developmental plans or policies which produce unwanted side effects by achieving goals on one of these pillars whilst negatively impacting the ones (Smajgl *et al.,* 2016; Mpandeli *et al.,* 2018). The WEF nexus aims to identify aspects which may yield gains or trade-offs when analysed together. This process aims to develop long-term sustainability and resilience through maximising the benefits of available resources (Huntington *et al.,* 2021). Increasing competition for resources across the pillars of WEF, as well as the increasing demands placed upon each pillar individually, presents communities across all scales with challenges of resource management and allocation. The WEF framework consists of key stages which can be adjusted based on the application of the framework. These stages are identification of drivers of change, identification of risk and exposure, nexus planning, and management outcomes (Nhamo *et al.,* 2020b). The application of this framework may yield helpful insight for farmers when applied to their own individual agricultural systems, helping identify which areas to prioritize as well as where potential synergies can be capitalised upon.

It is estimated that globally water demand will increase by 40% by 2030, with energy increasing by 50% and food by 35% (Endo *et al.,* 2017; Mpandeli *et al.*, 2018). This will place greater pressure on the agricultural sector, as food demands will increase while resource availability is likely to decrease. The WEF nexus applies quantitative and qualitative methods to understand such interactions between WEF resources and their feedbacks (Nhamo *et al.,* 2020a). This means that developmental strategies may have unintended negative outcomes, meaning that one issue may be solved while one or more issues may be created elsewhere (Huntington *et al.,* 2021). The WEF nexus is relevant to agriculture because it highlights the connections that exist between food and water (Huntington *et al.,* 2021). An example is a trade-off during drought, where water is allocated for agricultural activities at the expense of supplies for domestic use. In this case the trade-off would be increased pressure on agricultural systems. A mutual gain might exist for example, if agricultural systems implemented changes to their agricultural management practices so as to reduce the demand for water, which may result in increased availability of water resources for other purposes. Through a network map analysis which highlights relationships between the pillars of the WEF nexus, this framework can assist in demonstrating where negative outcomes can be mitigated against and where policy or developmental plans may be introduced. This is particularly useful in order to maintain balance between the WEF pillars when creating developmental plans (Smajgl *et al.,* 2016).

As demonstrated by Smajgl *et al.* (2016), a wide range of connections exist between the pillars of the WEF nexus and the nexus core (Fig. 1). For example, when applying the concept to commercial agriculture in South Africa, which is energy intensive through its demands for fuel, fertiliser, and labour, it can be seen how agricultural production can be impacted by the nexus-core and the pillars of the nexus (e.g. Matson *et al.,* 1998; Hole *et al.,* 2005; Mondelaers *et al*., 2009; Nazlioglu & Soytas, 2011; Meyer *et al.*, 2018, Cammarano *et al*., 2020; Aye & Odhiambo, 2021). Critically, the broader agriculture sector also has the ability to impact the WEF nexus, demonstrating the dynamic relationship which exists within the nexus. For example, climate variability may result in increased demands by the agricultural sector for resources in order to sustain production such as for water and agrochemicals. As demonstrated in Figure 1, climate variability would impact food production and the associated agricultural management practices. The strategy which farmers undertake in response to this driver would then impact the pillars of energy and water, as more energy may be required for the production and transport of agrochemicals, while increased water demands may result in changes in water allocation as well as increased energy demands for pumping. If the agricultural sector's response was to increase agronomic inputs in order to overcome climate variability, there may be a negative feedbacks in the form of nutrient runoff resulting in reduced water quality and environmental pollution. This has already been highlighted as a cause for concern in South Africa (Meyer *et al*., 2018; Horak *et al*., 2021).

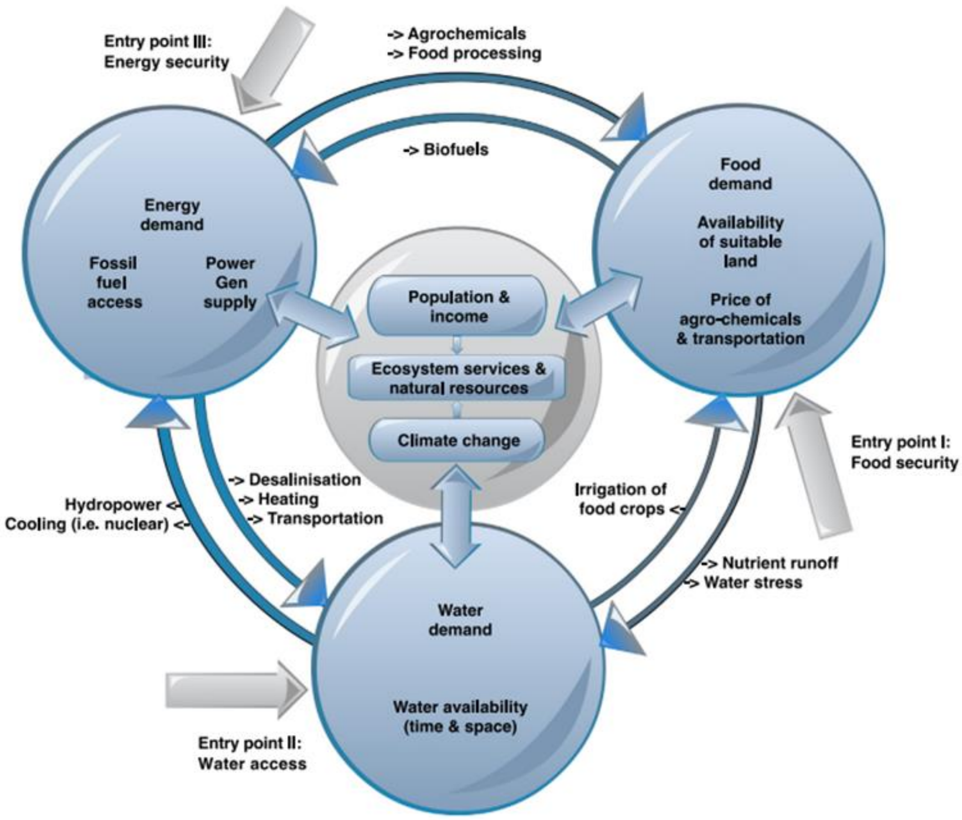

Figure 1: Broad overview of the Water-Energy-Food nexus (from Smajgl *et al*., 2016).

2.7. Conclusions

Commercial maize agriculture in South Africa is a highly complex system which is influenced by a range of climatic and socioeconomic factors on various spatial and temporal scales. The Water-Energy-Food nexus highlights the complexities which challenge the agricultural sector in climate change adaptation. The sector only faces external socioeconomic and environmental drivers of change but is also susceptible to competition for resources from other domestic sectors such as mining and heavy industry (Endo *et al.,* 2017; Albrecht *et al.,* 2018; Nhamo *et al.,* 2020a). Factors that can significantly impact commercial maize agriculture include climate variability and extreme weather events; crime; international market fluctuations for critical inputs such as fuel, fertilisers, herbicides, and pesticides; trade tariffs, subsides and taxes; and institutional arrangements which may include government policies and support, as well as various agricultural organisations that farmers may be involved in (Wilk *et al.*, 2013; Raaijmakers & Swanepoel, 2020).

Commercial maize agriculture in South Africa has developed extensively through the use of conventional farming systems, following mechanisation of the industry in the 20th century. The concept of conservation agriculture is discussed as an alternative agricultural system throughout the literature relating to climate change adaptation. Conservation agriculture aims to maintain minimum soil disturbance in order to improve soil structure, infiltration, and water retention; year around organic soil cover to preserve soil moisture; and crop rotation (De Wit *et al*., 2015; Findlater *et al.,* 2019; Strauss *et al.,* 2021a). This agricultural system offers the best potential to build more environmentally sustainable systems for maize production, while reducing the need for inputs such as fertilisers and water, and in reducing fuel consumption. The adoption rates of conservation agriculture in South Africa, however, remain relatively low with an estimate of around 14.2% of commercial grain farmers adopting the system. This adoption is also uneven, with 83% of commercial farmers in the Western Cape using this compared to 20% in North West Province (De Wit *et al.,* 2015; Findlater *et al.,* 2019; Strauss *et al.,* 2021b). Precision agricultural techniques are management practices to gain increased resource optimisation and greater resource efficiency (Jacobs *et al*., 2018; Lowenberg-DeBoer & Erickson, 2019). Precision agriculture techniques can be applied to both conventional and conservation agricultural systems but it has not received much research attention in South Africa. This is a limitation as it is not clear which elements of precision agriculture might be most suitable for different types of farming operations in South Africa.

Maize agriculture is particularly vulnerable to climate change due to its sensitivity to high temperatures which can result in yield reductions (Lobell *et al.,* 2011; Li *et al.*, 2022). Future changes in temperature and rainfall are likely to mean that yield reductions are not spatially uniform, with some areas expected to be impacted more severely, while others may experience some yield increases. However, the total yield output across the continent and country are expected to decrease.

Commercial maize agriculture is a critical part of the South Africa's agricultural landscape and economy, with a critical role in maintaining food security both on a national and regional scale. Both climate change and socioeconomic factors have a significant impact on the agricultural output of maize farms, however these impacts may vary depending on agriculture type, farm location and size, as well as the agricultural system employed and demographic factors. This study explores these interrelationships in detail, through the conceptual framework of the WEF nexus, and using the specific case study of maize farmers in the Sannieshof region, North West Province.

3. Study Site

3.1. Location and description of the study area

Sannieshof (26.5314°S, 25.8100°E) is a small agricultural town located in the Tswaing Local Municipality within the Ngaka Modiri Molema District, North West Province of South Africa (Fig. 2). Sannieshof is located 58.5 km from Lichtenburg and 40.9 km from Delareyville. The Ngaka Modiri Molema District is the second largest agriculture district within the North West Province, with a total of 1419 commercial agriculture operations in 2017, consisting of commercial crop farms, livestock and mixed farms (commercial crop and commercial livestock). This accounted for 28.8% of the total farms within the North West (Stats SA, 2020). Within the district, 84% of farm operators/managers are white with 92% of all operators/managers within the district being male (Stats SA, 2020). According to Stats SA (2011), Sannieshof has a population of 11 016. The town is characterised by a backdrop of grain storage silos and is located within the South African maize belt (Fig. 3). The North West Province is the second largest maize producing province after the Free State, but has been identified as the region most vulnerable to climate change (Greyling & Pardey, 2019). South Africa's nine provinces are divided into 36 crop production regions, with the North West province including regions 12 to 20 (The Southern Africa Grain Laboratory NPC, 2022). Region 13, which is referred to as North West Central Region (Sannieshof), comprised of five Silo/Intake facilities which are utilised for summer grains including maize, sunflower and soybeans. These facilities are Sannieshof Silo, Biesiesvlei Silo, Bossies Silo, Oppaslaagte Silo and Gerdau Silo (Fig. 2). These facilities are owned and operated by NWK Limited, with railway infrastructure connecting the facilities of Sannieshof Silo, Bossies Silo, Oppaslaagte Silo and Gerdau Silo (Fig. 2). The facilities of the Bossies Silo and Sannieshof Silo are also connected to the N14, while the Biesiesvlei Silo is only connected via the N14. These facilities represent key infrastructure for commercial maize farmers within the Sannieshof region 13 and reduce the cost for farmers to access to markets following harvest.

