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Options for Managing Climate Risk and Climate Change Adaptation in Smallholder Farming Systems of the Limpopo Province, South Africa

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ABBREVIATIONS

Abbreviation	**Description**
%	Percentage
^oC	Degree Celsius
°E	East
°S	South
APSIM	Agricultural Production Systems sIMulator
BD	bulk density
cm	centimetre
cm^3	cubic centimetre
m	metre
km	kilometre
g	gram
kg	kilogramme
t	tonnes
ha	hectare
e.g.	for example / for instance
et al.	and others
GHG	Greenhouse gasses emissions
LSF	Limpopo Smallholder Farmers
PAW	Plant Available Water
pH	1:5 soil: water extract; measure of active hydrogen ion
RMSE	Root Mean Square Error
viz.	namely
WUE	Water Use Efficiency

CHAPTER 1. GENERAL INTRODUCTION

1.1. Background

1.1.1. South African agricultural sector's geopolitical landscape

The South African agricultural sector is dualistic in nature, with a highly capitalised well-integrated commercial sector in contrast to a large subsistence sector that is mainly located in the former homeland areas. The later was due to the policies of the pre-1994 apartheid government (Aliber and Hart, 2009; May and Carter, 2009). Consequently, the spatial distribution of the rural population follows race and cultural groupings, with black South Africans mainly located in the former homelands. These previously disadvantaged groups, based on the Land Act of 1913, did not have permission to buy or have ownership to land. The resettlement polices enabled the state move such groups to agriculturally marginal land to make way for commercial agriculture.

Throughout Apartheid era, the subsistence sector was systematically side-lined from participating in the economy, whereas the commercial sector benefited through tax concessions, subsidies and access to markets. Such laws deprived the previously disadvantaged groups (Black, Coloured and Asian) from owning land and resulted in the allocation of communal lands that often marginal, were not suited to arable agriculture and created very few opportunities to participate in the economy. Such land tenure laws coupled with water laws allocating water resources to commercial sector, further ensured subsistence farming could not cope with climate-related risk or benefit from irrigation and disaster relief programs (Turton and Henwood, 2002). The socio-economic repercussions of these now disbanded laws are still evident in communal farming systems, through various forms such as their inability to participate effectively in the market economy.

Although there are some successful examples of subsistence farmers commercialising, this sector still faced with challenges of lack of resources, poor knowledge of farming businesses, inadequate equipment and infrastructure (Baiphethi and Jacobs, 2009). Additionally, the smallholder sector is unable to compete successfully with overseas subsidised produce that are dumped in the country. These factors are major constraints to the advancement or competitiveness of agriculture, particularly the smallholder sector.

The pre-democratic water laws were directed towards allocating and regulating water use for commercial farming as key water user, in particular irrigation, while subsistence farming had no official rights as with land it was under communal laws (Turton and Henwood, 2002). The growing demands or competition for the limited water resources, even with reforms in water laws, makes it difficult for additional water users (such as subsistence farmers) to be allocated in current water system. Thus, making irrigation unattainable for subsistence farmers, and hence contributing to their inability to cope with climate-related risks.

Following the overthrow of Apartheid in 1994, the new national polices have attempted to deregulate and liberalise the system and related markets. The changes lead to the abolishment of tax concessions, subsidies, reformed labour legislation, implemented land reform programs, and access to global trade markets. These reforms failed to enable subsistence farmers to enter mainstream commercial agriculture, as they could not compete with commercial sector on open agricultural markets (Whitbread *et al*., 2011). Therefore, the current focus of the present government is on improving rural development and encouraging subsistence farmers to join local markets. Some accomplishments of the policy reforms with regard to subsistence farmers are evident. For example, Louw *et al.* (2007) reported that Limpopo subsistence farmer were supplying up to 30 % of fresh produce to local supermarkets. A third sector, called the emerging farmer, resulted from land reform policies, programs agricultural land, and educational support. This group is made up of those with and without prior farming experience attempting to transition to commercial agriculture.
.
The spatial architecture of the past apartheid government policies characterised by marginal agriculture land, uneven distribution of resources and access to water is still reflective and has influenced the industry, national parks, population groups and agriculture sectors (Lévite *et al*., 2003). At a glance, the smallholder farming sector does not appear to contribute towards overall agricultural outputs in South Africa. It does however make huge contributions to local economy and household food security as well as income (Aliber and Hart, 2009). The sector in 2012 reportedly contributed about 2.6 percent towards the national GDP, with maize as most grown crop, followed by wheat, oats, sugar cane and sunflower (DAFF, 2013).

In South Africa, the majority of the households vulnerable to food insecurity are located in rural areas, most of which reside in semi-arid to arid regions that are reliant on rainfed agriculture for their livelihoods (Baiphethi and Jacobs, 2009), often farming in water scarce, low fertility and limited arable land (Kurukulasuriya and Rosenthal, 2003). The scarcity of prime agricultural and the pattern of land ownership amongst subsistence farmers (reflecting past apartheid architecture) are amongst the reasons for low productivity and hence food insecurity (Cooper and Coe, 2011). On top of which, the dependence of subsistence agricultural sector on rainfed agriculture makes it susceptible to climate variability, directly affecting food production. In the Limpopo Basin, rainfed agricultural production experiences low productivity owing to prevailing dry spells, erratic rainfall and high atmospheric evaporative demand, coupled with limiting soil fertility and poor cropping practices, which often leads to crop losses (Humphreys and Bayots, 2009).

1.1.2. Climate science

Climate change, is the long-term change in average temperature and precipitation conditions, it is a normal cyclic change in the earths atmospheric conditions over time. This change has been occurring pre-industrial era and has been detected through various techniques, such as ice core analyses. Of concern is the progressive change in climate only detected after the beginning of the industrial era, correlated with use of fossil fuels and hence introduction of greenhouse-gasses into the atmosphere. The altered global atmospheric composition, through rises in greenhouse gas emissions concentrations has resulted in global warming and hence changes in rainfall patterns and other climatic parameters (Hardy, 2003).

The leading research group on climate detection, impact, vulnerability and adaptation analysis, *viz*. Intergovernmental Panel on Climate Change (IPCC), has over the past decades released compelling evidence on the causes of human-induced climate change, scientific evidence from measurements and others methods of altered global surface average climate (IPCC, 1994; IPCC, 2001; IPCC, 2014). Similar changes in surface air temperature were detected over South Africa, using temperature records over a 51 year period (Warburton *et al*., 2005), from 1950 to 2000. The IPCC 5th assessment report suggests that some of the climate change related impacts on the ecosystems are already evident across difference systems (biodiversity, agriculture, water resources, etc.), globally.

In addition to improvements in climate science, there has been substantial advancement in predicting future plausible climate with even more confidence or agreement amongst the models and emission forcing on the direction of changes in surface air temperatures. Climate models with anthropogenic forcing were found to be able to simulate historical mean global surface temperature changes in the 20th century, hence suggesting influence from activities on global climate conditions. The advancement in the GCMs ability to closely simulate prevailing climate conditions and reduction in signals noise for future climate conditions, gives confidence in their ability to project future conditions (IPCC, 2014).

1.1.3. Limpopo Province study area and biophysical environment

The Limpopo Province of South Africa boasts a vast Savannah biome conservation with two transboundary game parks and one metro city, *viz.* Polokwane, (Rutherford and Westfall, 1994; Low and Rebelo, 1998). Agriculture, tourism and mining industries are amongst key sectors driving the local and hence contributing towards national economy. Agriculture has been earmarked as one of the economic priority areas, others being mining and tourism, for development in the Province by the Provincial Government (Botha, 2006a). It is one of the nine Provinces which link South Africa to other sub-Saharan Africa both economically and hydrologically. It houses most of the national key points (i.e. land entry points into South Africa) and its rivers (i.e. the Marico and Crocodile River) contribute to the Limpopo River bordering Botswana, Zimbabwe and eventually flowing through Mozambique into the Indian Ocean (FAO, 2004).

The Province is located in the far northern Province of the South Africa and it links the country with the rest of Southern Africa (cf. Figure 1.1). It shares its international borders with Botswana, Mozambique and Zimbabwe and the domestic borders with Gauteng (termed an economic hub), Mpumalanga and North West Provinces. It not only has economic and water resources related linkages with southern African Democratic Countries, but nature (and culture) conservation as its home to two transfrontier parks (i.e. joint conservation areas between two or more countries), *viz*. the Kruger (northern part) and Mapungubwe National Parks. This highlights the importance and implications of decisions, policies and activities in the Province, as they affect both national and international interests.

Agriculture is a backbone of local economies and rural livelihoods through income generation from selling surplus in the local markets and household food security. Maize (*Zea mays L.*) is one of the most important field and grain crop in the country, with annual production output of 10 to 16 kg of grain for every millimetre of rainfall or irrigation water used (du Plessis, 2003). As a staple food, maize forms part of the basic subsistence farm household food requirements, with excess production thereof providing the much needed income (DAFF, 2013). Only 36.3 % of the households are regarded as agricultural (StatsSA, 2013) in the Limpopo Province.

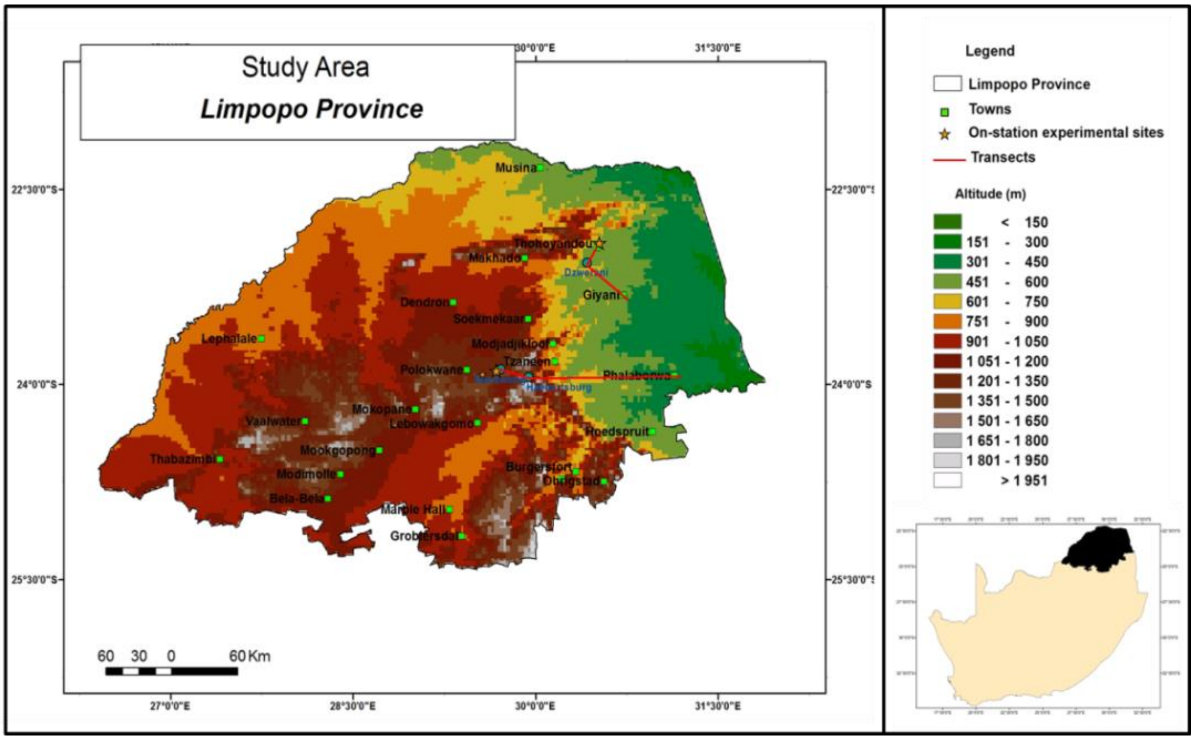

Figure 1.1 Map of the Study Areas altitude, with location on-station experimental sites and transects

To enable the use of biophysical models in assessing climate impacts on prevailing smallholder farming crop management practices, and to test climate-smart practise as plausible adaptation strategies over the study areas to projected future climate conditions, field experiments were conducted. The experimental farms were selected as they are representative of the broad agro-climatological characteristics in the Limpopo Province.

The field experiments were conducted to form a basis for biophysical model calibration and validation, over a duration of two cropping seasons (2013/14 and 2014/15). The field experimental sites were in Ha-Lambani Village (on-farm) located in the far northern parts of Vhembe District and the University of Limpopo Experimental Farm at Syferkuil (23 ^{o} 50' S; 29 ^{o} 42' E) in the Limpopo Province. These experimental sites were along the Limpopo Living Landscape SPACES Project transects (cf. Figure 1.1), of which this study forms a part of.

4.2.3.1. Climate

In the Limpopo Province, where most of the smallholder farming is rainfed, mean annual precipitation is usually a limiting factor to reaching potential agricultural yields, if other factors (i.e. photoperiod, temperature, soil fertility and topography) are not limiting. In Limpopo, rainfall decreases evenly from eastern escarpment (shown by yellow-green colour, ref. Figure 1.2, area receives over 750 mm per annum) towards the northern border with as low are less than 150 mm per annum.

The Province experiences early to mid-summer rainfall season, i.e. with peak rainfalls in December and January (respectively), identified using the Markham (1970) technique (Schulze and Maharaj, 2008). The short rainfall season was determined based on the rainfall concentration index of Markham's (1970). In contrast, the mean annual temperatures are highest long the northern border of the Province and decrease up the escarpment (ref. Figure 1.3). Temperature not only affects agriculture, but also its yield reducing factors, such as pests, diseases etc. (Coakley *et al*., 1999; Goulson *et al*., 2005).

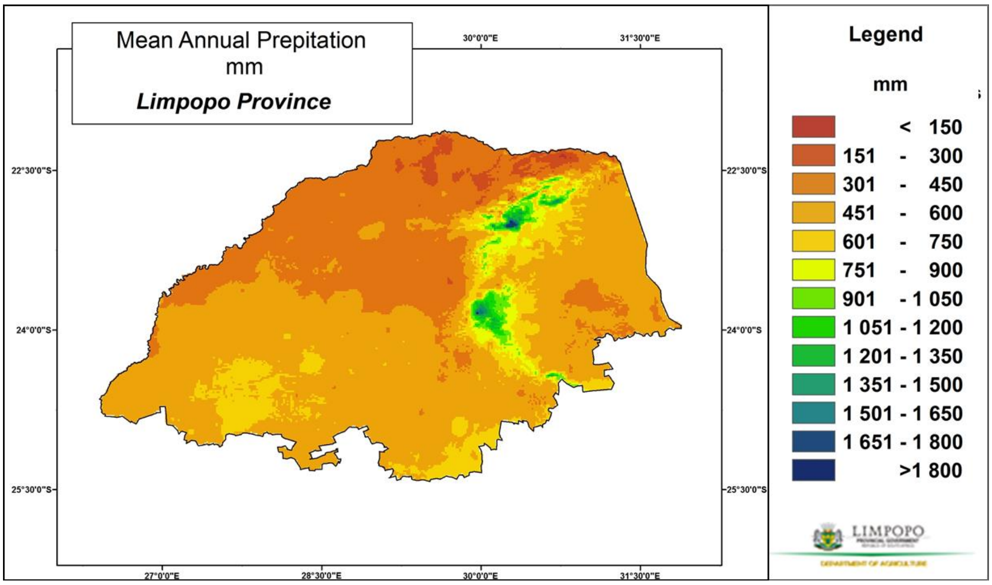

Figure 1.2 Mean annual precipitation (mm) of the Limpopo Province

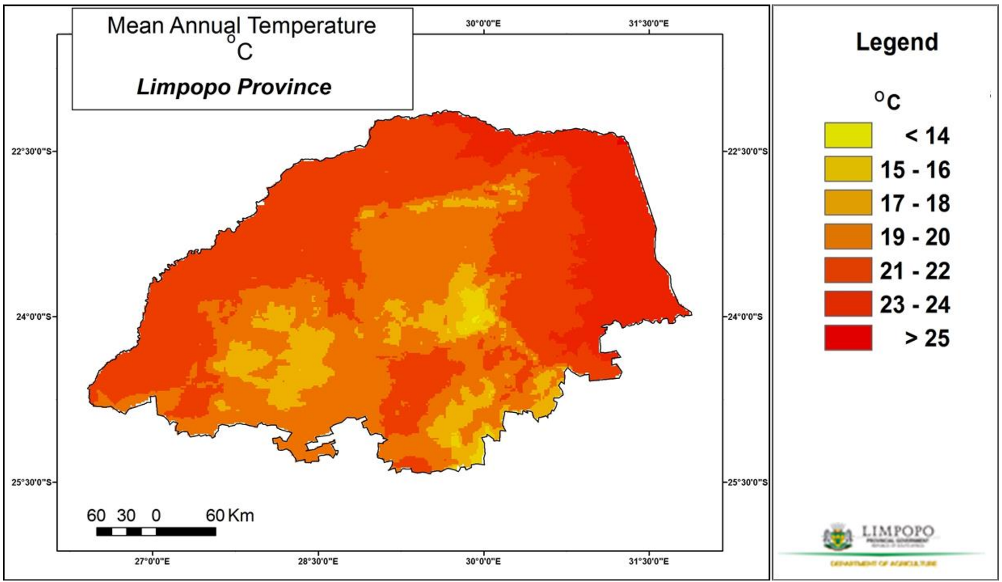

Figure 1.3 Mean annual temperature (°C) of the Limpopo Province

4.2.3.2. Land cover

The Province is spatially dominated by Savanna biome and to a lesser extent the Grassland and Forest biomes, these are amongst the eight biomes identified for South Africa by Low and Rebelo (1998). These biomes represent vegetation distribution based on the range in amount and frequency of rainfall, and temperature.

1.2. Literature Review

The agricultural sector faces numerous production risks, *viz.* pest and disease infestations, extreme weather events, soil fertility and degradation and market related shocks, which are more pronounced for smallholder farmers owing to high exposure, limited resources and lack of adaptive capacity (Harvey *et al*., 2014; Morton, 2006; O'Brien *et al.*,2004). Typically smallholder farmers are reliant on agriculture for their livelihoods and thus any changes in productivity will have a ripple effect on their livelihoods and food security through to local economy which they contribute to (Kurmar *et al*., 2006; Hertel and Rosch, 2010; McDowell and Hess, 2012).

Across the sub-Saharan region, smallholder farmers operating on less than 2 hectares of farmland represent a substantial portion (about 80 %) of farmers, of which is about 8 % of global smallholder farmers (Nagayets, *et al.,* 2005). Smallholder farmers are amongst population groups experiencing hunger, and hence their fate will largely be reliant on their ability in eradicating poverty and hunger. The development and rolling out new agricultural practices and technologies will determine how effectively farmers mitigate and adapt to it (Lybbert and Summer, 2012).

1.2.1. Limpopo smallholder dryland systems

The Limpopo Province is characterized by low and erratic rainfall patterns (prone to drought and flood events) upon which the agricultural sector depends on. The uneven rainfall distribution and high temperature regimes result in high evaporative water demand and generally low crop water use efficiency (Mzezewa *et al*., 2010). This result in most of the surface water resources lost as non-productive evaporative losses, quick flows (from intense rainfall after dry periods) into rivers, and deep percolation into groundwater reservoirs (Schulze, 2010).

The South African dryland agricultural systems range from subsistence farming to commercial enterprises, with commercial sector accounting for a huge proportion of market agricultural outputs (Hardy *et al*., 2011). The Limpopo Province agriculture accounts for nearly 60 % of fruit, vegetables, cereal crops (such as maize and wheat) and cotton grown in South Africa (StatsSA, 2013). This contribution is predominantly from commercial agriculture, and most of the small-scale agriculture is excluded from the mainstream agricultural markets and there is a lack of policy incentive for smallholder farmer (Meliko *et al*., 2012). Maize is most grown and important crop and other cereal crops such as wheat are grown in winter on rotation. Livestock, mainly cattle, forms an important component of the rainfed farming enterprises significantly contributing to food security and sustainability of, in communal farming systems (Hardy *et al*., 2011).

The smallholder agriculture in the Province is characterised by low productivity, poor soil fertility, rainfed agriculture, recurrence of drought and limited arable land (Mpandeli *et al*., 2015), vulnerable to yield limiting and reducing factors, dominated by retired and elderly female members of the population group (Ncube *et al.,* 2015). The smallholder farmers' vulnerability to climate risks in the region is exacerbated by their low adaptive capacity, low technology, lack of formal education, lack of access to finance, and low levels of resilience and high poverty levels (Mpandeli, 2014).

Meliko *et al*. (2012) findings on competitiveness and comparative advantage of farming systems in the Limpopo Province, showed dryland maize not to have positive private and social profits under present policies, with a return factor of production of land, management and water, suggesting low profitability and expansion opportunities compared to high value crops (potatoes, tomatoes and cabbage) were found to be more profitable (Meliko *et al*., 2012). For smallholder agriculture to be more profitable, policies geared towards creating an enable environment and empowering smallholder farmers are needed, to address gaps between commercial and smallholder agriculture (Baloyi, 2010).

The lack of adequate water poses a threat on agriculture activities and on attempts to develop economic activities. Irrigation is currently the only option used as a coping measure, mainly by commercial agriculture, of which is placing huge pressure on available scarce water resources (the agricultural sector at present consumes over 50 % of the available water resources) and hence there is no option for further expansion (Kauffman *et al.,* 2003).

The crop growing windows span over the November and April, with highly varied rainfall patterns, mostly short duration and convective extreme storms in nature covering ranges over several kilometres (Tadross *et al*., 2005) and it is highly variable within season and between the years. In Limpopo Province, the subsistence farmers only recently have access to weather information and forecasts, but most lack skill to interpret this into their daily operations and as a result still experience yield loss owing to climate-related risks. They still have a reliance on the use indigenous knowledge and/ or past experiences (i.e. planting at same time) of which has inherent uncertainty (Eakin, 1999).

Smallholder farmers and extension services, in the Limpopo Province, are supported with access to climate forecasts be used to cope with high climate variability. The system uses short messaging system to relay agrometeorological information. Moeletsi *et al.* (2013) found that the forecast information and response recommendations were always taken up, indicating trust in information; however some farmers had a huge reliance on indigenous knowledge. In the Vhembe District of the Limpopo Province Mpandeli (2014) indicated that most of the farmers have incorporated season forecast information into their farm management to manage climate risk. This adoption of climate forecast information is cited to be in both farming systems, i.e. smallholder and commercial farmers.

Limpopo smallholder farmers have adopted various coping responses to climate risks, crop diversification, early planting, drought resistant crops, use of climate forecasts and/or indigenous information, changing farming practices and adjusting fertilizer inputs (Mpandeli, 2014; Mpandeli and Maponya, 2013). The choice of coping response strategy was found to be influenced by the farm type, and education level (Rakgase and Norris, 2014)

1.2.2. Effects of insitu rainwater harvesting and surface organic mulch on agrohydrological responses

For greater farming systems production and sustainability to be realised, according to Kauffman *et al.* (2000), investment, of labour and finance, over time is required to address present food insecurity and projected pressure of population demands on land. This improved and sustainable agricultural production is thought to be attainable through improvement of available soil-water, restoration and improvement soil fertility and adoption of soil conservation techniques (Kauffman *et al.,* 2000). In this study the an interdisciplinary approach, through integration of water-, soil- and crop- management strategies was adopted to increase water productivity and hence agricultural productivity in rainfed system. These complex relationships are shown in Figure 1.4 and are further explained below.

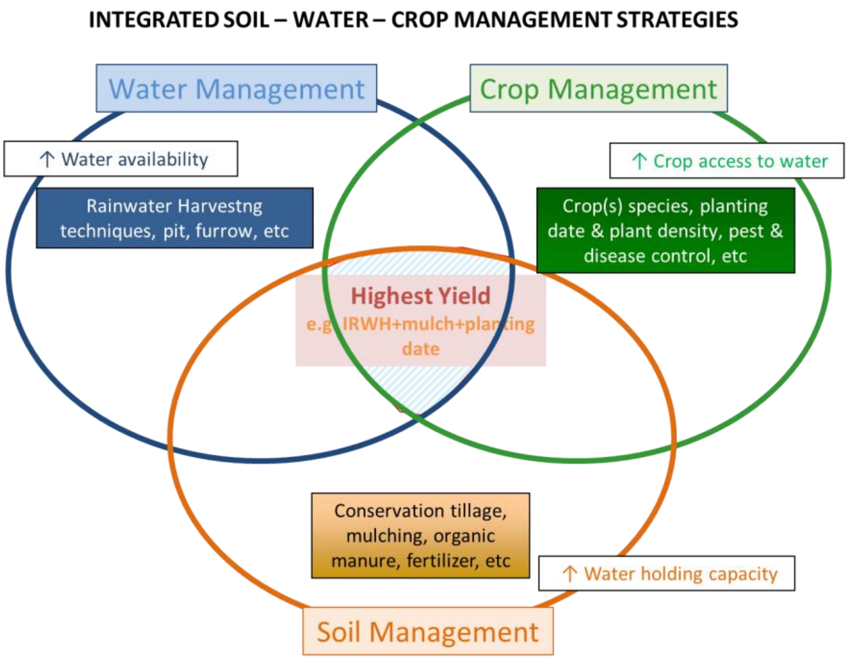

Figure 1.4 Illustration of the interactions and feedbacks of Integrated soil-water-crop management strategies (based on ideas from FAO, 2008)

The integration of management strategies is believed to increase soil organic matter levels, improve nutrient retention capacity and enhance soil biota, provide prime conditions for crop production. Further, improve available plant water through techniques of increase the soils water holding capabilities, water capturing and infiltration. In addition, combination of using most suitable crop, planting dates and other crop management practices to mitigating climate-related risk. This is by means of combining best techniques and management practices in order to obtain the highest harvestable yields, through an iterative process (FAO, 2008 and Kahinda *et al.*, 2009; Kauffman *et al.,* 2000).

Improvement of smallholder farmer rainfed agriculture offers good potential to alleviate food insecurities. Improving rainfed agricultural production through rainwater harvesting and conservation agriculture tends to require lower investment costs, as opposed to implementing irrigation schemes which have associated challenges, such as management, skill and competition with other users, and it is not viable in certain areas in sub-Saharan Africa (de Fraiture *et al*., 2009).

According to de Fraiture *et al*. (2009), in most rainfed settings the current yields are low and have a good potential to improve harvest and water-use-efficiency. In their analysis of upgrading rainfed production with water harvesting techniques they predicted an 80 % increment in the yield gap and postulated 85 % for the year 2050, in an optimistic yield-growth scenario via improvement the productivity of exciting lands (de Fraiture *et al*., 2009). van Rensburg *et al.* (2012) inferred from their findings on assessment of implements and procedures of applying insitu rainwater harvesting techniques on crop lands, that their benefits could be up-scaled to over millions of hectares across parts of sub-Saharan Africa, and hence would contribute towards improving food security, particularly within the southern African Democratic Countries (van Rensburg *et al.,* 2012).

Rainwater Harvesting is a process by which rainwater and runoff thereof is concentrated, collected and stored to be used either insitu or exsitu immediately or in the future; in either structures (such as tanks of roofs or impermeable surfaces, reservoirs, etc.) or directly into the soil profile (Ghimire and Johnson, 2013; Siegert, 1994). The main goal of rainwater harvesting techniques are to improve rainwater productivity by capturing rainfall insitu and/or capturing runoff generated and storing it for later use, as supplementary irrigation (Rockstrom, 2000). The rainwater harvesting systems have been used for centuries in arid and semi-arid climates predominantly for mitigating climate-related risk (such as water scarcity) which results in reduced yields and crop failures, owing to dry spells (van Rensburg *et al*., 2005; Bulcock and Jewitt, 2013).

Rainwater harvesting has been viewed as an option for improving livelihoods of small scale farmers (Ngigi, 2003) and the wide spread implications and limitations adoption of this technologies on agrohydrological responses are not well understood. It is worth noting that any landuse changes, more so large-scale landscape changes, have implications on the rainwater partitioning through vegetation and landtype on critical hydrological components, such as surface and subsurface flows (Costa *et al*., 2003) and hence crop production. Therefore, the up-scaling of a landuse, such as rainwater harvesting technologies, are expected to alter the soil and vegetation dynamics and hence have implications on the agrohydrological responses.

The insitu and exsitu rainwater harvesting techniques have the ability, as demonstrated in numerous studies, to improving soil-water, minimize runoff, increase groundwater recharge, provide relief from dry-spells, and increase agricultural production. The techniques reduce risks and have a positive impact on other ecosystems (Makurira *et al.*, 2010; Yosef and Asmamaw, 2015). Furthermore, they are an important source of high water quality where it is collected, for agricultural- and human-use, in light of the deteriorating water quality and decreasing water quantity status. The beneficial impacts of the rainwater harvesting systems extend beyond rainfed agriculture to ecological system (Ashton *et al*., 2008; Oberholster and Ashton, 2008; Yosef and Asmamaw, 2015).

There are various types of rainwater harvesting systems, ranging from ex-field or non-field (i.e. rainwater/runoff collection occurs outside of the field and used elsewhere as irrigation or domestic use) to insitu (i.e. runoff collection, storage and use from within the field) rainwater harvesting (van Rensbrug *et al*., 2005; Biazin *et al.*, 2012). In this study, the foci will be on insitu rainwater harvesting (IRWH) use particularly for rainfed agriculture. Recently, scientists in sub-Saharan Africa, the Middle-East and Southeast Asia have made considerable contribution to the development and testing (including development guidelines for optimal site conditions and implementation) of a wide range of insitu rainwater harvesting systems for agricultural use (Humphreys and Bayot, 2009; Oweis *et al.*, 2004; Rockstrom *et al*., 2002; Botha *et al*., 2014a & b).

IRWH, as defined by (Hensley *et al*. (2000), is made up of a rainwater no-tillage surface runoff generation area that flows into a basin collection area, this allows for direct storage in the soil profile and efficient use for agricultural crop production (cf. Figure 1.5) to mitigate dry-spells (Biazin *et al.*, 2012; Botha *et al*., 2014a; Oweis *et al*., 1999). The incorporation of mulch into IRWH techniques reduces the unproductive evaporation losses more by conserving much water and suppressing direct soil evaporation (Tesfuhuney, 2012; Tesfuhuney *et al*., 2013).

The mulch and IRWH integration method has been to result in higher soil-water stores and higher harvestable yields (Wang *et al.*, 2008; Li *et al*., 2000; Tesfuhuney, 2012; Tesfuhuney *et al*., 2013). The IRWH and mulch method increases infiltration and provides sufficient rainwater storage for maize crop through dry spells, particularly during critical growth stages, such as tasseling stage (Tesfuhuney *et al*., 2013). Further, findings by Uwah and Iwo (2011) on the effects of surface mulch application rates maize on productivity and weed growth, suggests that higher mulch rates (over 6 t/ha as compared to 0, 2, 4 t/ha) are likely not to improve soil moisture, but, will reduce weed infestation, increase the vegetative maize plant growth, and hence grain yields.

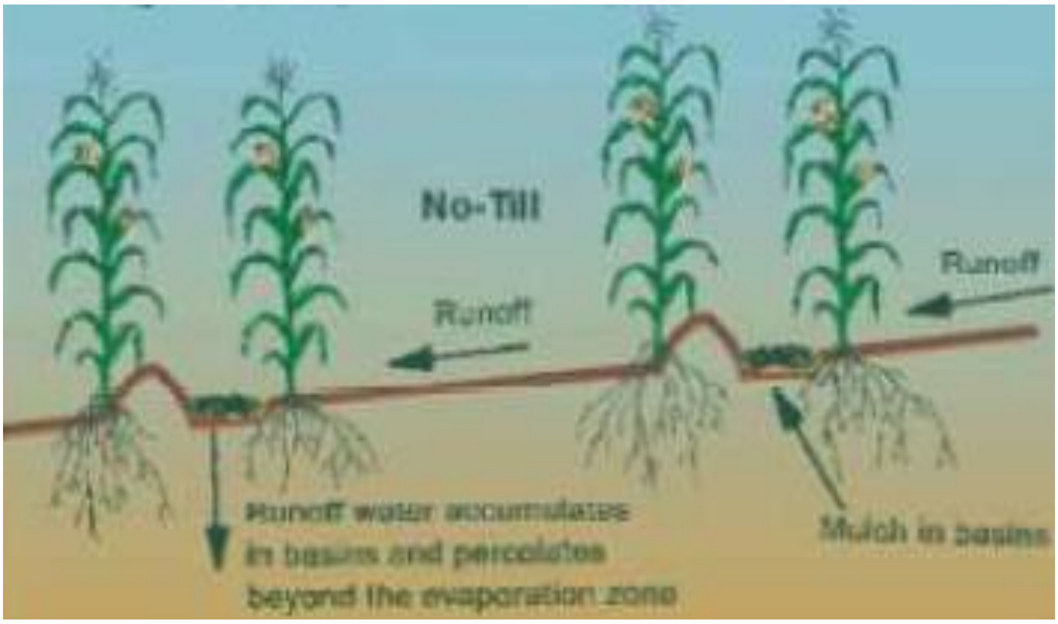

Figure 1.5 A schematic of an insitu rainwater harvesting technique, showing a runoff strips (catchment) and basin trip (collection area; Source: Botha, 2006b)

1.2.3. Climate change impacts and adaptation pathways in the agriculture sector

This inter- and intra-variability in rainfall has a direct impact on agricultural crop management (such as planting times, growing length, weeding and pest control, and harvestable crop yields), and hence resulting in the likelihood of loss of potential crop yields if planting is too early or too late in the season (Laux *et al,*. 2010). In addition to climatic related challenges, smallholder farmers are faced with numerous constraints, ranging from biotic (pests and diseases) and abiotic stresses to accessing resources. The main abiotic stresses faced by farmers in the region are drought, heavy rains, storms and soil fertility (Sibiya *et al.,* 2013; Tittonell and Giller, 2013). Moreover, low crop productivity is as a result of poor crop management practices, which Fanadzo *et al.*, (2010) identified as involving weeding, fertilization, soil-water management, late planting, low plant populations and use of varieties unsuitable for the environmental conditions (Fanadzo *et al.,* 2010). Further, these constraints have been highlighted to be more likely to inhibit farmers from adaptation (Bryan *et al*., 2009; Gbetibouo, 2009; Gbetibouo *et al*., 2010; Sibiya *et al.,* 2013). Climate change is postulated to be an additional stressor (Ziervogel *et al*., 2006) to a system that is already vulnerable.

The present climate variability already has caused substantial losses in agricultural production. The long-term adaptation, projections indicate that climate change will exacerbate the water-use and hence increase irrigation water demand in the South African agriculture (DEA, 2013). Numerous studies in the tropics and sub-tropics, suggest that most crops are already experiencing their highest temperature tolerance levels, and because of increases temperature crop yields in those regions would be significant reduced (McCarl *et al*., 2001; CEEPA, 2002; Peng *et al*., 2004). These additional stressors will affect the production risk, which is related to crop yields, the probability of experiencing more extreme events, the timing of field operations and investment in new technologies.

The impact of these stressors are likely to threaten the livelihoods and increase the risk of food insecurity in smallholder or subsistence farming communities, more so on those who are dependent on rainfed crops for food and income and well limited resources. The impacts of climate change on an already changed system will have varying impacts across the landscape and communities; hence, requiring a more dynamic response. Therefore, there is a need to identify existing climate-related impacts and current strategies for coping with them, and then undertake local assessments of vulnerability to projected changes in climate, based on that, make recommendations for future adaptation strategies (Schulze, 2010).

The study by Zabel *et al.* (2014) on suitable agricultural areas under climate change (in 2100, based on single ECHAM5 general circulation model for SRES A1B emission scenario) postulates that in sub-Saharan Africa the land currently under production is likely to deteriorate, owing to “a substantial global reduction of suitability for multiple cropping” (Zabel *et al*., 2014:8). Future projected climate not only affects land suitability for cropping, but also the start and duration of growing season(s). In their study, the adaptation measures suggested, such as increasing irrigation, the need to be adapted to lessen the effects on potential arable land. They further recommended alternative strategies for attaining global increase in agricultural production, without land expansion that would affect environment and/or protected areas (Zabel *et al*., 2014).

Further, it is projected to result in spatial shift in crop growing areas, change crop productivity, and changes in spatial distributions and reoccurrences of certain agricultural pests and parasites (DEA, 2013). The findings by Tibesigwa *et al*. (2016) over the Limpopo Province are in agreement with the above review, which suggest that the already drier conditions will make the Province more vulnerable to climate change. Warmer temperatures are likely to result in more incidences of heat stress in livestock, and thus reduction in milk productions and fertility of dairy cattle (Nesamvuni *et al.*, 2012; Dunn *et al.*, 2014).

Climate risks are said to be varied – spatial and temporal – across the regions with different frequency and severity based on prevailing location specific conditions (Gbetibouo and Hassan, 2005). Climate-related risks, such as floods, dry spells and droughts, are projected to change in terms of their intensity and severity over the southern African region. The changes in these climate-related-risks will have far-reaching implications on the agro-ecosystem, and thus livelihoods upon which the communities depend on. The projected decrease in rainfall and hence decline in flooding might be attributed to changes in frequency and more intense tropical cyclones making landfall (Malherbe *et al.,* 2013a). The projected decrease in cyclone landfall over the Limpopo Province, part of the Limpopo Basin, will result in wide spread reduction in important heavy rainfall. Malherbe *et al.* (2013b) found that climate change would affect the duration in rainy season, owning to shift in start and end of the rainfall seasons.

Climate impact studies, from both regional and international literature, confirm that the agricultural sector is more likely to be adversely impacted (IPCC, 2017; Pachauri, 2007; Schulze, 2010). The impacts are likely to be severe in developing countries, such as those in southern African region, where agriculture is the backbone of both livelihoods and economy. The sector contributes between 4 to 26 % towards the gross domestic product, with over 70 % population depended on agriculture for livelihoods, i.e. as sources of food, income and employment (Lesolle, 2012).

Impacts of projected changes in climate on commercial agriculture over South Africa, in a study by Tibesigwa *et al*. (2016), findings suggested that increase in temperature alone will have more negative impact on productivity than decrease in precipitation. Further, mixed farming systems were found to be least vulnerable compare to specialised crop farming systems. The findings from analysis of commercial agriculture were consistent with those from smallholder farmers in the sub-Saharan Africa (Tibesigwa *et al*., 2016). This suggests that both agricultural systems are equal in terms of their vulnerability to climate change and thus were requiring similar the adaptive response to make them more resilient.

The heavy reliance of the smallholder agricultural sector on rainfed production makes it to be highly vulnerable to climate variability and change. At local level climate change poses a threat to the already vulnerable livelihood systems, hence a better understanding on how best support those at risk owing to climate stress is important given the likely changes in the future climatic conditions (Ziervogel *et al*., 2006). The Province maize productivity is projected in future to range from 25 % decline and 10 % increase in potential yields compared to present climate conditions across a spectrum of various global climate models (DEA, 2013).

The adoption of integrated crop, water and soil management technologies, such as IRWH, in rainfed agriculture mostly found in semi-arid areas with highly variable rainfall, were found to be effective in alleviate inter-seasonal climate-related risk (dry spells) in smallholder farming systems, by increasing the rainwater use efficiency and thus water productivity. This technology not only improves soil-water storage and usage, but also conserving soil through reducing surface erosion (Botha *et al*., 2014a; Oweis *et al.,* 2001). Reduction in the reliance on irrigation could increase water availability to other fast growing water users such as human consumption and industry (manufacturing and mining).

In South Africa, adaptation efforts have thus far focused on biodiversity (Wise *et al*., 2014; Zievogel *et al*., 2014), and the direction in future responses are indicated in the Climate Change Response Water Paper of Department of Environmental Affairs 2011 and the Long Term Adaptation Scenarios (DEA, 2013). In response to this gap, a national study was conducted to develop a series of long-term adaptation scenarios across sectors. There are a numerous successful farm-level coping strategies adopted by farmers and from research studies (Botha, 2006b; Botha *et* al., 2014a; Mpandeli and Maponya, 2013; Mpandeli, 2014) of which present unrealised opportunities for scaling up to develop concrete plans.

Even though smallholder farmers are inherently vulnerable to climate change, Morton (2007) suggests that their resilience systems may negate some of the risk and vulnerabilities, such as access to family labor, diversification patterns away from agriculture and use and wealth of indigenous knowledge. Climate change and future climate uncertainties are projected to adversely affect rural population in developing countries (Morton, 2007). This highlights the pressing challenge of mainstreaming climate change adaptation pathways into decision making and planning in these least resilient communities. Uncertainties related mainly to climate projections and impacts add an element of complexity to the process (Ranger and Garbett-Shiels, 2012). The future planning strategies are influenced by combination of climate change impacts, and already vulnerable and at times inefficient production systems. Farmers in the region are already coping with, and adapting to climate variability.

Recent studies have highlighted a shift in climate adaptation thinking, introduced by Pelling (2011), to include transformative adaptation as a plausible pathway to ensure effective adaptive responses; this was an important theme in the 5th Assessment Report of the IPCC 2014 on impacts, adaptation, and Vulnerability. The inclusion of transformational adaptation as an adaptation pathway suggests a move away from incremental adaptation (i.e. a gradual increasing response to climate change impacts) transformative measures at landscape scale. This may be in response to large climate change vulnerabilities in a particular region or resources system and severe climate-related risks which threatens the robustness or resilience of human-environment systems to climate change (Kates *et al*., 2012).

Smith *et al*, (2011) presents a theoretical framework of adaptation pathways, the framework indicates adaptation options with respect to time scale and climate projection time line. The adoption of adaptation pathways concept in the mainstreaming of climate change adaptation provides a robust decision-making under uncertainty (Wise *et al*., 2014). The adaptation pathways proposed in various studies all start with gradual or incremental adaptation to present climate towards the mid-century, with a transitional or systemic adaptation phase over the mid-century and a transformational adaptation phase towards the end of the century (Rippke *et al*., 2016; Smith *et al*., 2011). The adaptation pathways indicated above might not occur in linear format, as most impact studies suggest that in some areas climate change risks and vulnerabilities may require transformative adaptation earlier than thought (Leclère *et al.,* 2014).

1.2.4. Crop modelling for climate impact and adaptation in smallholder farming system

Agriculture operates within a complex environmental system wherein it is influenced by yield reduction (i.e. weeds, pests, etc.) and limitation (i.e. water) factors (Tittonell and Giller, 2013). Keren *et al*., (2015) study indicates the importance of accounting for the interactions occurring within the agro-ecosystems. Smallholder agriculture, on the other hand, operates at a different scale with even more pressures owing to the inherent vulnerabilities of the farming system. These pressures are likely to be exacerbated by changes in climate. Smallholder agricultural systems, even at times neglected, are embodied within the local, regional, national and international trade systems and markets. These changes are postulated to result in a cascade of risks to agricultural production and associated factors which may lead to emerging agricultural production been severely affected (FAO, 2016; Harvey *et al*., 2014; Hill and Pittman, 2012; Lunt *et al*., 2016). Such complex impacts need a multifunctional approach to achieving resilience and adaptation.

Communities have historically responded to and adapted to variability in and extremes climate conditions, with different levels of success (IPCC, 2014). Further, for decades, agronomic crop research results have been used in formulating recommendations for improving farmer's production. The successes of these recommendations are limited by duration of studies and are characterised by the rainfall over the study period, owing to highly variability in rainfall seasonally and most of field-based studies are conducted over a short period and do not capture the long term effect of variability in rainfall (Dixit *et al*., 2011). The use of crop models enables a better understanding of the potential responses of cropping systems to long term variations and different management practices. The most common modelling approach is the use of detailed process-based mechanistic models (such as DSSAT (Jones *et al*., 2003) and APSIM (Keating *et al*., 2003).

The Agricultural Production System siMulator (APSIM) model has been used widely to better understand at the field level, plant crop growth and development in response to different environmental conditions and management practices (Keating *et al*., 2003). The modular modelling framework (which includes plant, soil, water and management modules) of the model gives it a unique capabilities to simulate complex farming systems interactions. It has been proven to simulate occurring farming systems and their interactions with the environment, such as crop yields as a function of cropping system diversification (crop rotation, intercropping, etc.), crop (cultivars, growth and development rates), management practices (tillage, planting date, fertilization and irrigation), soil properties (soil organic matter content, water holding capacity, and nitrogen availability), and climate change and variability, including carbon dioxide fertilisation (Ahmed *et* al., 2013; Sultan *et al*., 2014).

Process-based models, such as APSIM model, provide a robust simulation of agricultural and hydrological (runoff, surface and sub-surface flows and groundwater) responses to change environmental conditions and management. The process-based models are suitable in climate change impact and adaptation modelling approaches for projecting future agricultural productivity owing to their ability to account for impacts of future projections of environmental conditions, soil processes, management and cultivars on productivity (Asseng *et al.*, 2015; Elliot *et al*., 2014; Liu *et al*., 2013; Park, 2008).

Apart from the simulations of agricultural responses, the APSIM model has been shown to simulate both the agriculture and hydrological responses at catchment scale. This is demonstrated through a modelling framework by Paydar and Gallant (2008) which incorporates the farming system model into a catchment context, while accounting for lateral water fluxes (i.e. surface and sub-surfaces flows) and groundwater recharge and discharge. Similar to catchment hydrological models, this framework allows for simulations to be both in a lumped and distributed model. The distributed mode in modelling allows for outflows from upstream catchment to cascade to the downstream catchment, as occurs in the environment. The lumped mode assumes that there are no downstream contributions and allows for assessing effects of each catchment without inflows from other catchments. This framework allows for successful field scale practices to be assessed for large scale adoption, and their impacts and spatial-temporal variability on agrohydrological responses. This type of analysis is demonstrated in a study by Petheram *et al.* (2016) wherein they evaluated the economic impacts of adopting water harvesting for irrigation from field to catchment scale in the semi-arid tropical catchment of northern Australia.

1.3. Research Statement

The productivity of rainfed agriculture in semi-arid cropping systems, especially where supplementary irrigation is not an option, is driven by rainfall, which is often low and erratic. Farmers must therefore cope with climate risk by managing efficiently captured rainfall through soil-water conservation and rainwater harvesting technologies. Even with ample evidence that such technologies improve on-farm water management and can close water-related yield gaps, there has been limited wide-spread adoption, specifically for smallholder farmers in semi-arid regions. The effects of the technologies remain unclear when scaled up spatially over diverse areas, in terms of soil properties and climate conditions, on closing the water-related yield gap. In this study, an integrated soil crop water management approach was used to determine to what extent yield gaps could be reduced under the conditions of rainfed smallholder farming for current and future climate. The concept of rainwater harvesting is not new and has been widely used at varying degrees and types by farmers in sub-Saharan Africa who are depended predominantly of rainfed agriculture (Biazin *et al*., 2012). Further, there is a wealth of information from research, ranging from likely attainable yields to its potential to increase soil moisture and effective rainfall (i.e. green rainwater) in South Africa and across numerous developing countries. IRWH techniques research in sub-Saharan Africa indicate that it could reduce runoff by up to 100 %, improve soil-water content by 30 % dependent on the rainfall and soil characteristics, and up to six times crop yields of traditional practices were obtained from using of both insitu rainwater harvesting and fertilizer (Kongo and Jewitt, 2006, Biazin *et al.*, 2012).

The rainwater harvesting technique proposed is IRWH, composed of a runoff generation no-till and infiltration basin. This technique has been tried and tested in South Africa by Agricultural Research Council together with smallholder farmers and found to greatly improve yields, as well as mechanized for potential large scale use (i.e. commercialization), however, this was tested on limited climate zones and soil types (Botha *et al.* 2014a and Botha *et al.* 2014b). In this study, the feasibility of soil-water conservation and IRWH, planting dates and different maturing cultivars at different soil profiles, climatic zones and over long-term (i.e. climate variability and change) was researched, to assess its long-term efficiency and impact of upscaling these climate-smart practices on crop productivity and hence reducing the yield gap.

In South Africa, there is a wealth of research on climate change impacts on agriculture and other sectors (Ziervogel *et al*., 2014); however, there is limited research on climate adaptation response for future planning. There significant and inadequate opportunities for scaling up successful approaches, particularly on farm-level coping strategies to climate-related stresses, and assessing this approaches under projected future climate conditions to scales where decision making and planning occurs. The development of effective adaptation strategies in the agricultural sector are recognized as key to efforts for reducing climate-related risk and vulnerability, which also feeds into policy development and planning.

1.3.1. Research hypotheses

The following research hypotheses were tested in this study,

a. Smallholder farmers concerns and constraints arising as a result of likely future impacts of anthropogenic climate change, will have a significant influence on their decision making, and hence motivate their adaptation behaviours;
b. Increasing surface residue application leads to higher soil-water retention, and thus crop yields; Insitu rainwater harvesting in combination with conservation agriculture leads to higher yields which are more stable than using conventional practices;
c. Farmers need to develop and implement risk management strategies that help them to efficiently capture and conserve rainfall through soil-water management strategies;
d. The crop management practices of resourced poor farmers will be highly vulnerable to future climate change and variability due to a lack coping mechanisms and limited options to adjust their farming system;
e. Incremental adaptation will not be sufficient to reduce projected impacts of climate change, and hence will require shift in climate adaptive responses to more transformative adaptation.

1.3.2. Research objectives

The overall objective of this research was to develop and evaluate potential strategies for attaining resilience and adaptation pathways in the Limpopo smallholder farming system to climate variability and change. The above aims are addressed through the following series of sub-objectives,

a. Undertake a survey to better understand challenges faced by smallholder farmers and their perceptions of resilience and adaptive capacity to climate variability and change (cf. Chapter 2);
b. To assess the perceptions and/or beliefs of Limpopo smallholder farmers of past and projected future climate conditions and how perceptions of paet climate experiences, future extreme climatic and local adaptation constraints may influence their willingness to adopt climate-smart adaptation practices (Chapter 2);

c. To conduct on-farm experiments on the effects of soil-water-crop management practices (i.e. tillage practices and organic mulch levels) on soil-water and maize crop growth and yields (cf. Chapter 3);
d. To parameterise, calibrate and validate the APSIM model for three tillage practices, i.e. conventional tillage, insitu-rainwater harvesting and no tillage (cf. Chapter 3);
e. To couple APSIM Modelling system and a Geographical Information System to simulate the effects of on-farm field experimental treatments across different soils, climates and locations at a sub-catchment scale, in the Limpopo maize growing areas (Chapter 3);
f. To assess the resilience and/or vulnerability of the Limpopo smallholder crop management practices for present and projected mid-century climate conditions (cf. Chapter 4); and
g. To evaluate plausible climate change adaptation pathways for the Limpopo smallholder farming system, from adaptation options developed from successful on farm management practices (cf. Chapter 4).

1.4. Structure of the PhD Thesis

This PhD thesis is composed of 5 Chapters, with the first being an introduction to the research followed by four research chapters and ending with a general discussion and conclusion. Chapter I gives a general introductory and background as well as a brief overview literature review and ends with the overall research hypothesis and objectives. The results from the research work are presented in chapters two, three, and four, written as journal manuscripts. The last chapter (i.e. Chapter V) is the general discussion and conclusions and summarises all the findings and addresses the overall objectives, then presents recommendations for further research.

Chapter II

The first research chapter Lekalakala, R.G., Hoffmann, M., Ayisi, K., Odhiambo, J. and Whitbread, A.M. entitled "*Factors likely to influence the Limpopo Smallholder Farmer Climate Change Adaptation Strategies*" presents a field survey of smallholder farmers past experiencing, perceptions and adaptive responses, and a multiple-mediation statistical modelling used to assess influence of past climate experiences, future extreme climatic events concerns and local adaptation constraints of the Limpopo farmers triggers their willingness to adapt climate-smart agriculture practices. The aim of this assessment was in two parts, firstly, to establish if the smallholder farmers' perceptions of past and future climate conditions are comparable with the observed and projected future climate, and lastly determine factors (past climate experiences, future extreme climatic events concerns and local adaptation constraints) which influence the Limpopo smallholder farmers willingness to adopt climate-smart adaptation practices

Chapter III

The second research chapter Lekalakala, R.G., Hoffmann, M., Ayisi, K., Odhiambo, J. and Whitbread, A.M. entitled "*The impacts of climate-smart practices on the climate resilience of smallholder farmers in diverse landscapes of the Limpopo Province, South Africa*" indicates on-farm experiments on the effects of insitu rainwater harvesting and conservation practices, for optimizing rainwater availability for maize growth and production, on maize (grain and biomass) yields and soil-water conducted over two distinctively different planting season (i.e. first with above and second season with below average rainfall over a 65 year record). Further, the use of these experimental data and other secondary data to parameterise, calibrate and validation a mechanistic process-based model (i.e. APSIM model), and upscaling this field based model through coupling with geographical information system to catchment scale. Finally, the evaluation of the effects of these practices on agro-hydrological responses, through APSIM-GIS coupled modeling systems, across maize growing sub-catchments with different environmental conditions (i.e. soil properties, climate) in the Limpopo Province over a period of 50 years. The aim of this research was in three parts, first to conduct on-farm research experiments on the effects of insitu rainwater harvesting and conservation practices on agro-hydrological responses. Then, use the field experimental data to parameterize, calibrate and validate the APSIM model and upscale the field experiments to catchment levels through coupling it to GIS system. Finally, assess the effects of the practices across maize growing areas over the Limpopo Province on agricultural productivity and soil-water content.

Chapter IV

Lekalakala, R.G., Hoffmann, M, Rötter, R., Gummadi, S., Ayisi, K., Odhiambo, J. and Whitbread, A.M. entitled "*Effects of Climate Variability and Change on the Limpopo Smallholder Farmers' Crop Management Practices under Dryland Conditions*" shows selection of representative envelope from empirically downscaled climate models over the Limpopo Province for purpose of reducing computing power and time; characterisation of farming systems, based on 201 smallholder farmers across six villages, in the Limpopo Province; and assess of climate change impacts on agriculture in the Limpopo Province based on characterized farming systems and calibrated APSIM model. Furthermore, three plausible climate adaptation pathways in response to climate change, in each pathways a representative adaptation option was selected based on literature and likely options to be adopted in the area. These adaptation pathways were evaluated for projected future climate conditions using the median of the empirically downscaled climate models over the Limpopo Province. The aim of this study was to assess the resilience and/or vulnerability of the LSFs' crop management practices for present and projected mid-century climate conditions; and to evaluate plausible climate change adaptation pathways for the Limpopo smallholder farming system, from adaptation options developed from successful on farm management practices.

CHAPTER 2. FACTORS LIKELY TO INFLUENCE THE LIMPOPO SMALLHOLDER FARMERS CLIMATE CHANGE ADAPTATION STRATEGIES

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Abstract

Recent climate impact studies project that the effects of climate change on agricultural industries are likely to be far greater than previously thought and more so in regions prone to climate-related risk, poorly resourced, with limited expertise, low-income and production. Thus, climate change is highly likely to threaten farming livelihoods of the rural poor more because of their low capacity to adapt. Climate adaptation starts as an individual action, with ripple effects from local to global scale, the success of which hinges in part on the understanding of factors motivating farmers' adoption and/or implementation of appropriate practices.

A growing body of evidence suggests that farmers past climate experiences to the effects of changing climate, and psychological distance related to their concerns and constraints of the impacts are likely to influence their behaviour. In this study, a representative sample of smallholder farmers from the Limpopo Province of South Africa were surveyed from across six villages, representative of major soil, climate, farm system and locations. The survey was designed to investigate (1) whether the Limpopo Smallholder Farmers (LSF) perceived past and future climates are in agreement with scientific evidence, and (2) how farmers' inclination to adopt climate-smart adaptation practices is influenced by past climate experiences, as well as their constraints and concerns about climate change?

The findings indicate that most of the farmers noticed changes in climate and their related risks as well as believed that climate change was occurring. The LSF perceived increase past and likely raise in future temperature regimes (from 59 and 41 % farmers, respectively) were consistent with those from climate observations and future projection. In addition, the multiple-mediation analysis of farmers' past climate experiences (mainly drought frequency and temperature) had a significant direct effect on their adoption of climate-smart adaptation practices (with direct effect coefficient of 0.47 and 0.43 for cropping patterns, 0.26 and 0.093 for retreat or abandon, 0.45 and 0.34 for farm management, 0.26 and 0.49 for agricultural water management, and 0.24 and 0.54 for alternative adaptation measures, respectively). While flood frequency only had a direct effect on farm management (with coefficient of -0.20), the length of rainfall season had a direct effect coefficient of 0.23 on cropping pattern and 0.27 on alternative adaptation measures, and start of rainfall season have a direct effect coefficient of 0.34 on cropping pattern and -0.17 on agricultural water management. The LSF future extreme event concerns, physical adaptation constraint and economic adaptation constraint (in descending order) had a significant indirect effect on their decision making and/or adaptation behaviour.

This study suggests that the LSF willingness to adopt climate-smart agriculture adaptation practices are directly influenced by changes in temperature and drought, with some swayed by the length of rainfall season and start of the rainfall season. Further LSF willingness to adopt was found to be indirectly influenced by their local future extreme event concerns as well as economic and physical adaptation constraints.

Keywords: *adaptation constraints and concerns, climate-smart adaptation practices, climate change, smallholder farmers*

Chapter II: Factors influencing the Limpopo Smallholder Farmers Selection of Climate Adaptation Strategies

2.1. Introduction

Anthropogenic climate change is an inevitable phenomenon, even with the recent emissions reduction and mitigation targets set by the Intergovernmental Panel on Climate Change and agreed upon at 21st United Nations Conference of Parties in Paris (to cap global warming at 2 °C increase) (Wong, 2015). It is worth noting that the pre-industrial anthropogenic greenhouse levels are said to have contributed to a mean 0.85 °C raise in global average surface temperatures (between year 1880 and 2012). This rise in surface temperatures is said to be already experienced in tropics, especially during warm seasons whereby climate variability increases away from the equator and, there is a rise in the intensity and occurrences of extreme events, *viz*. record setting droughts, desertification, frequency and occurrences of forest fires, increase in weather extremes, and others (Bindoff *et al.*, 2013). The impacts of climate change on the environment, natural resources and regional economies within which smallholder farmers operate will continue pose a threat on their livelihoods. These impacts are postulated to be more pronounced in regions already vulnerable to climate-related risk and other stressors (Ewert *et al*., 2014). Thus, climate adaptation efforts will still be important more so at local scale, as climate impacts are likely to be area specific with regional and global implications.

Sub-Saharan African countries are vulnerable and at risk to climate change, more so in smallholder agricultural based economies (IPCC 2014), given their dependency on weather and a low adaptive capacity. In southern Africa, climate impacts are postulated to be significant on already vulnerable systems, through changes in the first and second order climate variables (such as temperature, precipitation, evapotranspiration and soil-water). The changes in the first and second order climate variables have a direct impact on crop growth, grain yield and crop quality (Palanisami *et al*., 2014). The magnitude of these impacts on agricultural production is said to be depended on the prevailing conditions in each area, such as soil fertility, climate, water availability, and management practices of crop-water-soil, amongst others (Rosenzweig *et al*., 2014).

The maize yield losses on average were projected over sub-Saharan African by 2050 (relative to 1990) to be in excess of 22 %, and even more pronounced in South Africa (Schlenker and Lobell, 2010). There is a general global consensus amongst farmers in the region, based on studies by Hartter *et al*., 2012; Nyanga *et al.*, 2011; Rao *et al*., 2011, that temperatures have increased over the past decades and while precipitation was variable. Such farmer observations and/or experiences are often supported by scientific evidence of warning from decadal analysis of temperature, which strongly points to increased warming trends, consistent with the human-induced climate change presented in the Fifth Assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014). Therefore, it is important for farmers to have a better understanding of the prevailing or expected and potential impacts of climate (Ziervogel *et al*., 2006), to be better placed to develop effective coping and hence adaptation strategies to address the effects of changing climate.

The adoption of adaptation strategies in response to multiple risks varies as impacts of climate change are unevenly distributed between and within locations, and largely influenced by the prevailing conditions (such as climate, natural resources, activities and ability to cope with and adopt to). Thus, to increase the adaptive capacity a better understanding of the drivers and barriers for adoption of new climate-smart technologies are required (Howden *et al.,* 2007). At the farm level, common adaptationstrategies can include income and, crop diversification, soil and water conservation and irrigation (Nhemachena and Hassan, 2009). Limitations in capabilities to adopt coping measures are likely to undermine the sustainability of livelihoods and food security, resulting in poverty traps and increased inequalities (Ziervogel *et al*., 2006).

In this study, a survey of households heads (n = 201) was undertaken in 6 rural villages of Limpopo Province to understand (1) the smallholder farmers perceptions and/or beliefs towards experienced and projected future climate conditions, and (2) how farmers' past climate experiences, their future extreme climatic events concerns (i.e. drought and flood events) and local adaptation constraints (i.e. social, economic and physical constraints), may influence their willingness to adopt climate-smart adaptation practices. The smallholder farmers concerns and constraints arising are a result of likely future impacts of anthropogenic climate change, will have a significant influence on their decision making, and hence motivate their adaptation behaviours.

This hypothesis was similar to other studies from across sub-Saharan Africa, which indicates that a farmer's decision to adapt and the pathway taken were mainly influenced by responses to experiences and concerns associated with socio-economic and environmental conditions. Factors such as drought severity, extent of depletion in groundwater and surface water resources, education level, access to climate information, and support available to farmers were amongst the key drivers found having significant influence on farmers' adaptation decisions.

Previous studies have assessed only the climatic factors as limiting factor which farmers are faced with and hence its influence on their decision making and/or adaptation behaviour; while in this study additional limiting factors of which farmers contend with are evaluated, i.e. social, economic and physical adaptation constraints.

2.2. Materials and Methods

2.2.1. Study area

The study was conducted across six villages (Figure 2.1), *viz.* Ndengeza, Gabaza, Marafana, Selwane, Vyeboom, and Ha-Lambani, within five local municipalities of Limpopo Province, RSA. These villages are located in the low veld (lower altitude) and along the eastern border of the Province (Figure 2.1). The majority of smallholder farmers do not benefit from most agriculturally suitable farmlands in the region, owing to the remnant architecture of the Apartheid Government policies relegating the black African to marginal and agriculturally least suitable areas (Baiphethi and Jacobs, 2009). Presently, areas with moderate to high agricultural production suitability are still occupied by the commercial agricultural sector. This resulted in a dualistic farming system, made up of smallholder and commercial farming (Aliber and Hart, 2009; Whitbread *et al*., 2011).

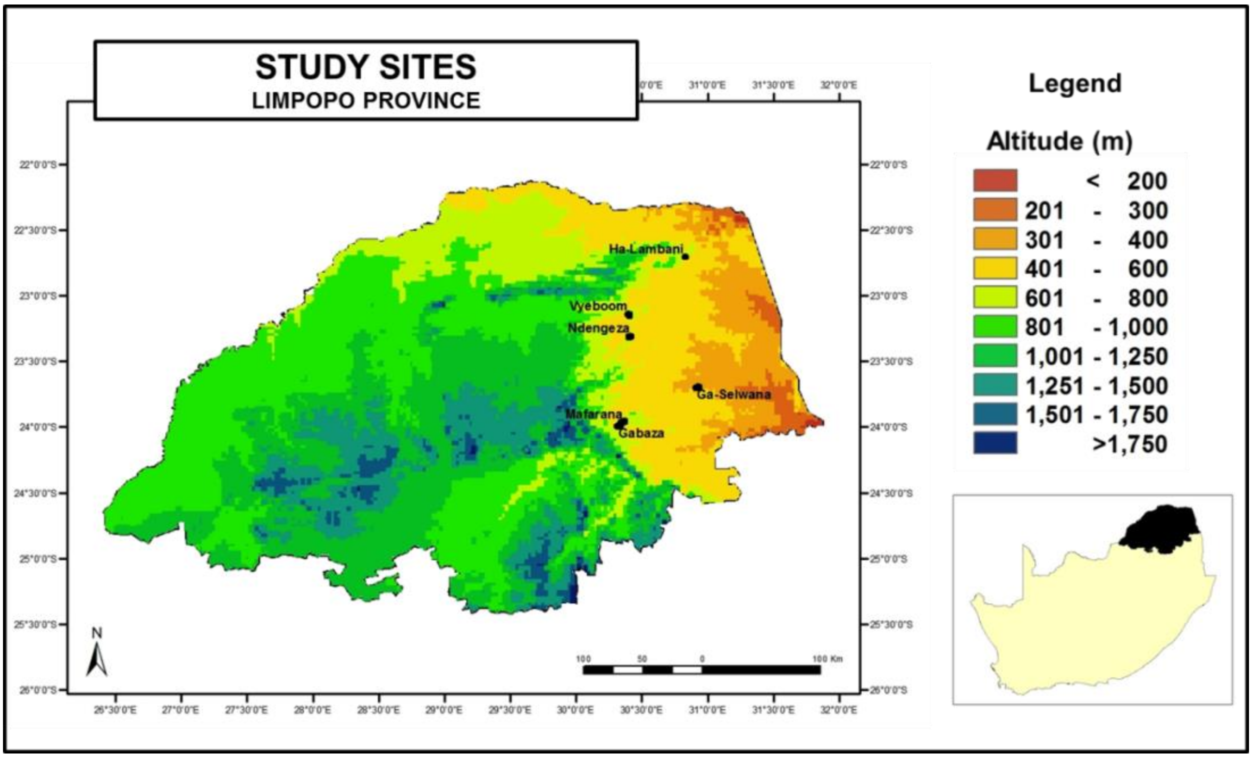

Figure 2.1 Altitude of the study sites in the Limpopo Province, RSA

2.2.2. Survey instrument, sampling, and data collection

The survey instrument was developed with inputs from academic researchers, agricultural officials, and local agricultural extension advisors. Data was collected using a structured closed farmer questionnaire collected from 201 household heads across six villages from high rainfall central plateau escarpment (part of Drakensberg Mountain) to lowlands in the northeastern parts of the Limpopo Province. The survey questionnaire was conducted during the 2014/15 summer planting season with the aim of gaining a better understanding of the LSFs perceptions on climate variability and change, and their adaptive capabilities within the context of their activities.

The survey components ranged from baseline household characteristics information, market access and income sources, agricultural production and management, through to farmer perceptions on climate impacts and barriers to adoption on new technologies. In this study, survey questionnaire components on farmer perceptions to climate (i.e. change and variability), and adaptations (both made by farmers at present and likely to be if conditions changes), barriers to adaptation, and impacts of changes in water resources on agricultural production were used (Appendix: Survey Questionnaire).

The selected villages are representative of the two major Veld Types, i.e. the Inland Tropical Forest type, and Tropical Bush and Savannah type. Criteria used in selection of smallholder farmer were that they should be representative of the area in main agricultural activities, crop and mixed (crop and livestock) farming, and must have been farming for more than 10 years. A driver climate station representative of each of the 6 villages was selected based on the long term record (over 20 years), proximity to the village, and having similar altitudes and mean annual rainfall as the village (Lynch, 2004). The station climate data sets with 50 years of record, i.e. from 1950 to 1999, used in this analysis (source data: Schulze and Maharaj, 2004). The data analyses were conducted using a Predictive Analytic Software, SPSS version 23.0.

2.2.3. Multiple-mediation modelling: Assessment of the Limpopo farmers willingness to adopt climate-smart agricultural adaptation practices

The survey questionnaire variables data was subjected to a correlation analysis test, to determine if the is correlation between the variables, and the variables that do not correlate with each other were excluded from the Factor Analysis (FA). The analysis process involved a correlation matrix (a test for indicating if there was a relationship amongst the variables), the Kaiser-Meyer-Olking (KMO; a test for assessing sampling adequacy and evaluation of any correlations, of which is acceptable at values > 0.500), and the Bartlett's test (with a $p < 0.05$). Thereafter, a correlation test was conducted on the saved component scores to determine if there is a correlation (Lewis-Beck, 1993).

The KMO for individual variables on the principle diagonal exceeding 0.5 from the anti-image correlation were extracted. These variables or factors were then extracted using the maximum likelihood extract method, and rotated using direct oblimin method (i.e. oblique rotation), which permits correlation between factors and the degree of correlation is determined by a constant value called delta. This delta value was set to zero to ensure that high correlation between factors is not permitted (Field, 2009).

The sets of factor loadings higher than 0.50 (Field, 2009) were used in constructing various dependent, mediator, independent and control variables. The coefficient of internal consistency, i.e. the Cronbach’s alpha, was used in assessing the reliability of the item sets, of which all yielded an alpha acceptable higher than 0.70 (Nunnally, 1978). Further information on the variable statistics and measure of reliability across the models is indicated in Table 2.1. Six variables on farmers’ perceptions of changes in past climate experiences were considered for factor analysis – i.e. precipitation, temperature, length of growing (rainfall) season, flood frequency, drought frequency, and crop yields. The crop yields were not included, as they did not meet the requirements for consideration of a factor loading scale > 0.500. The past climate experiences were treated as individual variables as the Cronbach’s alpha was less than 0.70, i.e. below acceptable coefficient for testing correlation and internal consistency between variables to form a scale.

A bivariate correlation analysis (with Pearson correlation and a two-tailed significance test) was conducted as a requirement before any mediation analysis could be conducted. The variables that showed a correlation were selected, and those, which did not, were excluded from further analysis. The constructed variable sets from factor analysis were used to build a series of multiple-mediation models for predicting farmers’ purpose to adopting climate-smart adaptation practices (Table 2.1). The models (ref. Appendix: Figure 6.11) assess if the direct, indirect and total effects of the independent variables on a dependent are mediated by one or more additional variables (Hayes, 2013).

An additional extension, by Hayes (2013) called PROCESS version 2.13.2 tool, was added to the SPSS statistical package). The tool was used to test for how the perception of past climate experiences (i.e. independent variable) affects climate change related concerns and adaption constraints (i.e. mediators), and thus the adoption of climate-smart adaptation practices (i.e. dependent variables). A series of the multiple-mediation models were built for across all farm types and locations within the Limpopo Province. The models were designed to determine how the farmers’ climate experiences across the Province influenced their concerns and constrains, and how these are and/or will affect the adoption of climate-smart adaptation practices. The control variable in Table 2.1, i.e. location of village (indicating six different surveyed villages), is amongst the cited factors often significant and positively related to adoption rates (Prokopy *et al.*, 2008), were used as co-variate in the models. Arbuckle Jr. *et al.* (2013) found that location had a significant correlation with soil, nutrient and water management. The indirect mediation effects within the models were tested using the bias corrected bootstrapping (n = 1000) confidence intervals (95 % confidence; Preacher and Hayes, 2008). This approach builds on the work by Niles *et al.* (2014) and Zhao *et al*. (2010).

Table 2.1 Model variable means and measure of reliability

No.	Name of variable	Scale	Factor loadings	Mean ± Standard deviation	**Cronbach's alpha**
	***Perceived changes in local climate* (Independent variable)**				
	Has local _____ (see below) changed over the past 5 years				
1	Temperature	**Three point scale**		1.62 ± 0.76	
2	Precipitation	1 – increased / earlier		2.55 ± 0.74	
3	Drought frequency	2 – no change		2.27 ± 0.84	
4	Flood frequency	3 – decreased / later		2.32 ± 0.84	
5	Length of growing (rainfall) season			2.12 ± 0.88	
6	Start of rainfall season			1.97 ± 0.90	
	***Local Adaptation constraints* (Mediator variables)**				
	Do you perceive the ______ (see below) as a constraint to adoption of new climate-smart technologies or practices				
	Social (includes knowledge and technology) constraints				
7	Uncertainty in technologies	**Three point scale**	0.771	2.10 ± 0.91	**0.82**
8	Education or knowledge	1 – yes	0.706	2.03 ± 0.92	
9	Financial costs of implementing new strategies	2 – do not know / uncertain 3 – no	0.659	2.06 ± 0.88	
10	Access to weather forecast		0.615	1.89 ± 0.92	
11	Expand or implement irrigation		0.587	2.21 ± 0.85	
	Economic constraints				
12	Lack of access to credit		0.981	1.78 ± 0.91	**0.91**
13	Lack of access to markets		0.869	1.81 ± 0.92	
14	Lack of access to crop insurance		0.807	1.77 ± 0.91	
15	Lack of expert advice based on weather forecast		0.501	1.81 ± 0.93	
	Physical constraints				
16	Access to climate projection information		0.642	1.77 ± 0.88	**0.70**
17	Access to early warning systems to drought (and/or floods) and climate risk information		0.823	1.66 ± 0.84	
18	Extension support or expert advice		0.506	1.56 ± 0.82	
	***Future local extreme events concerns* (Mediator variables)**				
	How do perceive the effects of future project changes in water resources (below) on agricultural production?				
19	Increase in risk of droughts	**Five point scale**	0.849	1.87 ± 1.06	**0.75**
20	Increase in risk of floods	1 – very negative 2 – negative 3 – no effect or relevant 4 – positive 5 – very positive	0.719	1.85 ± 1.01	
	***Adaptation : willingness to adopt climate-smart adaptation practices* (Dependent variables)**				
	What is the likelihood of employing the following climate-smart management practices in your farming system, above and beyond current practices, should you experience conditions above and/or extreme normal climate?				
	Adaptation 1 Cropping patterns				
21	Plant early maturing crops	**Five point scale**	0.951	2.93 ± 1.34	**0.72**
22	Plant drought tolerant crops	1 – very likely	0.856	3.08 ± 1.34	
	Adaptation 2 Retreat or abandon	2 – Likely 3- More likely than not			
23	Lease-out part of the land	4 – Unlikely	0.727	4.26 ± 1.01	**0.77**
24	Leave farming	5 – very unlikely	0.593	4.15 ± 1.19	
25	Sold livestock		0.725	3.95 ± 1.19	
	Adaptation 3 Farm management				
26	Altered application of nutrients/fertiliser		0.881	3.16 ± 1.45	**0.90**
27	Altered application of insecticide/pesticide		0.651	3.25 ± 1.31	
28	Altered application of herbicide		0.856	3.35 ± 1.36	
	Adaptation 4 Agricultural water				

	management				
29	Supplementary irrigation		0.744	3.36 ± 1.27	**0.92**
30	Conservation agriculture		0.746	2.81 ± 1.31	
31	Soil-water conservation technologies		0.867	2.94 ± 1.34	
32	Invest in farm dams (rainwater harvesting)		0.906	3.15 ± 1.35	
	Adaptation 5 Alternative adaptation measures				
33	Additional information gained		0.859	2.36 ± 1.32	**0.84**
34	Followed improved crop production practices		0.670	2.53 ± 1.41	
35	Any other adaptation measures		0.580	2.73 ± 1.32	
	Control variables				
36	Location of village	1 – Selwane; 2 – Ndegenza; 3 –Vyeboom; 4 – Ha-Lambani; 5 – Mafarana; and 6 – Gabaza		3.55 ± 1.64	

2.3. Results

The selected villages are representative of the common maize-based farming systems (including mixed crop-livestock farming), dominant ethnic groups, and relative challenges (such agro-climatic conditions) experienced by the smallholder farmers in the Limpopo Province. The spatially and temporally diverse climate in the Province influences the vegetation and agricultural activities (Table 2.2 and Table 2.3). Further, they represent the dominant aridity indices within the Limpopo Province, particularly the arid, semi-arid and dry sub-humid areas (Appendix: Figure 6.1).

The survey data indicated that there is a general division in agricultural duties along gender lines among the farmers, with males being largely responsible for farm activities with large ruminants and females responsible for crops. This phenomenon has been observed in various studies across sub-Saharan Africa. Further, age played a huge role across the villages with majority of the farmers being adults and retired members of the community, and a huge proportion female (Appendix: Figure 6.2). There are a number of factors that are likely to contribute to such disproportional age distribution of smallholder farmers, such as youth and male family members' migration to cities, culture, etc. (Table 2.2). The dominance of older adults and those at retirement age in the community engaging in agriculture, suggests a lack of interest in the sector by youth even with high levels of unemployment averaging 53.6 %, amongst them.

The mean household size of the surveyed smallholder farmers ranged between 5.15 and 6.19 across the six villages, as shown in Table 2.2, were higher than at the district municipality scale with an average range of 3.5 to 3.9. The smallholder farmers have access to farmland ranging in mean size from 1.09 to 22.78, with only the Ha-Lambani village having high average communal farmland sizes. According to Stats SA (2015) 93.5 % of the household depended on agriculture as an additional sources of food, while 0.9 % depended on it as main source of household food and only 4.3 % was for both main and additional source of income. An issue of food security appears to be a main driver for the Limpopo Provinces' households for participating in the agricultural sector.