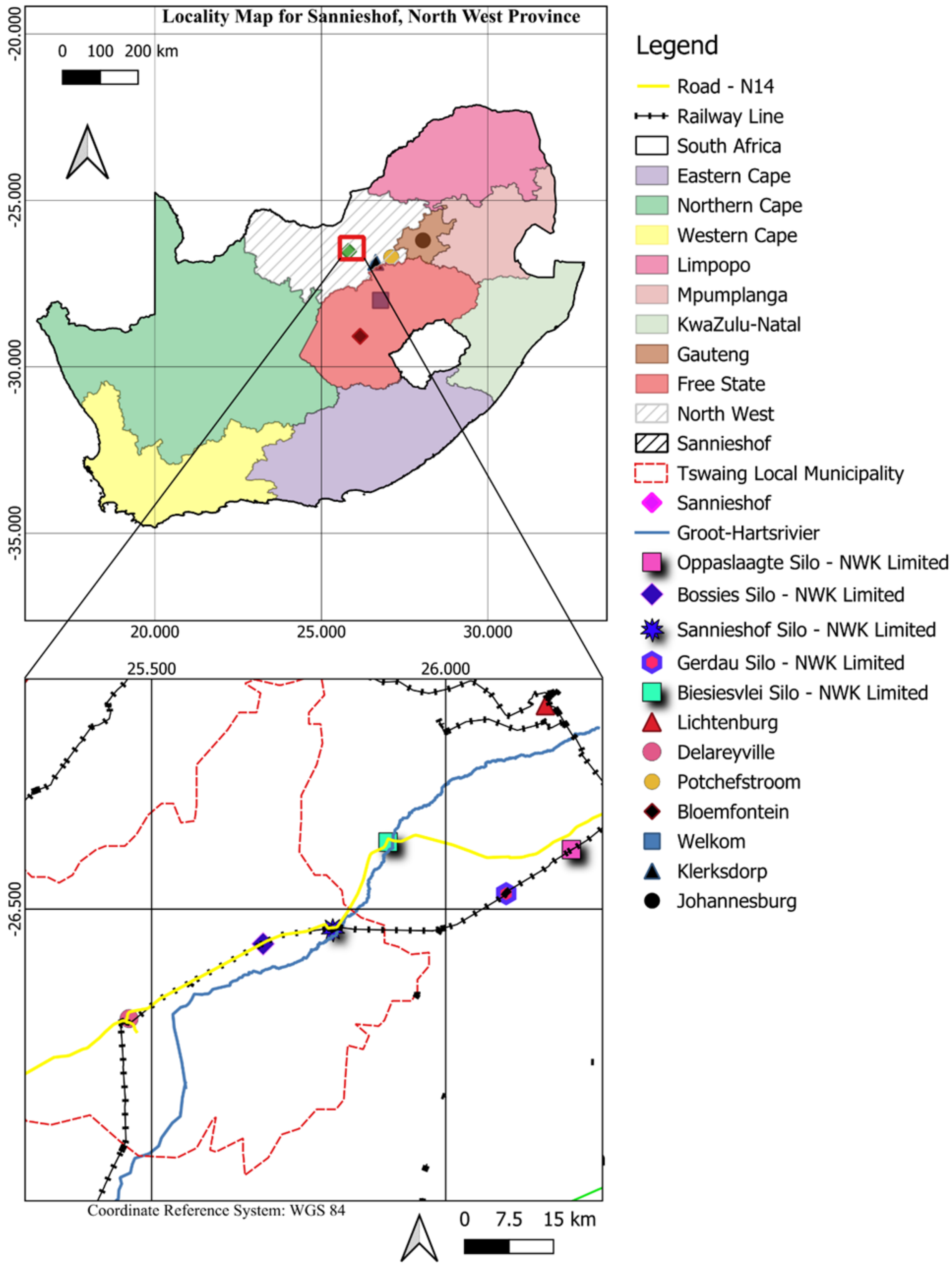

Figure 2: Location of Sannieshof, North West Province, South Africa.

Figure 3: Sannieshof Grain Silo/Intake facility, North-West Province.

3.2. Geology, soil and topography

The study site is located on the Ventersdorp Supergroup which is situated on the Kaapvaal Craton (Van Der Westhuizen *et al.*, 1991; Vorster & Dixon, 2005). The Ventersdorp Supergroup is the largest and most widespread sequence of volcanic rock located upon the Kaapvaal Craton and spans across parts of the North West Province, Free State, Gauteng, Northern Cape, and southern Botswana (Van Der Westhuizen *et al.*, 1991). The region is characterised by Basalt, Andesite, Porphyry, Tuff volcanic rocks, and Clastic sedimentary rocks (Johnson *et al.*, 2008). The study area has a dominance of Cambic Arenosols soils with the southeastern area having Ferric Luvisols soils (FAO, 2007). Arenosols are characterised by their coarse texture, which accounts for their high permeability (IUSS Working Group WRB, 2015; Smith *et al.*, 2021). They have a generally low capacity to store water and nutrients, making it more difficult for agricultural management (IUSS Working Group WRB, 2015). The Groot-Hartsrivier runs through the study area and is the only watercourse in the area (Fig. 2). The Sannieshof region is generally flat with an average elevation of 1383 m asl.

3.3. Climate

The North West receives an average of 487 mm of rainfall per year, with the majority received during the summer season between October and March (Fig. 4). During winter, the region is dry. The region has a Köppen classification of BSk and the agroecological zone is classified as semiarid (Climate Change Knowledge Portal, 2021). The region is vulnerable to drought due to its relatively low amount of annual rainfall and arid conditions. The Sannieshof region has experienced droughts in 1992, 2013 and 2015-2016 with the frequency of droughts expected to increase in the future under climate change (Pienaar *et al.*, 2021).

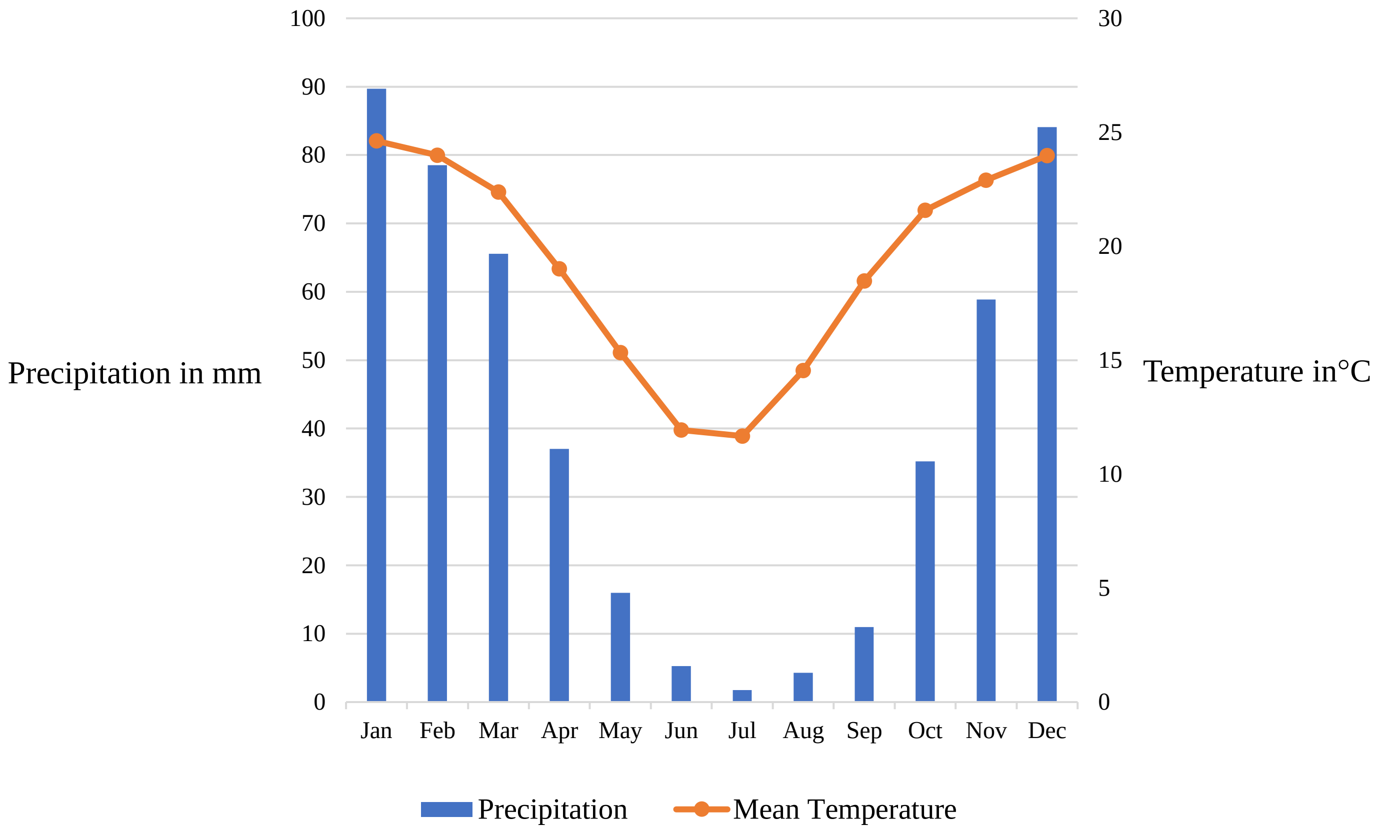

Figure 4: Monthly Average Precipitation and Temperature of North West Province from 1991-2020 (Climate Change Knowledge Portal, 2021).

3.4. Land cover and types of agriculture

The study area is surrounded by commercial agricultural land. Dryland agriculture relies on rainfall and other agronomic inputs in order to produce profitable yields. There is also commercial agricultural land which is irrigated, as well as subsistence cropland to the northwest of Sannieshof (Fig. 5). The Ngaka Modiri Molema district is the main area for commercial crop agriculture output in the North West Province and was responsible for 58.9% of its total commercial maize production in 2017, alongside 69.6% of its sunflower seed, 42.3% of soybean and 23.3% of groundnuts (Stats SA, 2020). Land use in the Sannieshof region is split between commercial dryland crop production and grazing land for livestock (Stats SA, 2020). Field crops account for 52.2% of the total gross income by commercial agriculture in the district, while livestock and animal products account for 47.2%. As seen in Figure 5, the Sannieshof region has a variety of land use applications, highlighting the variations in agricultural production systems and resource management. The majority of land is classified under commercial dryland crop production, which incorporates the production of maize, sunflower and soybeans. Within the Sannieshof region a total of 542 201 ha was utilised for crop production in 2017, with specifically 261 487 ha (48%) for dryland maize production, and 619 477 ha was utilised for livestock grazing (Stats SA, 2020).

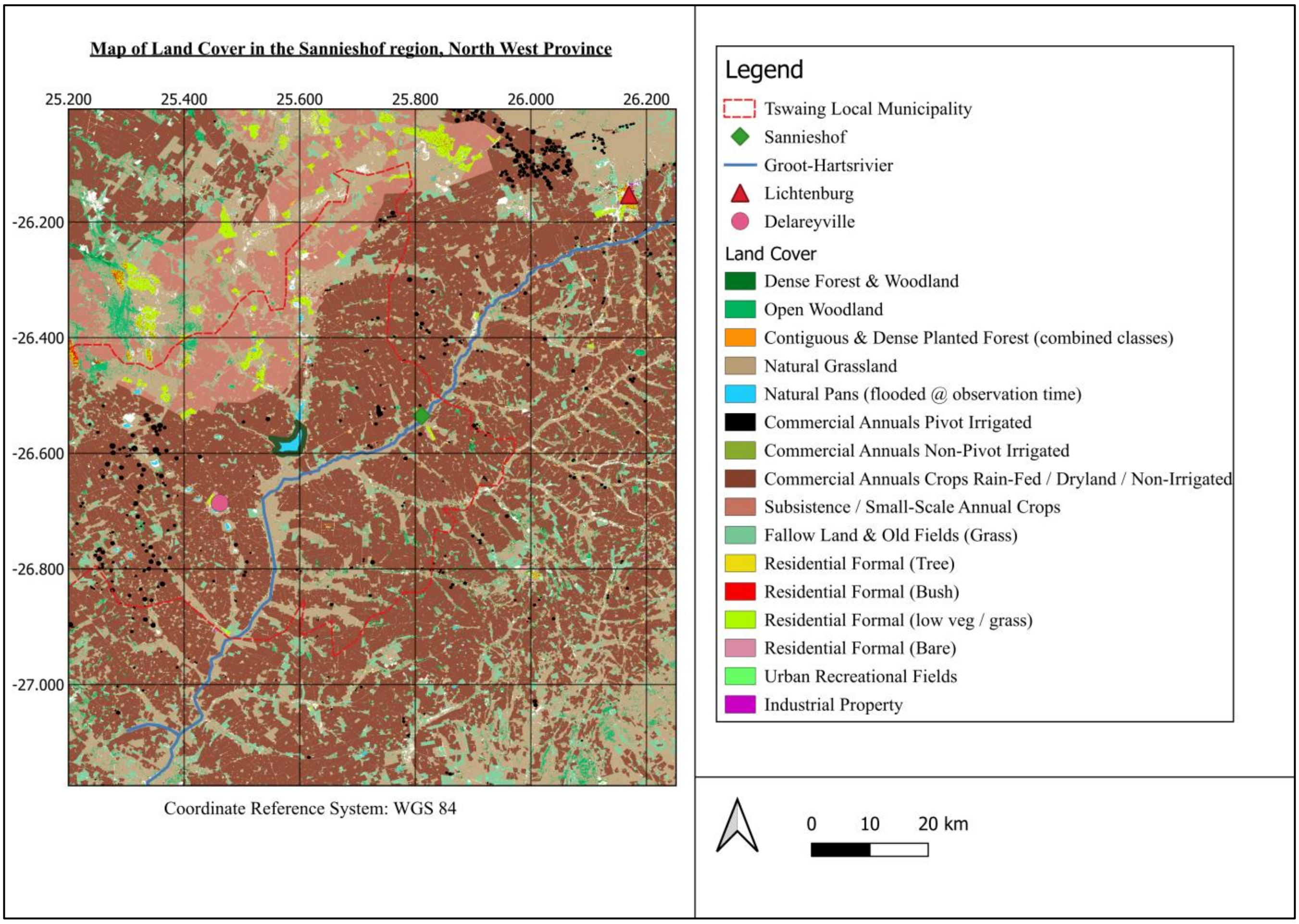

Figure 5: Map of land cover (2020) in the Sannieshof area, North West Province.

4. Methodology

A qualitative method was adopted in this study, utilising a qualitative descriptive approach in order to develop an understanding of the management practices of commercial maize farmers in the Sannieshof region area. This approach was adopted as it offered the best chance to develop an in-depth understanding of the agricultural management practices specific to this region.

4.1. Sampling

In this study, an online questionnaire was used for data collection from commercial maize farmers in the Sannieshof region. For participant recruitment, an acquaintance in the area assisted in the process of identifying and contacting potential farmers. Farmers who agreed to take part were asked to forward the link to any other commercial maize farmers in the area who they knew of. This was therefore a snowball sampling strategy (Maree & Pietersen, 2016b), which was seen as the best approach due the fact the information relating to potential participants was difficult to fine because the general limited accessibly to individual farmers in the area. A target of 20-25 participants was set for the questionnaires as it was believed that this sample size would provide an adequate range of responses. All farms within the sample group fall within the same agroecological zone.

4.2. Data collection

4.2.1. Online questionnaire

The online questionnaire was distributed to potential participants through a link sent over email and WhatsApp. The questionnaire was provided in both English and Afrikaans, allowing for farmers to use the language they were most comfortable with. The questionnaire was comprised of both open and closed questions (Appendix A). The questionnaire was also completed anonymously as the name of individual farmers or farms was not requested.

4.2.2. Field observations and photographs

Five farmers were contacted in order to arrange farm visits; however due a cattle show in the Lichtenburg area three of them were unable to find a suitable meeting time. One farmer who had offered to assist had to cancel the site visit on short notice due to ill health. Following discussions with farmers, it was suggested that one farmer who had hosted the farm visit should be a representative for them and the broader cluster of neighbouring farms. This is due to the long-standing relationship that they have with one another. The large commercial farm that was visited was therefore well positioned to provide an informed overview of the major issues facing maize farmers in the area.

Observations made by the researcher on this farm provided an opportunity to gain a deeper understanding of management practices and the infrastructure/equipment available. Field notes on these issues were recorded and photographs of farm infrastructure and equipment were taken with the consent of the farmer. The observations made and the informal conservations conducted with the farmer during the visit were guided by the initial questionnaire responses.

4.3. Data analysis of questionnaires

The process of data analysis began with the preparation of datasets in order to be processed. This first involved translating of questionnaire responses from Afrikaans into English. As stated by Nieuwenhuis (2016), it is important for a researcher to take time to organise the collected data in order to easily locate information within the dataset. The process of data organisation is critical for effective analysis, therefore the field notes, observations and questionnaire data were grouped in batches. This allowed for data to be managed more effectively. Thematic analysis of the data was conducted as described by Nieuwenhuis (2016). This starts with initial coding of the data, whereby potential codes were created. This was followed by the identification of elements within the dataset which meet the criteria of the created codes (Nieuwenhuis, 2016). Following this, extracts from the questionnaire data were collated with their respective codes. These codes were then grouped according to corresponding themes, which were then reassessed. Themes that were similar were reconsidered, to achieve distinct boundaries between created themes. This process allowed for prominent patterns in the data to be identified. Similarities in the responses of different farmers were identified and grouped together in this process, as well as identifying key differences between responses.

4.4.Ethics

Ethical clearance (protocol number GAES_2023_07_004) was obtained from the School of Geography ethics committee prior to the initiation of the study (Appendix B). The University of Witwatersrand's code of ethics was followed in order to maintain research integrity. Participant information sheets were provided electronically in both English and Afrikaans to potential participants, as well as being present on the landing page for the online questionnaire (Appendix C). This was done in order to explain the purpose of the study and to explain was required of participants. A consent form for participants was provided on the questionnaire landing page as well as obtained in person during the farm visit (Appendix D).

5. Results

5.1. Demographic data

A total of 21 complete questionnaire responses were received, with 15 (71%) of the responses being in Afrikaans and 6 (29%) in English. All farmers were male. The majority of farmers were in the age bracket of between 46 and 60 years old (Table 1). The farming experience of the farmers can be seen in Table 2. The amount of land utilised for maize cultivation by farmers ranged from 70 ha to 1200 ha, with the average area utilised for maize cultivation being 478.1 ha and the median of the dataset being 359 ha (Fig. 6).

Table 1: Age distribution of farmers who took part in the questionnaire (N=21).

Age Range	Number of Farmers	Percentage
18 to 30	1	4.76 %
Between 31 and 45	3	14.29 %
Between 46 and 60	12	57.14 %
Between 61 and 70	4	19.05 %
Older than 70	1	4.76 %

Table 2: Respondent years of farming experience (N=21)

Mean	29.29 years
Median	25 years
Mode	18 years
Range	47 years
Minimum	13 years
Maximum	60 years

5.2. Management practices

The majority (62%) of farmers grow a combination of maize, sunflowers, and soybeans for commercial purposes, while the remaining (38%) grow only maize and sunflowers for commercial purposes. The seed varieties for all commercially grown crops by respondents, which were selected stem from three companies, namely Pannar, Pioneer and Dekalb; 33% of farmers selected Pannar, 33% selected Pioneer, 24% selected Dekalb; while 10% of farmers selected either Pioneer or Pannar based on seed price for that season. The reasons for the choice in seeds were based on historical performance on each farm and the price of the products.

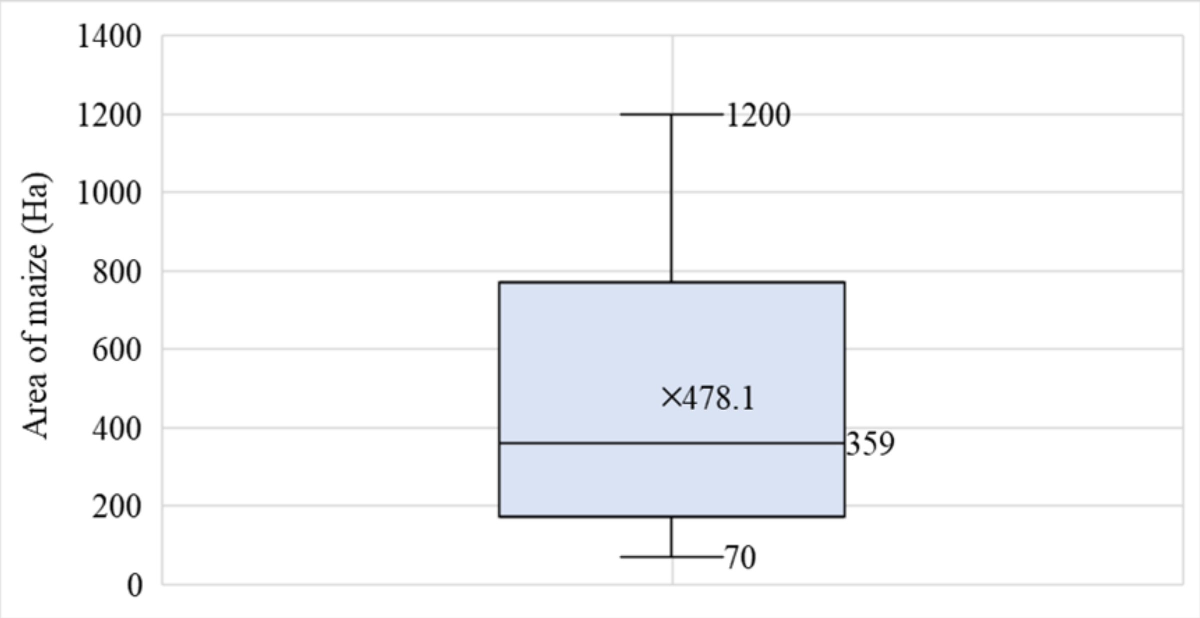

Figure 6: Cultivated area of maize utilised by farmers in the study area.

All farmers (100%) stated that they consulted with agronomic companies in order to assist with their crop production each season. Several services are utilised from these companies (Table 3). The most common is soil analysis which is utilised by 95% of farmers, while these least utilised are budgeting advice, cultivar trials, tillage practices and planting. Both of the farmers who consulted on tillage practices said this was done only if there was soil compaction and it is cheaper for them to rent equipment rather than purchase it. Most (90%) farmers use Microsoft Excel to manage administrative tasks including budgeting, tracking of expenses and resource usage, while 10% of farmers stated they did not make use of any software platforms.

Table 3: Agronomic consultation services utilised by farmers in the study (N=21)

Service	Number of responses
Soil Analysis	20
Spray Programs	14
Fertiliser Recommendations	10
Lime Recommendations	6
Planting/Plant stand	2
Tillage	2
Cultivar Trials	2
Budget	1

Only one farmer used irrigation for their maize production, with 95% of farmers practicing dryland maize production, meaning they only rely on rainfall and soil moisture for cultivation. All (100%) farmers stated that they targeted planting dates between the middle of November, up until the middle of December, with the decision of when to plant being based on soil moisture, temperature, and sunshine conditions. All farmers utilised chemical based fertilisers rather than organic or any other type.

Tillage practices varied and field conditions were cited by farmers as the reason for the implementation of selected practices (Table 4). Just under half (38%) of farmers utilise no-till practices meaning they plant directly into the previous season's crop residue. An example of a no-till planter can be seen in Figure 7 as observed on farm 1, with the field conditions whereby this equipment is utilised can be seen in Figure 8. A combination of disc ploughing and rip-on-row is utilised by 33% of farmers, dependent on field soil compaction. Farmers who have implemented no-till practices also made use of crop rotation and crop residue mulching, demonstrating that a higher degree of conservation agriculture techniques are utilised.

Table 4: Tillage practices utilised by farmers within the study area (N=21).

Type of tillage practice	Number of responses
No-till	8
Disc and Rip-on-Row	7
Rip-on-Row	2
High speed disc	2

Disc	1
High speed disc and Rip-on-Row	1

Figure 7: No-Till Planter as observed on Farm 1.

Figure 8: Maize crop residue left on fields during winter period.

Farm 1, which was the farms that was visited, had recently changed their cultivation practices towards a reduced tillage system with no-till planting. On the day of observation, high speed disc ploughs were preparing the fields for sunflower cultivation, following four seasons of maize (Fig. 9). The high speed disc plough allows for the previous season's crop residue to be chopped and integrated into the soil (Fig. 10). This process aids in increasing soil organic matter content. The farmer stated that this shift in cultivation practices has been gradually implemented over the last 10 years, as it requires extensive planning and changes in the equipment and implements used.

Figure 9: High Speed Disc Plough in operation on Farm 1.

Figure 10: Soil following high speed disc ploughing on Farm 1.

Farmer 1 highlighted how financing the change in equipment and equipment delivery time slowed down the transition in cultivation practices. Another aspect is that multiple implements and equipment are required and that using the same implements on different fields is required for consistency. This represents a significant cost to the farm as a change in practices can be seen as not only purchasing a single set of implements but rather sets of three, four or more depending on the size of the farm. Farm 1 had three tractors working simultaneously on the same field, to prepare it for cultivation. Farmer 1 stated that the main issue is timing so fields have to be prepared prior to specific windows of opportunity for planting. It was also highlighted that with current practices, each tractor can complete around 25 ha of work per day, with the trio of tractors being able to complete roughly 75 ha per day. This highlights the importance of having multiple tractors and sets of equipment available if the farm is large. Too long a preparation time would impact on sowing dates, which will have knock on effects across the season.

The timing of tasks is also critical when there are multiple crops being cultivated. As highlighted during the site visit, there needs to be balance between field preparation for plots for soybeans, sunflowers and maize. Sowing of seeds need to be conducted in a calculated manner in order to have harvest times which do not overlap, particularly if there is only one harvester available. For example, if both maize and sunflower crops are ready to be harvested at the same time, the time it takes to complete the harvest will cause yield loses while the other crops wait to be harvested. For example, Farm 1 is divided up into multiple fields in order to adequately manage soil conditions, sowing and crop rotations. As explained by farmer 1, a typical rotation will be one year of soybeans, followed by 3-4 years of maize planted using a no-till system, which then is followed by one year of sunflowers. With a no-till system, the implement as seen in Figure 7 can be utilised to directly plant into field conditions, as seen in Figure 8. However, before changing to sunflowers, a high speed disc is utilised in order to chop down the maize residue from the previous season. This assists in accelerating the breakdown of crop residue into soil organic matter as well as levelling the fields (Figs. 9, 10). Sorghum is only planted to provide cattle feed. The goal highlighted by farmer 1 is to plant roughly 66% maize, 15% soybean, 15% sunflower and 4% sorghum each season, with crop rotations aiming to maintain these ratios (Table 5).

Table 5: Land use for cultivated crops on Farm 1 relating to the 2023/2024 season.

Field	**Maize (ha)**	**Soybeans (ha)**	**Sunflowers (ha)**	**Sorghum (ha)**
A1	110	-	-	-
A2	110	-	-	-
A3	110	-	-	-
A4	-	30	-	30
A5	-	-	-	10
A6	-	-	-	8
A7	-	110	-	-
A8	90	-	-	-
B1	75	-	-	-
B2	90	-	-	-
C1	-	-	170	-
C2	-	30	-	-
C3	45	-	-	-
C4	115	-	-	-
Total (ha)	**745**	**170**	**170**	**48**

5.2.1. Fuel management

Fuel management is a critical element of commercial agriculture due to the number of large-scale equipment utilised throughout the farming operation. As highlighted from the questionnaire responses, the management of fuel represents a key challenge from two key aspects: (1) the tracking of fuel dispensing and its allocation as per the South African Revenue Services (SARs) requires detailed logbooks. Farm 1, where observations were conducted, has recently upgraded its fuel management system as per the recommendations from neighbours who operate a similar system. Farmer 1 used a physical logbook to track information relating to vehicle operating time, fuel consumption, operational tasks and the amount of fuel dispensed from the storage tanks at a given time. At beginning of 2023, farmer 1 upgraded the system to be automated allowing for greater control over the system and improved accuracy of the data collected. This system only allows for diesel to be pumped from the system using a magnetic identification token. This limits the members of staff who have the ability to authorise diesel dispensing. The use of the magnetic token is then followed by an activation pin, followed by the identification token for the specific vehicle that will receive fuel (Fig. 11).