The smallholder farmers on average indicated that they have experienced an increase in temperature regimes, and early start of the rainfall season. Furthermore, the farmers said there was a decline in precipitation as well as frequency of drought and flood occurrences, and shorter planting windows. The constraints identified by the smallholder farmers to have significant impact on their local adaptation strategies were social (includes knowledge and technology), economic, and physical in nature (Table 2.1). These constraints, concerns and likely adaptation strategies were grouped and have indicated a high reliability (indicated in Cronbach's alpha, suggesting that there are statistically correlated with high reliability factor over 0.7).

Additional factor identified to influence the farmers adaptation pathways were their concerns for future local climate extremes, which were perceived on average to have negative impacts of their future agricultural activities. Climate-smart adaptation strategies were grouped into six likely adaptation responses, which could be implemented to address changes in local climate. These are cropping patterns, retreat or abandon, farm management, agricultural water management and alternative adaptation measures.

Table 2.2 Physical and socio-economic characteristics of study sites in the Limpopo Province, South Africa

Characteristics	**Local Municipality**	**Greater Tzaneen**		**Ba-Phalaborwa**	**Thulamela**	**Greater Giyani**	**Makhado**
	Village	**Gabaza**	**Mafarana**	**Selwane**	**Ha-Lambani**	**Ndegenza**	**Vyeboom**
Physical [+]							
Altitude (m)		660	658	385	580	663	666
Mean annual precipitation (mm)		730	670	422	948	690	778
Annual temperature (°C)		-0.2 to 41.6	-0.3 to 41.8	0.7 to 43.2	2.8 to 42	2.8 to 41.2	2.7 to 41.0
Veld type		Lowveld Sour Bushveld		Mopani Veld	North-eastern Mountain Sourveld	Arid Lowveld	Lowveld Sour Bushveld
Topography		Hills and lowlands		Slightly irregular plains	Low mountains	Moderately undulating plains	Slightly irregular plains
Socio-economic							
*at Municipality Scale**							
Total population		390 095		150 637	618 462	244 217	516 031
Households		108 926		41 115	156 594	63 548	134 889
Female headed households (%)		47.8		39.5	54.4	57.3	52.1
Mean household size		3.5		3.6	3.9	3.8	3.7
Sex ratio Male per 100 females		87.1		94.1	70.1	79.4	84.8
at Village Scale of Smallholder Farmers							
Mean household size		5.18 (±2.08)	5.79 (±2.15)	5.15 (±2.22)	6.19 (±2.54)	5.86 (±3.01)	5.82 (±2.24)
Farm size (ha)		1.15 (±0.38)	1.09 (±0.38)	1.97 (±1.83)	22.78 (±26.89)	3.89 (±2.34)	1.92 (±1.21)

***** *Source data: Census 2011 Municipal Fact Sheet published by South African Statistician General* (Stats SA, 2011)

\+ *Source data: School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg campus*

Table 2.3 Economic and agricultural production characteristics of study sites in the Limpopo Province, South Africa

Characteristics	Local Municipality	Greater Tzaneen		Ba-Phalaborwa	Thulamela	Greater Giyani	Makhado
	Village	Gabaza	Mafarana	Selwane	Ha-Lambani	Ndegenza	Vyeboom
Main Economic Sectors at Municipal Scale*							
		Community services, finance, trade, agriculture, and manufacturing		Mining, agriculture, manufacturing, and tourism	Agriculture	Agriculture, tourism, retail, and transport	Community services, finance, trade, and transport
Labour market*							
Employment rate		36.7		37.4	43.8	47.0	36.7
Youth unemployment rate (15 to 34 years)		48.5		50.2	58.3	61.2	49.6
Agricultural Production Activities							
Smallholder farmer crops		Maize, pumpkin, beans, cowpea, sweet potatoes, and groundnuts		Maize, watermelon, pumpkin, beans, cowpea, sorghum, Bambara nuts, and groundnuts	Maize, pumpkin, beans, cowpea, and groundnuts	Maize, pumpkin, beans, amaranthus, cowpea, and groundnuts	Maize, pumpkin, beans, cowpea, and groundnuts

***** *Source data: Census 2011 Municipal Fact Sheet published by South African Statistician General* (Stats SA, 2011)

2.3.1. Observed past climate trends and anomalies

In this section, results of climate anomalies and trend analyses (computed using Mann-Kendall Test) of time series data recorded in the Limpopo Province over time are presented in Table 2.4 and Appendix from Figure 6.3 to Figure 6.10. The Mann-Kendall trend test was performed to assess the hypothesis that there is a no trend in the climatic parameters, and hence if any trend exists establish the direction of the trend (i.e. either an increase or decrease). The Mann-Kendall's trend test suggests a significant increase in the annual mean of daily mean and maximum temperatures across all the villages recorded over a period from 1950 to 1999, and no-trends (continuous fluctuations) were found for the annual mean of daily precipitation (Table 2.4).

The temperature anomalies plots of the villages are in agreement with the Mann-Kendall Trend test, i.e. positive increasing anomaly of which suggests increase in temperatures over same time period. Similarly, the Mann-Kendall Trend test showed no significant trend (i.e. neither a rise nor drop) in the mean daily precipitation observation that can be observed in the precipitation anomalies as a continuous fluctuation over recorded time period.

Table 2.4 Mann-Kendall's trend analyses of precipitation and temperature parameters recorded in Limpopo Province, p = 0.025

Annual mean of daily	Village	Gabaza	Mafarana	Selwane	Ha-Lambani	Ndegenza	Vyeboom
precipitation	*Sig. (2-tailed)*	Non-significant		Non-significant	Non-significant	Non-significant	
	Kendall's tau b	0.000		0.000	-0.006	-0.002	
minimum temperature	*Sig. (2-tailed)*	Significant rise		Significant rise	Non-significant	Non-significant	
	Kendall's tau b	0.014		0.016	0.003	0.007	
maximum temperature	*Sig. (2-tailed)*	Significant rise		Significant rise	Significant rise	Significant rise	
	Kendall's tau b	0.040		0.040	0.036	0.040	
mean temperature	*Sig. (2-tailed)*	Significant rise		Significant rise	Significant rise	Significant rise	
	Kendall's tau b	0.027		0.028	0.020	0.024	

Figure 2.2 depicts mean annual days with climatic extremes events affecting agricultural production over the Limpopo Province, derived from historical data, for the 1950 – 1999 periods. Further statistic of minimum, maximum, coefficient of variation (%), median (50%), and 20 and 80% quartile values of the extreme events are presented in Appendix Table 6.1, Table 6.2 and Table 6.3. Figure 2.2 a. depicts mean annual consecutive days with heat wave, defined as daily maximum temperature with more than 30 ^{o}C on ≥ 3 consecutive days, for the period 1950 – 1999. Consecutive mean annual days with dry spells over the Limpopo study areas, shown in Figure 2.2 b., characterised as 3 or more days with less than 0 mm of precipitation.

Figure 2.2 c. shows mean annual days with more than 10 mm of daily precipitation over a 50 year period, which is limitation of agricultural field operations as well as a field onset indicator for stormflow and sediment flow production (Schulze, 2007). Based on the definition, villages more likely to experience more days on an average year of limited agricultural field operations, such as tractability, are Ndengeza, Vyeboom followed by Gabaza, Mafarana and least being Selwane. Selwane is generally a dry area (ref. Table 2.2).

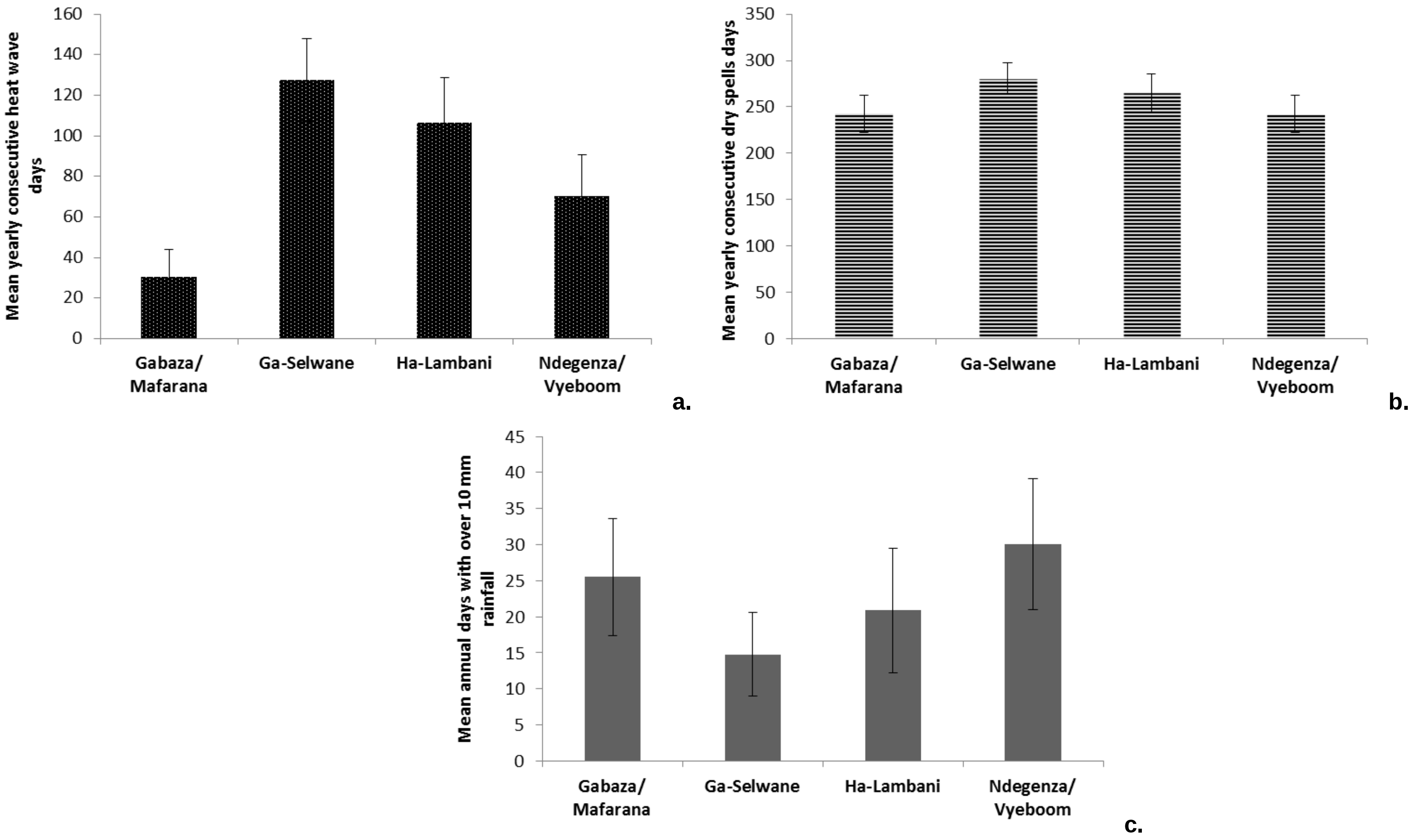

Figure 2.2 Mean annual consecutive days with heat waves (a), consecutive days with dry spells (b), and days with over 10 mm of precipitation over the period 1950 to 1999 with standard deviation bars

2.3.2. Farmers perceptions of past climate and future climate change

Across the six villages surveyed in the Limpopo Province, the smallholder farmers have observed a number of changes in climate and extreme events over time. An overview of the observations is presented in Figure 2.3. A large proportion of farmers indicated that there was a decline in precipitation (76 %), flood frequency (53 %), drought frequency (50 %), and length of rainfall season (44 %). 59 percent of the farmers reported to have experienced increase in temperature and 41 % late start of rainfall season. A small portion of the farmers reported to have experienced an increase in extreme events, i.e. frequency in the occurrence of drought (27 %) and flood (26 %) events.

A similar pattern to past climate experiences was observed in the farmers perceptions to changes in future conditions, wherein the frequency of extreme events are likely to further decrease (including precipitation and length of the rainfall season) and similarly temperature likely to increase further by 41 percent (Figure 2.4). In contrast, to LSF reported past on-set of the rainfall season, they belief that in the distant future it is likely to occur earlier. It is worth noting that some farmers preferred not to answer or speculate on what they thought about the likely future climate conditions.

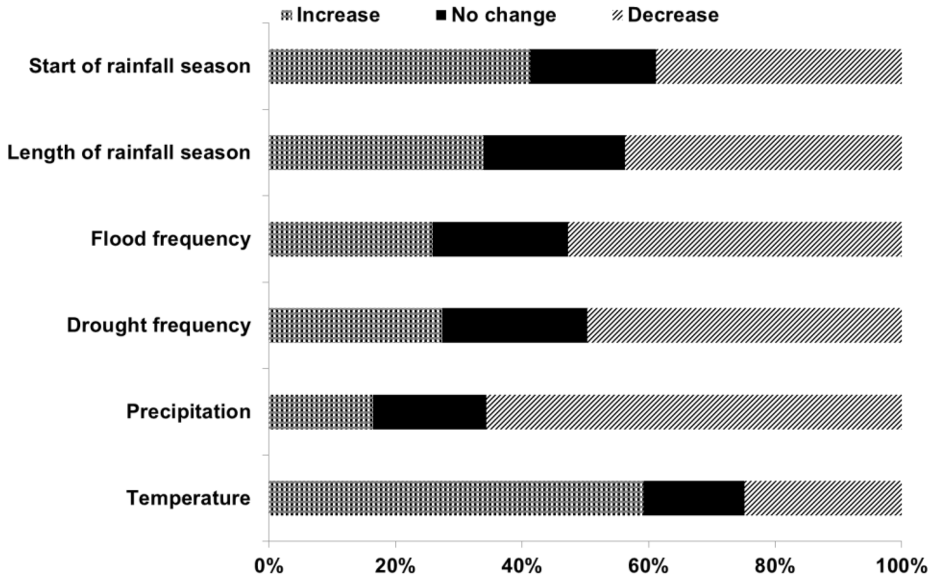

Figure 2.3 Limpopo smallholder farmers' perceived past changes in climate

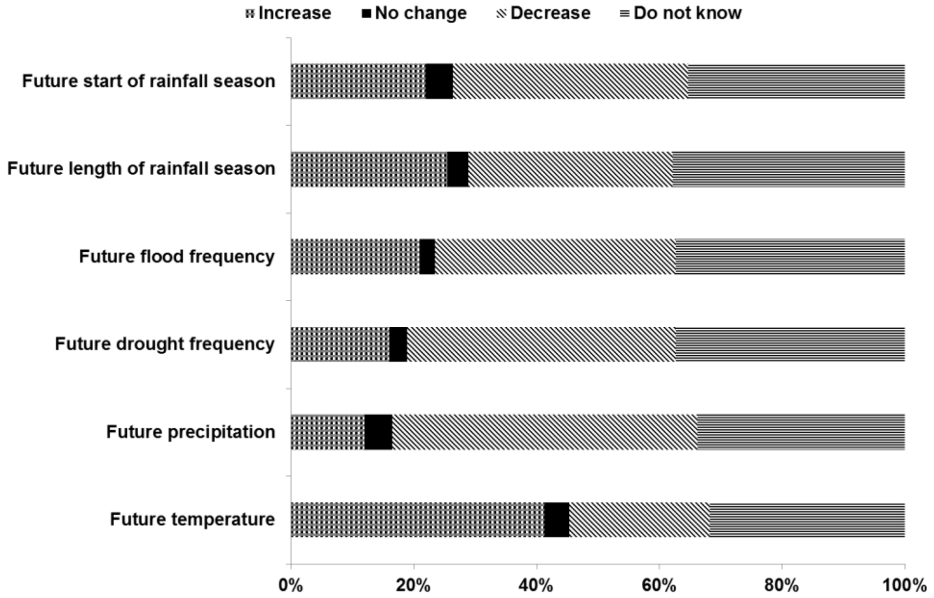

Figure 2.4 Limpopo smallholder farmers' perceptions of future climate conditions

2.3.3. Limpopo smallholder farmers future concerns and adaptation constraints

The average level (and standard deviations) of farmers perceived future extreme events concerns on their agricultural production (1 - very negative to 5 - very positive), and adaptation constraints (i.e. social, economic and physical) on their likelihood to impact their adoption of climate-smart adaptation practices across the six villages, are presented in Table 2.5. Extreme events concerns were on average found to be a high concern in Ha-Lambani, Mafarana and Gabaza villages. Adaptation constraints for farmers' to adopting climate-smart adaptation practices were found to be on average higher in Ha-Lambani village for both social and economic; whereas physical constraints were reported to be greater for farmers in Selwane and Gabaza villages.

A comparison of the farmers' future extreme events concerns and adaptation constraints across the six villages, as presented in Table 2.5, indicated that there were no statistical differences found in the smallholder farmers' extreme events concerns. Despite this, the model results indicate that the smallholder farmer concerns for future local extreme event has an effect on the farmers' past climate experiences to drive the willingness to adopt climate-smart adaptation practices. However, there was a statistical difference between the villages in economic, social and physical adaptation constraints.

Table 2.5 Mean levels of Limpopo smallholder farmers' future concerns and adaptation constraints, including their statistical differences (p = 0.05) across the six villages

Villages	Extreme events concerns	Economic constraints	Social constraints	Physical constraints
Selwane	1.58 ± 0.67	1.74 ± 0.77	1.79 ± 0.61	1.93 ± 0.64
Ndengeza	1.68 ± 1.03	1.64 ± 0.84	1.5 ± 0.52	1.5 ± 0.52
Vyeboom	1.77 ± 0.92	2.00 ± 0.87	1.82 ± 0.73	1.76 ± 0.75
Ha-Lambani	1.98 ± 1.06	2.11 ± 0.94	2.41 ± 0.71	1.31 ± 0.47
Mafarana	1.98 ± 0.88	1.68 ± 0.73	1.94 ± 0.69	1.82 ± 0.72
Gabaza	1.98 ± 0.87	1.57 ± 0.73	2.00 ± 0.74	1.96 ± 0.82
Total	1.86 ± 0.93	1.86 ± 0.85	2.04 ± 0.73	1.65 ± 0.68
Scale	very negative (1) to positive (5)	yes (1) – do not know/ uncertain (2) – no (3)		
Significant levels	0.249	0.023	0.000	0.000

2.3.4. Evaluation of the Influence of limiting factors on agricultural adaptation

The total direct model effects coefficients from the multiple-mediation models, presented in Table 2.6, of pathways farmers' past climate experiences and their willingness to adopt climate-smart adaptation practices. The LSFs' past drought frequency experiences had significant effect on cropping patterns, farm management, and agricultural water management and alternative adaptation measures; whereas temperature experiences had no significant effect on retreat or abandon adaptation practices. Flood frequency experiences had a significant effect only with farm management adaptation practices.

Table 2.6 Coefficients of total direct model effects from multiple-mediation models of farmers' past climate experiences on their willingness to adopt climate-smart adaptation practices

Climate-smart practices	Precipitation	Temperature	Drought frequency	Flood frequency	Length of rainfall season	Start of rainfall season
Cropping patterns	-0.10 ± 0.12	0.43 ± 0.11*	0.47 ± 0.11*	-0.068 ± 0.10	0.23 ± 0.10*	0.34 ± 0.095*
Retreat or abandon	-0.054 ± 0.088	0.093 ± 0.075	0.26 ± 0.091*	0.031 ± 0.76	-0.78 ± 0.71	-0.094 ± 0.069
Farm management	0.092 ± 0.11	0.34 ± 0.10*	0.45 ± 0.10*	-0.20 ± 0.95*	0.44 ± 0.098	0.15 ± 0.092
Agricultural water	-0.086 ± 0.11	0.49 ± 0.092*	0.26 ± 0.10 *	0.21 ± 0.093	0.16 ± 0.92	-0.17 ± 0.74*

management						
Alternative adaptation measures	0.022 ± 0.10	0.54 ± 0.10*	0.24 ± 0.098*	-0.0099 ± 0.093	0.27 ± 0.089*	0.18 ± 0.0093

The bold values with * denote models with significant effects

The cumulative total indirect effects (i.e. both significant and non-significant, $p<0.05$) derived from a multiple-mediation models for testing the effects of famers past climate experiences, local adaptation constraints and future local extreme event concerns on their willingness to adopt climate-smart agricultural practices are presented in Figure 2.5 and Figure 2.6. The total indirect effect (i.e. combination of both none and statistically significance effects) indicates contributions of the constraints and concerns, including the direction of the effect are shown in Figure 2.5.

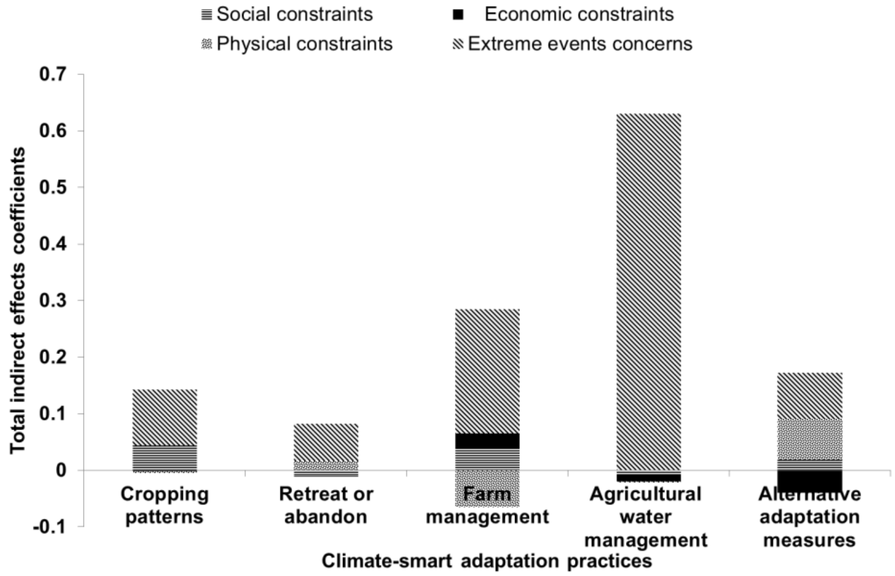

Figure 2.5 Total indirect effect coefficients of Limpopo smallholder farmers' future concerns and adaptation constraints on willingness to adopt climate-smart adaptation practices

Table 2.7 indicates mediators influencing the farmers' adoption of climate-smart adaptation practices for each of the past climate experiences. Drought frequency had no significant mediation with either of the local future extreme event concerns and adaptation constraints. Local extreme event concerns had a significant mediation effects on pathways past climate experiences (excluding drought frequency) to adoption of agricultural water management and alternative adaptation measures. Further significant mediations were between past start of rainfall season, length of rainfall season and flood frequency experiences to farmers' willingness to adopt cropping pattern adaptation practices. Local economic adaptation constraints had direct effect on both past start of rainfall season experiences and farm management adaptation practices, while local physical adaptation constraints mediation between past length of rainfall season and flood frequency experiences, and alternative adaptation measures.

There was no significant indirect effect in the pathway farmers' climate experience, social adaptation constraints and the adoption of climate-smart adaptation practices (Appendix: Table 6.4). The extreme event concerns were found to be a statistically significant driver of the LSFs likely selection behaviour of climate-smart adaptation practices, as well as, the physical adaptation constraints which influenced the selection of alternative adaptation measures and the economic adaptation constraints that triggered the LSF to adopt on farm management practices (cf. Figure 2.6).

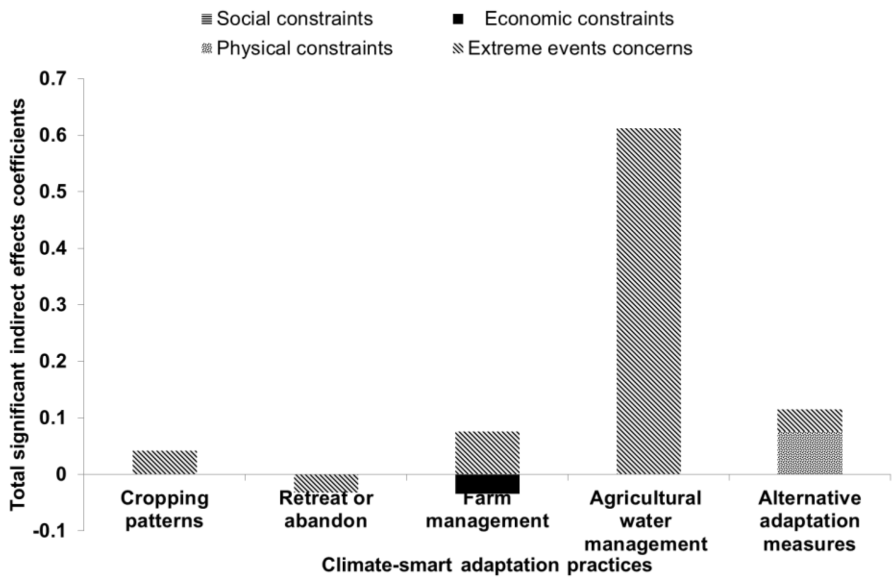

Figure 2.6 Total significant indirect (p <0.005) effect coefficients of Limpopo smallholder farmers' future concerns and adaptation constraints on willingness to adopt climate-smart adaptation practices

The multiple-mediation models in addition indicated an increase in the perceived temperature, precipitation, length of rainfall season and start of the rainfall season were likely to strongly influence the LSFs' willingness to adopt climate-smart adaptation practices (cf. Figure 2.7). Farm management practices were consistently favoured more, and followed by adoption of agricultural water management practices. The adoption of cropping patterns was significant and effect was lesser amongst farmers' perceived change in length of rainfall season and start of rainfall season. There were no significant indirect effects of drought frequency on famers' adoption of climate-smart adaptation practices. Whereas for the farmers' perceived increase in drought frequency the direction of effect suggests a high decline in likelihood to adoption of agricultural water management and a likely reluctance to retreat or abandon agricultural practices. There is however, a positive strong will to seek or adopt alternative adaptation measures.

The significant direct effects of farmers' past climate experiences (*viz.* temperature, drought frequency, length of rainfall season and start of rain season) influencing the LSF adoption adaptation practices, shown in Figure 2.8, suggests that increase in the above mentioned climate experiences (excluding temperature) would increase the likelihood of farmers in adopting cropping patterns, farm management to alternative adaption measures in descending order of effect.

Table 2.7 Summary of indirect effects of the local adaptation constraints (denoted in *bold italics*) and future local extreme events concerns on the pathway of farmers' climate experiences and adoption of climate-smart adaptation practices. Drought frequency had no significant mediation effects with the local adaptation constraints or future local extreme events, and hence was excluded from the table

Climate-smart adaptation practices	Precipitation	Temperature	Flood Frequency	Length of rainfall season	Start of rainfall season
Cropping patterns			Extreme event	Extreme event	Extreme event
Retreat or abandon			Extreme event		
Farm management	Extreme event	Extreme event	Extreme event	Extreme event	Extreme event / ***Economic***
Agricultural water management	Extreme event	Extreme event	Extreme event	Extreme event	Extreme event
Alternative adaptation measures			***Physical***	Extreme event / ***physical***	

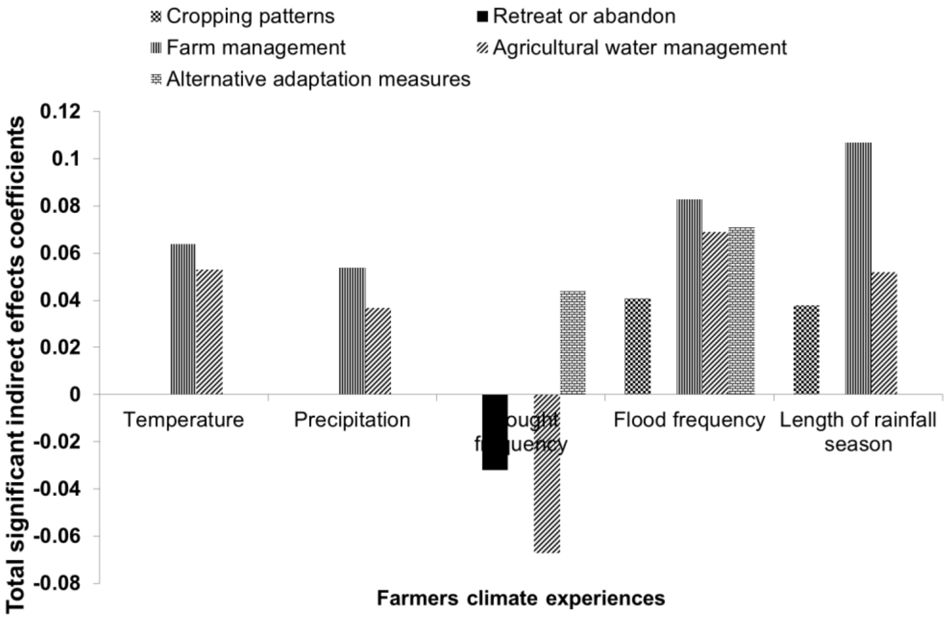

Figure 2.7 Total significant indirect (p <0.005) effect coefficients of Limpopo smallholder farmers' climate experiences on willingness to adopt climate-smart adaptation practices

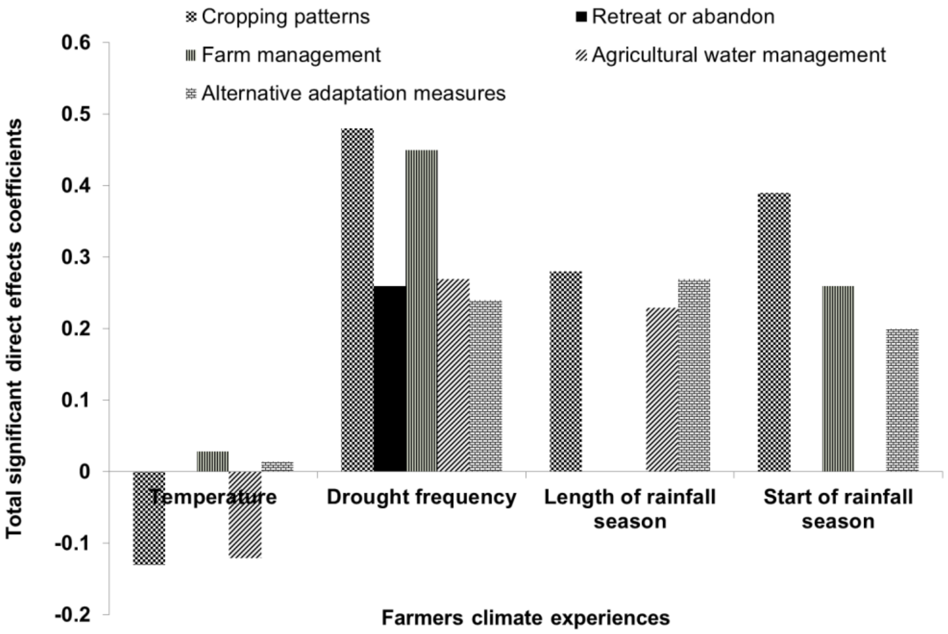

Figure 2.8 Significant direct (p <0.005) effect coefficients of Limpopo smallholder farmers' climate experiences on willingness to adopt climate-smart adaptation practices

2.4. Discussion

The South African Statistician General Census report of 2011, indicate that there is a huge unemployment, as depicted in Table 2.3, in the Limpopo Province. Even with huge unemployment, particularly amongst the youth, it is worth noting that major of smallholder farmers interviewed were above age of 35 across the villages. Further, majority of the youth do not view agriculture as an economically viable path, which is attributed to the polarised agricultural systems (i.e. commercial farming dominating the sector and subsistence farmers battling to break into mainstream commercial sector) in the country. This observation of very low interest in agriculture as an employer or economically beneficial, has been documented earlier in the region by Aliber *et al.*, (2013), wherein the sector is not being considered as career or an important component of their livelihood strategy amongst the rural youth. The lack of interest in agriculture could be attributed to low productivity and hence a lack of financial viability of industry, particular for smallholder and emerging farmers (Whitbread *et al*., 2011).

2.4.1. Comparison of perceived climate with observed and future projected conditions

The high inter-annual variability in precipitation across all the villages (Appendix: Figure 6.4; Figure 6.6; Figure 6.8; Figure 6.10), indicate a history of high climate-related risk resulting in high fluctuations in agricultural productivity and water resources over the Limpopo Province as reflected in agricultural statistic of the Province (DAFF, 2016). This highly unreliable precipitation and the associated implications on agricultural production have been noted in numerous studies across same region such as that of Mzezewa *et al*. (2010).

The smallholder farmers across the six surveyed villages reported different rainfall experiences, with a majority highlighting a decrease over past years. This observation could have been influenced by the marked dry spells seasons and flood events, and hence their corresponding low crop yields, having had huge impact on their livelihoods and their farming systems still recovering from those events, therefore, the memory been easily recalled as opposed to the years wherein better yields were experienced. This is due to the LSF account contradicting the rainfall observations analysis pointing to fluctuations over the surveyed period. It is worth noting the micro-climate effect, in particular of rainfall distribution, which might have been captured by the climate station as it was about 15 km away from the village. In contrast, the farmers' perceived increase in temperature were found to be in agreement with the general increase trend of historical climate in the presented statistical analysis, including literature in the Province (Tshiala *et al*., 2011)

Majority of the famers' believed that temperature regimes are likely to further increase in future, and that the frequency of extreme events (i.e. drought and flood), precipitation and length of the rain season would continue to decrease. A clear signal from the global models (Engelbrecht *et al*., 2015; IPCC, 2014) indicates an increase in temperature of which is consistent with farmers' perceptions of past experiences. Compared with farmers' perceptions on changes in precipitation, global models do not point to a clear direction of change, but fluctuations with some GCMs suggesting an increase while other models indicate a decrease, as presented in IPCC (2014), with varying magnitudes of projected change. Further, GCMs point to an increase in the frequency of future warm and dry seasons, and decrease in wet season, which were found to be in contrast with farmers' perceived changes in extreme events.

Worthy of noting is that most farmers' seemed to better recall extreme events, such as dry and wet seasons as this had the most significant impact on their production, including flood events of which most were related to above normal rainfall from cyclone events. This psyche might explain the reported decrease in precipitation by farmers in the Limpopo Province and similarly farmers' in Kenya (Ogalleh, *et al.*, 2012).

2.4.2. Evaluation of factors influencing Limpopo smallholder farmers willingness to adopt climate-smart adaptation practices

In the study, a correlation between the LSFs' climate experiences, constraints and concerns, and the adoption of climate-smart adaptation practices was demonstrated. Precipitation experiences seem to have no significant effects on adoption behaviour of the smallholder farmers to adopting climate-smart adaptation practices. Their experiences to flood frequency only had a significant effect to adoption of farm management practices. The smallholder farmers' drought frequency experiences had direct significant effects on adoption of all climate-smart adaptation practices, whereas temperature experiences had the opposite effects.

There were no significant indirect effects on most of the "social adaptation constraints" pathways, however, past climate experiences mediated by local adaptation constraints had a significant influence on the farmers' willingness to adopt climate-smart adaptation practices. Similarly, the physical and economic adaptation constraints had no significant indirect effects on most of the adoption of climate-smart adaptation practices, except the alternative adaptation measures. The extreme climate events concerns were found to have major influence on the LSFs adaptation behaviour, of which is attributed to the fact that agriculture practiced in the area is dominantly rainfed, and is prone to frequent drought and/or flooding events. The soil and water management strategies were introduced in some parts of the Province areas to mitigate the dry spells and hence improve expected yield (Mpandeli, 2014; Botha *et al.,* 2014).

Consistent with findings from studies by Haden *et al*. (2012) and Niles *et al.* (2015) in California and New Zealand (respectively), the LSFs water resource related concerns, in this study being drought and floods, had a strong influence on their decision making and/or adaptation behaviour. New contributions to such studies were the evaluation of social, economic and physical constraints effects on farmers' adaptation behaviour, which found that the social constraints did not yield any significant effects, expect for economic and physical constraints to certain adaptation practices.

Findings in this study were generally in agreement with those by Arbuckle Jr. *et al*. (2013); Haden *et al.* (2012); Niles (2015) which suggested that farmers past climate experiences and influencing factors within their farming system may impact their adaptation responses. Further, a farmer's ability to adapt to changes, at any scale, may be constrained by forces outside the system (Adger *et al.,* 2005). The range of adaptation options and opportunities available to farmers may be drastically reduced by multiple constraints, and hence limit adaptation potential. The LSFs' future extreme events concerns were found to be likely to trigger farmers to adopt all the adaptation strategies, while their economic and physical adaptation constraints would influenced farm management and alternative adaptation measures adoption. Social adaptation constraints were found not to have any significant effect on the surveyed farmers' adopt of adaptation practices.

Similar to the LSFs', perceptions of local farmers' in the Middle Yarlung Zangbo Valley River Valley, Tibet to climate change and adaptation strategies were found to be based on their indigenous knowledge and own experiences (Li *et al*., 2013). Further example is from a study in Zambia by Nyanga *et al*. (2011), which indicates that the farmers adopted conservation agricultural practices in response to experienced changes, such as changes in climatic variables, timing of planting season and extreme events. Further majority of the farmers in Zambia did not perceive adoption of conservation agriculture to be an adaptation strategy for coping with climate change.

Poor-resourced farmers, such as those surveyed in the Limpopo Province, have the likelihood to follow a natural pattern of undertake adaptation measures that are regarded as basic, requiring low input costs and technical expertise, and generally do not require collective action. Most of such adaptation measures are likely to result in relatively low impacts in response to postulated effects of future climate (Van *et al*., 2015). This finding of low adaptability of LSF might be owing to limited understanding of the impacts, and access to resources to implement and select appropriate adaptation strategies.

2.5. Conclusion

Findings from the surveyed Limpopo smallholders farmers suggests they have an understanding of changes in climate as well as the likely impacts posed on their agricultural production, based on past experiences of local conditions. Further, they were able to postulate most likely future changes in climate in their area. The comparative analyses indicated that their perceptions particularly to changes in temperature correlated with climate observations and GCM outputs.

In agreement with the main hypothesis, the multiple-mediation analysis suggested that the farmers' perceived local past climate experiences, mainly changes in temperature and flood frequency, had significant direct effects on their willingness of adapting climate-smart adaptation practices. Changes in length of rainfall season and start of the rainfall season had direct significant effects to some of the climate-smart agriculture adaptation practices. The indirect effects of the model were mediated through local future extreme events concerns for all adaptation practices, whereas, the physical and economic constraints mediated alternative adaptation measures and farm management (respectively). These findings suggest that adaptation amongst the Limpopo smallholder farmers is motivated primarily by their local future concerns and adaptation constraints, in addition to changes in climate. The LSF physical and socio-economic constraints were found to have a significant effect and hence limiting factors to adaptation.