Figure 11: Magnetic identification tokens, Farm 1.

(2) Furthermore, data collected will also include the operator's identification, operating time of the equipment, fuel consumption, the specific task the machine was doing at the time, and how much fuel is dispensed. At the end of each month, the data collected is then transferred to a USB where it can be viewed in Microsoft Excel and processed. The key advantage of this system is that it reduces the amount of time spent managing the data, reduces costs related to purchasing of physical logbooks, and reduces storage requirements which are associated with filing of physical log books. Furthermore, this system aids in improving security as fuel cannot be dispensed without authorisation. As highlighted by the farmer, fuel management and storage become more challenging when a lot of tillage is required, with neighbouring farms that operate rip-on-row requiring more fuel for their operation and subsequently greater on-farm fuel storage. An example of fuel storage infrastructure can be seen in Figure 12. This type of automated system is also used by neighbouring farmers. Records are required to be kept relating to fuel deliveries, with the date, amount, invoice number and supplier of the fuel. It is essential for accurate records are kept in order to comply with the fuel rebate laws. These data

are required to be stored for up to five years and forms a significant proportion of the administrative work which is required of each commercial farmer. An example of a fuel log book can be seen in Table 6. Fuel management is a critical element within commercial agriculture, particularly given increased fuel costs, with farmers stating the current cost per hectare is extremely high, placing more pressure on maintaining high yields in order to cover the increased costs.

Figure 12: Fuel storage infrastructure. Farm 1.

Table 6: Example of fuel log book entries, Farm 1.

GPS co-ordinates										
Balance (L) Opening	**Balance (L)** Closing	**Date**	**Time**	**User ID**	**Vehicle ID**	**Operator ID**	**Operating time of Equipment (Minutes)**	**Fuel consumption**	**Task**	**Fuel Pumped (L)**
12 500		18/10/2023	10:42	F1	Tractor 1	O1	327	60L/Ha	Disc plough	400
			10:53	F1	Tractor 2	O2	334	56L/Ha	Disc plough	390
			11:01	F1	Tractor 3	O3	311	62L/Ha	Disc plough	410
			11:15	F2	Pick Up 2	F2	371	11.8L/100km	Checking Fence lines	74
			13:22	F1	Pick Up 1	F1	427	10.2L/100km	Transporting Staff	82
			15:42	F2	Tractor 4	O4	280	17L/Ha	Stock Organisation	110
	11 034									
11 034		19/10/2023	07:10	F2	Tractor 1	O1	301	59L/Ha	Disc plough	390
			07:21	F2	Tractor 2	O2	303	57L/Ha	Disc plough	374
			07:32	F1	Tractor 3	O3	287	34L/Ha	Herbicide Spraying	220
	10 050									

5.2.2. Input management and organisation

A significant number of inputs including herbicides, insecticides, fungicides, pesticides, pH balancers for water, and fertilisers had been delivered on the day which observations were conducted on Farm 1. This process is a critical part of commercial farm management as these products are critical for a successful agricultural season, as well as making up a significant portion of capital investment. Reduced and no-till systems require a greater number of inputs relating to weed management when compared to more conventional based systems in which tillage practices such as forms of rip-on-row and ploughing are used to control weeds rather than through the use of herbicides. This is one of the key differences which was highlighted by farmer 1 and one of the key challenges in adapting from a conventional system towards a conservation system as the timing of weed spraying is critical. Delivery of these items was followed by moving the pallets into storage room and then organising them (Fig. 13). The storage facility was divided into a section for each crop which was planned for the 2023/2024 season, and the products organised in the order in which they would be used. For example, herbicides which would only be required once the maize plants reach the reproductive stage are packed towards the back of the facility. Input products which would be required during the vegetative stages of the plant's development were packed towards the front. This process took about 45 minutes and required several staff members to assist. The use of a smaller tractor with a forklift attachment was used to move pallets from where they were offloaded, to the entrance of the storage facility where they were unpacked and organised. The majority of these products are liquid concentrates, coming in sizes of 1 L, 5 L, 10 L, 20 L and 25 L bottles.

Figure 13: Tractor with forklift attachment during stock organisation, Farm 1.

The fertiliser mixes arrive in 1-ton bags which are set on wooden pallets to allow for easier storage and movement. Urea fertiliser which is added to the mixes arrived in 50 kg bags and is stored with their corresponding 1-ton counterpart (Fig. 14).

Figure 14: 1-ton fertiliser bags, Farm 1.

5.2.3. Water management

Although irrigation of crops is not utilised by the majority of farmers (95%), water remains a critical part of any agricultural system including in dryland maize production. As previously discussed, critical inputs such as herbicides, insecticides, fungicides, and pesticides come in various sized concentrates. This means that they need to be mixed in large tanks with the corresponding water ratios in order to be applied through crop spraying. This may take place through the use of drones, various forms of boom sprayers or a tow-behind sprayer. The water can be received through municipal supply lines, which have a water meter in order to track usage as well as a municipal cost which is billed. However as observed on Farm 1, as well as on neighbouring farms, borehole water is utilised. Farm 1 derives all (100%) of its water demands from multiple boreholes on the property, using this for both crops and livestock as well as domestic use. Water usage is tracked using a water meter to maintain compliance with water usage licenses. The data collected on the meter are entered into a spreadsheet. Farmer 1, however, mentioned that most of the neighbouring farms use borehole water only for agricultural production with municipal supply being used for domestic use.

The configuration of the water management system is a critical element of the farm with recent changes being implement to improve the efficiency of the water infrastructure and to build climate resilience. Two large steel water reservoirs are connected in series allowing for a gravity feed system between the two. Piping is laid from the various boreholes sites and connected into the reservoir system with water being pumped when the system drops below 75% total capacity in order to maintain suitable reserve capacity. The pumps are fully powered by solar energy which has reduced the farm's production costs when compared to previous years where this was powered by municipal electricity supply. Furthermore, the use of solar energy pumps has also negated the impacts of loadshedding which previously affected pumping and increased costs through the use of generators.

The borehole water which is used for the various input concentrates is pumped into large portable tankers where the pH level is checked and any pH balancing inputs can be made. The concentrates can then be added and the portable tankers pulled with a tractor to the fields for the distribution to the spraying equipment.

5.2.4. Equipment maintenance

The maintenance of agricultural machinery is a critical component of commercial farming and represents a significant element in the management practices for a farmer. This is needed for farms of all sizes, as equipment must be ready to perform tasks as delays can have significant knock-on effects during the season, such as yield loss due to harvesting delays. As observed on farm 1, scheduled equipment maintenance is undertaken, with tractors having their oil levels checked, and spraying equipment nozzles and supply lines checked to assess for leaks or blockages. No-till planters were oiled in preparation for the planting season. The maintenance of equipment becomes important when precision agriculture techniques are used as equipment needs to be calibrated and working as intended. This was emphasised by farmer 1, who stated that if machinery is not calibrated correctly it is possible to use more or less fertiliser than is required in certain areas of the field.

5.2.5. Precision agriculture

Precision agriculture is viewed positively by questionnaire respondents, with 71% of farmers stating they felt it was beneficial and a good investment overall, with equipment GPS guidance, auto-steer on tractors and yield mapping being the most commonly identified tools (Fig. 15).

Key beneficial aspects of precision agriculture identified were the reduction in costs for production, highlighted by 38% of respondents, and the ability to increase yields/profits, highlighted by 48% of participants. The main drawback of precision agriculture was that it is expensive to implement (38% of respondents). The cost benefit of investing in precision agriculture depends on the size of the farm (33%), with smaller farms not as likely to make the adoption of the equipment financially viable. Only 10% of farmers stated that they found precision agriculture complicated, and adoption of the equipment and techniques depends on compatibility with current machinery.

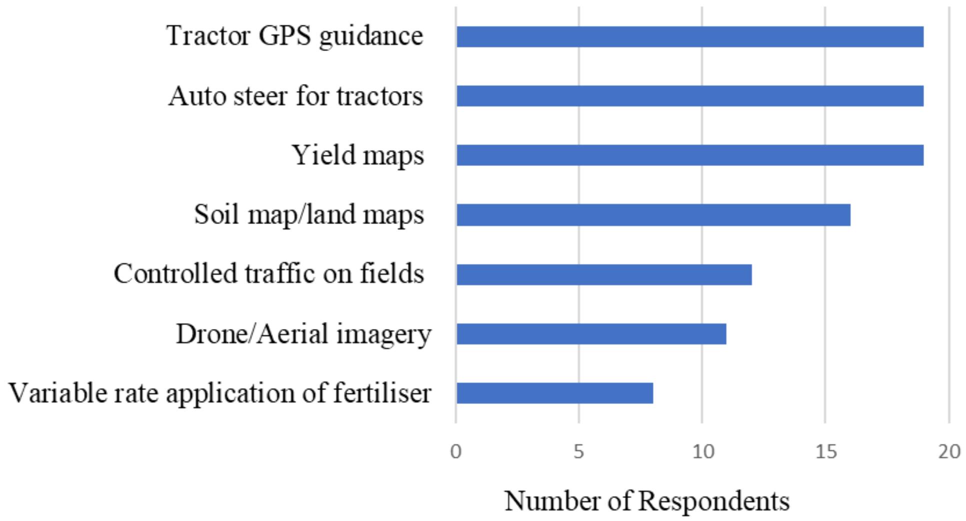

Figure 15: Aspects of precision agriculture utilised by farmers in the study area.

In detail, the majority of farmers (91%) use yield mapping, GPS guidance and auto-steer for tractors. Most (76%) also use soil/land mapping, with 57% of farmers using controlled traffic on their fields. A little more than half (52%) make use of drone/aerial imagery to monitor field conditions. The least utilised aspect of precision agriculture is variable rate application of fertiliser, which is only implemented by 38% of farmers (Fig. 15). Those who use this have a greater area of maize cultivation, ranging from 525 ha to 1200 ha. The use of controlled traffic on fields aids in reducing fuel consumption as well as field compaction which was highlighted as being a key benefit by farmers who utilise this method.

A large high powered drone is one the key investments that farmer 1 has made in the last two years (Fig. 16). This drone is able to perform two key tasks which can save time and money. The first is scouting, particularly useful for assessing crops following emergence as well as throughout their growth stages. Aerial photographs can be taken and potential problems can be identified such as discolouration of leaves which the farmer can then address, reducing the amount of time spent in the field. The drone is also capable of spraying inputs and has a capacity of 40 L, allowing for targeted spraying to be conducted remotely without impacting on the soil from large scale machinery. This process is cheaper and quicker for spot specific applications field. Farmer 1 also shares his technology with neighbouring farms. Common practices such as planting and spraying are often conducted early in the morning or late afternoon/evening to reduce impacts associated with heat, as there may be soil moisture loss during planting as well as evaporation during spraying if the temperatures are high. Often large-scale spraying is performed at night in order to reduce evaporation. GPS guidance and auto-steer on tractors is particularly useful when operating in reduced light, with a high degree of accuracy achieved regardless of visibility. Tractors are also fitted with large spotlights for this aspect of the operation.

Figure 16: Commercial drone, shown in its travel case on Farm 1.

5.2.6. Conservation Agriculture

Conservation agriculture is generally viewed positively by farmers with 81% of farmers highlighting the benefits for maintaining soil moisture and quality. Some (24%) farmers stated that is a relatively new concept/practice within the agricultural sector, and 43% of farmers highlighted challenges with the adoption of conservation agriculture techniques due to increased pressures on management practices such as the timing of herbicide inputs and weed control. All (100%) farmers stated that they practice crop rotation with 81% of farmers utilising mulching/crop residue mulching (Fig. 18). However, none of the farmers used cover crops. This may be attributed to the low winter rainfall received in the Sannieshof region (Fig. 4). This was highlighted by farmer 1, who felt that the use of cover crops had a high degree of risk as they may draw a large amount of soil moisture which may negatively impact later summer crop production, particularly of maize. Farmer 1 also stated that cover crops require continued management during the winter months. This element of conservation agriculture is therefore viewed with a degree of caution by farmers, but its potential for adoption has not been ruled out. There is a degree of overlap between conservation agriculture principles and the use of precision agriculture, as where minimal soil disturbance overlaps with the use of controlled traffic on fields. Furthermore, practices such as the use of no-till planters (Table 4, Fig. 7) also aids farmers in adopting conservation agriculture principles, particularly with regards to minimal soil disturbance while ensuring the soil remains covered with organic matter.

Figure 17: Example of land with crop residue mulching, observed on Farm 3.

5.3. Climate Change Adaptation

All farmers (100%) felt that there was not enough information provided by the government in relation to weather and climate change. The majority (81%) of farmers used Yr Weather as their main source of weather and climate data as they felt it was most accurate (Fig. 18). Most (76%) farmers felt it is important to adapt their agricultural activities to climate change, while 24% of farmers do not see it as important as they did not believe climate change was a serious threat. Farmer 16 in their questionnaire response stated that "Every year presents its own challenges relating to weather, you have to make the best of the conditions which are presented for that season. The climate has always been changing in the Sannieshof area."

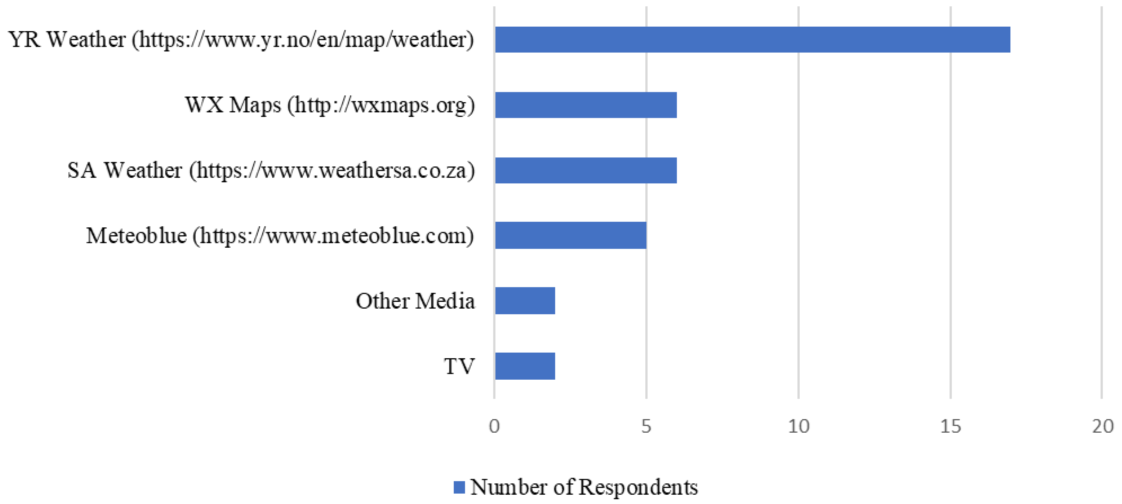

Figure 18: Weather and climate data sources used by farmers in the study area.

Farmers utilised a variety of information sources for climate change adaptations (Fig. 19). All farmers stated in the questionnaire responses that wind erosion is a concern, however their common use of crop residue mulching (Fig. 20) might be used as mitigation against this.

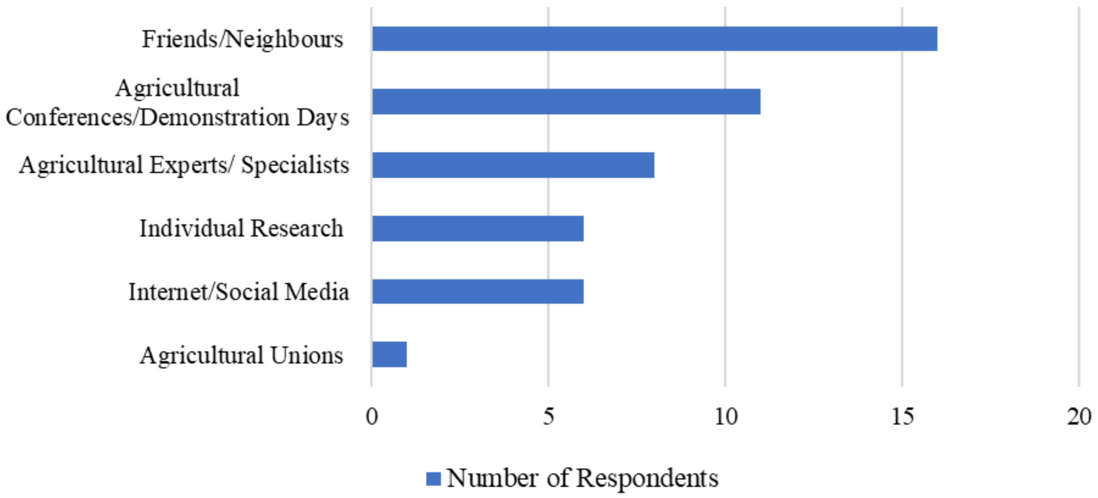

Figure 19: Sources of information for climate change adaptations utilised by farmers in the study area.

All farmers stated that the main barrier to implementing adaptation techniques and developing their agricultural operations is the financial cost of new machinery. However, 38% of farmers also highlighted the time it takes to develop new skills and training in order to implement these techniques. Different adaptation techniques have been used by respondents, with the most common being mulching, adjusting of planting dates and the use of precision equipment (Fig. 20). Planting dates can be shifted forwards or backwards depending on the timing of summer rainfall. Other adaptation techniques include changing of plant population density according to rainfall. The selection of seeds is also important, as different maize hybrids can be selected based on rainfall forecasts. Planting depth can also be varied according to rainfall forecasts with seeds planted deeper for seasons with lower rainfall. Farmer 1 stated that during drier seasons seeds are planted 3-5 cm deeper while in wetter years they are planted a few cm shallower.

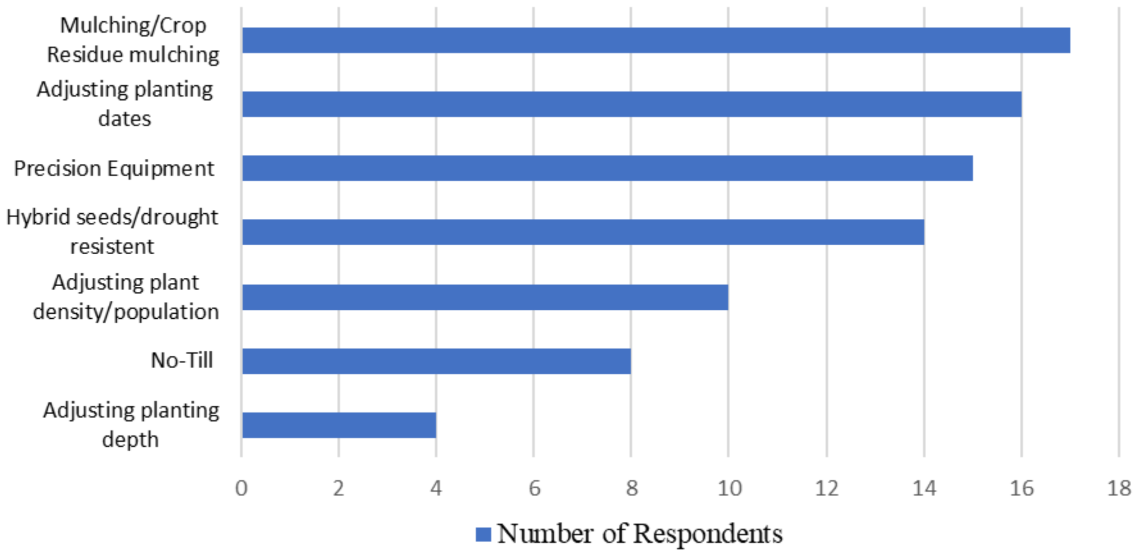

Figure 20: Implemented adaptation techniques utilised by farmers within the study area.

5.4. Socio-economic impacts on farming activities

All farmers stated that increased fuel prices have a negative effect on agricultural activities, where the cost of production per hectare increases significantly. Fuel costs are in the range of 15% to 22% of total production costs for the farmers which is a significant portion of seasonal expenses. A few (14%) farmers highlighted the increased risk of storing expensive fuel on the farm due to the potential of diesel theft. Other impacts identified were changes in work schedules due to load shedding disruption and increased cost of production due to the use of generators (Fig. 21).

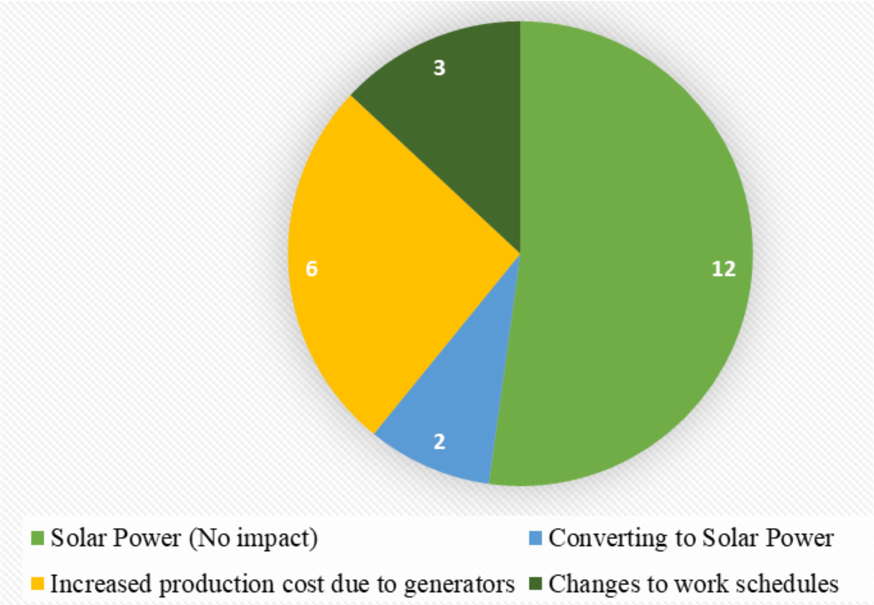

Figure 21: Impacts of load shedding experienced by farmers in the study area.

Load shedding has a varied impact on agricultural activities, with 57% of farmers stating they have switched to solar power and a further 10% of farmers currently in the process of implementing solar power. It was highlighted, however, that this is expensive. Farmer 13 stated that they have been financing the development of solar infrastructure over 4 years due to the cost of infrastructure. Farmer 1 stated that their solar power system was financed over 6 years. Farm 1 is fully powered by solar for all aspects of agricultural production and domestic use (Fig. 22). Farmer 1 highlighted how this investment is critical in the long-term development of his farm as it makes the farm more sustainable, particularly from an economic perspective. Furthermore, solar energy removes any issues relating to load shedding.

Figure 22: Solar energy invertors. Farm 1.

Socioeconomic factors such as fluctuations in prices of fuel, seeds and agronomic inputs have a significant impact in the seasonal planning and year-to-year planning. All farmers highlighted for more detailed budgets in order to manage price fluctuations. For example, farmer 4 said “Due to price increases I have to get more quotations from suppliers and workout which combinations provide the best value, it takes a lot more time dealing with multiple companies rather than just one.” All farmers stated they do not receive assistance from government in relation to climate change adaption, and expressed that they often felt neglected by government. Several government policies were identified as impacting on agricultural activities (Fig. 23). It was highlighted that the increased amount of detail required in order to maintain compliance with labour regulations, water use licenses and fuel logbooks, results in more time being spent on administrative work.

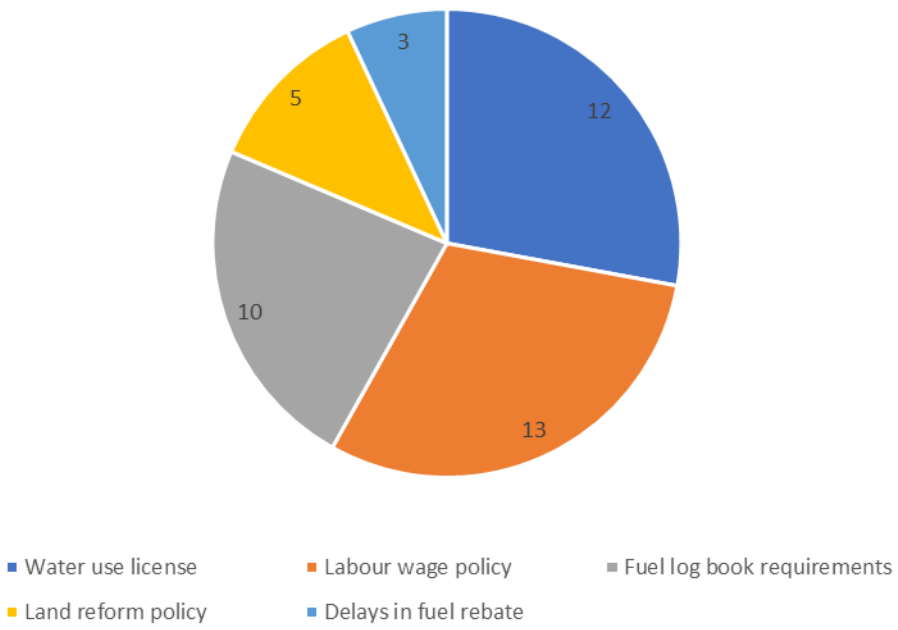

Figure 23: Identified government policies which impact farmers in the Sannieshof region.