This study suggests that implementing climate-smart agriculture adaptation practices successfully at farm-level may not only be triggered as a response to direct impacts of climate change, but adoption of specific adaptation practices maybe brought about by the farmers future local extreme events concerns and constraints to adaptation.

CHAPTER 3. THE IMPACTS OF CLIMATE-SMART PRACTICES ON THE CLIMATE RESILIENCE OF SMALLHOLDER FARMERS IN DIVERSE LANDSCAPES OF THE LIMPOPO PROVINCE, SOUTH AFRICA

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Abstract

The productivity of rainfed agriculture in the Limpopo Province is typically low, increasingly threatened by high climatic variability in the form of dry-spells, erratic rainfall and high evaporative demand. Rainwater harvesting and soil-water conservation management practices (conservation agriculture, surface residue management) have some potential to mitigate these effects and improve the sustainability of the maize-based smallholder systems in this region. There is however, a lack of information available to government authorities on how best to and where target such interventions. Thus, field scale tested climate-smart practices (CSP) were parameterized and calibrated for a daily process-based farming systems model, APSIM - Agricultural Production Systems sIMulator , to allow for assessing the possible management practices under a wide range of environmental conditions. We adopted this approach and tested following hypothesis: (i) Increasing surface residue application leads to higher soil-water retention, and consequently higher maize yield; (ii) Insitu rainwater harvesting in combination with conservation agriculture leads to higher yields than conventional practice.

Four datasets were used in deriving parameters, calibration and validation of APSIM-maize model. The model calibration indicated a positive strong relationship between predicted and observed maize grain yields and biomass with an r coefficient of 0.96 and 0.92, respectively. The model validation using field experimental data and three secondary independent datasets suggest that the model is capable of simulating soil-water, biomass (r = 0.82 and RMSE of 572 kg.ha^{-1}) and grain yields (r =0.76 and RMSE = 2 577 kg.ha^{-1}). A cascading in hydrological responses from runoff generating to a collection soil profile, concept adopted from PARCHED-Thirst model, to simulate insitu rainwater harvesting in APSIM model yielded a strong correlation with observed data.

We adopted an APSIM-GIS coupling approach to upscale the validated APSIM simulator modules to mimic the impacts of climate, soils and CSP on agro-hydrology of the Limpopo Province. The available soil-water content increased with increments in surface residue, but was negated in parts of the Province with high rainfall and/or drainage losses. A similar trend to soil-water content was observed for maize grain yields, wherein more sub-catchments in the Province experienced higher yields and a few decline in yields with increments in surface residue application rates. The combination of both tillage and surface residue yielded higher maize grain yields in IRWH combination and less so in No-tillage. The results suggest that for the beneficial effects of climate-smart practices to optimize agricultural productivity, they would need to be targeted and adapted to a specific biophysical condition.

Keywords: *Climate change, rainfed agriculture, climate-smart agricultural practices, APSIM model, maize croplands, upscaling*

3.1. Introduction

3.1.1. Yield Limiting and Reducing Factors

The agricultural sector is the backbone of local livelihoods with significant contributions to the national Gross Domestic Product (GDP). Maize is an important cereal grain crop in South Africa, as it is both a major feed grain and staple food for a large portion of the population. In 2013, white maize which is consumed primarily by humans, constituted 48 % of the total maize and the remainder (yellow maize) mostly used as an animal feed. In Limpopo Province, maize production accounts for 2 % of the total national maize crop (DAFF, 2014). Such statistics capture only commercial production, while information on subsistence production remains unavailable as produce is for home consumption or trading is normally through the informal sector, and hence contributing to local economy (Aliber and Hart, 2009).

The agricultural sector as a whole faces numerous production risks, *viz.* pest and disease infestations, extreme weather events, soil fertility and degradation and market shocks, among others, which are more pronounced for smallholder farmers (mostly subsistence) owing to high exposure to extreme climate events, limited resources and lack of adaptive capacity (Harvey *et al*., 2014; Morton, 2006; O'Brien *et al*.,2004). Typically smallholder farmers are reliant on agriculture for their livelihoods and thus any changes in productivity will have a ripple effect on their livelihoods, food security and the local economy which they contribute to (Kurmar *et al.*, 2006; Hertel and Rosch, 2010; McDowell and Hess, 2012). Smallholder farmers are amongst population groups experiencing hunger, and hence their fate will largely be reliant on their ability to sustain productivity in the midst of uncertain rainfall conditions prone to extreme climate events such as dry spells.

The smallholder agriculture largely rainfed and thus agriculture is at risk, owing not only to climate extremes (such as heat waves and droughts), but also recurrences of the high inter-seasonal variations and frequent dry spells over the rain season (Mzezewa *et al*., 2010). Prolonged periods of exposure to this climate-related extremes aggravates the challenges and constraints already affecting agriculture, such as poor soil fertility, pests, crop diseases, and lack of access to resources and improved seeds (Tittonell and Giller, 2013).

3.1.2. Climate-Smart Agriculture

Climate-Smart Agriculture (CSA) is an approach that transforms and changes the direction of agricultural development under human-induced climate change. CSA practices aimed at reducing small-scale farmers' exposure to climate-related risks and increasing their productivity, while improving their resilience and adaptive capacity to climate variability and change were identified. The practices were selected on bases of incorporating an integrated soil, water and crop management strategies approach, to increase and sustain crop productivity by increasing water availability, crop access to soil-water and soil-water holding capacity (FAO, 2010; Steenwerth *et al.,*2014).

The agricultural sector, in South Africa, has been declining since 1990s in terms of its contribution to the national GDP (from 4.6 in 1994 to 2.3 in 2013) as result of faster growth in other sectors (Greyling *et al*., 2015), and 31 % decline in number of commercial farms (between the years 1993 and 2007) owing to rise in water scarcity, reduction in farming profitability and changes in landuse (Agricultural Statistics, 2013; Goldblatt, 2010). This has led to the loss of farmland to other uses (such as game farming and mining) and merging into large farms to be economically beneficial. According to Agricultural Statistics (2013), in the Limpopo Province, only 14.2 % of the land is potentially arable and the remainder is used for grazing (74.0 %), nature conservation (9.7 %), forest (0.5 %) and other landuses (1.5 %). Even with irrigation accounting for 60 % of the fresh water resources in South Africa (NWRS, 2013), there is insufficient land suitable for crop production and limited water resources to meet the growing demands of population growth and the challenges associated with climate change.

In light of this, alternative pathways to increase and sustain dryland agricultural productivity are needed under changed environmental conditions. One such approach is adoption of climate-smart practices (CSP), in this case, soil-water management that have the likelihood to improve and/or sustain agricultural productivity through efficient water management in rainfed agricultural systems. The improvement of soil-water management under rainfed systems is said to be achievable by adoption of soil conservation techniques that result in rainwater capture and retention, and soil fertility and crop management that increase crop growth and yield, and hence water use efficiency (FAO, 2013; Oweis *et al*., 1999).

Harvesting rainwater has been shown be beneficial to farmers, under low and erratic rainfalls conditions to grow their crop and to sustain their livelihoods through alleviating their crops from dry spells (Botha *et al.*, 2014a). Rainwater harvesting techniques, i.e. insitu and ex-situ, have been shown to improve soil-water, reduce runoff, increase deep drainage into the groundwater, ease effects of dry spells and increase agricultural production (Makurira *et al.*, 2010; Yosef and Asmamaw, 2015). Insitu rainwater harvesting (IRWH), within the context of this study, is referred to as the generation of rainwater runoff from no-till runoff area, collection within micro-catchment in the field, direct storage in the soil profile and efficient use for agricultural crop production to mitigate dry-spells (Botha *et al*., 2014a; Oweis *et al*., 1999). The incorporation of mulch into IRWH techniques reduces the unproductive evaporation losses more by conserving much water and suppressing direct soil evaporation. The mulch and IRWH integration method was found to result in higher soil-water stores and higher harvestable yields (Tesfuhuney *et al*., 2013).

Given the potential benefits of climate-smart practices, particularly insitu-rainwater harvesting, conservation tillage and organic surface residue application, on smallholder farming in sub-Saharan Africa, the objective of this study was to determine the plausible wide-spread adoption of these practices on farm-level agro-hydrological responses (i.e. maize yield and soil-water response) across diverse landtype and climate. This study contributes towards the biophysical evaluation of likely site-specific uptake of climate-smart practices, to cope with prevailing climate-related risks. This was achieved through model calibration and validation based on field experiments and simulation of long-term agro-hydrological responses to the practices over different landtypes and climate conditions across four sites in the Limpopo Province. Then, the following hypotheses were tested: (i) Increasing surface residue application leads to higher soil-water retention, and thus maize yield; (ii) Insitu rainwater harvesting in combination with conservation agriculture leads to higher yields than conventional practice; and (iii) Limpopo farmers need to develop and implement risk management strategies that help them to efficiently capture and conserve rainfall through soil-water management strategies.

3.2. Materials and Methods

Four datasets were used for deriving essential parameters, calibration and validation of APSIM model; details of the studies used are shown in Table 3.1. The datasets are field experiments conducted over the period 2008 to 2015, with Experiment 1 (Experiment 1) was conducted at Syferkuil Research Farm (on the Syferkuil-Hutton soil form) over two growing seasons (2013 to 2015). The soil was classified based on the South African Soil Classification System (Soil Classification Working Group, 1991). The first growing season was used for model parameterization and calibration. The other three datasets from independent studies conducted at Towoomba Research Station (Experiment 2 – 3) and Lambani Village (Experiment 4), were used for both model calibration and validation, conducted at different soils and locations over three and four growing seasons from 2008 to 2012.

All experimental datasets had same fertilizer application rates of 45 kg/ha of nitrogen and 42 kg/ha of phosphorus at sowing, with the exception of Syferkuil and Ha-Lambani were top dressing fertilizer was applied. Further, they all had similar tillage practices, *viz*. NT, IRWH and CT, main differences were the runoff generation strip with Syferkuil being 1 m width and others 2.4 m. The approach of using different datasets from similar studies to perform APSIM model evaluation was adopted from Hill *et al.* (2006).

Table 3.1 Details of the datasets used to derive module parameters, calibrate, and validate APSIM-Maize, under rainfed conditions.

Experiment		**Source**	**Location**	**Soil form (ype)**	**Cultivar**	**Sowing density (plants.ha^{-1})**	**Sowing date**	**Harvest date**
	MC	Author	Syferkuil Research Farm, Limpopo Province	Hutton (Loam)	ZM421	22 000	10/12/2013	07/07/2014
	MV				ZM421	22 000	05/12/2013	12/06/2015
2	MC	Botha *et al.* (2014a)	Towoomba Research Station,	Hutton (Loam)	ZM 523	20 000	24/11/2009	24/03/2010
	MV				ZM 523	20 000	08/12/2010	07/04/2011

	MV		Limpopo Province		ZM 523	20 000	13/12/2011	12/04/2012
3	MC	Botha *et al.* (2014a) Ngwepe (2015)	Towoomba Research Station, Limpopo Province	Arcadia (Clay)	PAN 6P-563R	20 000	25/11/2009	25/03/2010
	MV				PAN 6P-563R	20 000	02/02/2011	01/06/2011
	MV				PAN 6P-563R	20 000	11/01/2012	11/05/2012
4	MV	Botha *et al.* (2014a)	Lambani Village, Limpopo Province	Shortlands (Loam)	PAN 6P-563R	20 000	08/12/2009	21/04/2010
	MV				PAN 6P-563R	20 000	29/11/2010	12/04/2011
	MV				PAN 6P-563R	20 000	01/12/2011	15/04/2012

MC = Model Calibration; MV = Model Validation

Weekly weather forecast from the Norwegian Meteorological Institute and the Norwegian Broadcasting Corporation (www.yr.no, provided more forecast information in terms of the amount and duration in hours of precipitation and at finer spatial scale (village or town scale instead of a district), further they were found to be more precise than forecasts from other sources) and weather, data from *insitu* manual rainguage and daily weather station were used in the planning of all find activities; the requirements that had to be met before sowing was more than 2 consecutive days of rainfall followed by rainfall forecast within next 3 days or 15 mm over a 3 day period. Whereas, for top dressing a minimum of 10 mm over 5 days followed by a forecasted rainfall within 5 days (this was to ensure that the nitrogen was effectively utilised).

3.2.1. Experimental Study for Derivation of Parameters and Calibration

The dataset used in model calibration (Experiments1 – 3 first growing seasons; Table 3.1.) The Experiment1 research was carried over two consecutive growing seasons, i.e. 2013/14 and 2014/15 seasons, at the University of Limpopo Experimental Farm at Syferkuil (23 ^{o} 51' S; 29 ^{o} 42' E, ~ 1250 m above sea-level) in the Limpopo Province, South Africa. Calibration information was derived from the first growing season of the experiment.

A randomised complete block design in split plot arrangement with four replications was used. The main plot treatment was tillage practice consisting of in-situ rainwater harvesting (IRWH), no-till (NT) and conventional tillage (CT) practices. The sub plot treatment was mulch application consisting of 0, 3, 6 and 12 t.ha-1 rates) on maize crop. Each sub-plot measured 5 x 10 m and experiments were repeated within same plots for the two consecutive years. An open pollinating maize cultivar, ZM421, was planted using a tractor mounted planter at 1 m row spacing and 0.45 m inter-row spacing for all the tillage practices. IRWH tillage practice was established based on the principles developed and defined by Hensley *et al.* (2000). This composed of a 1 m NT runoff generation strip and a 0.18 m^3 volume (i.e. 1 m Length x 0.6 m Width x 0.3 m Depth) runoff collection basin, the maize crop was planted 0.2 m along each side of basin with same spacing as other tillage practices. Soil fertility was kept constant with uniform application rate of fertilizers (i.e. 42 P $kg.ha^{-1}$ and 45 N $kg.ha^{-1}$) at planting. Further, weeds (and pests) were continuously controlled over the growing season.

Timing for key field operations are presented in Table 3.2, including dates when plant biomass was collected at different physiological stages. The aboveground matter from the previous season was cleared during field preparations. Planting and fertilizer application were only applied if more than 20 mm was received and further rainfall was predicted within next seven days afterwards. In second season, sprinkler irrigation had to be used only at planting as above conditions were not met; an average of 50 mm was applied across the field. The supplementary irrigation was used to enabled for easy of using planter and ensuring there was soil-water at seeding.

Analysis of variance (ANOVA) in Statistix 9.0 (Statistix, 2008) was used to determine the significance of soil-water content, maize grain yield and water use efficiency.

Table 3.2 Timing for cropping operations and biomass collection

Season	Field preparation	Planting	Fertilizer application	6 weeks	Flowering	Harvesting
2013/14	30 Nov 2013	10 Dec 2013	10 Dec 2013	29 Jan 2014	05 Mar 2014	07 Jul 2014
2014/15	28 Nov 2014	05 Dec 2014	5 Dec & 23 Jan	23 Jan 2015	22 Feb 2015	12 Jun 2015

The soil-water content was determined throughout the two cropping seasons at various physiological stages of maize crop growth (*viz.* planting, flowering and harvesting periods) at different soil profile depths, i.e. 15, 30, 45, and 60 cm. Crop parameters, such as plant height, biomass and grain yield samples, were determined using 1m transect with 2 samplings per treatment plot. The crop and soil wet weight were measured in the field, then taken to the laboratory and oven dried at 75 and 105 ^{o}C (respectively) for 72 hours and thereafter weighing again.

Water-use efficiency

Water-use-efficiency (WUE) was derived from the harvested grain yields (kg.ha^{-1}) over, the total precipitation received between sowing and harvesting plus the plant water available (PAW) at sowing and harvesting stages (mm) from the different treatments for each growing season (Whitbread *et al*., 2014).

$$\text{WUE (kg.ha}^{-1}\text{.mm}^{-1}\text{) = Grain yield / (total rainfall + (PAW}_{\text{sowing}}\text{ + PAW}_{\text{harvesting}}\text{))} \quad 3.1$$

Seasonal climate conditions

During the first growing season of the trials, above average annual precipitation was received (Table 3.3), whereas in the second season below average annual precipitation. The in-crop precipitation received in the first and second growing seasons were 1004 and 245 mm (respectively) with annual average being 440 mm.

Table 3.3 Monthly precipitation received over planting season and long-term period at Syferkuil Research Farm

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Planting season (Oct - Jun)
1950-2015	105	88	79	43	13	6	5	9	27	69	70	113	627	440
2013/14	112	177	581	52	0	0.3	9	50	278	125	49	82	1515	1004
2014/15	44	24	15	82	0.3	0.5	1.3	10	0	34	94	80	385	245

The South African Weather Services define meteorological drought as a degree of dryness in comparison to average rainfall of a particular area and over a dry period duration, whereby 75 % less than average rainfall is defined as meteorological drought and at 80 % likely to cause crop and water shortages. In the context of the study area and based on above definition of drought, there was no meteorological drought in the first growing season or year as rainfall was 242 % of average rainfall based on over 65 years of daily historical data. In the second growing season, however, there was meteorological drought with 23 % of average rainfall and was near the threshold to cause crop and water shortages. The Experiment 2 - 3 datasets for first growing seasons were used to calibrate the maize varieties in the ASPIM-maize module.

3.2.2. Experimental Studies for Derivation of Validation

The experimental datasets Experiment 1 – 4, shown in Table 3.1, were used in the model evaluation. The main objectives of the studies were to evaluate the effects of IRWH and CT on maize growth and yields. The tillage practices in Experiment 3 – 4 are similar to those described above (i.e. Experiment 1), with minor difference been in the IRWH run generation area been 2.4 m width as opposed to 1 m. Furthermore, there was no mulch application included as part of these study datasets. Fertilizer was applied at sowing (i.e. 42 kg.ha^{-1} phosphorus and 45 kg.ha^{-1} Nitrogen rate) with planting depth of 70 mm and planter inter-row at 1000 mm (Botha *et al.,* 2014a; Ngwepe, 2015).

3.2.3. APSIM Model Configuration

The APSIM model was configured or parameterised for field experimental soil, water and crop management (i.e. soil profile, and tillage practices with different mulch levels) and climate conditions, as described below. APSIM version 7.5 r 3008 was used to simulate the tillage/surface water management practices and varying mulch level effects on soil-water dynamics and maize growth. The model requires daily minimum and maximum temperature, daily mean precipitation and solar radiation were obtained from an on-farm automatic weather station, managed and quality controlled by Agricultural Research Council in South Africa. The missing records, owing to short period of operation length (less than 8 years, 3 January 2008 to date) and maintenance, were patched using an approach described by Warburton *et al*. (2012) for selection of a representative nearby stations with a reliable record and altitude (and mean annual precipitation) of the station similar to target station location.

The data used in the configuration of the model was soil physical parameters (Table 3.4 and Table 3.5), including layer-based bulk density, saturated water content, soil, and water at field capacity and wilting point. The simulations were initiated using the soil parameters outlined in Table 3.4 for a 0.7 m soil profile depth. The field management operations were input as part of the simulation treatments, i.e. uniform band place of nitrogen at planting and after 6 weeks, tillage practices, and mulch levels near flowering. Further, the simulation initialisation dates were set using dates shown in Table 3.1. The initial plant available water (PAW) was set at 60 mm for Experiment 1 on the first cropping season and 27 mm for the second cropping season; while for Experiment 2 - 4 the initial soil-water was set at 100 %, to correspond with maize trial planting times over the cropping season.

Table 3.4 Soil-water holding capacity properties of the Syferkuil Research Farm, and the values used in specifying the APSIM model simulation at initialisation of cropping season

Layer number	**1**	**2**	**3**	**4**	**5**
Soil layer depth (cm)	15	15	15	15	15
Water content at air dry (mm/mm)^a	0.035	0.096	0.133	0.141	0.149
Crop lower limit (mm/mm)	0.069	0.137	0.141	0.157	0.149
Drained upper limit (mm/mm)*	0.268	0.268	0.319	0.286	0.286
Saturated water content (mm/mm)	0.408	0.408	0.413	0.401	0.393
SWCON	0.500	0.500	0.500	0.500	0.500
Bulk density (g/ cm^3)*	1.57	1.57	1.51	1.51	1.51
Soil texture	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy clay loam
Organic carbon (%)*	0.501	0.501	0.390	0.395	0.228
pH*	7.73	7.73	8.32	8.32	8.32

* Data obtained from study by Whitbread and Ayisi (2004) at the same location,

[a] Air dry at depth of 60 cm that the sequence would be 50%, 70%, 90%, and then 100% of crop lower limit for the remainder of the profile

Table 3.5 Soil-water holding capacity properties of the soil form at Ha-Lambani village and Towoomba research station, and the values used in specifying the APSIM model simulation at initialisation of cropping season

	Lambani-Shortland		**Towoomba-Hutton**		**Towoomba-Arcadia**			
Layer number	1	2	1	2	1	2	3	4
Soil layer depth (cm)	300	900	300	900	300	300	300	300
Water content at air dry (mm/mm) *	0.058	0.078	0.083	0.200	0.034	0.034	0.047	0.061
Crop lower limit (mm/mm)	0.117	0.087	0.165	0.223	0.068	0.068	0.068	0.068
Drained upper limit (mm/mm)*	0.239	0.188	0.260	0.295	0.153	0.153	0.153	0.153
Saturated water content (mm/mm) *	0.406	0.469	0.273	0.301	0.434	0.437	0.490	0.517
SWCON	0.500	0.500	0.500	0.500	0.300	0.300	0.300	0.300
Bulk density (g/ cm^3)	1.48	1.30	1.9	1.8	1.40	1.39	1.24	1.16
Soil texture	Loam	Loam	Loam	Loam	Clay	Clay	Clay	Clay
Organic carbon (%)	0.902	0.902	0.744	0.395	0.902	0.902	0.902	0.902
pH*	6.42	6.42	6.38	6.48	8.26	8.18	8.18	8.18

The experiment was established each growing season at the same location. The drained upper limit (DUL), saturation (SAT), lower limit (LL) were derived from soil-water measurements made in the conventional tillage treatments. A sowing depth of 30 mm was used in the simulation in each tillage system. The average plant stand was 2.2 plants per m-2 and 1 m spacing for both growing seasons. All treatments were kept weed free over the duration of the experiment.

3.2.3.1. Soil-water infiltration and movement module calibration

The soil-water (and solute) dynamics within the soil profile for a specific agricultural system were simulated in the APSIM environment through the soil-water infiltration and movement (SWIM3) model platform. Most of the soil parameters in this platform have been calibrated and used in semi-arid southern Africa region for various studies (Mupangwa *et al*, 2011). The main soil-water parameters considered in the calibration of the CT, NT and IRWH tillage practices were the volumetric water content, (LL), saturation (SAT), drained upper limit (DUL), bulk density (BD), and MSWCON or saturated hydraulic conductivity (K_s) at different soil layers, and surface pond (max_pond).

The tillage practices, particularly NT and IRWH, have a direct effect on mechanisms of lateral flow, infiltration, storage, runoff, redistribution and residence times, this was reported in studies by Kosgei *et al*. (2007) and Salem *et al*. (2015). To capture these soil-water movements through soil profile in the APSIM model for NT practice, NT specified in the model's crop management and soil water module, based on the above mentioned calibration parameters. These soil physical parameters required in APSIM calibration to simulate specific tillage practices were obtained from field observations and derivation based on observed soil properties from literature.

The SAT, DUL and LL values were used to describe the soil-water retention, while lateral soil-water outflow was described by the are slope and the lateral resistance (KLAT), the infiltration down the soil profile by the above saturation flow (i.e. MWCON or K_s values) were set as indicated in Table 3.6, to allow soil-water flow down profile when the soil-water rises above the saturation..

Table 3.6 Soil-water infiltration and movement calibration parameters used

Layer number	Tillage	1	2	3	4	5
Soil layer depth (cm)		15	15	15	15	15
MWCON	CT	1	1	1	1	1
	NT	1	1	1	1	1
	IRWH (Province collection)	1	0	1	1	1
	IRWH (runoff generation)	1	1	1	1	1
KLAT (mm/day)		0.500	0.500	0.500	0.500	0.500

To simulate IRWH as a two-dimensional and distributed mode, with zero-till runoff generation and a Province collection area in SWIM3, an approach presented in Figure 3.1 was adopted. This approach is able to utilise the current one-dimensional and lumped mode SWIM3 parameters to represent a two-dimensional surface. The IRWH complex runoff generation and Province rainwater collection were simulated in two parts or model runs (cf. Figure 3.1). The model runs were interlinked through cascading process, based on the assumption that all soil-water outflows (i.e. surface runoff and subsurface lateral outflows) from the zero tillage runoff generation soil profile flows, at a slope less than 2 %, flows into the runoff collection Province profile. The maize crop is only planted on the runoff collection Province soil profile. This IRWH conceptual system of one runoff generation flowing into planted runoff collection areas was adopted from the PARCHED-THIRST model (Mzirai *et al*., 2004; Mzirai and Tumbo, 2010). The represent the runoff collection Province in the field, the max_pond functionality (based on the Province dimensions) together with MWCON as indicated in Table 3.6 were used.

The main limitation in using APSIM model in simulating complex surface management system is in the process of multiple modelling runs requiring more detailed soil physics parameterisation. We attempted to perform such analyses using low data and relayed on other research literature to be able to mimic as close as possible the observations in the field experiments. The limitations of only having a tipping bucket soil-water module in APSIM model has implications on the simulations soil-water dynamics of complex systems, such as insitu-rainwater harvesting. This includes the inability of the model to simulate runon-runoff, and lateral flow based on natural soil layer breaks.

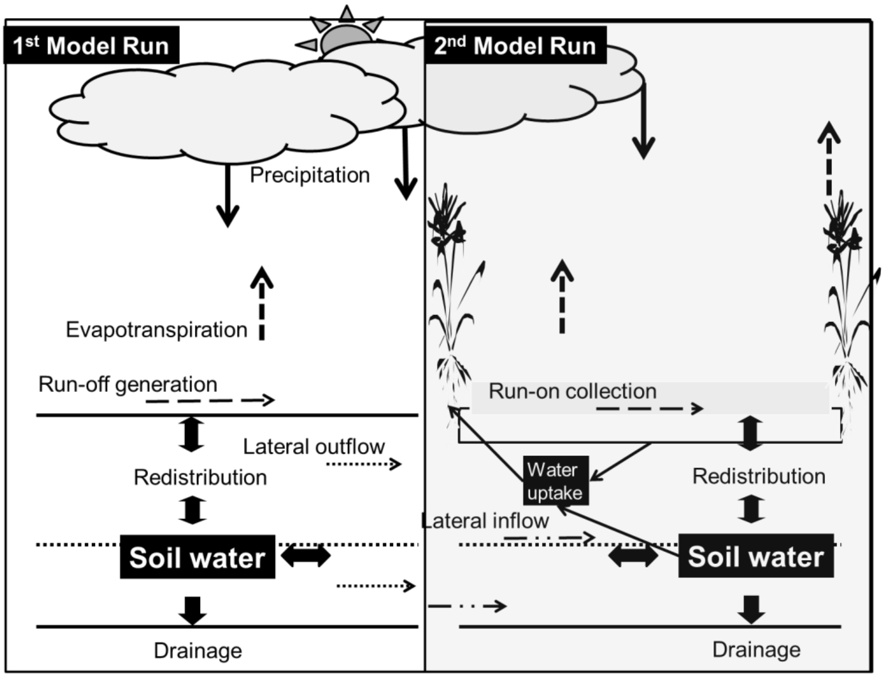

Figure 3.1 A crosssectional schematic of the insitu rainwater harvesting simulation as performed in the APSIM model

3.2.4. APSIM-Maize Calibration

The first stage of model evaluation involved calibration and testing the performance of the model on the experiments described above (Experiments 1 - 4). Three maize cultivars were calibrated from the four datasets by adjusting thermal time of growth stages to match date to flowering and maturity (Table 3.7). The maize calibration involved changing the thermal time requirements for emergence to end juvenile in degree-days, photoperiod slope in degrees per hour, and flower to maturity in degree-days.

Table 3.7 Genetic coefficients fitted for APSIM-Maize

Cultivar parameters	Unit	ZM 421	ZM521	PAN 6P-563R
Grain Growth				
head grain no max (Maximum grain size)	-	500	550	500
grain growth rate units (Grain growth rate from flowering to grain filling)	$mg.grain^{-1}.day^{-1}$	9.0	9.0	9.0
Phenology				
tt_emerg_to_endjuv (Thermal time needed from sowing to end of juvenile)	^{o}C.days	270	200	190
tt_flower to maturity (Thermal time needed in anthesis phase)	^{o}C.days	1100	770	700
tt_flag to flower (Thermal time from floral initiation to flowering)	^{o}C.days	10	10	10
tt flower to start grain (Thermal time from start of grain filling to maturity)	^{o}C.days	120	170	170
photoperiod_slope	$^{o}C.hour^{-1}$	10.0	10.0	10.0

3.2.5. APSIM-Maize Validation

In the second stage of the model evaluation, three datasets were used primarily for independent testing of model performance (Experiment no. 2 – 4; Table 1). The model was initially evaluated by testing its performance against the experimental data described above.

In the second stage of the model evaluation, data from independent datasets (i.e. Towoomba-Hutton and – Arciadia; Lambani – Shortlands soil form), none of which were used in the calibration and representing different soils, climates and maize cultivars. The model evaluation was to test the models performance in simulating of tillage practices effects. This validation enables the assessment of tillage effects on agrohydrological response (i.e. grain yields, biomass, soil-water, etc.) under various agro-climatic regimes (such as different soils and climate conditions), discussed below.

The calibrated APSIM model was validated using independent datasets related conditions described above to simulate the phenology, grain yield, biomass, and plant available water content. The model's output variables were validated by comparing the simulated values with the field experimental data.

3.2.6. Statistical Analysis

The model evaluation analysis was conducted using both graphical and statistical methods. The statistical methods employed for comparison of simulate and observed calibration parameters were the root mean square (RMSE), and Pearson's coefficient of correlation (r). The root mean square error (RMSE) was used to test a goodness of fit between observed and simulated data, as

$$\mathrm{RMSE} = [(\sum (O_i - P_i)^2/n)]^{0.5} \qquad 3.2$$

whereby; O_i and P_i are the paired observed and predicted data and
n is the number of observations.

3.2.7. APSIM-GIS Coupling and Configuration for Scenario Analyses of Surface Water Management Practices on Catchment Scale Crop Productivity

To simulate the spatio-temporal effects of climate-smart practices on maize productivity over different climate and soil conditions, sub-catchments within which maize production areas are found were selected in the Limpopo Province. Spatial data collected via aerial survey and collated by selected farm visits, commissioned by the Limpopo Department of Agriculture and Rural Development over two seasons in 2011/12 (i.e. summer and winter cropping seasons), was used to select farms of interest (i.e. for areas regularly producing maize) in the Province (Figure 3.2). The maize producing farms presented, represent irrigated and dryland farms under both small-scale and commercial farming systems. These spatial maize production farm units were used to identify sub-catchment within which they form a part of. These 368 sub-catchments (known as quinary catchments) were used to represent maize farms, as most of the available biophysical data is at this spatial scale (Figure 3.3). The simulation of catchment using a point model, such as the APSIM Model, was conducted using the *FLUSH* framework of which has been demonstrated in a study by Paydar and Gallant (2008) using APSIM model in Australia (Simmons Creek catchment) to simulate hydrological response under different landuses. They applied a *FLUSH* framework that provides hydrological linkages for existing 1-D water balance to enable them to operate in a catchment context.

The approach involved upscaling the research farm trails to catchment scale, by coupling a crop model and a Geographical Information System (GIS) to assess the soil-water and crop responses. This scaling up approach was adopted from coupling of GIS with environmental models concept (Tao *et al*., 1996; Ruelland *et al*., 2007). The two separate entities, *viz.* APSIM model and GIS systems communication and interaction were interfaced through outputs and inputs from both systems. The APSIM-GIS interface consisted of area weighted outputs derived from GIS spatial features representative of each sub-catchment (such as soils properties, climate, etc.) to setup the APSIM modules and then the output from the APSIM model feed into GIS to produce maps.

The APSIM model was coupled with GIS to enable the upscaling of point or field scale (m^2 paddock; Waha *et al*., 2015) experimental trials to catchment level. The GIS platform was used in generating and then populating the APSIM model with daily historical climate data (from 1950 to 1999) and spatially representative soils inputs. Each sub-catchment was assigned a specific daily climate driver station using an approach by Warburton *et al*. (2012), thereafter the associated soil profile from the Landtype memoirs (Landtype Survey Staff, 2012.) were derived by using ArcGIS to select a dominant soil form as representing each sub-catchment via area weighing, and extracted the soil form's physical and chemical properties from the Landtype memoirs to build APsoil module for each sub-catchment, with some parameters derived using protocol defined by Dalgliesh *et al.* (2012).

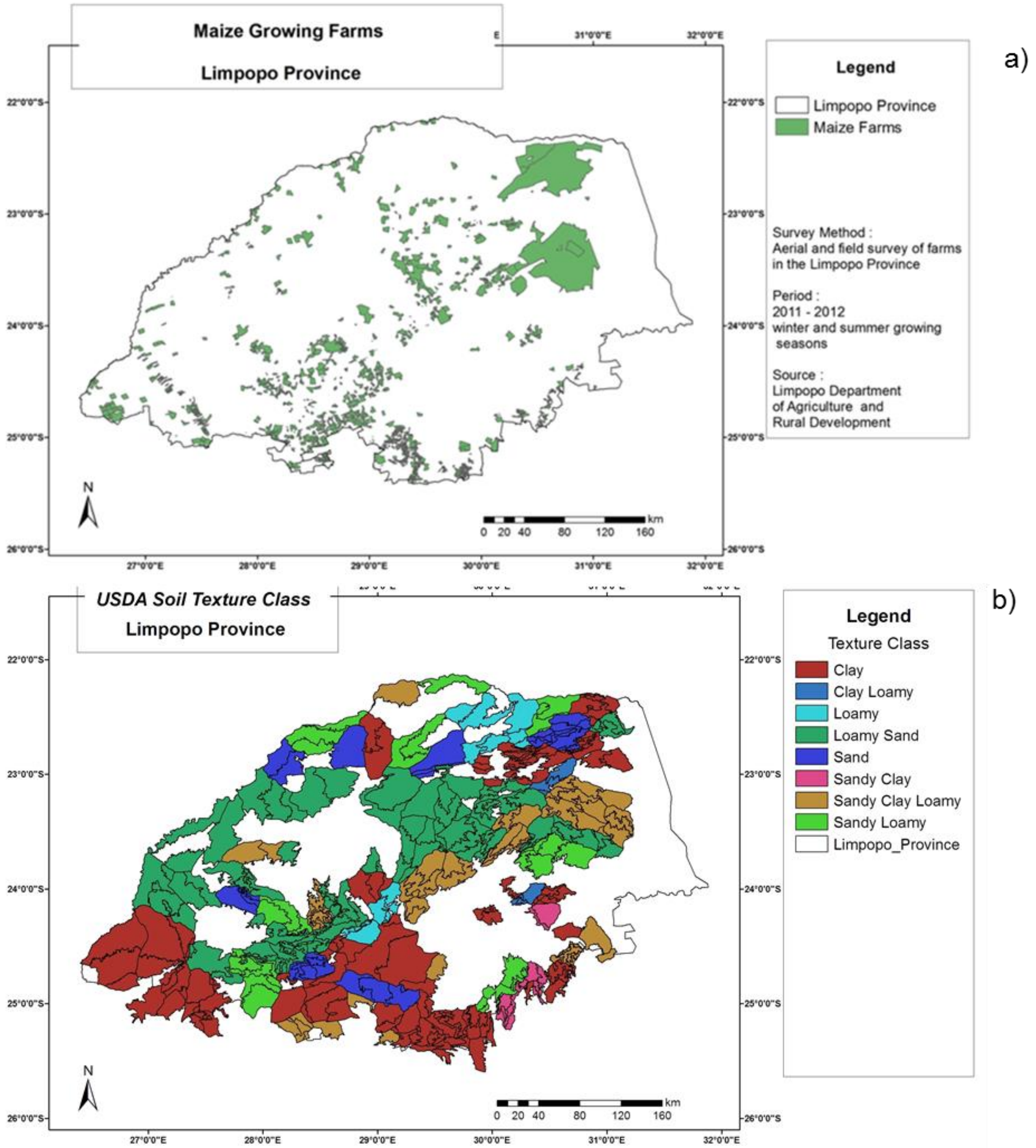

Figure 3.2 Limpopo Province maize growing farmland (a) identified through aerial and field survey over 2011/12 summer season, and soil texture classes of quinary catchment within which the maize farmland are found (LDARD, 2013)

The surface organic mulch cover was reset to zero on the first of October annually following the experiments earlier presented. The sowing period used was between 15 October to 15 December, to allow for spatial varying onset of rainfall season (Schulze and Maharaj, 2007), and planting took place when more than 20 mm of rainfall was received over 3 consecutive days. The other APSIM modules were populated similarly to the field experiment calibration and validation procedures mentioned above.

Figure 3.3a. and 3b. indicates the spatial variability of the sub-catchments making up the Limpopo Province in terms of soil properties and climate (suggesting spatial difference in potential agricultural productivity and soil-water holding capacity). The distribution of the Köppen-Geiger climate zones indicates that, based on long term monthly rainfall and temperature over the 1950 -1999 historical period, the Limpopo Province is dominantly hot dessert climate (BWh, dark blue colour) characterised by arid, hot and dry climate conditions. The APSIM model simulations, in this study, were conducted using a lumped mode with the assumption that there are no hydrological links between the sub-catchments downstream and hence the effects of upper catchment contribution are no accounted for in downstream sub-catchment.

The maize growing sub-catchments in the Limpopo Province receive between 280 to over 1080 mm of mean annual precipitation, as shown in Appendix E Figure 6.14, with high rainfall (> 600 mm))concentrated in central to northern border of the Province. The rainfall distribution is similar to that of mean annual temperature, with high temperature areas corresponding with low rainfall areas.