Rural crime remains a key issue, with 76% of farmers stating they have experienced it. A number of elements of crime were identified by farmers (Fig. 24). Diesel theft was experienced by 57% of respondents. The majority (76%) of farmers identified the high costs of security as taking resources away from agricultural activities. Several security measures have been invested in by farmers, including CCTV, alarm systems, camera systems, security flood lights, security gates and electric fences, as well as motion sensors.

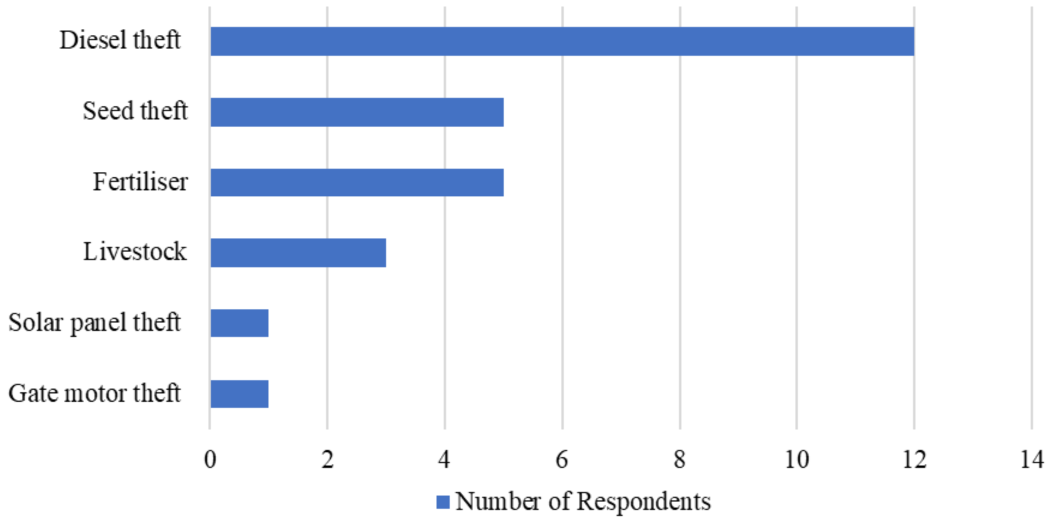

Figure 24: Aspects of crime which farmers in the study area have experienced.

6. Discussion

6.1. Introduction

The agriculture sector is highly complex with a number of interdependencies between socioeconomic variables, environmental factors, and agricultural practices (Cammarano *et al.,* 2020). The relationship between these variables is dynamic as they does not remain constant. This draws comparisons to the Water-Energy-Food nexus as the relationship of impacting variables can be understood from a similar perspective (Endo *et al.,* 2017; Albrecht *et al*., 2018; Nhamo *et al.,* 2020b). Commercial maize farmers deal with a number of challenges relating to environmental and climate conditions as well as socioeconomic challenges, while simultaneously managing their agricultural activities in response to changes (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020). The relationship between these variables may be clear such as through the relationship between rainfall and maize production, but there may be more complex relationships between crime and maize production, or trade-offs between crime and climate change adaptation. It is important to recognise the web of relationships between socioeconomic, climate change and farm management practices, while also considering that the impacts of changes within these relationships are not equal. For example, changes in climate conditions may have impacts on socioeconomic and farm management factors while socioeconomic disruptions may result in a lack of ability to respond or adapt.

Commercial maize farmers have to deal with a number of trade-offs when addressing challenges of climate change and variability, socioeconomic drivers and everyday agricultural operations (Fig. 25). The risks and exposure posed for agricultural operations may differ due to farm management practices, individual farm characteristics, and farmers' attitudes and perceptions. The severity of the drivers of change may also vary due to farm management practices, for example tillage practices can result in negative feedbacks in relation to soil conditions (Fig. 25). Figure 25, illustrates phase one of water-energy-food (WEF) nexus framework, highlighting how drivers of change interact with farm management practices, including potential feedbacks which may increase the severity of the drivers of change over various temporal and spatial scales. Phase two of the water-energy-food (WEF) nexus framework is illustrated in Figure 26, demonstrating how each farmer should therefore consider the drivers of change, which may vary due to geographic location of the individual farm, the current stage of development of their own management practices and infrastructure, as well as the operational budget and resource availability. Farmers would then prioritise which drivers of change need to be addressed through assessing the agricultural operations vulnerability or resilience towards the driver of change (Fig. 26). Once the drivers of change have been prioritised, adaptation strategies can be considered which involve considering environmental/socioeconomic feedbacks or trade-offs, with the goal of reducing the risk and exposure of the farmer towards the driver of change, as illustrated through the feedback loop illustrated in Figure 26. The environmental/socioeconomic feedbacks or trade-offs, would need to be considered over short, medium and long time scales. For example, if a driver of change was poor nutrient availability within the soil, the adaptation may be to increase fertiliser inputs which would address the issue on a short term basis, however the long term feedback may result in further depleted soil conditions. Financial limitations/budget constraints result in commercial maize farmers having to prioritise certain elements of their operation. For example, farmers who are negatively affected by crime have chosen to allocate a portion of their operational budget towards developing their on-farm security infrastructure. This aspect was identified by the majority of farmers (76%) as having a negative effect due to the high costs associated with security equipment. This may impact farms resilience and limit adaptation against climate change. This highlights one of the trade-offs which may be considered by commercial maize farmers within the study area.

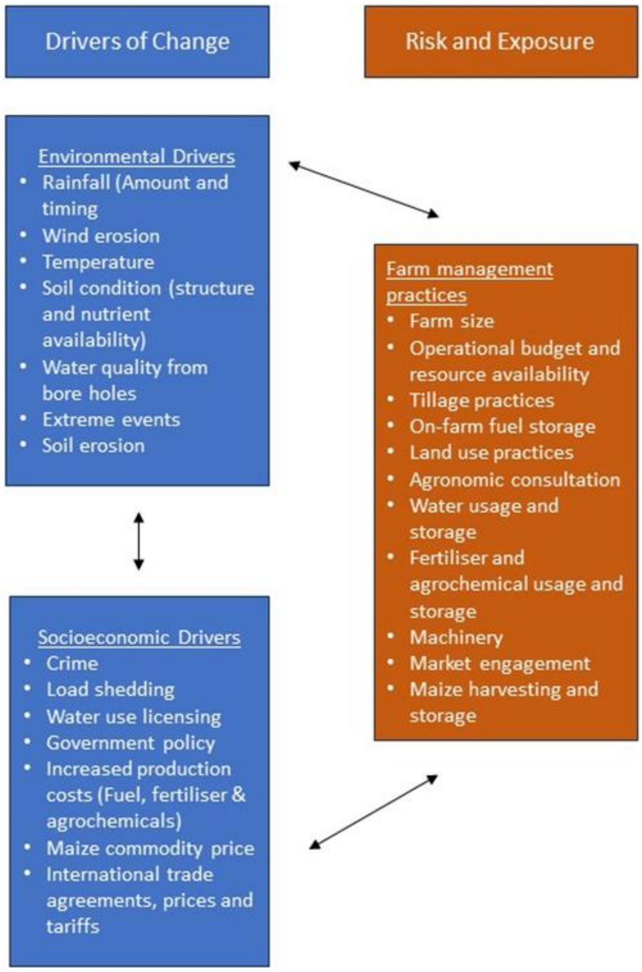

Figure 25: Phase one of adapted water-energy-food (WEF) nexus framework illustrating the relationship between drivers of change for commercial maize farmers with risk and exposure considerations.

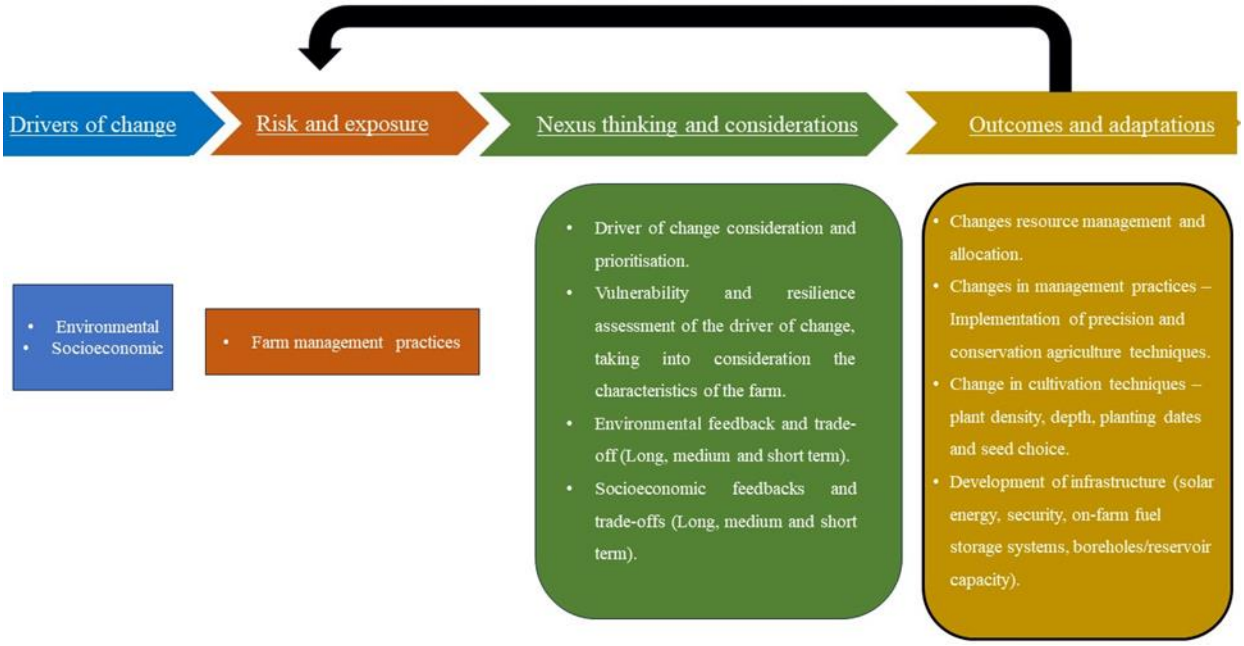

Figure 26: Phase 2 of adapted water-energy-food (WEF) nexus framework illustrating the process of determining driver of change prioritising and adaptation.

6.2. Agricultural management practices in the Sannieshof region

Commercial agriculture in South Africa has been largely developed through intensification of production (Matson *et al*., 1998; De Wit *et al.*, 2015; Erenstein *et al.*, 2022). This involves more agronomic inputs and data driven decision making in order to improve yields while maximising profitability (Bruwer & Khwidzhili, 2022). These management practices include capital investments towards production and management technologies, the use of hybrid seed varieties, high labour demands, single crops grown continuously, and the use of pesticides and fertilisers (Mondelaers *et al.,* 2009; Meyer *et al.,* 2018; Sumberg & Giller, 2022). Conventional maize farming practices are closely tied to the agribusiness sector informed by advice relating to soil management; crop protection of pests and weeds, and plant nutrition (Bruwer & Khwidzhili, 2022).

A number of these characteristics are applicable to the commercial maize farmers' management practices in the Sannieshof region, such as the use of agronomic consultation, agrochemical inputs (fertilisers, herbicides & pesticides) and hybrid seed varieties , however there are aspects where farmers differ. A key point of difference is the use of crop rotation. All farmers (100%) stated that they use crop rotation, with the majority (62%) growing a combination of maize, sunflowers, and soybeans and a minority (38%) growing only maize and sunflowers.

Agronomic companies and their services are part of the management practices of commercial maize farmers in the Sannieshof region, with all farmers (100%) stating that they consult with companies to advise on crop production, soil analysis, fertiliser recommendations and spray programs.

Dependence on chemical-based fertilisers has a negative effect on the environment, including groundwater and river contamination through leaching of these elements through the soil as well as through soil erosion (Mondelaers *et al.*, 2009; Meyer *et al.*, 2018; Smith *et al.*, 2021). Use of chemical-based fertilisers, as well as various other agronomic chemicals such as pesticides and herbicides, is a management practice routine within the broader commercial agricultural sphere, which has been criticised due to its lack of environmental and economic sustainability (Meyer *et al.,* 2018). Concerns surrounding the environmental impact of chemical-based fertilisers and agronomic inputs, can be highlighted through the management practices utilised. Table 3 reveals that 29% of farmers incorporate lime inputs, primarily employed as a soil pH balancer. Farmer 1 emphasised the necessity of pH balancers for borehole water.

Conventional commercial maize agricultural practices make use of various forms of tillage prior to cultivation, in particular as a form of winter weed control (Du Plessis, 2003; Meyer *et al.,* 2018). Tillage practices vary within the Sannieshof region and are largely dependent on the environmental conditions of fields (Table 4). This may include rip-on-row which is utilised in order to manage soil compaction. Deep tillage practices are usually only employed in response to soil compaction, and disc ploughing is often used in rotation when soil compaction is no longer an issue (Table 3) with 33% of farmers utilising these practices in combination. No-till practices are used by 38% of farmers.

Commercial agriculture is often highlighted as being energy intensive and requiring large amounts of fuel, to which tillage practices contribute significantly. De Wit *et al.* (2015) found a substantial reduction in fuel consumption per hectare when transitioning from conventional agriculture towards no-till methods in North West Province. This highlights the extent to which management practices can influence production costs and energy requirements of an individual farm.

6.3. Climate change adaptation

There is consensus that climate change will have a wide range of impacts on agriculture in Africa, with projections highlighting increased temperatures, changes in rainfall patterns and increased climate extremes (Mangani *et al*., 2019; Nhemachena *et al.,* 2020). Crop modelling projections have suggested that maize production has a high degree of vulnerability under future climates due to its sensitivity to heat waves, droughts and cold snaps which may cause yield loss as well as a reduction in yield quality (Fischer *et al*., 2005; Walker & Schulze, 2008; Lobell *et al*., 2011; Serdeczny *et al.,* 2015; Mangani *et al.*, 2018; Nhemachena *et al.,* 2020). Overall, sub-Saharan Africa is vulnerable to climate change due to its dependence on rainfed cropping systems (Walker & Schulze, 2008; Lobell *et al.,* 2011; Serdeczny *et al.,* 2015). This type of agricultural is predominately practiced in the Sannieshof region, with 95% of farmers using rainfed maize cultivation.

There is a need for maize farmers to adapt to the varying impacts of future climate change (Nhemachena *et al*., 2020). The majority of farmers in the study area (76%) said that they felt it was important to do this. However, 24% of farmers said that they did not consider climate change as a cause for concern, which is point of interest because climate change adaptation requires a long period in order to develop suitable adaptation techniques and to improve resilience. Previous research has focused on how farmers understand climate change adaption and what the challenges associated are, rather than understanding why they may not perceive the need for adaptation (Wilk *et al*., 2013; Raaijmakers & Swanepoel, 2020; Pienaar *et al*., 2021). This is important to consider in the application of the nexus framework, as the attitudes that farmers have will directly impact on the ways in which drivers of change are understood and prioritised (Fig. 26).

There is consensus among farmers that a lack of government support is a limiting factor for successful climate adaptation. This is further emphasised by farmers' dependence on agronomic companies for information and assistance, rather than from agricultural extension officers or similar independent rather than commercial sources. Farmers said that they feel neglected by the government as there are no connections between them and agricultural department officials. This similar to the sentiments of farmers elsewhere (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020; Pienaar *et al*., 2021).

Farmers in the Sannieshof region have a relatively strong position with respect to institutional arrangements, which refers to agricultural organisations and agronomic consultation (Table 3), despite the lack of governmental support. Farmers use a number of information sources to learn about climate change adaptation techniques, including friends or neighbours (76% of farmers) (Fig. 17). This demonstrates the importance of good social networks for information sharing. Agricultural conferences and demonstration days were also identified, alongside engagement with agricultural experts/specialists (Fig. 17). The importance of such institutional arrangements in relation to successful adaptation has been underlined elsewhere (Wilk *et al.*, 2013; Raaijmakers & Swanepoel, 2020). Strauss *et al.* (2021b) emphasised that the Conservation Agriculture Farmer Innovation Programme can provide opportunities for farmers to interact with each other and agricultural experts in order to develop their management practices. These aspects all assist in climate change adaptation (Wilk *et al.*, 2013; Raaijmakers & Swanepoel, 2020). However, financial constraints are still applicable, as there are clear trade-offs in determining where money is spent. An example is that 76% of farmers identified the high costs associated with improving on-farm security as taking financial resources away from agricultural activities.

Farmers have made use of a number of adaptation techniques (Fig. 18) which have been commonly used throughout South Africa (Benhin, 2006; Wilk *et al.*, 2013; Nhemachena *et al*., 2020; Cammarano *et al.*, 2020). Changing of planting dates is common practice, based on soil moisture content and temperature (Du Plessis, 2003). A contributing factor to determining planting dates is cultivar choice, as specific cultivars will have different requirements (Du Plessis, 2003). Adjustment of planting dates is utilised by 76% of farmers within the study area. Changes in plant density/population is also used in order to reduce competition between plants during drier seasons. Two thirds of farmers stated that they utilise hybrid/drought resistant seed varieties as a form of climate change adaptation. This was also highlighted as a climate change adaption technique by commercial farmers elsewhere (Benhin, 2006; Wilk *et al.*, 2013; Nhemachena *et al.*, 2020; Cammarano *et al*., 2020). The use of hybrid seeds with specific characteristics is common through the commercial agriculture sector, alongside the use of chemical-based fertilisers (Mondelaers *et al*., 2009; Meyer *et al*., 2018; Sumberg & Giller, 2022). Furthermore, adjustment of planting depth was cited as an adaptation technique by 19% of farmers (Fig. 18).

6.3.1. Conservation agriculture in Sannieshof

Conservation agriculture techniques such crop residue mulching is the most cited adaptation technique, with 81% of farmers using this (Figs. 7, 17). Overall, farmers viewed conservation agriculture positively, particularly for improving soil moisture and soil quality. Organic soil cover aids in retaining soil moisture as well as reducing wind and water erosion (Derpsch *et al*., 2014; Kassam *et al.*, 2019; Strauss *et al.,* 2021b; Van Antwerpen *et al.,* 2021). All farmers (100%) stated that they use crop rotation (Fig. 9), however none use cover crops due to concerns around loss of soil moisture. The implementation of minimum soil disturbance is only utilised by 38% of farmers, through the adoption of no-till practices (Table 4). Minimum soil disturbance aims to improve soil structure, infiltration, and water retention through no-till seeding (Fig. 8). Furthermore, soil disturbance should be limited from any other forms farm traffic such as delivery of fertilisers and harvesting (Derpsch *et al.*, 2014; Kassam *et al.*, 2019; Van Antwerpen *et al.*, 2021). This aspect overlaps with precision agriculture techniques, such as controlled traffic on fields, auto-steer, and GPS guidance. Most (57%) farmers control traffic on fields, while 91% of farmers make use of auto-steer and GPS guidance (Fig. 15).

The complete adoption of a conversation agriculture system requires all three principles (minimal soil disturbance, permanent soil cover, and crop rotation) to be implemented simultaneously (Derpsch *et al.*, 2014; De Wit *et al.*, 2015; Findlater *et al.*, 2019; Strauss *et al.*, 2021a; Van Antwerpen *et al.*, 2021; Kassam *et al.*, 2022). It is unclear whether conservation agriculture systems have been comprehensively adopted by farmers in the study area, because there are different interpretations of what constitutes a conservation agriculture system. This has been previously highlighted by Findlater *et al.* (2019) and Raaijmakers & Swanepoel (2020). Only a minority (38%) of farmers use what can be classified as full conservation agriculture, similar to the number identified by Smith *et al*. (2021) in North West Province. Findlater *et al.* (2019) suggested farmers adopt one or two of the principles and interpret this as a full conservation system. With relation to farmers in the study area, 100% use crop rotation while 81% use year-round organic soil cover (crop residue mulching). Van Antwerpen *et al*. (2021) state that farmers will only use those practices that they perceive to be relevant and suitable to their specific conditions/circumstances. This may relate to both environmental as well as financial circumstances, as the cost of machinery is a substantial factor in determining agricultural practices (Tieppo *et al.,* 2019). This has been highlighted by Smith *et al.* (2021) who stated that different soil types may require deep tillage practices such as rip-on-row in order to manage compaction. However, 38% of farmers also highlighted the time needed to develop new skills and training. Strauss *et al.* (2021b) underlined the importance of having networks available for farmers to develop their skills, such as the Conservation Agriculture Farmer Innovation Programme.

6.3.2. Precision agriculture in Sannieshof

The use of precision agriculture equipment was highlighted by 71% of farmers as an important element of climate change adaptation (Figs. 15, 20). Lowenberg-DeBoer & Erickson (2019) emphasised that precision agriculture is not a singular piece of equipment or technology, but rather a toolkit that individual farmers can utilise where it is applicable. Successful implementation of precision agriculture improves resource optimisation and efficiency while reducing input losses and production costs (Nyaga *et al*., 2021). This is critical given the current market prices for agronomic inputs and fuel, leading to current high costs of production. Precision agriculture allows farmers to manage their resources more efficiently. This approach is shared with commercial farmers in KwaZulu-Natal who identified resource management efficiency as a key element for climate change adaptation and in managing socioeconomic stresses (Wilk *et al.,* 2013). The use of drones is beneficial due its relative affordability, immediate access to data and the precision which the machinery offers, allowing for informed decisions to be made on input applications faster (Munghemezulu *et al*., 2023). The benefits of GPS guidance and auto-steer on tractors have also been identified in this study. As highlighted by Bora *et al.* (2012), these tools prevent farmers from overlapping during tasks such as planting or fertiliser delivery, reducing fuel consumption. These precision agriculture techniques are also common on commercial farms in the Free State and North West Province (Van Antwerpen *et al.,* 2021) where farmers in these regions identify the financial benefits (Jacobs *et al.,* 2018). This aspect was highlighted by 48% of farmers in Sannieshof. As stated by Jacobs *et al.* (2018) farmers who use of precision agriculture equipment, cited the cost of machinery as the major barrier. The cost of implementation was highlighted by 38% of farmers in Sannieshof. This is similar to values in the Western Cape and Free State (Maine *et al.,* 2010; Jacobs *et al.,* 2018; Raaijmakers & Swanepoel, 2020). Variable rate application of fertilisers can have positive economic benefits by improving profitability but was largely determined by the size of the farm (Maine *et al.,* 2007, 2010). This aspect was also addressed by Jacobs *et al.* (2018) who suggested that farmers with less than 500 ha under cultivation are unlikely to adopt precision techniques. Results from the Sannieshof region highlight this relationship, as the farmers who utilise variable rate applications of fertiliser have the largest areas of land under cultivation (Fig. 6).

6.4. Socioeconomic impacts experienced on commercial maize farms

A wide range of socioeconomic factors influence commercial farming activities and decision-making. These may relate to government policy, social issues such as crime, infrastructure issues such as loadshedding, and changes in local/global markets (Fig. 25). Changes within socioeconomic circumstances can have knock-on effects on the broader agricultural sector as well as individual commercial farming operations. Increases in agronomic inputs, agrochemical and fuel prices have negative impacts on the sector (Nkunjana *et al.,* 2023). Recent market instability has been highlighted as a key issue for agriculture, as well as the availability and price of inputs (Kriel, 2022).

Commercial maize agriculture can be considered energy intensive, both from the perspective of electricity consumption and also the fuel required to run machinery (Nazlioglu & Soytas, 2011; Aye & Odhiambo, 2021). Farmers stated that fuel consumption is a significant proportion (15-22%) of their production costs. This highlights the vulnerability of commercial maize agriculture towards fuel price increases (Nkunjana *et al.,* 2023). Furthermore, 14% of farmers stated the increased risk of theft from on-farm fuel storage and most (57%) had experienced farm theft (Fig. 24). Load shedding was highlighted by 29% of farmers, and this can result in increased diesel consumption and costs for generators (Hlomendlini, 2023). However, it has prompted others to shift towards solar power with over half (57%) of farmers doing this. The expense of this requires farmers to finance it over 4-6 years. Kriel (2023) stated that competition for financial resources between investing in machinery or solar infrastructure has resulted in farmers having to weigh up the potential trade-offs (see Fig. 26).

Fluctuations in prices of fuel, seeds, and agronomic inputs has been highlighted as significant challenges faced by farmers. This has resulted in more time being spent on detailed budgeting which was emphasised by farmer 4 who stated the need to source multiple quotations from suppliers to find the most affordable options. This was seen as time consuming but necessary in order to manage rising production costs. The high production costs per hectare have the negative outcome of placing more pressure on achieving higher yields, however this raises concerns related to environmental pollution and reduction in soil quality, both of which are opposed to a shift to conservation agriculture.

Government policies and relations identified include water use licensing, labour wage policies, fuel log book requirements, land reform policies and delays in fuel rebates (Fig. 23). A general lack of governmental support has been identified throughout the South African commercial agriculture industry (Wilk *et al.*, 2013; Raaijmakers & Swanepoel, 2020; Pienaar *et al.*, 2021).

6.5. Barriers and trade-offs to climate change adaptation

Climate change adaptation requires careful planning which is site specific, taking into consideration a number of factors which may vary between farms (Figs. 25, 26). These factors relate to environmental conditions, farm size, infrastructure, access to water and financial position. Climate change will not have an equal effect on all farms in any one region, due to differences in agricultural operations, adaptive capacity and farmers' attitudes and priorities. As illustrated in Figure 25, a relationship exists between environmental and socioeconomic drivers of change and farm management practices. The management practices will ultimately determine the degree of risk and exposure an individual farm will have to the identified drivers of change. For example, farm 1 has solar energy infrastructure (Fig. 22) and borehole water, which increases its adaptive capacity by reducing medium to long-term operational costs. It also improves the farm's position to manage price fluctuations related to fuel prices and agronomic inputs. This may be contrasted against a smaller farm with reduced financial resources which may not be able to afford such infrastructure. The starting position for each farm is different and there may be a significant variation in how farmers perceive what is most important and where their resources should be prioritised (Figs. 25, 26). Climate change adaptation can therefore not follow a one-size-fits-all approach and that variations in responses will exist between and within various regions.