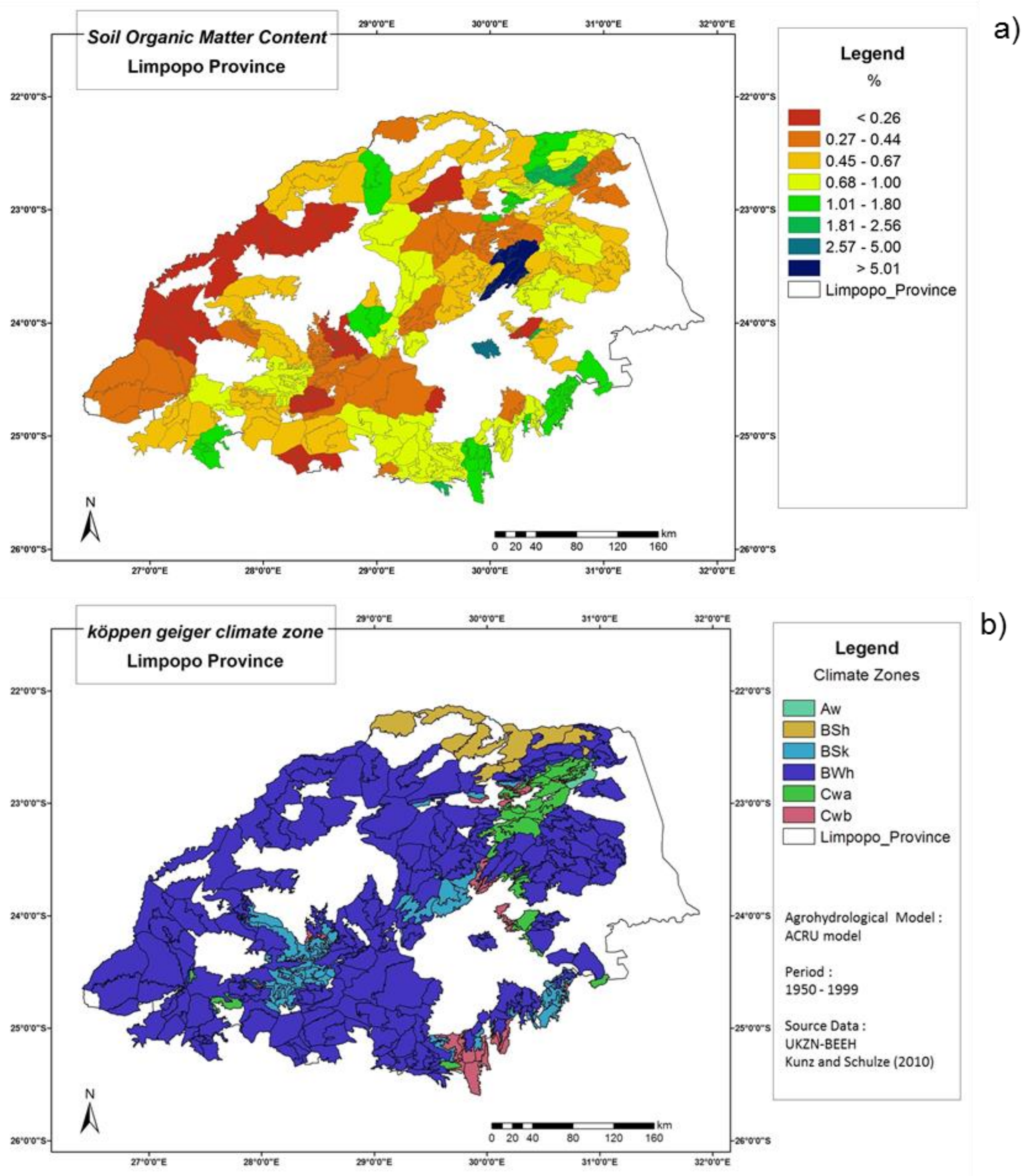

Figure 3.3 Soil organic matter content (a) and climate zones [Aw – tropical monsoon climate (tropical wet and dry winter season), BSh – hot semi-arid climate (semi-arid, hot and dry climate), BWh – hot dessert climate (aird, hot and dry climate), Cwa – monsoon-influenced humid subtropical climate (winters long, dry and hot climate), Cwb – subtropical highland climate or temperate oceanic climate with dry winters] (b), indicating spatial variability of the soils and climate within 386 sub-catchments within the Limpopo Province

3.3. Results

3.3.1. Field experiment data

3.3.1.1. Response of soil-water and plant available water to climate-smart practices

The soil-water (SW) measurements showed significant differences between the tillage practices at harvesting (Table 3.8) in 2013/14 season, similarly for the plant available water at 0 to 0.3 m soil depth. The IRWH had higher plant available water (PAW) than both NT and CT. Conversely, during the 2014/15 season (Table 3.10) there was significant difference at flowering stage between tillage practices in both SW and PAW, with CT having the highest SW and PAW available water followed by IRWH and then NT.

The surface mulch cover treatment showed no significant impact on either soil-water or plant available water over the maize crop growth stages. There was no statistically significant difference in SW and PAW at 0 to 0.6 m soil profile depth (Table 3.9 and Table 3.11) for both growing seasons (i.e. wet and dry season). This suggests that effect of tillage and mulch application have a great impact on top soil profile soil-water content.

Table 3.8 Total soil-water content (SWC) and plant available water (PAW) in the 0 – 0.3 m soil profile, at flowering and harvesting stages for 2013/2014 season, Syferkuil Farm

Treatment	Flowering SWC (mm)	Harvesting SWC (mm)	Flowering PAW (mm)	Harvesting PAW (mm)
Surface mulch (kg.ha^{-1})				
0	36.1^{a}	16.0^{b}	19.5^{a}	2.6^{b}
3 000	35.8^{a}	18.0^{ab}	19.1^{a}	6.7^{ab}
6 000	44.5^{a}	19.6^{a}	31.3^{a}	10.1^{a}
12 000	50.9^{a}	17.7^{ab}	39.5^{a}	6.1^{ab}
Tillage practice				
Conventional	40.6^{a}	16.1^{b}	25.3^{a}	2.6^{b}
No-tillage	47.1^{a}	16.6^{b}	34.8^{a}	3.8^{b}
Insitu-rainwater harvesting	37.8^{a}	20.8^{a}	21.9^{a}	12.7^{a}

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$)

Table 3.9 Total soil-water content (SWC) and plant available water (PAW), in the 0.0 – 0.6 m soil profile, at flowering and harvesting stages for 2013/2014 season, Syferkuil Farm

Treatment	Flowering SWC (mm)	Harvesting SWC (mm)	Flowering PAW (mm)	Harvesting PAW (mm)
Surface mulch (kg.ha^{-1})				
0	116.9^{a}	56.9^{a}	39.6^{a}	20.7^{b}
3 000	112.1^{a}	62.2^{a}	34.9^{a}	26.6^{a}
6 000	116.9^{a}	67.0^{a}	39.7^{a}	33.8^{a}
12 000	130.7^{a}	80.6^{a}	54.9^{a}	55.5^{a}
Tillage practice				
Conventional	122.2^{a}	56.9^{a}	45.9^{a}	21.9^{a}
No-tillage	127.6^{a}	62.2^{a}	50.3^{a}	26.9^{a}
Insitu-rainwater harvesting	107.7^{a}	81.2^{a}	30.5^{a}	21.7^{a}

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$)

Table 3.10 Total soil-water content (SWC) and plant available water (PAW), in the 0 – 0.3 m soil profile, at flowering and harvesting stages for 2014/2015 season, Syferkuil Farm

Treatment	Flowering SWC (mm)	Harvesting SWC (mm)	Flowering PAW (mm)	Harvesting PAW (mm)
Surface mulch (kg.ha^{-1})				
0	75.4^{ab}	32.7^{a}	82.1^{ab}	37.6^{a}
3 000	106.9^{a}	20.4^{a}	129.4^{a}	11.8^{a}
6 000	67.6^{b}	26.2^{a}	70.4^{b}	23.9^{a}
12 000	85.7^{ab}	30.9^{a}	97.6^{ab}	33.8^{a}
Tillage practice				
Conventional	110.5^{a}	24.1^{a}	134.8^{a}	38.6^{a}
No-tillage	66.6^{b}	33.2^{a}	68.9^{b}	19.5^{a}
Insitu-rainwater harvesting	74.6^{b}	25.4^{a}	80.9^{b}	22.3^{a}

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$)

Table 3.11 Total soil-water content (SWC) and plant available water (PAW), in the 0.0 – 0.6 m soil profile, at flowering and harvesting stages for 2014/2015 season, Syferkuil Farm

Treatment	Flowering SWC (mm)	Harvesting SWC (mm)	Flowering PAW (mm)	Harvesting PAW (mm)
Surface mulch (kg.ha^{-1})				
0	172.7 ^{ab}	91.0 ^{a}	183.4 ^{ab}	60.9 ^{a}
3 000	198.2 ^{a}	73.6 ^{a}	221.6 ^{a}	34.9 ^{a}
6 000	151.9 ^{b}	92.2 ^{a}	152.2 ^{a}	62.6 ^{a}
12 000	180.2 ^{ab}	101.1 ^{a}	194.6 ^{ab}	76.1 ^{a}
Tillage practice				
Conventional	229.0 ^{a}	98.2 ^{a}	267.8 ^{a}	71.6 ^{a}
No-tillage	150.7 ^{a}	73.6 ^{a}	150.4 ^{a}	49.8 ^{a}
Insitu-rainwater harvesting	147.5 ^{a}	91.0 ^{a}	145.6 ^{a}	54.2 ^{a}

Different superscripts within a row indicate a significant difference (P≤0.05); values with similar superscripts are not significantly different (P≤0.05)

3.3.1.2. Effects of climate-smart practices on maize grain yields and water-use-efficiency

During the first growing season (2013/14) there was no significant difference in the tillage practices, mulch levels and their combination on maize grain yields, biomass and WUE (ref. Figure 3.4; Table 3.12). The non-significant differences were attributed to the above average rainfall received over an average 65 year rainfall record over the growing period, as indicated in Table 3.3. Conversely, the effects of the treatments were observed during second growing season (2014/15), wherein below average rainfall was received in 65 years (ref. Figure 3.4). Effects of tillage and mulch treatments on maize biomass yields, in Figure 3.5, shows similar contrasting trend as grain yields between two seasons. The is a general increase in maize grain and biomass yields with increase in surface mulch levels for the second growing season, and for the first growing season, characterised as above average ‘wet’ year, had variation across mulch level.

In Table 3.12, the effects of increase in surface cover straw mulch and from CT to IRWH to NT tillage practices were found to increase the WUE in both seasons with increases more pronounced in the second season. The tillage practices and mulch levels treatments for the second growing season had significant difference in grain yields. The second growing season NT with mulch levels treatments had higher grain yield, water use efficiency and biomass followed by IRWH and then CT with mulch levels. A similar increase trend was observed between the two seasons in both grain yields and WUE increased from CT to IRWH and then NT, as well as with increments in mulch levels.

Table 3.12 Water use efficiency responses to tillage practices and mulch levels, for 2013/14 and 2014/15 planting seasons

Treatment	WUE (kg.ha^{-1}.mm^{-1}), first planting season (2013/14)	WUE (kg.ha^{-1}.mm^{-1}), second planting season (2014/15)
Surface mulch (kg.ha^{-1})		
0	4.95 ^{a}	7.50 ^{b}
3 000	4.56 ^{a}	8.70 ^{b}
6 000	4.98 ^{a}	8.22 ^{ab}
12 000	4.95 ^{a}	9.00 ^{a}
Tillage practice		
Conventional	4.91 ^{a}	7.50 ^{b}
No-tillage	4.94 ^{a}	9.29 ^{a}
Insitu-rainwater harvesting	4.75	8.28 ^{ab}

Different superscripts within a row indicate a significant difference (P≤0.05); values with similar superscripts are not significantly different (P≤0.05)

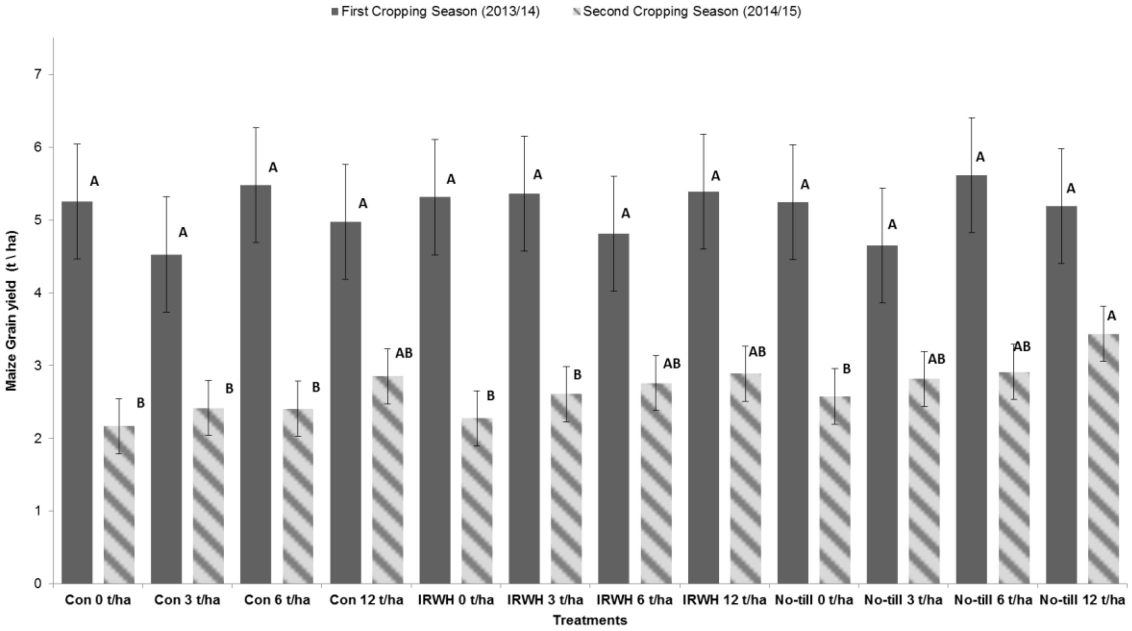

Figure 3.4 Mean maize grain yields responses to tillage practices and mulch levels over two distinctively different planting seasons (2013/14 and 2014/15) based on rainfall, with standard error bars and alphabets denoting significance differences (wherein different letters indicate a significant difference (P≤0.05) in a season, and values with similar letters show no significant difference)

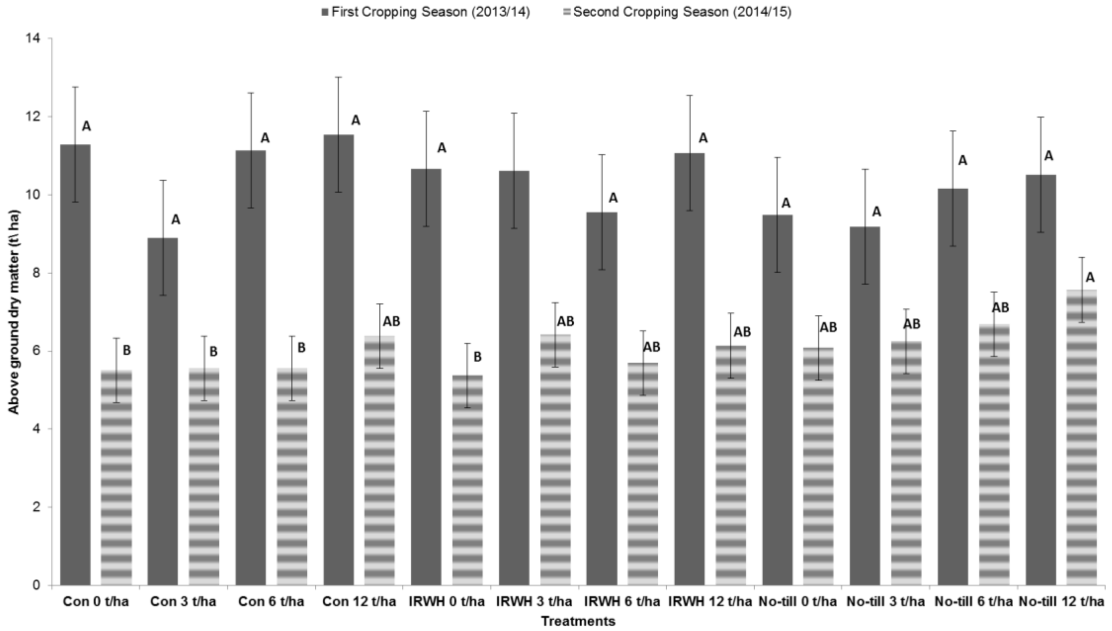

Figure 3.5 Mean maize biomass yields responses to tillage practices and mulch levels over two distinctively different planting seasons (2013/14 and 2014/15) based on rainfall, with standard error bars and alphabets denoting significance differences (wherein different letters indicate a significant difference (P≤0.05) in a season, and values with similar letters show no significant difference)

3.3.2. Modelling Agro-Hydrological Responses to Surface Water Management Practices

Following the calibration process of the APSIM model using the first season data, wherein minor changes were made to its crop coefficients and other variables (such as biomass partitioning, senescence and/or thermal time calculation or thermal time unit requirements) to closely mimic the field observations through a validation process using the second seasons data. Then, the validated APSIM model was used to assess the likely effects of wide-spread adoption of CSP on agrohydrological responses (i.e. maize yield and soil-water response), via adoption of APSIM-GIS coupling approach to diverse soils and climate conditions within the Limpopo Province. The model outputs were then used in addressing the questions below.

3.3.2.1. Model calibration

Field experiment data of the first growing season(s), conducted at Syferkuil research farm, together with secondary data from Towoomba Research Farm's two soil forms (Botha *et al*., 2014a; Ngwepe, 2015) were used in the model calibration. The crop traits from field experimental data, shown in Table 3.13, were used in the calibration process of the APSIM-maize modules. The calibration models show a general a close prediction of anthesis, maturity, biomass and yields. The models simulations were initiated with specified sowing dates, planting density, and observed initial soil-water and soil fertility conditions with default genotypic coefficients of ZM 401 variety. Thereafter, the parameters for phenology, biomass and grain yields at harvesting (Table 3.7) were adjusted to closely match the observed experimental data.

Table 3.13 Calibration results for APSIM-Maize models for five summer maize cultivars using experimental data

Crop Traits	**Units**	**ZM 421**		**ZM523**		**PAN 6P-563R**	
		Obs.	**Sim.**	**Obs.**	**Sim.**	**Obs.**	**Sim.**
Anthesis	DAP	79	61	62	63	64	50
Maturity	DAP	189*	129	120	133	120	93
Biomass at harvest	kg.ha^{-1}	11 291	7 838	3 321	3485	6 144	6 332
Grain yield	kg.ha^{-1}	5252	5 352	1101	1106	2 319	2 354

* harvest date

The calibration dataset contained 18 observations across the different surface management practices (i.e. tillage and mulch levels) and maize cultivars described above with a close fit found for maize grain yield between observed and predicted data (Figure 3.6a), . A similar strong correlation was observed for maize biomass (in Figure 3.6b).Furthermore, there was a strong correlation between predicted and observed tillage effects of both maize cultivars grain yields and biomass.

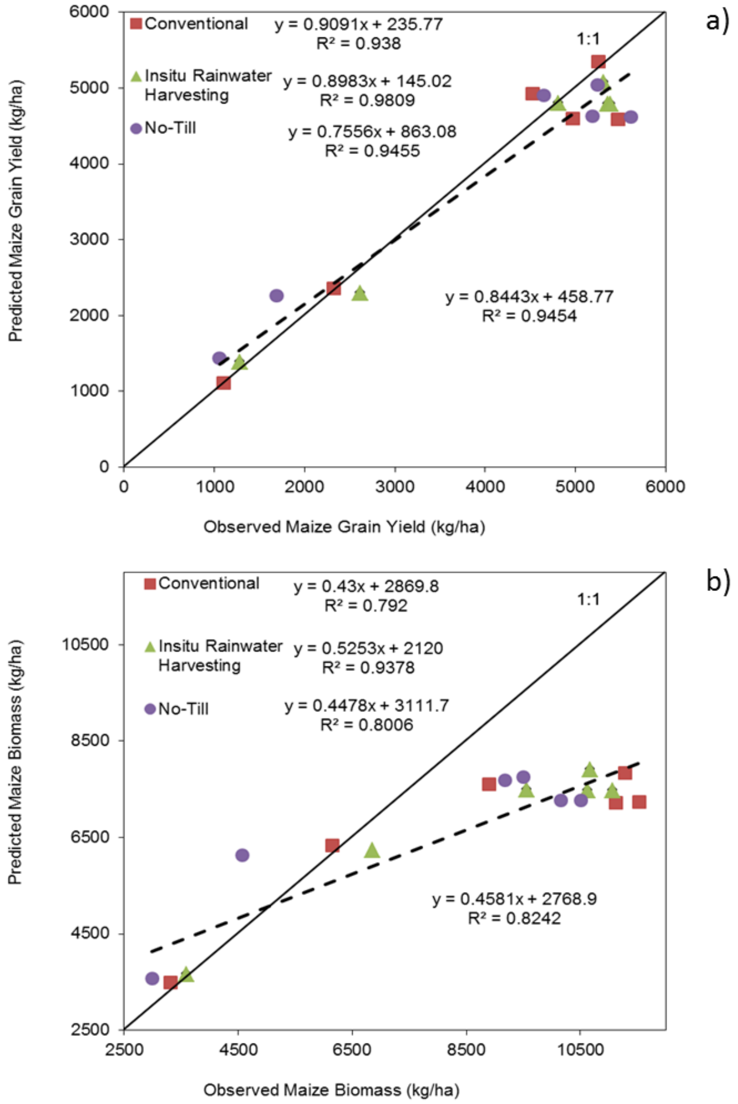

Figure 3.6 Predicted and observed maize grain yields (a, top graph with n = 18, r = 0.97 and RMSE = 463 kg.ha^{-1}) and biomass (b, bottom graph with n = 18, r = 0.91 and RMSE = 2467 kg.ha^{-1}) for calibrated datasets of three maize cultivars under different tillage practices and mulch levels treatments. The 1 : 1 line (solid) of perfect agreement is shown

3.3.2.2. Model validation

The APSIM model has been widely used and validated for various crop and soils within the Limpopo Province (Whitbread and Ayisi, 2004) and the wider region (Shamadzirira and Robertson 2002). Such studies wherein the APSIM model was validation for the biophysical conditions of the region gives confidence in the models ability to capture the agrohydrological processes in the Province. Following the APSIM model calibration to simulate field tested climate-smart practices. The APSIM model was validated to determine the confidence level in the calibrated model to simulate the experimental field conditions and treatments.

The maize grain yield validation analyses showed a strong relationship between predicted and observed with an r of 0.76 (R^2 of 0.77) and RMSE of 572 kg.ha^{-1}, representing 31 % of the mean (Figure 3.7 a). Similarly, a positive strong correlation for maize biomass, shown in Figure 3.7 b, with an r of 0.82 and RMSE of 2577 kg.ha^{-1}, represents 50 % of the data. The validation analyses of model to simulate the three tillage practices, in Figure 3.7 a and b, indicated a strong agreement between the predicted and observed maize grain yield with R^2 range between 87 and 97 % and biomass (R^2 between 60 and 94 %) at harvesting.

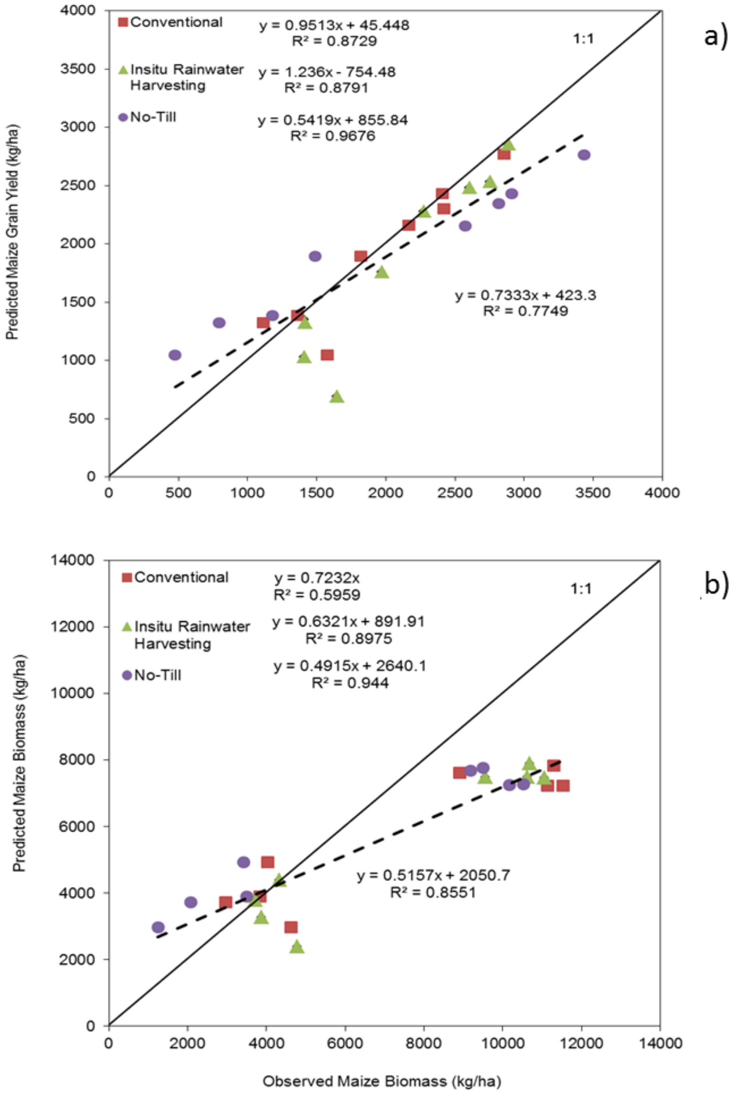

Figure 3.7 Predicted vs. observed (a, top graph with n = 33, r = 0.76 and RMSE = 572 kg.ha^{-1}) grain yield and above ground biomass (b, bottom graph with n = 33, r = 0.82 and RMSE = 2577 kg.ha^{-1}) of three maize cultivars under different tillage practices and mulch levels treatments. The 1: 1 line (solid) of perfect agreement is shown

Field experiment data from Syferkuil's second growing season, were used to test the goodness of it in predicted and observed biomass under the tillage practices over growing periods shown in Figure 3.8 (particularly at 7 weeks, flowering and harvesting). This indicates a good fit in simulation of biomass under CT, IRHW and NT practices. In Figure 3.9, a comparison between simulated and observed soil-water (i.e. volumetric water content) indicate a good fit with most of the measurements across the tillage practices, given the tipping bucket functionally of the model.

The model generally performed well in simulating the observed biomass, crop yields and soil-water of the maize crop under three tillage and four surfaces residue levels. The reliable prediction of total biomass gives confidence in the model to account for the soil-water balance. The simulation of crop crop water uptake and canopy cover are important feedback mechanisms in the soil-water balance processes, i.e. partitioning of rainfall into runoff and infiltration, and soil evaporation (Dimes and du Toit, 2008). Further, the validation analysis performed in this studies and other similar analysis in the area give confidence in APSIM model to be used for upscaling or simulation in different conditions within the Province.

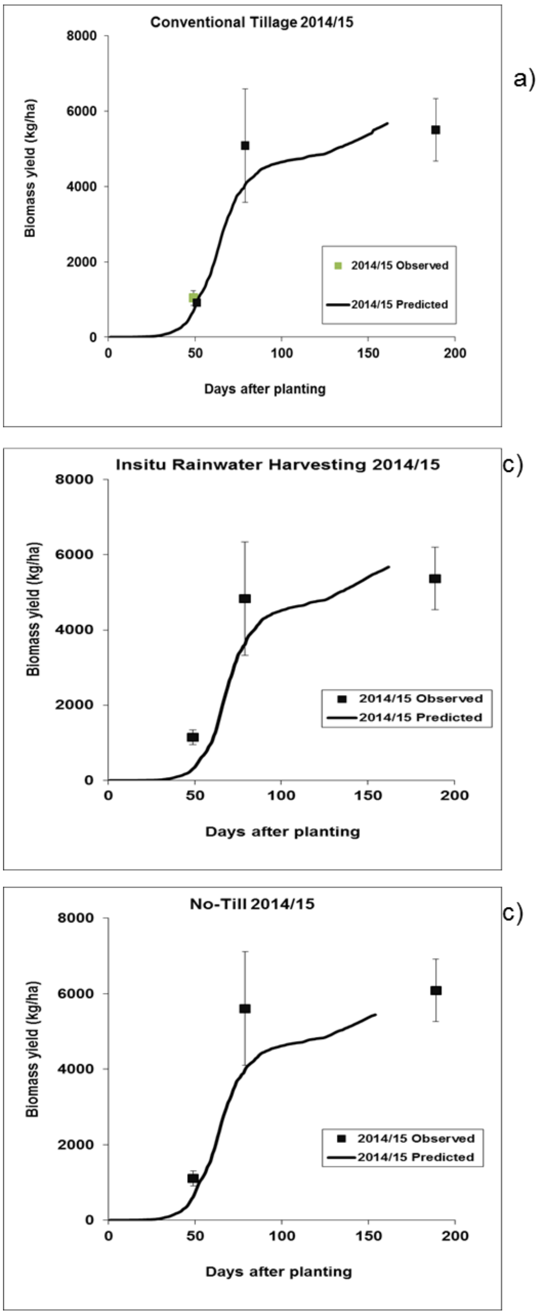

Figure 3.8 Predicted (lines) and observed (symbols) maize biomass of Syferkuil Research Farm for 2014/15 growing season under three tillage practices, i.e. conventional (a), insitu rainwater harvesting (b) and no-till (c)

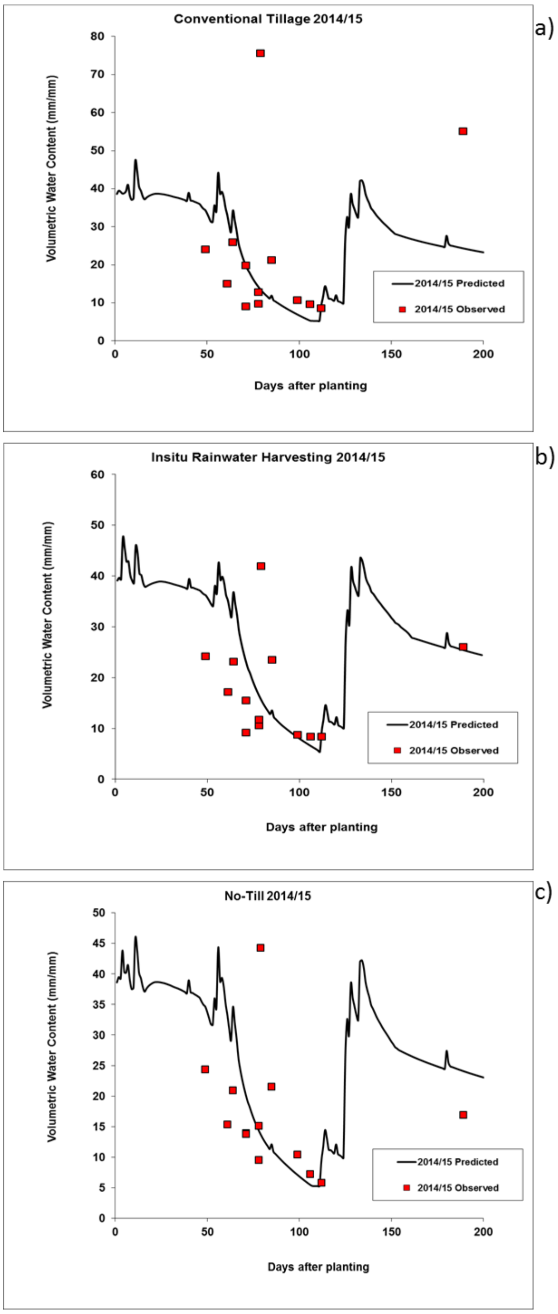

Figure 3.9 Predicted (lines) and observed (symbols) volumetric water content (mm/mm) at 30 cm depth of Syferkuil Research Farm for 2014/15 growing season under three tillage practices, i.e. conventional (a), insitu rainwater harvesting (b) and no-till (c)

3.3.2.3. What are the contributions of location specific conditions on maize crop yield responses under different surface residue application and tillage practices?

The soil fertility within the Limpopo Province, as depicted by the organic matter content (cf. Figure 3.3), ranges between 0.21 and 1 % over majority of the maize growing farmlands. Soil organic matter has significant impact of agricultural potential of soils (Tiessen *et al*., 1994) and soil-water holding capacity (Rawls *et al*., 2003). The spatial variability in both soil organic matter and climate zones within the Province, offer an opportunity to assess the impacts of the surfaces water management practices (i.e. tillage and surface mulch cover) test at research station on the water holding capacity and agricultural productivity under different conditions.

The long term simulated conventional tilled maize grain yield over the Limpopo Province (Figure 3.10) varied spatially, with over 1 576 kg per ha covering more than 60 % of the sub-catchments. The variation in maize grain yields could be attributed to spatial differences in combination of soils and climate conditions. In a median year, the maize grain yield under no-tillage practices, as shown in Figure 3.11b, overall had no significant difference in yields simulated under conventional tillage. Conversely, the IRWH (Figure 3.11a) showed significant increase and decline in parts of maize grain yields in a median year relative to CT in most sub-catchments as compared to potential reduced yields. This spatial variation in effects of IRWH is depended on specific sub-catchment biophysical conditions. This implies that the effects of tillage practices on maize grain yield differ depending on location properties (i.e. soils and climate conditions), and hence some areas would benefit more from a particular tillage practice in a median year than others.

In Figure 3.12, the effects of surface residue application (from 3 000 to 12 000 kg per ha) on maize grain yield suggest that the application of mulch could improve potential harvest. The higher the surface residue the more areas are likely to experience increase in maize grain yields, and conversely some areas would see reduction in yields.

Following the simulation results on the effects of the tillage practices on median annual maize yields, we conducted a further assessment on the response of NT and IRWH in the driest year in five. Figure 3.13 depicts potential maize yield in the least productive year in 5 over a 50 year climate record in the Limpopo Province. There is a significant spatial coverage of yield above 1 275 kg/ha towards the southern interior of the Limpopo, largely corresponding with sub-catchment having over 0.7 % of soil organic matter.

The effect of the tillage practices on maize in the direst year in 5, as shown in Figure 3.14, both IRWH and NT show similar potential higher and lower maize yields relative to CT. This suggest that adopt of either practices during the driest year in 5 would yield similar produce.