Overall, farmers identified financial limitations as the main barrier towards implementing adaptation techniques as well as developing their agricultural operations. This is similar to other commercial farmers across South Africa (Wilk *et al.,* 2013; Raaijmakers & Swanepoel, 2020; Pienaar *et al.,* 2021). The cost and maintenance of new machinery is highlighted by Tieppo *et al.* (2019) as one of the most costly investments for commercial farmers. However, new machinery purchases face increased competition from other investments such as solar energy (Kriel, 2023). This requires farmers to evaluate potential trade-offs based on the availability of different resources. The decisions that farmers make have trade-offs and the cost-benefit analysis of these decisions should be considered against the potential impacts which may come in the future (Fig. 26). For example, the decision to invest in solar energy infrastructure was done in response to the impacts of load shedding. However, as stated by farmer 1, the investment in solar infrastructure will assist in the long-term sustainability of the farm but its short-term finance may have compromised other potential farm investments.

7. Conclusions

Commercial maize farmers in the Sannieshof region of North West Province experience a range of challenges with respect to climate change as well as socioeconomic factors which impact on their agricultural practices. This places farmers in a position whereby constant adjustments to their management practices are required in order to sustainably maintain production. This has become increasingly challenging due to rising production costs and changing climatic conditions (Smith *et al.,* 2021; Nkunjana *et al.,* 2023). The management practices utilised by commercial maize farmers in the study area are similar to the broader management practices utilised under conventional management practices (Mondelaers *et al.,* 2009; Meyer *et al.,* 2018; Sumberg & Giller, 2022). This includes the usage of hybrid seeds, agronomic chemicals such as pesticides and fertilisers, large capital investments towards production and management technologies, and agronomic consultation. However, farmers in the study area have also begun to develop their management practices and utilise crop rotation rather than monocultures, due to the benefits on soil quality, amongst others.

Socioeconomic factors such as government policies, market instability relating to agronomic input and fuel prices, load shedding, and crime have significant impacts on decision-making. This is due to the financial resources which are needed in order to manage these issues, which can draw resources away from specific agricultural investments. This may have implications for future climate change adaptation due to the financial constraints that farmers face. In the Sannieshof region, issues such as crime and load shedding have taken priority. Farmers need to consider the impact of long-term investments in order achieve the best possible future returns (Fig. 26). For example, investment in solar energy may reduce the long-term operation costs of and free up capital to be invested in machinery or agronomic inputs, but this is not a simple trade-off decision.

Farmers in the Sannieshof region expressed positive views relating to both conservation agriculture and precision agriculture. Most farmers (81%) highlight the benefits that conservation agriculture practices can have for maintaining soil moisture and quality. Most farmers (71%) also believe that precision agricultural techniques are beneficial. Aspects of conservation agriculture are utilised by all farmers within the region, with particular emphasis on maintaining soil moisture content through use of crop residue mulching. Crop rotation is used by all farmers but only 38% employ no-till agriculture. The majority of farmers adopt two out of the three main elements of conservation agriculture. A limiting factor for its complete adoption remains the issue of dealing with soil compaction.

Precision agriculture techniques are viewed positively, particularly in increasing yields, resource optimisation and improving profits. Yield maps, GPS guidance and auto-steer for tractors are used by the majority of farmers, with soil mapping, controlled traffic on fields and the use of drones being used by more than half of farmers. Variable rate application of fertiliser was only utilised by farmers with greater than 525 ha of cultivated land, an aspect highlighted elsewhere in the province (Jacobs *et al.*, 2018). The cost of implementing precision agriculture machinery is a key drawback in its implementation, as is lack of governmental support and the time it takes to implement new techniques, which have been highlighted by farmers elsewhere (Wilk *et al*., 2013; Raaijmakers & Swanepoel, 2020; Pienaar *et al*., 2021).

Both conservation agriculture and precision agriculture can be used to develop more effective climate change adaptation strategies for commercial farmers. However, this study shows there are significant trade-offs in balancing the needs for climate adaptation versus addressing socioeconomic challenges that are commonly perceived to be more immediate and more important. Commercial maize farming is highly complex, with farmers in the study area facing a wide range of challenges which all impact production to varying degrees. Factors influencing the decision making of management practices are related through different feedback loops (Figs. 25, 26) but this can provide farmers with improved resilience to deal with future challenges, both climatic and socioeconomic. This study highlights how farmers make use of a variety of techniques and do not limit their adaptive capacity towards one aspect of farming such conservation or precision agriculture, rather implementing any technique they deem to offer value. This aspect contributes towards the broader discourse surrounding sustainable agriculture and the associated techniques which fall within it, as often the literature compares different techniques or agricultural approaches against one another rather than considering how they can be integrated. Famers should continue to move towards the adoption of conservation agriculture practices in order to improve agriculture resilience to climate change. These practices offer a wide range of benefits in the process of developing more resilient agricultural operations while simultaneously not requiring large investments. The governmental departments should work towards developing improved relations with commercial farmers within the region and this may be done through creating communication networks where climate change adaptation information can be shared directly with farmers, while providing a platform for farmers to engage with agricultural extensions officers more easily. This study offers insight into the broader agricultural issues faced by commercial farmers not only for farmers within the Sannieshof region, but may also highlight wider issues faced in other small agriculturally based towns in South Africa.

7.1. Limitations of the study

The project timeline under the University schedule does not align with the commercial maize farming schedules, meaning that opportunities to engage with potential participants only occurred during the winter off-season when a number of agricultural demonstration days and conferences take place within the region were missed. The sample size of this study is not large and this may have limited the scope and depth of the data obtained. Farmers were sometimes unwilling to engage without the support of the local key informant.

7.2. Future research directions

Future research may consider the financial impacts that crime and load shedding have on the operational budgets of farmers in the region. It could also look in more detail at the impacts of different tillage practices on soil quality, as well as a cost comparison between the conventional and no-till systems in relation to operational costs and profits. Finally, future research could focus on understanding the climate change adaptation decision-making strategies employed by farmers in order to evaluate how drivers of change are evaluated and prioritised.

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Appendix A: Questionnaire

1. How old are you?

□ Younger than 30

□ Between 31 and 45

□ Between 46 and 60

□ Between 61 and 70

□ Older than 70

2. What is your gender?

□ Male

□ Female

□ Prefer not to say

□ Other: ___________________

3. How many years have you or your family been farming for?

____

4. Approximately how much maize do you plan to cultivate this year?

___________________________ha

5. What seed variety do you typically use for maize cultivation and do you cultivate any other crops for commercial purpose?

____

6. Do you consult with agronomist companies to assist you with crop cultivation? If so, what aspects do they assist you with?

____

7. Do you make use of any farm management software platforms? If so, what platform/s do you use and what tasks do you use them for?

____

8. Where do you source information relating to weather forecasting and climate? Do you think the government provides enough weather and climate data?

____

9. Do you use irrigation on your farm for maize?

□ Yes

□ No

Other: ____________________

10. Which product do you use as fertiliser?

□ Chemical

□ Organic

□ Combination of chemical and organic

□ Manure

Other: ____________________

11. When do you typically target your sowing date? What factors do you consider when determining this date?

____

12. What do you think of precision agriculture?

____

13. Do you make use of any of these precision agriculture techniques for maize agriculture? Please select all appropriate boxes.

□ Variable rate application of seeds

□ Variable rate application of fertiliser

□ Variable rate application of irrigation

□ Soil mapping

□ Yield mapping

□ Drone/Aerial imagery

□ Tractor GPS guidance

□ Auto steer for tractors

□ Controlled traffic on fields

Other: ______________________

14. What do you think of conservation agriculture?

____

15. Do you make use of any conservation agriculture techniques for maize agriculture? Please select all appropriate boxes.

□ Crop rotation

□ Cover crops

□ Mulching/crop residue mulching

□ Minimum soil disturbance

Other: ___________________________

16. What tillage system do you utilise?

____

17. What impact has increased fuel prices had on your agricultural operations?

____

18. What impact has loadshedding had on your agricultural operations?

____

19. How does socioeconomic factors such as fluctuations prices/availability of fuel, fertilisers, seed, and agrochemical products influence your seasonal/year to year planning?

____

20. Do you receive any government assistance for climate change adaptation? How do government policies influence your decision making on your farm?

____

21. Has crime had an impact on your farm? If so, how has this influenced your farms development?

____

22. How does wind impact your farm?

____

23. How important do you perceive the need to adapt your agricultural operations to climate change?

____

24. Where do you source information relating to adaptation techniques/approaches? Please select all appropriate boxes.

□ Friends/Neighbours

□ Agricultural days

□ Agricultural experts/specialists

□ Agricultural Unions

□ Internet/Social Media

□ Individual Research

Other: ____________________

25. What agricultural adaptation techniques have you implemented to deal with climate related stresses across your farming operation?

____

26. What are the main barriers you see in adopting adaptation technology/techniques for your agricultural operation?

____

Appendix B: Ethics Clearance

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

SCHOOL OF GEOGRAPHY, ARCHAEOLOGY AND ENVIRONMENTAL STUDIES

ETHICS COMMITTEE

CONSTITUTED UNDER THE UNIVERSITY HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)

ETHICS CERTIFICATE

PROTOCOL NUMBER: gaes_2023_07_004

PROJECT TITLE

Commercial maize farmers' adaptations to climate change in Sannieshof, North West Province, South Africa

INVESTIGATOR

Benjamin Dunn (1904499)

SCHOOL/DEPARTMENT OF INVESTIGATOR

SCHOOL OF GEOGRAPHY, ARCHAEOLOGY AND ENVIRONMENTAL STUDIES

DATE CONSIDERED

20 JUNE 2023

DECISION OF THE COMMITTEE

APPROVED UNCONDITIONALLY

EXPIRY DATE

On submission of project report for final assessment

ISSUE DATE OF CERTIFICATE 26 June 2023 **CHAIRPERSON** ____________________

(DR ALEX WAFER)

cc: Supervisor : Jasper Knight

DECLARATION OF INVESTIGATOR

To be completed in duplicate and **ONE COPY** returned to the Chairperson of the School/Department ethics committee.

I fully understand the conditions under which I am are authorized to carry out the abovementioned research and I guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.

____
Signature

Date 13 /09 /2023

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES

Appendix C: Participant Information sheet

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Dear Sir / Madam

My name is Benjamin Dunn. I am a Masters student in Environmental Sciences at the University of the Witwatersrand, Johannesburg. My supervisor is Prof. Jasper Knight. I am conducting a research study about commercial maize agriculture and its adaptation to climate change. The study title is Commercial maize farmers' adaptations to climate change in Sannieshof, North West Province, South Africa.

I am inviting you to take part in an interview. If you decide to take part, your participation in this research study will last between 30-45 minutes. The interview will take place at an agreed upon location and time, or on the phone, organised ahead of time.

With your permission, I would like to audio record the interview and take photographs of agricultural machinery/equipment/general farming activities. This data will be stored in a password protected laptop for 2 years, with all identifying features removed. After 2 years has elapsed, the data will be destroyed. Only the researcher will have access to the data.

During the research activity, I will need to ask for some personal information about you, including information relating to your age and farming experience.

The interview will be confidential and anonymous. When I share the results of the research study, I will not include your name or anything else that could identify you or your farm.

If you decide to take part in the research study, it should be because you want to volunteer. You do not have to take part. You can stop being in the study at any time. You do not have to answer any questions if you do not want to. You will not get any direct benefits if you choose to join the research study. You will not lose any services, benefits or rights you would normally have if you decide not to join. Taking part in the research study will not cost you anything. The risks for this research study are no more than what happens in everyday life.

This research study will be written up as a research report. If you would like to receive a summary of this report, I will be happy to send it to you.

If you have any questions during or afterwards about this research study, feel free to contact me or my supervisor on the details listed below. If you have any concerns or complaints about the ethical procedures of this research study, you are welcome to contact the University Human Research Ethics Committee (Non-Medical), telephone +27(0) 11 717 1408, email hrecnon-medical@wits.ac.za.

Yours sincerely,
Benjamin Dunn

Researcher:
Benjamin Dunn, 1904499@students.wits.ac.za, 071 490 8827

Supervisor:
Professor Jasper Knight, Jasper.Knight@wits.ac.za, 011 717 6508

Appendix D: Consent Form

Commercial maize farmers' adaptations to climate change in Sannieshof, North West Province, South Africa.

Benjamin Dunn.

I, …………………………………….., agree to participate in this research project.

I agree to the following:

(Please circle the relevant options below)

The research study was explained to me. I understand what this study is about.	YES	NO
I understand that I can volunteer to take part in the study.	YES	NO
I agree that the interview may be audio recorded.	YES	NO
I agree that direct quotations from my interview may be used by the researcher in their research report.	YES	NO
I agree that my participation will remain anonymous (my name or other identifying data will not be used by the researcher in their research report).	YES	NO
I agree that photographs of machinery/equipment/general farming activities may be taken.	YES	NO

…………………………………… (signature)

…………………………………… (name of participant)

…………………………………… (date)

…………………………………… (signature)

…………………………………… (name of researcher)

…………………………………… (date)