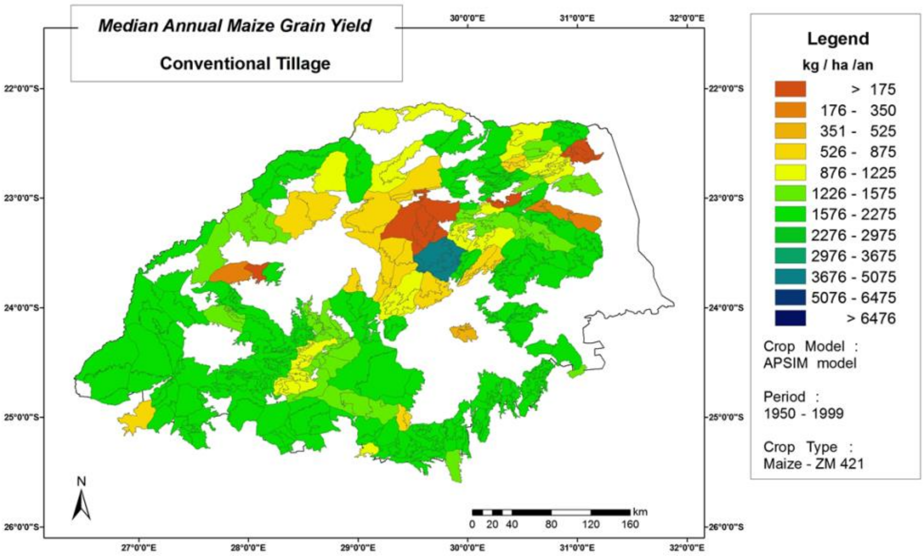

Figure 3.10 Median maize grain yield under conventional tillage practice over the Limpopo Province

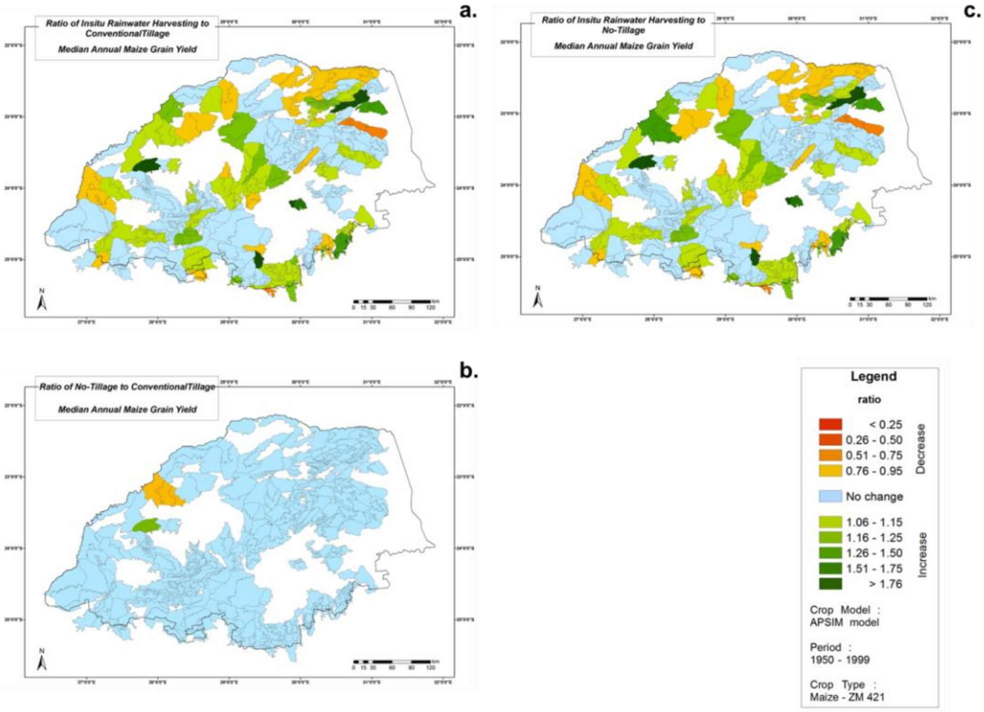

Figure 3.11 Effects of insitu rainwater harvesting relative to conventional tillage (a), no-tillage relative to conventional tillage (b), and insitu rainwater harvesting relative to no-tillage (c) on median annual maize grain yields in the Limpopo Province

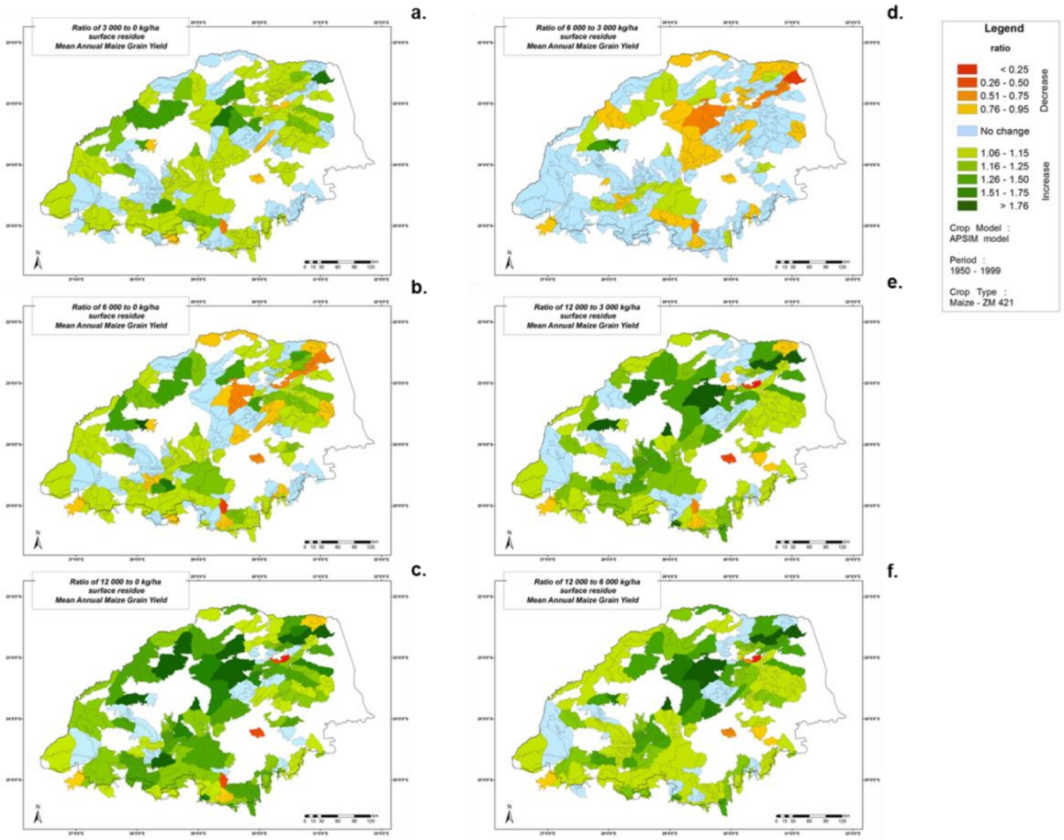

Figure 3.12 Effects of 3 000 relative to 0 (a), 6 000 relative to 0 (b), 12 000 relative to 0 (c), 6 000 relative to 3 000 (d), 12 000 relative to 3000 (e), 12 000 relative to 6 000 (f) kg per ha surface residue on median annual maize grain yields in the Limpopo Province

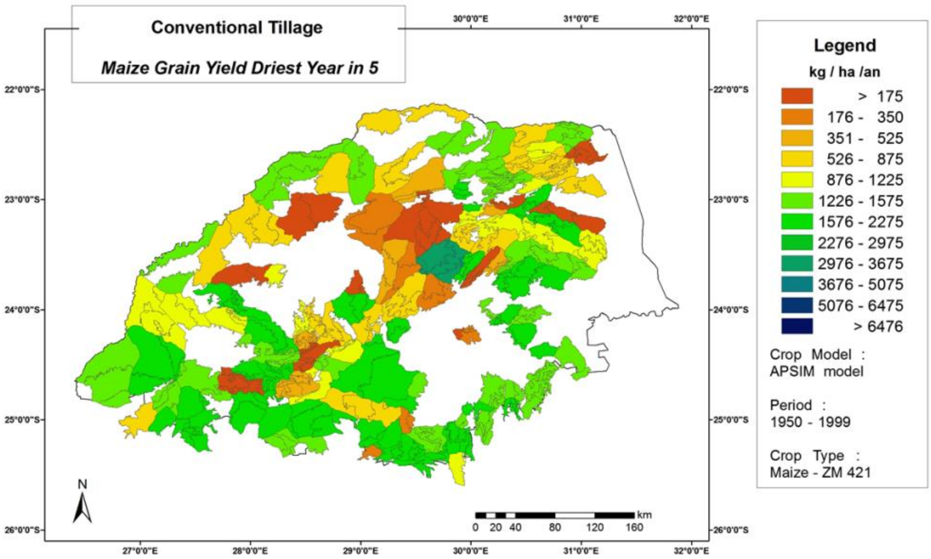

Figure 3.13 Maize grain yields in the driest year in 5 under conventional tillage in the Limpopo Province

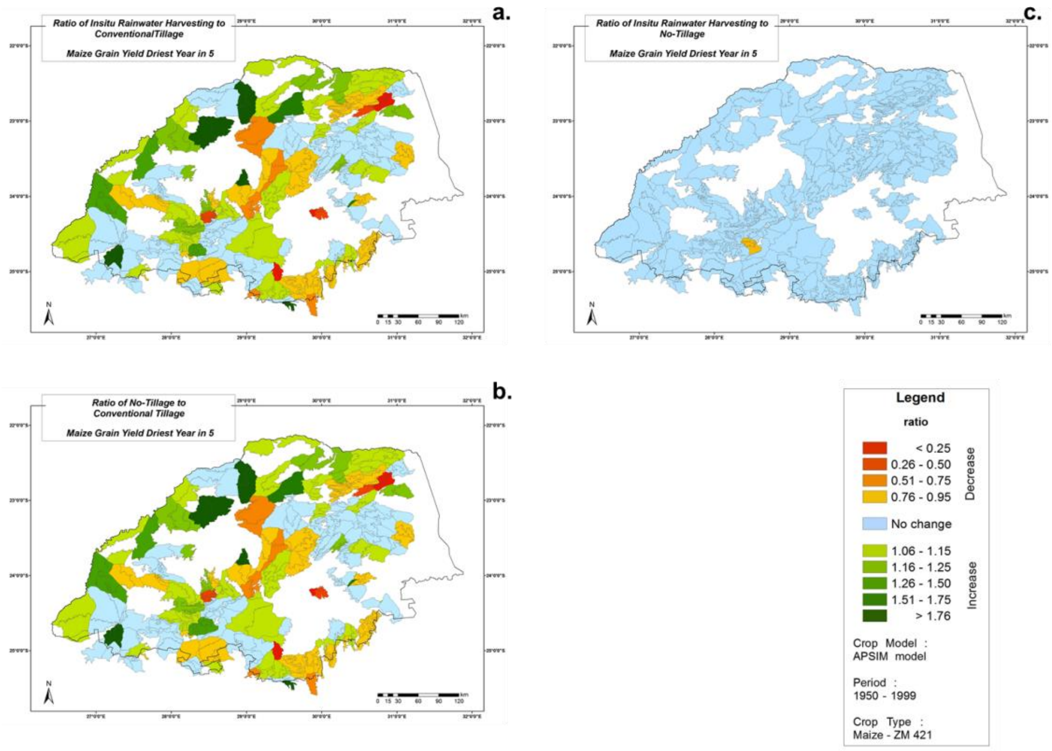

Figure 3.14 Effects of insitu rainwater harvesting relative to conventional tillage (a), no-tillage relative to conventional tillage (b), and insitu rainwater harvesting relative to no-tillage of maize grain yields in the driest year in 5 in the Limpopo Province

3.3.2.4. To what extent are the interaction effects of tillage practices and surface mulch application on maize yields are driven by site- specific conditions (landtype and climate)?

Surface residue application, is part of the soil conservation practices, and has numerous benefits to both soil and plants, *viz.* reduces soil and nutrient loss, improved soil-water through reduction in surface evaporation and improving infiltration for crop growth, and thus increase yields (Busari *et al.*, 2015). Presented in Figure 3.15 are four different surface residue levels compared with three tillage practices on potential maize yield in the Limpopo Province.

The analysis was conducted based on field observation to establish the likely effect of the interaction effects of the treatment on different biophysical conditions with the Limpopo Province. The overall findings suggest that combination of IRWH with surface residue application would produce higher yields compared to NT with surface residue, when both are compared with CT at 0, 3 00, 6 000 and 12 000 kg/ha residue levels. The IRWH practices out performed NT at various surface residue combination levels across most sub-catchments, with some areas shown to benefit more from NT combination.

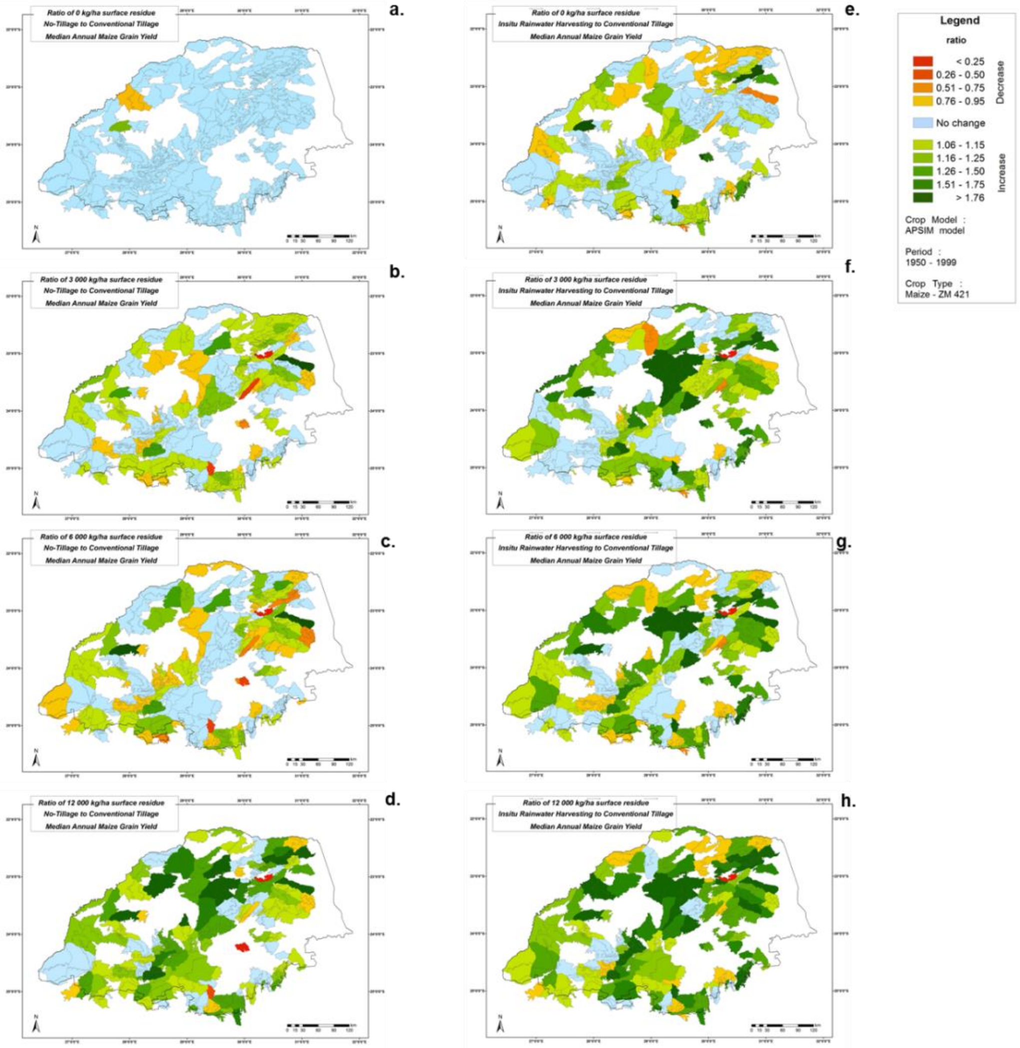

Figure 3.15 Effects of 0 kg per ha (a) 3 000 kg per ha (b), 6 000 (c), 12 000 kg per ha (d) surface residue with no-tillage relative to conventional tillage; 0 kg per ha (e), 3 000 kg per ha (f), 6 000 kg per ha (g), and 12 000 kg per ha (h) surface residue with insitu rainwater harvesting relative to conventional tillage on median annual maize grain yield in the Limpopo Province

3.3.2.5. What are the contributions of location specific climates and soils on soil-water responses under different surface residue application and tillage practices?

Figure 3.16 shows simulated soil-water, in the soil profile for each sub-catchment, under CT with maize crop cover. The scattered distribution in the mean annual soil-water content resembling's the soil profiles organic matter content distribution map (ref. Figure 3.3a). The distribution of available soil-water content across the sub-catchments is strongly influenced by the soil organic content, including climate conditions. A comparison of the effects IRWH and NT practices relative to CT on available soil-water content, as depicted in Figure 3.17, suggests that both practices have similar effects on available soil-water. There is a general increase effect of available soil-water content.

The application of surface residue was found to have an effect on the available soil-water content, as shown in Figure 3.18, with 3 000 kg/ha relative to 0 kg/ha of surface residue having an increasing effect on some of the sub-catchments. Whereas at 6 000 kg/ha relative to 0 kg/ha of surface residue a further increase was observed and more pronounced effects at 12 000 kg/ha relative to 0 and 3 000 kg/ha of surface residue. The 12 000 kg/ha relative to 0 kg/ha of surface residue surface residue application showed a huge contrast in the effects of residue cover on the available soil-water content at varying degrees.

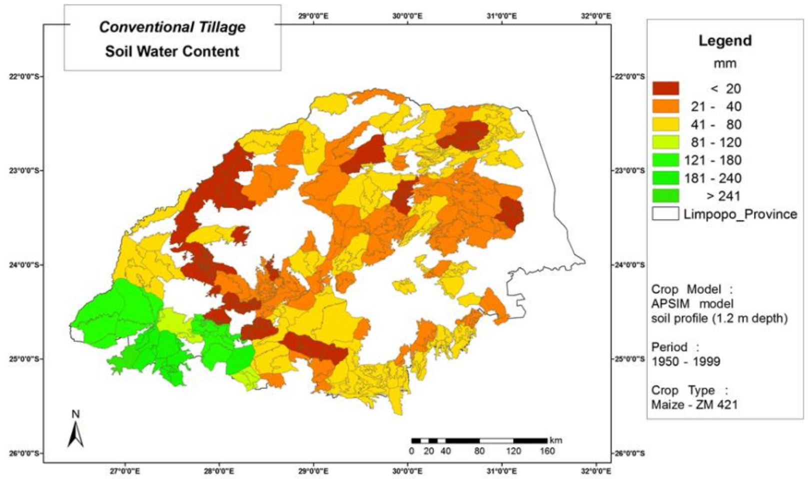

Figure 3.16 Mean annual available soil-water content under conventional tillage practice over the Limpopo Province

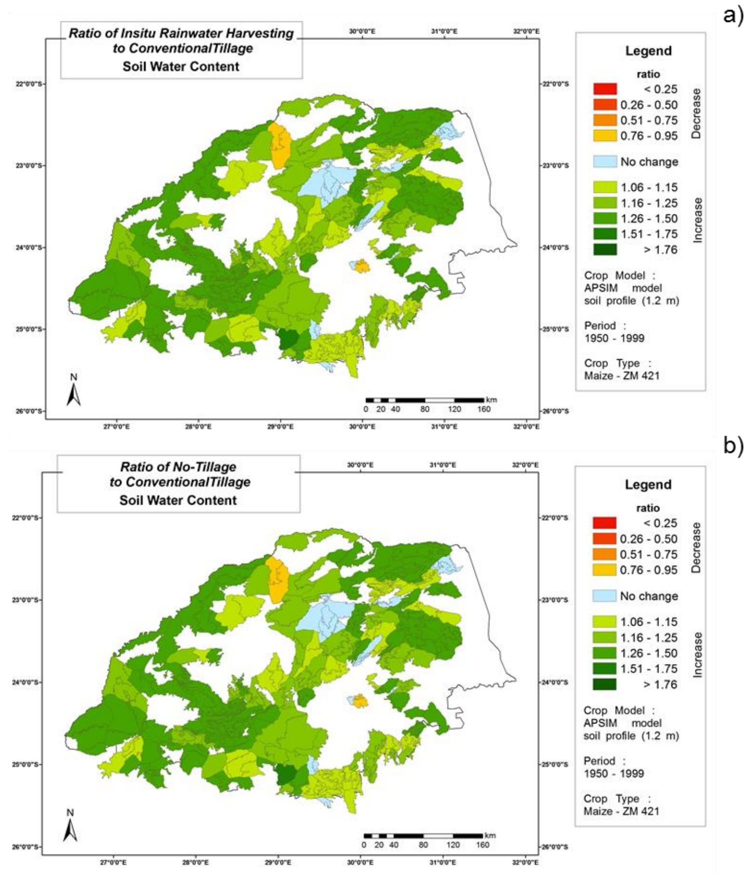

Figure 3.17 Effects of insitu rainwater harvesting relative to conventional tillage (a), no-tillage relative to conventional tillage (b) on mean annual available soil-water content in the Limpopo Province

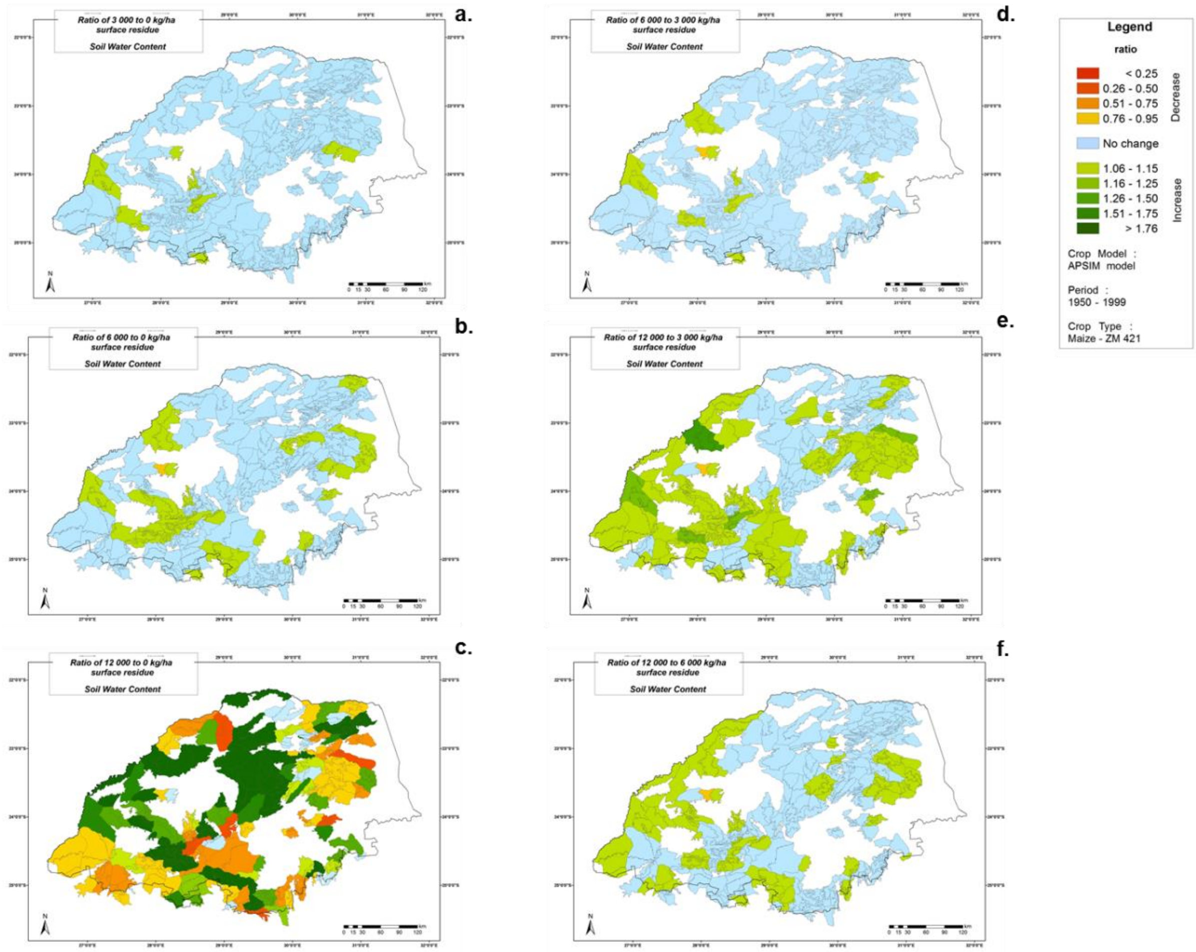

Figure 3.18 Effects of 3 000 relative to 0 (a), 6 000 relative to 0 (b), 12 000 relative to 0 (c), 6 000 relative to 3 000 (d), 12 000 relative to 3 000 (e), 12 000 relative to 6 000 (f) kg per ha surface residue on mean annual available soil-water content in the Limpopo Province

3.4. Discussion

Effects of tillage and mulch levels on soil-water, plant available water, and maize grain and biomass yields

In this study, field experiments were conducted to assess the effects of three tillage practices (CT, NT and IRWH) with four different mulch levels on soil water content, and maize grain and biomass yields over a two growing seasons at the University of Limpopo Syferkuil Research Farm, Limpopo Province. The data from this field study, together with other secondary data from similar studies in the region were used to parameterise, calibrate and validate a daily biophysical APSIM model, and then assessed the effects of the field treatments over the Limpopo maize growing farms. This study was conducted to evaluate the likely effects of up-scaling this treatments to maize growing areas on alleviating high climate-related-risks posed by dry spells and soil-water deficits, cited in the study by Mupangwa *et al*. (2016), in which they are shown to be some of the factors hindering productivity in smallholder cropping systems over the Limpopo Basin (i.e. countries along the Limpopo River, South Africa, Botswana, Zimbabwe and Mozambique). The first growing season was characterised by high rainfall events, at times hindering field tractability owing to heavy wet soils, while the second growing season received below average rainfall, over a 65 year period.

There were no significant differences in maize grain yields and biomass for the first growing season. A statistical difference was observed in SWC and PAW only at harvesting from both tillage and mulch treatments; IRWH had high SWC and PAW at 30 cm depth compared to NT and then CT, and increased with surface mulch treatment levels. This might have been due to ending of the rainfall season (less wet condition) and hence the effects of the treatments becoming more apparent, as opposed to over the growing season wherein the effects were negated by above normal rainfall. This observation was similar to that found by Botha *et al*. (2014a), wherein at maturity PAW decreased from IRWH to CT and then NT.

In the second growing season, the below normal rainfall received resulted in the treatment effects observed on maize grain yields, biomass and SWC (at flowering stage). CT had the highest SWC and PAW at flowering and harvesting stage followed by NT and then IRHW over the whole soil profile, whereas at 30 cm depth the effects of the tillage techniques were different with IRWH showed high SWC and PAW compared to NT at flowering and reverse at harvesting stage.

Botha *et al*. (2014) field experiments in Limpopo, Free State and Eastern Cape Province on IRWH and soil conservation found that tillage practices effects on maize crop production and soil-water varied across different soil types and climate conditions. In Limpopo Province IRWH was found to perform better in Hutton soil form at Towoomba and Shortlands soil form at Lambani (1577 and 1238 kg per ha of maize grain yields, respectively) followed by CT (1464 and 1012 kg per ha of maize grain yields, respectively) and then NT (1051 and 572 kg per ha of maize grain yields, respectively). Whereas, in the Free State Province on Glen/Oakleaf soil form NT performed better than CT and then followed by IRWH. Finally, in the Eastern Cape Province, maize grain and biomass yields performed better in IRWH followed by NT and then CT on Fort cox/Valsriver soil form.

The effects of above and below normal rainfall seasons (ref. Table 3.3) are more apparent, as shown in the Figure 3.4 and Figure 3.5, and depicted by the difference in maize grain and biomass yields between the two growing seasons across all the treatments. In the first growing season, maize grain and biomass yields averaged 5 and 10 tons per hectare (respectively), amounting to nearly half amount of yields in a drier year. The higher maize grain and biomass yields with increase in surface mulch levels were similar to those observed by Qin *et al.* (2015) from 74 studies across 19 countries. For second growing season with below normal rainfall, the treatments had a statistically significant difference, with grain yields increasing by 12, 15 and 31 % for 3000, 6000 and 12 000 kg/ha to no surface cover straw mulch, while for biomass yields 7, 6 and 19 % increase was observed. The effects of rainfall seasonality were observed with wetter first growing season compared to second resulted in a doubling of maize yields under mulched treatments. This observation was similar to that of in study by Ogban *et al.* (2008) on cowpea yields. The effect of tillage practices on maize grain yields were higher for NT followed by IRWH and then CT, and a similar effect was observed for biomass yield (6.65, 5.90 and 5.75 ton per ha, respectively).

Conversely, the variation in ‘wet’ season, in particular decreases in grain and biomass yields were observed with mulch increase in the study. Qin *et al.* (2015) observed similar phenomenon and attributed it to increase in water. Thus, suggesting that application of mulch in wetter season or high rainfall areas might reduce the potential yield, however, this might be counter by application of more nitrogen fertilizers. Increments in surface cover mulch resulted in increase in WUE, with more pronounced increases observed in the second growing season. Similarly, the WUE was found to differ amongst the tillage practice, increasing from CT to IRWH and then NT. Our findings in the order of tillage practices with WUE were slightly different from those by Botha *et al.* (2014) who reported an increase from NT to CT and then IRWH, at plant maturity. The difference might be attributed to length of period in which the practices were established. Their study was conducted for over four seasons, and our experiments were conducted only for two seasons and were established on a previously conventional tillage experiment plots. It was assumed there was no tillage from the first season of implementation as no ploughing was done during land preparation.

For smallholder farmer, buying additional fertilizers might not be financially viable during wet season and would be more beneficial to capitalise on available resource and conditions. Those farmers located in drier areas will benefit more from application of surface cover straw mulch, which acts by improving yields and increase water use efficiency. Surface cover mulch reduction in water loss through reducing evaporation, encouraging soil-water infiltration and hence increasing soil-water available for productive use.

APSIM model calibration and validation

To determine the effects of upscaling IRWH treatments (with and without surface mulch cover), an approach used in SWAT model was adopted for use in the APSIM model. This rudimentary approach to simulating IRWH, was found to be effective in simulating field observed maize grain and biomass yields with a correlation coefficient of 89.8 % and 87.9 %, respectively, based on the validation analysis.

The overall performance of the model in simulating all the treatments (i.e. CT, NT and IRWH with different surface mulch cover levels) was successful, as it was able to predict the observed maize grain and biomass yields with correlation coefficients of 76 % and 82 % respectively, using Pearson correlation analysis. The validation analysis on the model performance gives confidence in the ability of the calibrated model to represent the treatments and also to enable it to make predictions in other areas and environmental conditions.

What are the contributions of location specific conditions on maize crop yield responses under different surface residue application and tillage practices?

In this section, the responses of the tillage practices and surface mulch levels were evaluated across different climate and soil conditions over maize growing areas in the Limpopo Province. The long term climate simulation of maize yields, based on calibrated APSIM model, suggest that maize yields in the Province have potential to produce over 1 576 kg/ha, in more than 60 % of the area under no fertilizer and conventional tillage practices.

The results of the study suggested that, not all areas under historical climate conditions would benefit from IRWH when compared with conventional and no-tillage practices. Areas were IRWH resulted in higher yields could be regarded as having high suitability for implementing the practice. This observation of areas or sub-catchment specific improvement in median maize yield is due to the suitability of IRWH and NT practices, based on soil physical properties (Botha *et al*., 2014b) on, most sub-catchment in the Province might not be suitable for the practice(s).

Tillage practice, IRWH, had varied effects on maize yields under NT and CT in the Province, which were found to be dependent on a combination of soil properties and climate conditions (Figure 3.3, Figure 6.14 and Figure 3.11). A combination of high rainfall and loamy to clay soils were found to characterise high yielding areas. The characteristics of high yielding areas for IRWH were found to be similar to those of Botha *et al*. (2014a) where soils with clay content, over 18 % (loamy soils with clay content range 18 to 30 % and clay soils with over 30 % clay) givien as a guideline for implementing IRWH.

There were no significant differences between NT and CT tillage practices; the significance level was with -5 and +5 % percent difference. NT is said to perform better in rainfed farming systems in dry climates, while in average climates match CT yields of different crops in diverse climates (Pittelkowa *et al.*, 2015). The presentation of average yields, indicating average climate conditions wherein the yields were obtained, could have factored in there been no significant difference between the two practices. The use of a 5 % significant level could have not captured the small differences between the practices. Pittelkowa *et al.* (2015) in their review of over 670 peer-reviewed studies found that across 50 crops and all locations in temperate, subtropical and tropical climates no-tillage practices reduced yields by 5.1 %. Their observations are in agreement with our simulations wherein over 80 % of the Province showed no significant difference in NT compared to CT.

The effects of different surface mulch application rates on maize yields varied from 0 to 12 000 kg/ha, with yields varying spatially with increments in mulch rates based on variation in climate conditions and soil characteristics of a particular sub-catchment. Rusinamhodzi *et al*. (2011) found that application of straw mulch in CT with lower rainfalls resulted in an increase in maize yields (i.e. 600 mm), whereas 1 000 mm of rainfall resulted in lower maize yields. Thus, areas of receiving lower rainfall are more likely to benefit from surface residue application. This finding was similar to observations made in this analysis that the mulch effects were depended on climate and soil properties.

To what extent are the interaction effects of tillage practices and surface mulch application on maize yields are driven by site- specific conditions (landtype and climate)?

The interaction effects of the tillage practices (CT, NT and IRWH) with surface mulch levels on maize yields indicates that surface mulch application is likely to enhance the effects of the tillage practices. The maize yields were observed to significantly increase in IRWH tillage with increments in surface mulch application and less so for NT with mulch, when both treatments were compared to CT with mulch.

Conversely, some sub-catchments had decrease in maize yields with increase in surface mulch more so when combined with NT, than IRWH in high rainfall areas. The negative effects of both NT and

IRWH with surface mulch residue levels on maize yields, particularly in some sub-catchments, highlights the importance of targeting the climate-smart practices to specific biophysical conditions that can optimize yields. Scopel *et al*. (2004) found that the advantage of surface residue to be counteracted by increase in drainage losses and as a result the effects of residue on yields are lower than expected.

Further likely reason that might contribute to the low maize yields, in particular for NT and mulch residue treatments, could have been due to the treatment effects resulting in reduced soil N minerals availability and hence N uptake by maize crops as found in Masvaya *et al*. (2017) study on the impacts of tillage, mulch and fertilizer on soil nitrogen availability in Zimbabwe.

What are the contributions of location specific climates and soils on soil-water responses under different surface residue application and tillage practices?

IRWH and NT relative to CT had a similar effect on soil-water content, whereas surface residue mulch generally had a positive effect on mean annual soil-water availability in the Province, with increase in application benefiting areas of low rainfall, specifically those with less than 600 mm per year (ref. Figure 6.14). This observation is in agreement with a study by Rusinamhodzi *et al*. (2011) which suggests that low rainfall areas are likely to experience the benefits of surface residue as opposed to high rainfall areas.

Ogban *et al.* (2008) study found that there was no significant difference in soil water content between CT and NT over the two growing season, but the difference was between the seasons. Cowpea yields were higher in CT than in NT. The applications of surface residue mulch in CT and NT practices showed improved soil-water content, and lead to higher cowpea yields. Mupangwa *et al.* (2013) observed similar improvements in soil properties and maize yields in Zimbabwe. Tan *et al*. (2015) long term effects of conservation tillage, suggested that soil nitrogen and total organic matter increased in NT and straw mulch over a period of 6 years, except for conventional tillage. This suggests that tillage practices may have impacts of soil structure, soil-water retentions and soil fertility.

van Rensburg *et al*. (2016) evaluated the potential of mechanisation and upscaling IRWH, by developing implements and procedures which were tested together with subsistence farmers, their findings suggested a likely uptake of the technique over millions of hectares across sub-Saharan Africa owing to positive response from the farmers and on improvement of yields. The mechanisation potential, would not only reduce labour costs, but also the potential of up-scaling and/or commercialisation IRWH and similar tillage practices, particularly in low and highly variable rainfall areas. This study attempted to indicate areas or conditions likely to benefit from large scale adoption of tillage practices and surface mulch application. The overall findings were that based on biophysical properties the treatment benefits are highly dependent on soil properties and climate conditions. Thus, such analysis might be useful first step in determining the feasibility of any large scale implementation of new technologies.

3.5. Conclusion

Field experiments, assessing the effects of conservation tillage (IRWH and NT, with CT as control) and diverse surface residue levels were carried out in 2013/14 and 2014/15 growing seasons at Syferkuil Research Farm, to form the basis of this modelling study. During the first growing season above normal rainfalls were received, and conversely below average rainfall over the following season (i.e. it marked the start of an El Nino period being currently experienced in the region). The climate conditions over the two seasons yielded high and low maize crop growth and yield parameters, respectively. The effects of the tillage practices and surface mulch cover were more pronounced during the second drier season.

The field results suggest potential increases in grain yields of up to 18.4 % from insitu rainwater harvesting and 20.9 % from no-tillage with mulch practice. The field data was then used in parameterising, calibrating and validating the daily time-step APSIM model, together with secondary data from similar studies conducted in the region for different cultivars, soils and climatic conditions. The soil module was adjusted using concepts from model to capture insitu rainwater harvesting tillage practices. The model yielded a strong positive correlation and goodness of fit in the prediction of soil-water, biomass at harvesting and grain yields. The validation and calibration exercise was done to examine the potential for using the model to represent field scale processes and responses. The validated model was used with the coupled GIS and APSIM model to perform simulations at sub-catchments within which maize (grain) producing farms are found in the Limpopo Province, with unique daily climate and soil profile information collated from various sources.

The APSIM-GIS coupled simulations on the effects of tillage practice on maize yields over the Limpopo Province suggested that NT would have no significant impact on maize yields, over most of the Province, compared to CT in a median year. The effects of NT were more pronounced during the direst year in 5. Conversely, IRWH practices seem to have impact on yields in both median and least productive years, with potential gains and losses in yields strongly associated with specific biophysical conditions. There were no significant difference in available soil-water between IRWH and NT, of which might be a model related factor owing to APSIM model being centred on a tipping bucket water balance.

NT and IRWH practices were found to have similar effects on mean annual soil-water content, with nearly all sub-catchments benefiting for the practices. Similarly, both practices were observed to have similar effect on maize yields on the driest year in 5 (ref. Figure 3.13). In the field experiment, during below normal rainfall, NT performed slightly better than IRWH. This observation suggests that these practices are likely to be more of benefit during dry spells and/or below average rainfall years.

The median maize grain yields increase with increments in the different levels of surface residue application, and also the surface residue had inverse effects. The lower yields were attributed to higher rainfall and/or soil-water drainage losses. The surface residue had similar effects to the available soil-water content, with more pronounced effects in higher levels of surface residues. The combination of both surface residues and the tillage practices (i.e. IRWH and NT) yielded increase in maize grain yields. Overall, the interaction effect of IRWH and surface residues resulted in higher yields and available soil-water.

Further suggestions are that for both conservation practices (i.e. NT and IRWH) to improve yields require a more site-specific targeting approach to cope with specific biophysical conditions, might be needed. Recommendation for future research is to improve upon the current calibration of the APSIM model in simulating IRWH, more specifically simulation of runoff and infiltration components. This will be of benefit, particularly for assessing impact of upscaling IRWH to basin scale, on surface water and recharge groundwater or deep percolation.

CHAPTER 4. EVALUATING CLIMATE CHANGE IMPACTS AND ADAPTATION PATHWAYS IN THE DRYLAND LIMPOPO SMALLHOLDER FARMING SYSTEMS

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Abstract

South African smallholder farmers are faced with numerous challenges, *viz*. high climate variability, limited access to capital, land and irrigation, low soil fertility, a degraded landscape and poor market access. Climate change comes on top of that, and is projected to have profound effects, via interaction effects of direct and indirect impacts on agriculture (for example, affecting pests' reoccurrence and distribution, which will affect crop yields). While climate science shows general agreement on the likelihood of temperature rise, for precipitation however, there are large differences amongst the climate model projections. The consequences of higher temperatures and less rainfall attributed to climate change are hypothesised to result in decline in agricultural productivity. Further, that the current autonomous and incremental adaptation strategies will not be sufficient to sustain productivity to projected climate change effects. This may, hence, require development of completely new production systems.

The aim of this study was to assess the likely impacts and opportunities of the Limpopo smallholder farmer's crop management practices under changing climate and other environmental conditions, and identify the likely promising adaptation pathways – using mas as an indicator crop. Climate model projections based on CMIP3 models for A2 emission scenarios empirically downscaled daily time series to climate station level using techniques presented by Christensen *et al.* (2007), and daily averages were used for assessing climate change impacts, with maize crop productivity as an indicator.

In the absence of downscaled CIMP5 data on climate model projections for the study region, projections from a global climate model ensemble based on CMIP3 datasets representative of the 4th Intergovernmental Panel on Climate Change (IPCC) Assessment Report were selected for this climate impact analysis. The representative ensemble members were chosen based on their availability, quality controlled and sound documentation of the daily downscaled data at the time of the study. In terms of quality control, their prediction skill of past climate conditions was a criterion, and in terms of representativeness, their suitability to capture the uncertainty of possible changes in temperature and precipitation variables was for the targeted projection period was considered. Crop management practices, for poor (with no N fertilizer and/or mulch application as management practices) and better resource endowed (with N fertilizer and mulch application) farmers both planting on different dates within a growing season, were constructed from outcomes of survey questionnaire conducted across 6 villages. The practices identified were different sowing dates (early and delayed), N fertilizer and surface mulch application, and interaction effects of the practices. Recommended rates of N fertilizer for the region of 45 kg/ha and 2 tons/ha of surface mulch application rate were used, owing to most farmers being unable to provide quantity or rate used over past 5 growing seasons. For adaptation options, the median values of the GCM outputs were used to assess adaptive responses falling within the three adaptation models (i.e. incremental, systemic and transformational). There were cultivars with different growth durations as for incremental adaptation, shift from rainfed to irrigated agricultural systems (a systemic adaptation), and a high proportion of land used changing from cereal based cropping to combined grassland and livestock (i.e. a transformational adaptation). The above mentioned climate change impact scenarios and adaptation variants were assessed across present maize growing areas at sub-catchment scale, using a daily time-step biophysical APSIM model coupled with GIS, the interface allowed for scaling up responses to sub-catchment level.

The final selection of a sub-set of the representative ensemble of empirically downscaled climate projections, g22, gi2 and cn2 for the A2 (low mitigation) emissions scenario, was made on their rank in simulating historical climate conditions and other criteria such as capturing the uncertainty in precipitation projections. Based on these climate projections and the impact model and spatial data used in this study, for the Limpopo Province, it is suggested that in the year 2065, N fertilizer application will lead to a 28 % increase in yields across 47 percent of the sub-catchments, whereas for surface mulch application only 5 % increase and 12 % decline of maize yields. An early sowing date had a significant effect resulting in 48 % increase in maize yields over 58 % of the Province. The interaction effects of all the management options are likely to result in 17 % higher yields, this varied cross the Province owing to prevailing conditions, i.e. soil properties and climate. Poor-resourced farmers' potential maize yields; under projected future climate will be negatively impacted, with some gains arising from those who plant early and do not apply surface mulch. Better-resourced farmer, are projected to be better off compared to their counterparts mainly due to their ability to access and use N fertilizer. The traditional cropping systems assessed in this study indicated spatially varied potential gains and losses in yields. If farmers adopted better cropping practices and sowing dates they possibly could benefit from change climate. Projected increase in temperature, with or without the effects of changes in precipitation, was found to lead to significant reduction in maize grain productivity.

Analysis of changes in future relative to present climate, for both incremental and systemic adaptation options showed decreased in productivity in some parts of the maize growing areas over the Limpopo Province, with some spatial variation. Conversely, for transformational adaptation, a general increase in grass productivity and livestock stocking rates was projected, particularly, in areas spatially corresponding to those indicating decrease in maize yields under incremental and systemic adaptations. Inter-annual variation was used to test robustness of the adaptation options and it was shown that there is spatial variation in the effectiveness and risk associated with the adaptation options in all the three modes, from incremental to transformational adaptation. Based on visual assessment, incremental adaption seems to have a lesser areas of high year to year variability compared to the other two. This may suggest that it is still more robust into the mid-century that the other modes. The transition in adaptation modes, i.e. from incremental to systemic to transformational adaptation, might be disrupted by risk and vulnerabilities, and hence, in some cases trigger early, unplanned and abrupt transformative response.

Keywords: *APSIM, GIS, biophysical modelling, agriculture, climate change adaptation, climate change impact, Limpopo smallholder farmer*

4.1. Introduction

4.1.1. Climate change and agriculture

There is a growing body of irrefutable scientific evidence pointing to anthropogenic climate change with unprecedented global warming (IPCC, 2013, 2014). Between 1880 and 2012 there was a global temperature rise of 0.85 ^{o}C., The start of acceleration in temperature increases is directly coinciding with the establishment of the industrial (and economic) revolution (sometimes also referred to as human induced climate change; Hartmann *et al*., 2013). Further, this human-induced global warming has been shown to be directly related to the recently observed change in climate system (e.g. change in frequency and severity of extreme weather events such as droughts and flooding). Human-induced global warming has also been directly related to changes in managed systems. The most reported attribution of human-induced climate change has been to global warming and shifts in rainfall patterns, at continental or global scales, shifts or changes in these climatic variables have had substantial negative impacts on yield trends for certain agricultural crops (Cramer *et al*., 2014). In sub-Saharan Africa, evidence for and attribution of anthropogenically driven climate change is restricted by limited monitoring, such as weather recordings (Niang *et al*., 2014).

The signals emerging from the climate projections by General Circulation Model (GCM) are relatively consistent with observation on increased temperatures. Combined with, recent record of extreme and record breaking temperature and impacts of the rise in temperature cited in the IPCC 5th Assessment report (AR5), the evidence that GHG emissions have led to increased global mean temperatures is strong.

However, even with advancement in climate modelling the projections of precipitation made by different models are still highly variable across the IPCC GCMs (IPCC, 2014).

Climate influences the physical environment in which the agricultural sector operates and hence any changes will impact on its production and /or productivity. Climate change is said to alter agricultural productivity through changes in precipitation, temperature, carbon dioxide (CO2) fertilization, climate variability, and surface water runoff (World Bank, 2008). Changes in climate are projected to have both direct and indirect impacts on agricultural crop production. The direct climate change impact originates from changes in temperature, precipitation and CO_2 fertilisation (see. Rötter and van de Geijn, 1999) and indirectly agriculture is impacted through changes in the availability of irrigation water, soil-water and changes in yield reducing factors (such as pests and weeds) (Rosenzweig and Hillel, 1998; Rötter and van de Geijn, 1999).

The agriculture sector in South Africa is highly diverse with regard to its activities and socioeconomic, with the current realities of the commercial and smallholder farming sectors strongly influenced by the apartheid-era policies (Louw *et al.*, 2007). The commercial farming sector in general has better access to markets and resources, credit and more suitable land for agriculture. This makes their practices to be more resilient to prevailing climate and less vulnerable to climate change related shocks. In contrast ,the smallholder farming sector must do with more limited resources, infertile soils, and lack of financing, and hence making this sector less resilient and more vulnerable to coup with climate related stressors, such as extreme climatic conditions (i.e. droughts and flooding; Tibesigwa *et al.*, 2016).

The agricultural livelihoods, upon which the smallholder farmers depend on, are highly influenced by their physical environment conditions that are affected by climate change. These farmers are faced with numerous risks and constraints hindering their response to climate change which increase their vulnerability to climate impacts (Harvey *et al*., 2014). These risks very often related into increased temperatures and more uncertain/highly variable precipitation regimes (DEA, 2013). The changes are likely to negatively impact sub-Saharan Africa, by threatening food security and water availability, increase frequency and intensity of extreme weather events, and these are likely to result in cascading impacts to interrelated systems (Niang *et al*., 2014). In South Africa, the Agricultural Technical Report of Long Term Adaptation Strategies (DEA, 2013) on risk and opportunities suggests that projected future rise in irrigation demands will average 4 to 6 % annually under warmer wetter scenario and 15 to 30 % for hotter drier scenario; while rainfed maize yields were projected to change by -25 to +10 % in in the mid-century for summer rainfall regions, such as the Limpopo Province (DEA, 2013; Ziervogel *et al*., 2014).

Growing food demand, as a response to growing population, coupled with increasing competition for water amongst water users, places pressure on the already limited and scarce water resources (Wisser *et al*., 2009). With water availability further threatened by climate change the role of irrigation as an adaptation strategy will possibly be limited (Denton *et al*., 2014), especially in areas were water supply availability are expected to worsen by 2050 due to increasing temperatures and hence there would be less water to meet demands for irrigation expansion into current rainfed system, such as the Limpopo River Basin or South Africa (Zhu and Ringler, 2012). With climate change implications including its spatial extent and severity of impact becoming better understood, it is now being viewed as a sustainable development issue, with the potential for either capitalising on any positive effects or hindering successful development (Munasinghe, 2010). Studies suggest that developing countries, amongst others characterised by limited infrastructure, human capacity and a dependency on natural resources, are more vulnerable in near future with growing water demands for food, environment and industries (Hertel and Lobell, 2014).

Given the far-reaching impacts of climate change on agricultural crop and livestock production, and changes in their associated yield-limiting (water resources) and -reducing (pests, diseases) factors, adaptation actions relevant to most vulnerable farmer, communities and regions to climate change, and use of adaptation and mitigation combination strategies (such as climate smart practices) while ensuring food security will required (Campbell *et al.,* 2016). Further, the unevenness in the spatial and temporal impacts of climate change are said to have profound implications on the adaptation strategies (Ebi *et al*., 2016). There are a lot of promising technical options for incremental adaptation, most of which are referred to or promoted as best management practices (such as conservation tillage, cover crop, agroforestry, residue and/or nutrient management, etc.). For scaling-up these practices and/or transition to new practices, farmers, investors and governments alike, would require better information on the associated costs, financial viability and investment required (Campbell *et al.,* 2016). Ebi *et al.* (2016) suggests adaptation planning that incorporates more variations in the understanding of how the development of processes can interact with climate change to change future risks and vulnerabilities.

In this study, we undertake to understand smallholder farmers' vulnerability to climate variability and change, by evaluating their current crop management practices as well as various alternatives of adaptation against long term historical and projected future climates. Even though all South African farmers experience the same climate, the smallholder farmers amongst them operate at a disadvantage, with lesser access to land, irrigation as an option and resources than their commercial counterparts. These limitations basically result in a lower adaptive capacity of smallholder farmer.

4.1.2. Climate adaptation pathways for the Limpopo farming system

At the 21st Conference of Parties at Paris (COP21) 175 countries of the United Nations agreed to limit global warming of considerably below 2 °C, and if possible 1,5 °C (as compared to pre-industrial). Climate model projections combined with associated impact projections, accounting for geophysical, technological, social, and political uncertainties, were instrumental to provide data for informing policy makers about the limits below which greenhouse gas (GHG) emissions through global mitigation efforts should be reduced to avoid dangerous climate change (Denton *et al*., 2014). Achieving this agreed upon target of reducing GHG emission footprint, has in recent days, been threatened by global political uncertainty and/or perceptions defying the evidence presented by the scientific community, and thus there is a likelihood of the temperature threshold being surpassed. Smith *et al*. (2011) argued that a world with future global surface temperatures over 2 ^{o}C is more likely, this view is also supported by Wise et al. (2014) study, owing to weakening prospects for prompting mitigation, hence long lead times adaptation efforts would become more uncertain and complex. Thus, adaptation to a future with over 4 ^{o}C will be more substantial, continuous and transformative process, compared to that of a 2 ^{o}C future climate (Smith *et al*., 2011).

Adaptive responses to change in climate and other environmental conditions will be crucial in rural communities, whose livelihoods are climate dependent, owing to the projected risks and vulnerabilities. These vulnerable rural communities' are predominantly located in developing countries, accounting for about 70 % of the world's poor, where their livelihoods depended mainly on agriculture (Molden *et al*., 2007). The Limpopo Province is characterized by rural areas mostly depended on rainfed subsistence and smallholder farming for their livelihoods at varying degrees; the Province is also characterised by low productivity owing to highly variable rainfall, low soil fertility, land degradation (from erosion and over grassing) and lack of access to resources. Present recommended adaptive responses are better soil-water management, through improving productive efficiency of rainwater, soil moisture, and supplementary irrigation (Molden *et al*., 2007). Denton *et al*. (2014) suggested that increment adaptation might be a sufficient response to consequences of climate change in most local and contexts, if the magnitude and rate is kept minimal or moderate. This may not be the case in locations with there is already high vulnerability, thus transformational adaptation may be required.

Adaptation is generally regarded as a gradual change in the ecosystems responses to natural changes in climate and its associated variability, moderating the impacts or capitalizing on the beneficial opportunities. Similarly, adaptation to anthropogenic climate change is postulated to occur as increments to reduce and/or sustain desired systems function into the future (Pelling *et al*., 2015). Majority of current climate adaptation research focuses on gradual (incremental) adaptation (Wise *et al*., 2014). Wise *et al*. (2014) review of status in adaptation practices efforts indicated that even though there are some on the ground coping or an adaptation effort in South Africa, there is however, a lack of opportunities in scaling up some of the successful approaches to formulate concrete plans.

Smith *et al*, (2011) presented a review of mapping adaptations options (decisions) with respect to time scale, which occurs concurrently with projected change in climate, and their consequence period. Wherein, global warming is indication to increase by 2 ^{o}C from year 2030 and over 4 ^{o}C from the year 2060 towards the end of the century, simultaneously, the adaptation options would change from autonomous and incremental to planned and transformative, with different consequences from short to long term (Smith *et al*., 2010). This view suggests that transaction from one adaptation option to another might also be influence by time scale wherein climate is projected to change. In this study, the aim was firstly to introduce the various concepts of climate adaptation modes (incremental, system and transformational adaptation), when each is applicable and/or more suitable, and then to assess the effects of this climate adaptation modes within the Limpopo Province, with emphasis on agricultural sector.

The IPCC defines transformational adaptation as an “adaptation that changes the fundamental attributes of a system in response to climate and its effects” (Field *et al*., 2014: 40). Transformation pathway is suggested to occur in areas and for some systems wherein the impacts and risks may be far greater, abrupt and wide spread making gradual adaptation as a climate-resilient pathway insufficient. It is said to be triggered or implement by individuals to a group or community adopting a set of response measures, and as policy directive from government and other organizations in response to anticipated or experienced environmental impacts. Further, it does not occur in isolation from other adaptation modes (Rickards and Howden, 2012). Three classes of transformational adaptation highlight its difference to incremental adaptation, identified by Kates *et al*. (2012). These classes are, transformational scale (existing adaptations that are adopted at a much larger scale or intensity), transformative idea (those that are truly new to a particular region or system), and transformation of location (those that transform place-based social-ecological systems or shift such systems to other locations. Transformational adaptation is necessary when there are large vulnerabilities in certain regions and resource systems, and when the severity of climate change threatens the robust human-environment systems.

The transformational adaptation can occur abruptly in response to risk and vulnerability or as incremental transformation, wherein the incremental adaptation could transition systems towards transformation (Pelling, 2011). In this case, for sustainable development in ecosystem systems to be attained, within the context of climate change, climate-resilient pathways may require significant and permanent transformation. Denton *et al*. (2014) defines climate-resilient pathways as continuous development trajectories, which combine flexibility, innovation and involving participatory problem solving, for effectiveness in adapting and mitigating climate change to attain sustainable development. The pathways could be enabled by transformations in economic, social, technological, and political decisions and actions. Kates *et al*. (2012) explains how the transformational adaptation may affect decision making and resource distribution of individuals and society as adaptive response to climate change. Further they may The transformation pathway is likely to be triggered by a number of mechanisms, in response to limitations in incremental adaptation, mitigation and sustainable development, such as reaction, induced, and deliberately through social and political processes (Pelling *et al*., 2015). Pelling *et al*. (2015) highlighted that transformation, as an adaptive measure, could open new areas of policy response, wherein its used in conjunction with development pathways (such as social justice and sustainable development) to address entrenched causes of risk and vulnerability.

Transformational adaptation could result in transformation of farming systems, depending on trigger factors, implementation pathway (from autonomous to collative and policy response), etc., such as changes in the type of crops growing in particular area (such as breeding more tolerant crop varieties to climate impacts, and introduce new crops with higher tolerance to heat and drought), improving irrigation systems, switch to alternative livelihoods strategies (e.g. livestock, non-agricultural activities), and migrating to other areas (Rippke *et al*., 2016). Transformation is more likely result in significant and perhaps unpredictable costs; with the poor, likely to be most exposed to the short term transactions costs (Pelling *et al*., 2015). Further barriers to implementation of planned transformational adaptation are about the uncertainties ranging from climate risks to their plausible benefits. To bridge the barriers to anticipated transformational adaptation may require mainstreaming it in frameworks on risk management, and exploring more innovative and alternative transformational adaptations through research. Not forgetting the institutional and behavioural stands of maintaining the status core of resource systems and policies (Kates *et al*., 2012). There are plausible great benefits posed by implementation of transformational adaptation, and risks related to it (Rickards and Howden, 2012). Rippke *et al*. (2016) propose that monitoring capabilities for tracking farming systems and climate are required, in order to align or bridging gap between policies and production triggers.

The assessment in this study are in two parts, first on the climate change impact assessments on Limpopo Smallest Farmers (LSFs) based on their current crop management practices, and the second on the assessment of likely adaptation pathways of the LSF may undertake. The rationale for performing climate impact assessment is based on the premise that, when new downscaled climate scenarios become available the assessment needs updating as such analyses form the basis upon which adaptation and mitigation strategies in different locations can be identified and evaluated against. Further, this study will provide insight on the effects of Limpopo smallholder farmers (LSF) management decision making on their production and impacts of changes in environmental conditions. The main question is that, are current crop management practices contributing to their vulnerability to climate change and variability?

For the Limpopo Province, it is hypothesized that climate change will result in a rise in temperatures and less rainfall, which would lead to further constraints in available water resources and soil moisture, and thus reduced cropland productivity. Further, that the current gradual adaptation strategies will not be sufficient to sustain productivity to projected climate change effects, and hence requiring development of completely new production systems. The objective of this study was to determine how the projected future climate will affect the LSFs, based on their current crop management, with maize crop productivity as an indicator, and the likely adaptation pathways. The objective was addressed through the following questions,

- what are the LSF's crop management practices, and
- do the farmers' crop management practices affect their likely productivity?
- what types of future climates are projected to impact the Limpopo Province?
- what are the likely future adaptation pathways for the Limpopo Smallholder Farming?

4.2. Materials and Methods

4.2.1. Study area – Limpopo Province

There are a couple of basic assumptions underlying this study. One assumption is that the expansion in agricultural land and irrigation intensification is limited, owing to competition in the landscape with other sectors for this finite resource. The assumption is that future shifts in cropping patterns will be restricted within prevailing location and there would be no potential for expansion into urban and conservation areas. The climate impact assessment was therefore confined to current farming areas within Limpopo Province (Figure 1.1).

The changes in landuse on farmlands has been mainly limited to changes from one agricultural system to other systems (for instance, change from growing crops (agricultural croplands) to livestock or game farming, owing to changes in climatic suitability and as a result making crop farming financially not viable. The landuse change was detected through the use of satellite imagery from 1990 to early 2000s and aerial farm surveys when compared to climate records between time periods – was part of a study commissioned by the Limpopo Department of Agriculture in 2011).

4.2.2. Limpopo smallholder farmer agricultural management variants

To assess the agricultural productivity in the Limpopo Province, a series of plausible management variants or options were defined and developed around the key crops and management practices used by smallholder farmers. The options were based on information collated from a survey interview and correspondence with experts in the region. The parameterisation of crops to be simulated in APSIM was collated from various studies in the Province (ref. Chapter 3).

A structured closed farmer interview survey questionnaire was conducted during the 2014/15 summer season across 6 villages (i.e. Ndengeza, Gabaza, Marafana, Selwane, Vyeboom, and Ha-Lambani) yielding 201 crop and/or mixed farming respondents after data quality control (ref. Chapter 2). The information collated from the interview survey was used to form the basis for crop selection and derivation of typical smallholder farmer management decision scenarios. The survey showed that almost all smallholder farmers planted maize, 53 % of which was intercropped: 40 % with groundnuts, 23 % with beans (cowpea and lablab) and 24 % with other crops (such as sorghum, etc.). The farmers reported yields averaging 0.51 (± 0.45) $t.ha^{-1}$ of maize grain and 1.60 (± 13.7) $t.ha^{-1}$ of groundnut for the 2012/13 growing season, averaged across the surveyed villages. Based on these estimates, as well as literature for Limpopo (Maponya and Mpandeli, 2012; Mpandeli and Maponya, 2014,) it was evident that productivity using available land and rainwater could be substantially increased.

Follow-up questions indicated that about 31 % of the farmers utilize half or less portion of available land, owing to lack of labour and inputs. Further most farmers the farmers reused seeds for multiple seasons (negatively affecting germination and crop vigour), only 19 % applied fertilizer (i.e. cow manure and NPK), and 60 % reported leftover maize stover from the previous growing season. Typically, maize stover is feed to livestock during the dry season. The farmer’s low yields might be further attributed to the marginal and agriculturally least suitable areas (Baiphethi and Jacobs, 2009).

The farmers indicated their planting months between August to January, over the 2010 to 2014 period, with majority of them citing the months of October to January (i.e. 12, 53, 14 and 4 percent, respectively. This huge variation in planting dates could be attributed to the difference in the rainfall seasonality (i.e. the median concentration of rainfall) over the Limpopo Province (Schulze and Maharaj, 2007), with the Province defined as having early (December) and mid (January) summer rainfall seasonality based on 50 year climate record from 1950. The detailed survey data was used to characterize the LSFs, in SPSS version 23.0. A factor analysis-maximum likelihood (statistically significant with a Kaiser-Meyer-Olkin measure of sampling adequacy of 0.646) was performed with oblique rotation method to determine factors that influenced the classification. The selected factors, *viz.* farmland size, percent of farmland cultivated, farming activity (mono or mixed farming), some level of formal education, selling of excess produce, soil and water conservation measures, use of climate information, access to extension and expert services, and accessing markets (for farming inputs and outputs). Furthermore, the analysis was used to perform K-means cluster analysis to determine the number of clusters. Two clusters of farmers were identified, i.e. better- and poor-resourced farmers, across the 6 villages surveyed in the Limpopo Province, as shown in Table 4.1.

Majority of the better-resourced farmers were mainly female, reflective of the perceived gender roles in the region wherein females engage predominantly in crop farming and their counterparts in other practices (such as livestock and none agricultural activities). Further, these farmers were observed to use their farmland more efficiently with use of mixed farming or crop diversification and selling produce to local markets. This system made their livelihood systems to be better off and less at risk of shocks, compared to the poorly resourced farmers. In Table 4.2, crop management scenarios were constructed for poor and better-resourced farmer practices under rainfed conditions based on the information collated from the survey interviews, local expert knowledge and literature. Two planting dates were selected as they were most typically used in the region (i.e. November and December used by 63 and 17 percent of surveyed farmers, respectively) and a ZM 421 open pollinating maize variety crop was selected for simulation, as local farmers plant a similar variety which allows them to replant it annually.

Table 4.1 Classification of 201 surveyed smallholder farmers across 6 villages in the Limpopo Province (a), female farms, female farmers, fertilizer application, stover residue visible at sowing and types of crops grown for the different classes observed in the detailed smallholder farm characterisation (b)

a.

Cluster no.	Name referred to in this study	Description	Relative frequency (%)
I	Better-resource farmers	Farmers tends to have small individual farm sizes which are used effectively (cultivated the whole farm), practices more mixed crop farming, and sell their access produce	82
II	Poor-resourced farmers	Farmers tend to have small farms (most particularly in Ha-Lambani Village share large piece of land, wherein they plant together) which are not used effectively (less than 50 % of the farms cultivated). Do not sell any access produce and have to some extent mixed farming systems.	18

Both farmer groups were aware or had access to some level of formal education, soil and water conservation measures, use of climate information, access to extension and expert services, and accessing markets (i.e. for farming inputs and outputs), slightly more so for poor-resourced farmers.

b.	Female farmers	Use fertiliser	Stover residue visible at sowing	Types of crops grown (number of farmers)			
				Maize	Groundnuts	Cowpea and beans	Sorghum
Better-resourced farmers	63 %	13 %	47 %	162	71	39	3
Poor-resourced farmers	13 %	6 %	13 %	37	10	8	0

Table 4.2 Crop management practices scenarios under rainfed conditions

Scenario no.	Cultivar	Fertilizer N (kg.ha^{-1}), at sowing	Surface residue cover (kg.ha^{-1})	Planting date
Poor-resourced farmer				
1	ZM 421 [a]	0	0	15 November
2	ZM 421 [a]	0	0	15 December
3	ZM 421 [a]	0	2000	15 November
4	ZM 421 [a]	0	2000	15 December
Better-resourced farmer				
5	ZM 421 [a]	45	0	15 November
6	ZM 421 [a]	45	0	15 December
7	ZM 421 [a]	45	2000	15 November
8	ZM 421 [a]	45	2000	15 December

[a] (early duration) Open pollinated – variety developed for smallholder farmers for its short duration, resistance and drought tolerance

4.2.3. Climate database

4.2.3.1. Historical climate data

The climate data requirements of the APSIM model include daily rainfall totals, daily average minimum and maximum temperature and daily solar radiation, which were sourced from Schulze (1997). The historical climate datasets (i.e. daily minimum and maximum temperatures, daily precipitation amount and daily solar radiation) were obtained from Schulze (2007), for the period 1950 to 1999, which has been quality controlled and collated for South Africa. The data quality control used to develop the datasets included patching missing station records and using daily minimum and maximum temperature to derived solar radiation values, if they were not available from the weather station records.

The reasoning for using daily minimum and maximum temperatures as surrogates for estimation of solar radiation at unmeasured locations is provided in Richardson and Reddy (2004). Schulze and Chapman (2008) modified the Bristow and Campbell (1984) equation that was used in estimation of solar radiation, presented Appendix equation 6.2. An approach described by Warburton *et al*. (2012) was used to choose a representative climate station with daily records for each sub-catchment. Each sub-catchment was paired with a driver climate station, by visually linking in ArcGIS based on similar altitude and mean annual precipitation. The selected driver station had to be within a 20km radius and have more than 50 years of continuous record length.

4.2.3.2. Climate change scenario values

The climate change scenarios used, in this study, were the same as those referred to in the IPCC (2007) 4th Assessment Report (AR) GCM outputs. These were the only available and quality controlled statistically downscaled GCMs to a point scale (representative of climate station) at the time of this analysis. Climate Systems Analysis Group at University of Capet Town statistically downscaled 10 of the IPCC AR4 coupled climate models (from the for the Coupled Model Intercomparison Project (CMIP3) dataset) for the A2 emissions scenario – sometimes coined 'business as usual ' or low mitigation efforts scenario variant of SRES emissions scenario family (for details, see. Hewiston *et al.,* 2013). The emission storyline is for likely range of 2.0 to 5.4 °C, which seems plausible in light of current mitigation efforts which are still fairly limited (IPCC, 2014; Smith *et al.,* 2011).

In this study, approaches to reduce this uncertainty through the use of an ensemble of regionally downscaled GCMs, to consider a wide range of plausible future scenarios (ref. Table 4.3). Further, an approach by Schulze (2010) of using catchment resolution to address the spatial discontinuity at which GCMs outputs (10^4 to 10^5 km) are and scale at wherein local decisions and adaptation are made (10^1 to 10^2 km), was adopted.

The downscaled daily minimum and maximum temperature and precipitation values were used to derive solar radiation by the Bristow and Campbell (1984) equation, which was further refined by Schulze and Chapman (2008). The data was obtained from Schulze (2015). In this study only two time periods of the downscaled GCM daily climate values were used, i.e. present climate [1971 – 1990], and future climate [2046 – 2065]. Each sub-catchment was assigned a representative climate and soil file (ref. Chapter 3).

4.2.3.3. Selection of the most representative ensemble GCMs

In order to reduce computational costs related to performing climate impact modelling and time, GCMs ensembles were reduced to the most representative in terms of projection signal. The approach used in the selection of representative ensemble of climate models was adopted from Lutz *et al.* (2016) comprising of three steps, first step being the selection based on projected changes in climatic extreme indices; followed by the detection of changes in climatic means, an assessment of GCM skill in against a historical climate record and uncertainty analysis. Lastly, mean precipitation projection envelope (Figure 4.1).

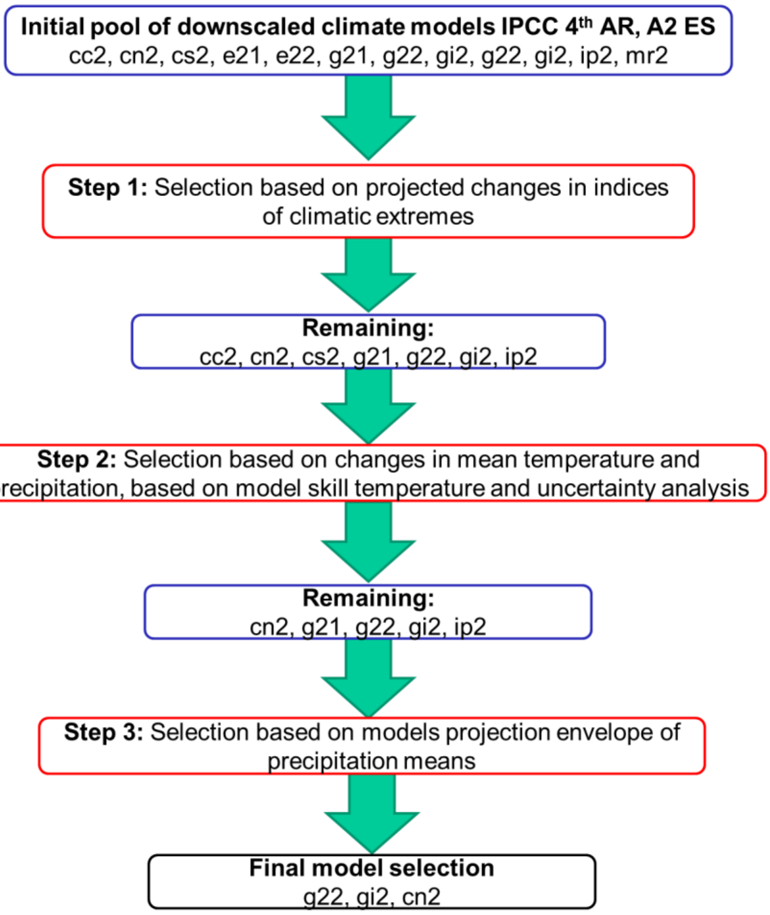

Figure 4.1 Schematic diagram illustration of protocols used in climate model selection

4.2.3.3.1. Initial selection – selection of representative emission pathways

The A2 emission scenario was selected, as it has been widely used in impact analysis (Schulze, 2010; Ziervogel *et al*., 2014), and most plausible based on prevailing mitigation efforts. The A2 emission storyline assumes a very heterogeneous future wherein there is a continuous growth in global population and a regional economic growth path that is uneven and slower compared with other storylines (Myhre *et al*., 2014). The use of GCMs introduces additional uncertainty in the simulation results, although this is outside the scope of this study it is worth noting, and inherent uncertainties are well documented in various studies (e.g. Cox and Stephenson, 2007; Giorgi *et al*., 2008; Jacob and van den Hurk, 2009). The assessments of future climate impacts are based on these GCMs and hence various approaches have been suggested to reduce bias in projecting precipitation (Asefa and Adams, 2013) and uncertain future developmental pathways.

The initial GCM model selection was made based on, the availability of the most recent empirically downscaled daily GCM climate values. In this study, 10 GCMs (Table 4.3) out of the 21 GCMs used in the IPCC 4th Assessment Report were initially selected for the A2 emissions (low mitigation) storyline. Different to Lutz *et al*. (2016) analyses, only downscaled GCMs were used and hence removing the need for resampling. This reduces the selection error as downscaled GCM runs have local climate adjustment as opposed to regional or global GCM runs.

Table 4.3 General circulation models used for climate scenarios, for A2 emission storyline of which were empirically downscaled by CSAG to point scale

No.	Institute	GCM	Acronym
1	Canadian Center for Climate Modelling and Analysis (CCCma), Canada	Name: CCCMA CGCM3.1(T47) Website: http://www.cccma.bc.ec.gc.ca/models/cgcm3.shtml	cc2
2	Meteo-France / Centre National de Recherches Meteorologiques (CNRM), France	Name: CNRM-CM3 Website: http://www.cnrm.meteo.fr/scenario2004/indexenglish.html	cn2
3	Queensland Climate Change Centre of Excellence and Commonwealth Scientific and Industrial Research Organisation, Australia	Name: CSIRO MK36 Website: http://coastalresearch.csiro.au/?q=node/162	cs2
4	Meteorological Institute, University of Bonn, Germany	Name: MIUB_ECHO_G Website:	e21
5	Max Planck Institute for Meteorology (MPI-M), Germany	Name: ECHAM5/MPI-OM Website: http://www.mpimet.mpg.de/en/wissenschaft/modelle.html	e22
6	NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA	Name: GFDL_CM2_0 Website: http://data1.gfdl.noaa.gov/CM2.X/	g21
7	NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA	Name: GFDL_CM2_1 Website: http://data1.gfdl.noaa.gov/CM2.X/	g22
8	NASA / Goddard Institute for Space Studies (GISS), USA	Name: GISS-ER Website: http://www.giss.nasa.gov/tools/modelE	gi2
9	Institut Pierre Simon Laplace (IPSL), France	Name: IPSL-CM4 Website: http://mc2.ipsl.jussieu.fr/simules.html	ip2
10	Meteorological Research Institute (MRI),Japan	Name: MRI_CGCM2_3_2A Website: http://www.mri-jma.go.jp/index_en.html	mr2

4.2.3.3.2. Final selection based on changes in climatic means

There are three 20 year time periods available from the downscaled GCMs, i.e. present (1971 - 1990), future (2046 - 2065) and distant future (2081-2100) climate scenarios, used in projection studies. For this study only the present and future climate time periods were used. This climate model selection is based on a range of changes in climate (specifically, changes in daily mean temperatures and annum precipitation) projections between 1971 – 1990 and 2046- 2065 averaged over four randomly selected in the Limpopo locations.

The 10th and 90th percentile values were determined for the point scale changes in temperature and precipitation, downscaled daily GCM climate scenarios. The values represent spectrum of projections for precipitation and temperature, i.e. “warm, dry or wet and hotter, dry or wet” spectrums. The 10th and 90th percentiles were chosen to avoid selection of climate anomalies. Further, the models proximity to the 10th and 90th percentile was derived from the climate models percentile rank scores corresponding to their change in climate projections with respect the entire range of projections in the ensemble,

$$D_{piT,\ pjD} = \sqrt{(|\mathrm{P}_i{}^T - \mathrm{P}_j{}^T|)^2 + (|\mathrm{P}_i\mathrm{i}^P - \mathrm{P}_j{}^P\ |)^2} \qquad 4.1$$

where, $D_{piT,\ pjD}$ is the distance of the model,
j is change in temperature (P_j^T) and precipitation (P_j^P), and
i is 10th and/or 90th percentile of the score of change in temperature (P_i^T) and precipitation (P_i^P), for the entire ensemble.

Five climate models were selected at each corner, wherein the D values were the lowest, from the GCM ensemble.

4.2.3.3.3. Second selection – prediction of past climate conditions (GCM forecast skill) and uncertainty

The selected models were subjected to a validation test against observed data. The skill assessment was conducted for the period 1971 – 1990, and skill scores are calculated for each model. The skill of the GCMs to predict reference climate conditions were based on the comparison of its forecast of downscaled daily climate values and historical station datasets. The performance of the selected GCMs was evaluated using skill metric (mean square error) and skill score, with a value of 0 and +1 denoting perfect forecast (respectively).

$$\mathrm{SS} = 1 - \frac{MSE_{forecast}}{MSE_{\ reference}} \qquad 4.2$$

where, SS is the skill score, and MSE is mean square error (for forecast and reference, respectively).

$$MSE_{forecast} = \frac{1}{n}\sum_{i=1}^{n}(\bar{\mathrm{y}} - \mathrm{y}_i)^2 \qquad 4.3$$

where, MSE is the mean square error or skill metric, $\bar{\mathrm{y}}$ is the forecast value, y_i is the observed value, and N is the number of observations or forecasts.

$$MSE_{reference} = \frac{1}{n}\sum_{i=1}^{n}(\bar{O} - 0_i)^2 \qquad 4.4$$

where, $\bar{O}$ is the mean, 0_i is observed

Following the assessment of past performance in the GCM to predict present climate, a framework for quantitatively assessing uncertainty in GCMs projection of future climate presented by the IPCC as an uncertainty guidance note (Mastrandrea *et al.*, 2010). This framework was adapted for selected empirically downscaled GCMs, presented in Table 4.4, to assess level of confidence in GCMs to project future climate.

Table 4.4 Scale of confidence levels for quantitative assessment of uncertainty adapted from the IPCC definition (Mastrandrea *et al.*, 2010) for this study

Confidence Terminology	Degree of confidence in being correct	Degree of confidence when 10 GCMs are used
Very high confidence	at least 9 out of 10 chance	> 9 out of 10 GCMs give same signal
High confidence	about 8 out of 10 chance	8 out of 10 GCMs give same signal
Medium confidence	about 5 out of 10 chance	5 out of 10 GCMs give same signal
Low confidence	about 2 out of 10 chance	2 out of 10 GCMs give same signal
Very low confidence	Less than 1 out of 10 chance	< 1 out of 10 GCMs give same signal

4.2.3.3.4. Final selection – Mean precipitation projection envelope

The final selection of climate model simulation outputs was based on the projection envelope range of precipitation for the climate models. Precipitation was used relayed on more in this final selections process as climate models projections of future precipitation is divergence in direction of change than temperature or other climatic variables.

4.2.4. APSIM model

The Agricultural Production Systems sIMulator (APSIM) model was selected for its ability to simulate bio-physically-based processes (such as crop growth, development and yields in response to interactions to management, soil-water, climate and landtype, including climate change and atmospheric carbon dioxide effects) at a daily-time step and scientifically well documented to operate in tropics, including the Limpopo Basin (Dimes, 2005; Holzworth, *et al*., 2014; Keating *et* al., 2003; Mpangane *et al.,* 2004; Whitbread and Ayisi, 2004; Twomlow *et al*., 2008; Whitbread *et al*., 2010).

Coupled with the models ability to simulate point scale agrohydrological processes, Paydar and Gallant (2008) introduced a framework wherein a one-dimensional model (such as the APSIM model) is capable of modelling in a catchment context. In this context, the model is capable of performing hydrological assessments on different landuses on different part of the catchment. The strong crop modelling component of the APSIM model enables for better represent of changes in catchment activities and hence related hydrological responses.

In this study, it was assumed that there were no upstream contributions to sub-catchments and hence the simulations were performed in lumped mode. Performing simulations in lumped mode increases the predictive accuracy by accounting for the inherent spatial variability within each sub-catchment. The APSIM model's crop prediction component has been verified at different locations for its water balance and crop simulation (Paydar *et a*l., 2005). The reasoning for performing the simulations using a hydrological approach in this study was primarily to use scientifically proven approach in the region for up scaling farm-scale agricultural responses to catchment level.

The APSIM model (version 7.6) parameterization, evaluation and validation were conducted from field experimental data conducted in the Limpopo Province, presented in Chapter 3. The control component of the field experiment was assumed to represent majority of the smallholder farmers management practices (derived from consultations with farmers and survey, discussed in Chapter 2), and hence formed the bases of this assessment, together with farm management practices from survey questionnaire.

4.2.4.1. Meteorological module

The APSIM model climate database (i.e. met files) was constructed for each Quinary Catchment, with a 10^1 to 10^2 km scale over the Limpopo Province. The visual basic (excel) and AgMIP tools (AgMIP, 2016) were adopted in this study primarily for the extracting and developing the APSIM met files for historical and future projected climate (Appendix: Table 6.10). The visual basic was used in extracting daily historical climate data and GCM-derived climate scenarios into an APSIM format. Then, the AgMIP Data Assistant version 0.3.7 was used to convert excel files into CSV files, which were later converted into APSIM met files using the QuadUI version1.3.7.

The concept of the Quinary Catchment is discussed in Schulze and Horan (2010), which is a hydrologically and agriculturally more homogeneous spatial unit than the 5th level delineation of Quaternary Catchments into upper, middle and lower sub-catchments created using an altitude based approach. Altitude was used in the sub-delineation as it is related to changes in hydrological drivers (i.e. temperature and precipitation) and buffers (such as soils and vegetation).

4.2.4.2. APsoil module

The assessment of landtype to each sub-catchment was based on the assumption that the most dominant, in terms of percentage areal cover, was representative of whole sub-catchment. This approach has been used extensively in catchment hydrological modelling and was adopted from work by Lekalakala (2011), Schulze (2010) and Warburton *et al.* (2012).

A landtype database representative of the major soil types, within each quinary catchment, in the Limpopo Province was developed, by use of overlay and areas weighting analyses in ArcGIS to select the most representative soil profile for each sub-catchment (of which was assumed to represent that particular local) and then extracting the soil profile information from the Agricultural Research Council – Institute for soil, climate and water's Landtype Memoirs (Loock *et al*., 2003; Loock *et al*., 2005; Sobczyk *et al*., 2012). Other soil property input data required in the APSIM model were derived using protocols defined by Dalgliesh *et al.* (2012). Each soil profile properties were used to populate the APsoil module for sub-catchment.

4.2.4.3. Populating the quinary catchments database for use with the APSIM model

The quinary catchments were used as spatial representation as they are units at which scale decisions managers from various sectors can make decision and most data is available at. The climate and soil databases were linked in the APSIM model using quinary catchment as a represent point of linkage.

4.2.4.4. Setting up APSIM model

The baseline setup of the APSIM model used in conjunction with the crop management options, discussed in section 4.2.2 and details shown in Table 4.2, are described below. Earlier mentioned the simulations were performed at a quinary catchment scale, with each sub-catchment having its unique soil and climate data. The model was calibrated using field experimental and secondary data, discussed in Chapter 3.

It was assumed that maize was planted at 90 cm row spacing and 2.2 plants per ha sowing density, and a sowing depth of 5 cm. Soil nitrogen and surface organic matter were annually reset at sowing, to match field experimental conditions used in model parameterisation, validation and calibration.

Harvest took place upon maturity or if that condition was unmet, harvest and at end crop command was set for 01 July.

4.2.5. Adaptation options

Many adaption options have been cited as suitable for adopted in the region, in response to climate change impacts. Expansion and/or introduction of irrigation has been cited in numerous studies as a likely adaptive response measure (Kang *et al*., 2009), including the South African Long Term Adaptation Scenarios reports. Similarly, including IRWH techniques have be highlighted to alleviate prevailing climate dry spells and soil-water deficit over the growing season (Mupangwa *et al.*, 2016), and has be demonstrated to be climate adaptation strategy (Lebel *et al*., 2015).

In this study, plausible adaptation options were developed based on expert knowledge and suggestion in the Literature (Leclère *et al*., 2014; Rickards and Howden, 2012), for the Limpopo agricultural sector, likely to cope with the effects of projected climate futures. For purpose of this study, only a few were selected, to demonstrate the different adaptation modes (Table 4.5). Smith *et al.* (2010) presents changes adaptation options from incremental to transformational adaptation, based on likely lead time scales, of different type of decisions from present time to 2100. The selected adaptation options were in response to future drought (soil-water deficit and dry spells), shift in growing seasons (including planting dates) and heat stress.

Table 4.5 Climate adaptation strategies and their associated implementation needs in terms of finance and knowledge level (Leclère *et al*., 2014; Rickards and Howden, 2012)

No.	Type	Adaptation Scenario	Description	Model configuration	Finance implications	Knowledge level
1	Incremental adaptation	Alter maize crop cultivar (adoption of shorter maturing and drought resistant cultivar)	Application of existing crop management practices	Adoption of early maturing and drought resistant maize crop	Low	Low
2	Systemic adaptation	Supplementary irrigation (Shift from rainfed to irrigated farming system)	Expansion in irrigated water use, and investment in new and/or increase in irrigation water infrastructure, such as groundwater extraction, large scale rainwater harvesting and storage, and inter-catchment/ reservoir transfers to meet the water use demands	Irrigate when there is soil moisture deficit, over growing period (December to February).	High	High
3	Transformational adaptation	Conversion of cropland into rangelands (Shift from cereal based farming system to grass and livestock production)	Large scale adoption of pasture was used as an indicator, over the cereal growing areas	Establish pasture under rainfed conditions , and determine number of beasts per hectare	High	High

Incremental adaptation: The management practices used in this adaptation assessment were parameterised, calibrated and validation for the Limpopo region, with maize varieties (ZM421 –early maturing presented in Chapter 3 and PAN 6479 – late maturing). The APSIM model maize crop management was setup for conventional tillage, residue removal and field preparations a day before planting (i.e. 14 November), sowing rate 2.2 plants per m^2 with row spacing of 900 mm and sowing depth of 50 mm, sowing was set for 15 November, and 45 kg per ha fertilizer rate for both incremental and systemic adaptation. Early planting was selected for this simulation, based on literature (Rurinda *et al*., 2013), that with late planting maize yields could be reduced by up to half.

Systemic adaptation: The APSIM model simulation was configured similar to that of incremental adaption with only ZM421 as maize crop. The supplementary irrigation was invoked when there is soil-water deficit only over critical growing months (i.e. December to February), this period is linked with critical growth stages (such as flowering and seed filling). Further, the irrigation efficiency was assumed to be at 75 %, which is well below most irrigation systems currently in use within the region (Reinders *et al*., 2010). It is worth noting that industry standard for commercial farming in South Africa, is a well-established industry and improved water use efficiency standards and guidelines, ranging from 78 % for traveling gun up to 90 % for drip irrigation (Reinders *et al*., 2010). Irrigation was assumed to be viable, on premise that there will be further groundwater exploration and surface water transfers from other states or reservoirs (similar to water transfers from Lesotho to Gauteng Province and/or between catchment within the country) in future to supply additional water to agricultural sector.

Transformational adaptation: The calibrated APSIM model for bambatsi grass in Zimbabwe (source by Whitbread, 2017) was used to simulate pasture production in the Limpopo Province. Both sites have similar climate conditions and are across from each other. The calibrated grasp module in APSIM model, together with Graz (for estimating stocking rate), were used in the simulation.

The inter-annual coefficient of variability of the adaptation options was used to compare the risk, i.e. the year to year variability in attaining mean yield over a set period. Inter-annual variability was selected as it allows for comparison of yields at different locations and management practices, to test the robustness of adaptation modes.

4.3. Results

4.3.1. Selection of General Circulation Models (GCMs)

4.3.1.1. Changes in climatic means (step 1)

The first selection process was based on changes in daily means temperatures and annual preciptation, between past and intermidate future climate time periods (i.e. 1971 -1990 and 2046 - 2065, respectively). The GCMs over the Limpopo Provice, for the future scenarios, suggest two likely climate conditions (i.e. warm and dry and hotter and wet). The distance to the 10th and 90th percentile values were determined for each GCM in the corners (ref. Figure 4.2), then five models with the lowest value of $D_{piT,\ pjD}$ (cf. Table 4.6) closest to the corners were selected, indicated by red squares. The selected GCMs for 10th percentile corner were cc2, cs2, g21, g22 and gi2 and for 90th percentile were cn2, cs2, g21, gi2 and ip2.

In Table 4.6 and Figure 4.3, the selected GCMs indicate a similar pattern of rise in 10th and 90th percentile mean temperature regimes, with two likely precipitation outcomes. The future likely directions of projections in temperature as similar to those noted in the Intergovernmental Panel on Climate Change, Physical Synthesis reports.). The selected ten daily downscaled GCMs from the A2 emission scenario projected two likely future climate projections, i.e. ‘warm’, ‘dry’ and ‘hotter’,’wet’, it is worth noting, that there were no ‘warm’,wet and ‘hotter’,’dry’ future conditions.

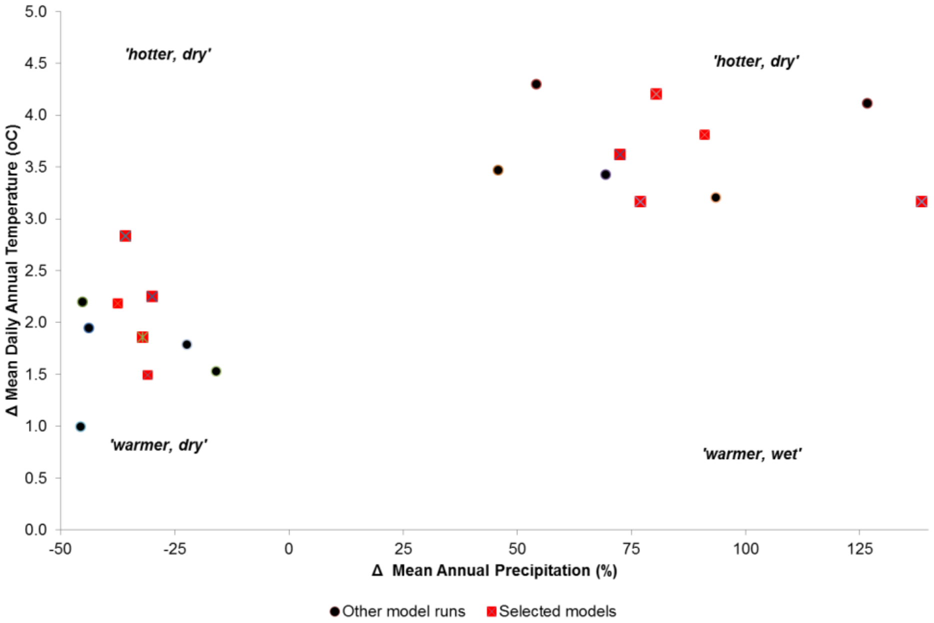

Figure 4.2 Projected changes in the 10th and 90th percentiles mean daily temperature and annual precipitation sum between 2046 - 2065 and 1971 - 1990 for the A2 emission scenarios GCM runs

Table 4.6 Summary of projected 10th and 90th percentile distance to model and climate statistics, for the period 2046 – 2065 in the Limpopo Province

GCM	Distance to model		Annual Precipitation (mm)			Annual Temperature (°C)		
	D10th	D90th	10th	50th	90th	10th	50th	90th
cc2	**1.7**	45.3	298	443	603	20.6	21.0	21.8
cn2	13.7	**8.8**	450	663	977	20.4	21.0	21.7
cs2	**4.2**	**9.7**	306	450	643	21.2	21.5	21.9
e21	9.2	35.6	464	570	829	20.7	21.2	21.7
e22	12.2	27.2	330	515	698	20.9	21.4	22.4
g21	**0.4**	12.0	379	527	714	20.0	20.7	21.0
g22	**0.8**	57.3	277	442	646	19.8	20.4	20.7
gi2	**5.9**	**1.0**	338	517	688	20.4	21.0	21.7
ip2	15.6	**4.4**	319	505	800	20.4	21.2	21.9
mr2	14.1	12.1	253	575	730	20.1	20.8	21.3

4.3.1.2. Past performance and uncertainty analysis of GCMs (step 2)

The second selection process is based on the validation of the GCMs prediction past climate conditions. The performance of climate model based on this selection process might have no significant barring on its projection ability, but merely forecasting power, as different GCMs have been constructed using different climate physics for projections. This analysis strengthens the confidence in the climate models capabilities to represent the regional climatic systems and in the projections used.

In Table 4.7, performance of the selected GCM climate prediction of prevailing climate as compared to observed data (1971 - 1990), based on skill score, suggested that there is a general agreement (value close to 1 suggest good correlation) in terms of prediction of temperature with cc2 out performing other models. The g22 and g21 GCMs were weaker of the ten GCMs in predicting prevailing temperature regimes. All the GCMs indicated divergent (over 93.7 to 193.6 mm over estimation) prediction of prevailing precipitation compared to observed data

Table 4.7 Skill scores for GCMs computed for precipitation and temperature

GCM	Temperature		Precipitation	
	MSE	SS	MSE	SS
cc2	0.7	1.0	193.6	-2.0
cn2	2.1	0.9	108.2	-0.7
cs2	2.0	0.9	147.2	-1.3
e21	2.3	0.9	108.9	-0.7
e22	1.4	0.9	127.7	-1.0
gi2	1.3	0.9	145.1	-1.2
g21	3.1	0.8	155.0	-1.4
g22	3.0	0.8	118.1	-0.8
ip2	1.3	0.9	117.1	-0.8
mr2	1.4	0.9	93.7	-0.5

MSE - mean square error, SS - skills score

To quantitatively assess the uncertainty in the GCM projections of future climate, the ratio of change in present to future climate was computed for all GCMs. Then, determination of agreement was constructed in terms of likely increase (ratio greater than 1.01), no change (ratio equal to 1.00) and decrease (ratio less than 0.99). Lastly, uncertainty confidence levels were computed across the GCMs for temperature and precipitation, as shown in Table 4.8. The uncertainty analysis suggests that there is a very high confidence in GCMs to project future increase in temperature, whereas for projecting future precipitation there was a 50 % chance with medium confidence for either a likely increase or decrease in precipitation.

Table 4.8 Confidence levels in GCMs to project increase, no change and decrease in future temperature and precipitation

Direction of change	Precipitation		Temperature	
	Degree of Confidence	Confidence	Degree of Confidence	Confidence
Increase	5 out of 10 GCMs	Medium confidence	10 out of 10 GCMs	Very high confidence
No change	0 out of 10 GCMs	-	0 out of 10 GCMs	-
Decrease	4.5 out of 10 GCMs	Medium confidence	0 out of 10 GCMs	-

4.3.1.3. Mean precipitation projection envelope (step 3)

In the final selection of the representative GCM ensemble, precipitation was heavy weighted, owing to GCMs not projecting a concise direction of change (GCMs show highly varied future precipitation conditions), and followed by temperature that was a consistent projected increase. The final selected GCMs represented median of maximum and minimum temperature, and precipitation envelope across GCMs (Figure 3, Table 4.9). There selected GCM were cn2 suggesting maximum, g22 minimum and gi2 middle of median precipitation and temperature envelope.

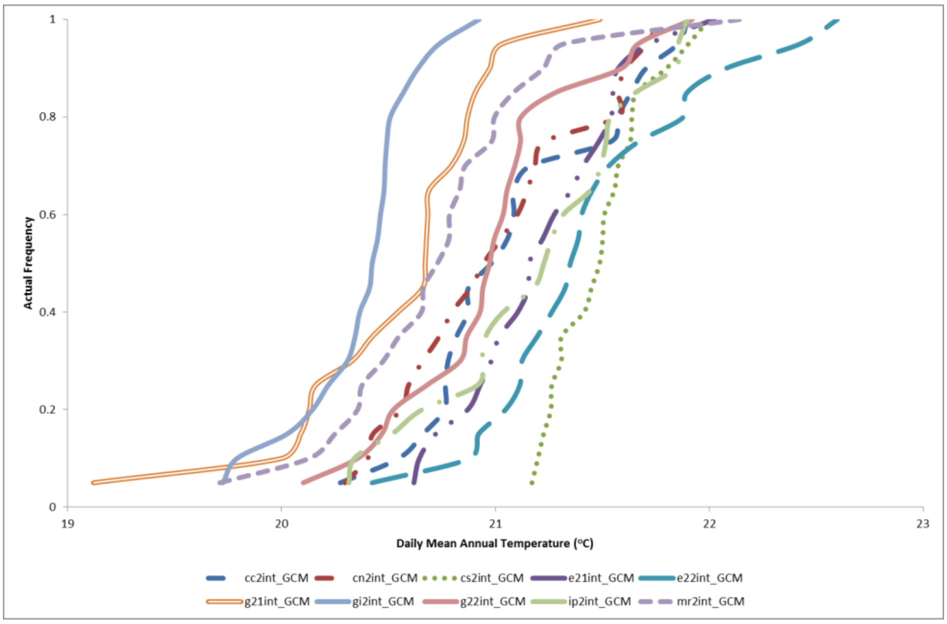

Figure 4.3 Cumulative frequency of daily mean annual temperature, for the period 2046 – 2065 in the Limpopo Province

Table 4.9 Final selected ensemble of GCMs climate projections

Projection	GCM	Median GCM ensemble representation	Median annual future		Mean change in present and future		Skill score	
			Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (%)	Temperature	Precipitation
warm, wet	-	-	-	-	-	-	-	-
warm, dry	gi2	Middle	20.44	517	2.56	-0.70	0.9	-1.2
	g22	Low	20.98	442	2.93	-1.39	0.8	-0.8
hotter, wet	cn2	High	20.99	663	2.66	21.79	0.9	-0.7
	gi2	Middle	20.44	517	2.56	-0.70	0.9	-1.2
Hotter, dry	-	-	-	-	-	-	-	-

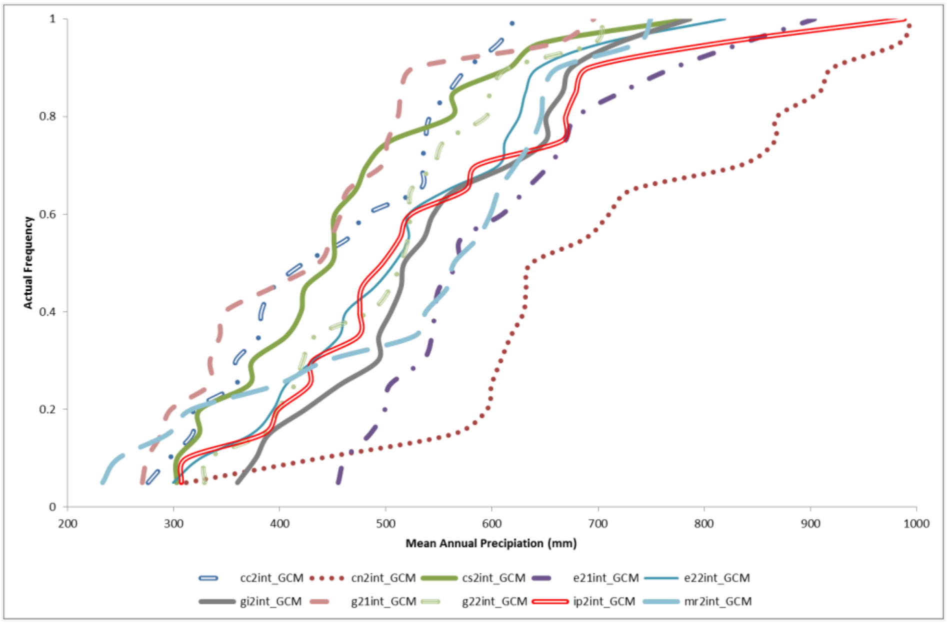

Figure 4.4 Cumulative frequency of mean annual precipitation (mm), for the period 2046 – 2065 in the Limpopo Province

4.3.2. Effect of smallholder farmers' crop management practices on potential maize productivity

To assess the effects of climate variability and change on LSFs crop productivity, a survey questionnaire was used to establish their farm management practices and yields attained under those practices. Those practices were used to develop two sets of scenarios, shown in Table 4.2, first representing the majority of the surveyed farmers who don't use fertilizer and remove maize stover for other uses–termed 'poor-resourced farmer', and an the others only incorporated previous year's residues back in the soil. Whereas, the 'better-resourced farmers' that were in the minority applied nitrogen fertilizer and also incorporated maize stover residues back in the soil. The period 1971 -1990 was selected as it correlated with the GCMs present prediction of climate and makes for easy comparison with simulations from the selected GCMs. In Figure 4, mean annual maize productivity for crop planted on 15 November without fertilizer and surface mulch for the period 1971 – 1990. This management scenario suggests that farmer who applied these practices in the central interior towards the northern border of the Province are likely experience potential yields ranging from less than 225 to 1 575 kg per ha per annum.

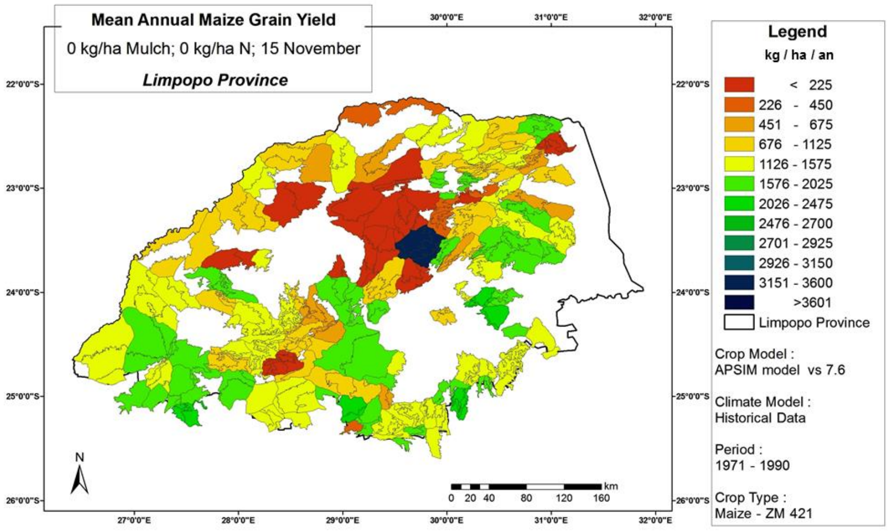

Figure 4.5 Mean annual maize grain yield sown on 15 November under no surface mulch cover and nitrogen fertilizer for the period 1971 to 1990, over the Limpopo Province

The effect of planting dates were assessed, based on dominate planting periods reported by LSFs, shown in Figure 4.6a, suggest that planting early (i.e. 15 November) over the period of review would have a positive effect of maize productivity rather than later. Increase in crop productivity of up to 86% in the central interior of Limpopo maize farms. If all farmers were to apply the minimum recommended 45 kg ha^{-1} nitrogen fertilizer are likely to experience an increase over all areas, as shown in Figure 4.6b. Conversely, as depicted in Figure 4.6c if they only applied surface mulch they are more likely to experience a reduction in maize grain yields over most areas. Figure 4.6d and e, indicate the interaction effects of applying mulch and nitrogen application over two planting periods (i.e. November and December, respectively), with increase in early planting showing overall increase in maize yields as compare to late planting having positive effect in some areas.

A validation analysis, adopted from Lekalakala (2011), was conducted to determine the simulation of maize yields from selected GCMs present climate scenario is representative of the similar simulations for historical climate conditions, presented in Figure 4.7. Cn2 GCM shows an over estimation of simulation in historical climate conditions compared to the other GCMs. The GCMs indicate agreement with historical climate simulations in different and sparse distributed areas, indicated by yellow colour within an acceptance range of ± 10 %. Further analysis, to determine if there is a correlation between GCM prediction of present and observed climate, was to conduct a regression analysis and a Pearson correlation test, denoted by r (cf. Figure 4.7). The analysis, in which the regression was forced through zero, indicates a sparsely distribution and a positive moderate correlation between the projected and observed climate predictions of maize yields across all the GCMs.

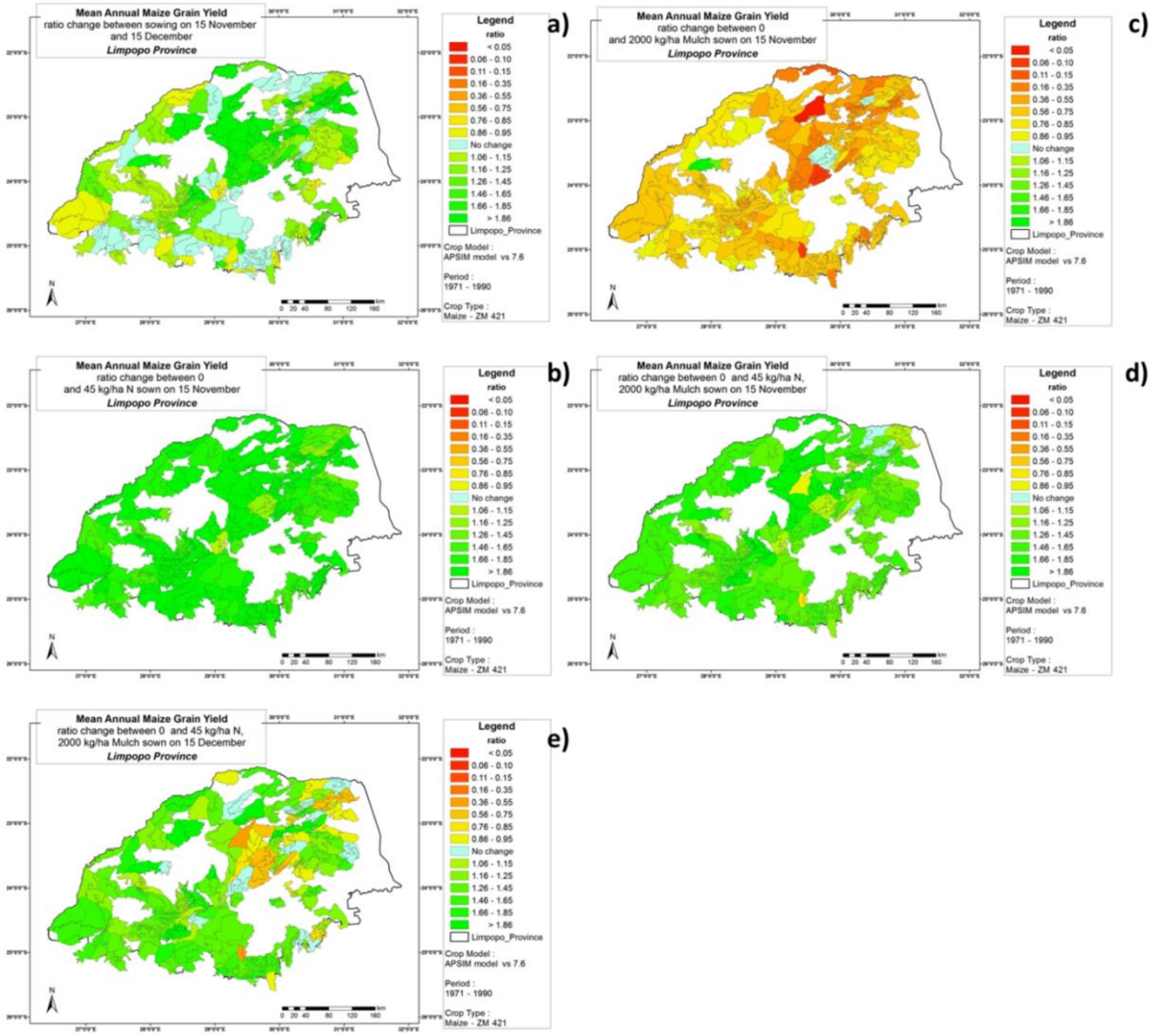

Figure 4.6 Ratio of change in mean annual maize grain yield under no surface mulch, N fertilizer sown on 15 November and that sown on 15 December (a); 45 kg/ha N fertilizer applied at sowing (b); 2000 kg/ha surface mulch (c); 45 kg/ha N fertilizer applied at sowing, 2000 kg/ha surface mulch sown on 15 November (d); and 45 kg/ha N fertilizer applied at sowing, 2000 kg/ha surface mulch sown on 15 December (e), over the Limpopo Province

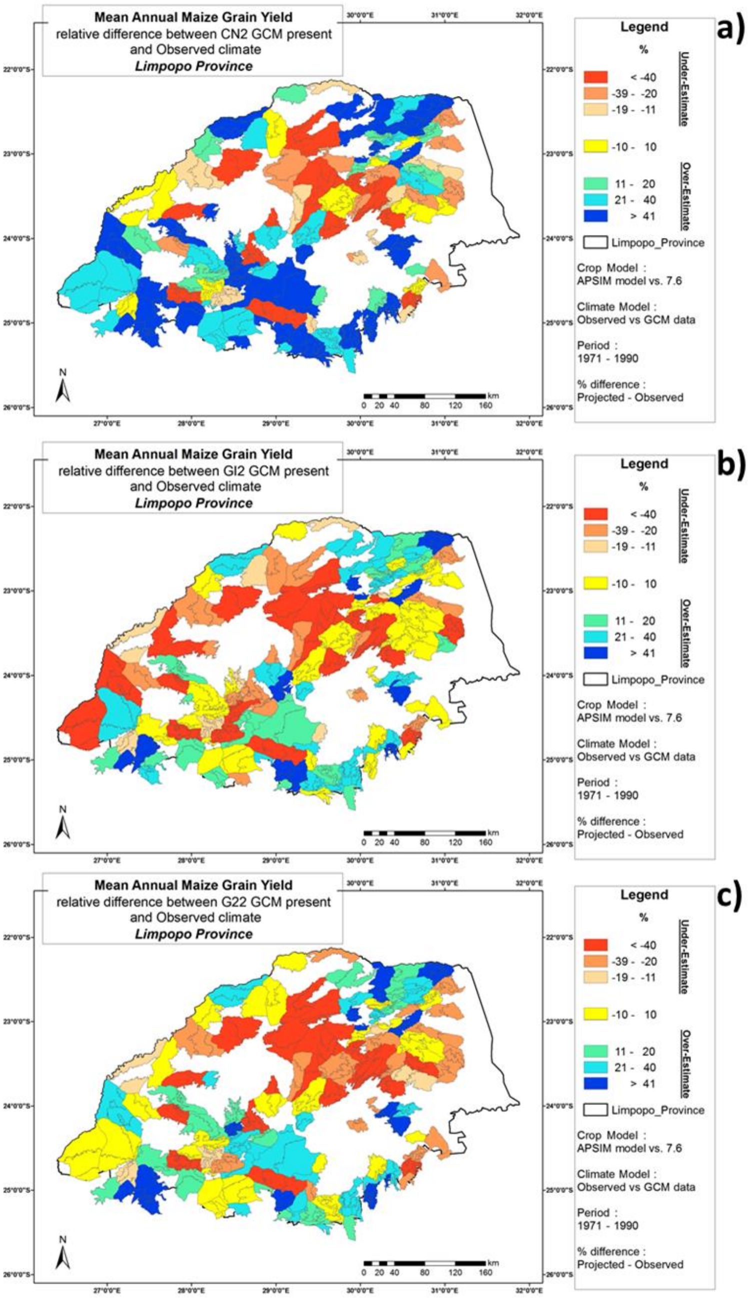

Figure 4.7 Relative difference in the mean maize grain yield generated from the CN2 GCM (a), GI2 GCM (b), and G22 GCM (c) present climate scenario vs. baseline climate conditions for the same time period over the Limpopo Province maize growing areas

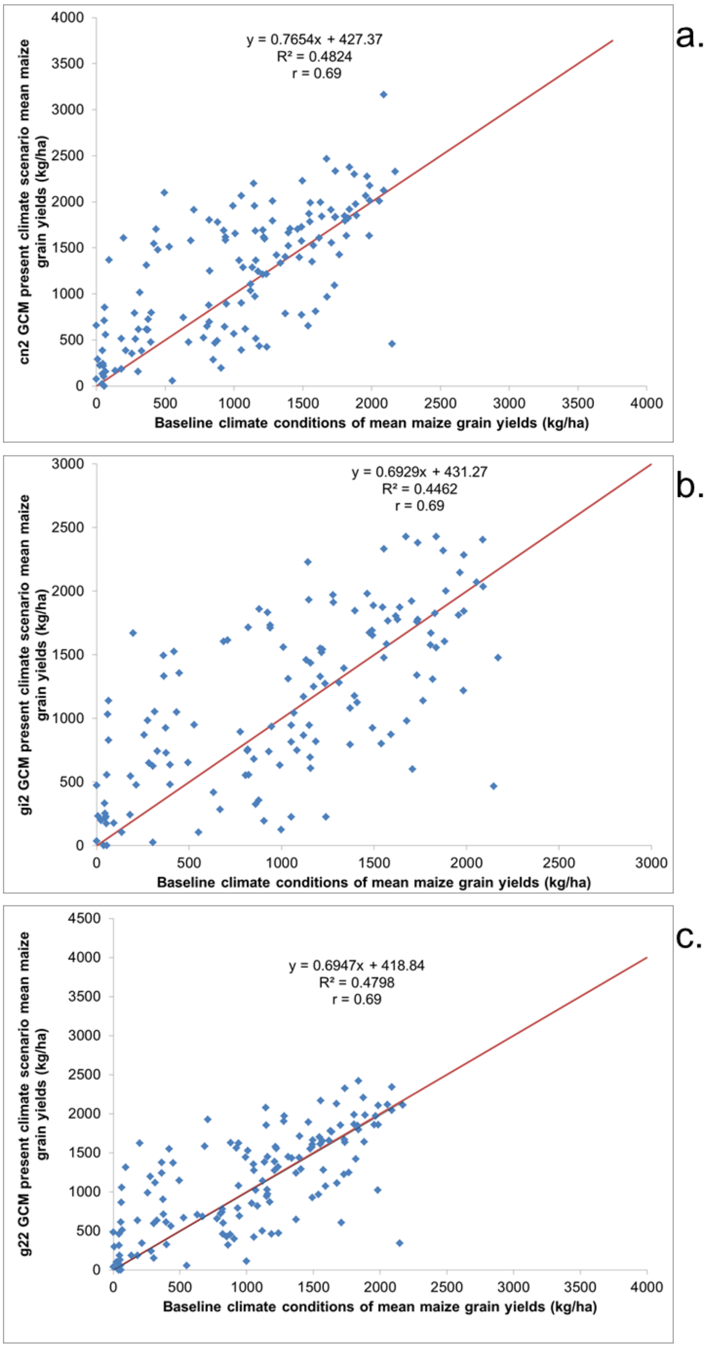

Figure 4.8 Relationship between mean annual maize grain yield, simulated in APSIM mode, for GCM present climate scenario relative to baseline climate conditions for the same period [1971 -1990], with each point representing a catchment

4.3.3. Effect of projected future climates on the Limpopo smallholder farmers

In this section, the effects of future projected climate on the LSFs' management practices were assessed across the three selected GCMs ensemble. In Figure 4.9, the ratio change between GCMs future climate projections on mean annual maize grain yield under no nitrogen fertilizer and surface mulch application sown on the 15 November are shown. The ratio change projected future maize yields indicate significant differences amongst the GCMs, with overwhelming decrease between g22 and gi2 GCM across the Province (Figure 4.9d). However, the ratio change between cn2 with g22 and gi2 GCMs (Figure 4.9b; Figure 4.9c, respectively) varies spatially with some areas likely to experience high, no change and decline in maize yields.

The ratio change in projected present and future maize yields across the GCMs with differences in two time periods with any crop management (Figure 4.10a.; Figure 4.10f.; Figure 4.10k.), planting dates (Figure 4.10b.; Figure 4.10g.; Figure 4.10l.), N fertilizer application (Figure 4.10c.; Figure 4.10h.; Figure 4.10m.), surface mulch application (Figure 4.10d.; Figure 4.10i. ; Figure 4.10n.), and interaction effect of N fertilizer and surface mulch (Figure 4.10e.; Figure 4.10j.; Figure 4.10o.), indicated the crop management responses under the three projected futures. The overall effect are similar to those simulated for prevailing climate conditions, with difference been in changes in areas experiencing increase and decline in yields.

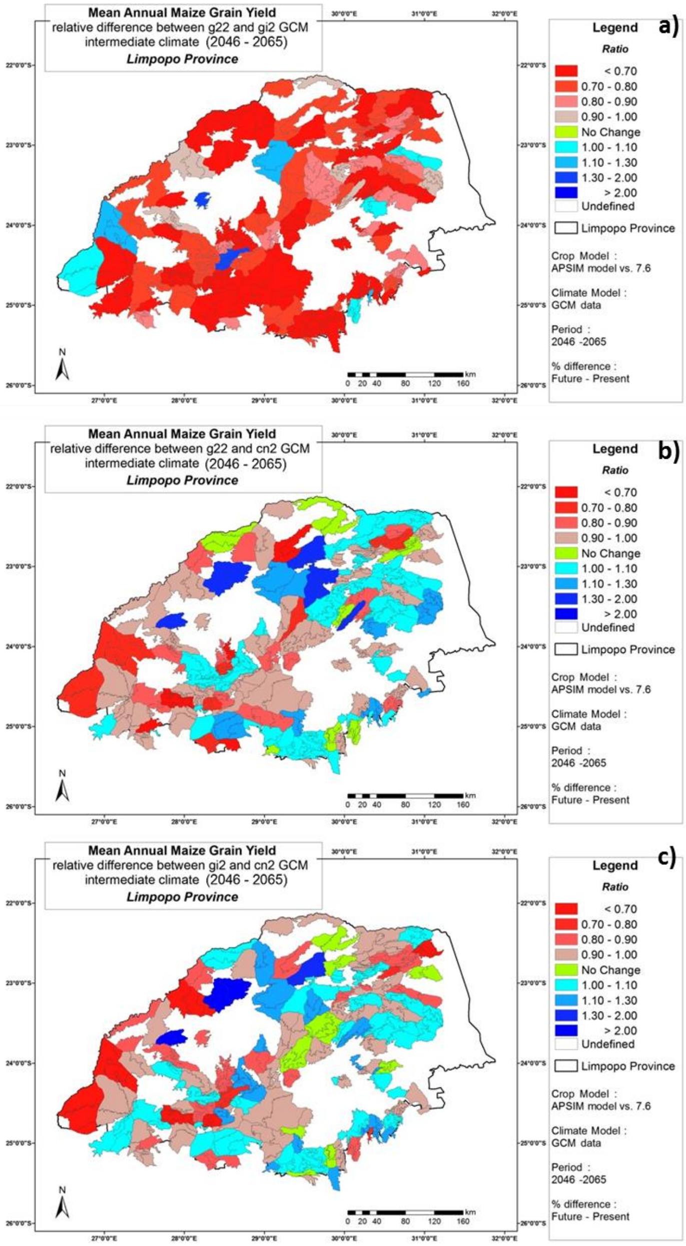

Figure 4.9 Ratio change in GCMs future maize yield productivity projections, relative difference between g22 and gi2 GCMs sown on 15 November (a), g22 and cn2 GCMs sown on 15 November (b), gi2 and cn2 GCMs sown on 15 November (c)

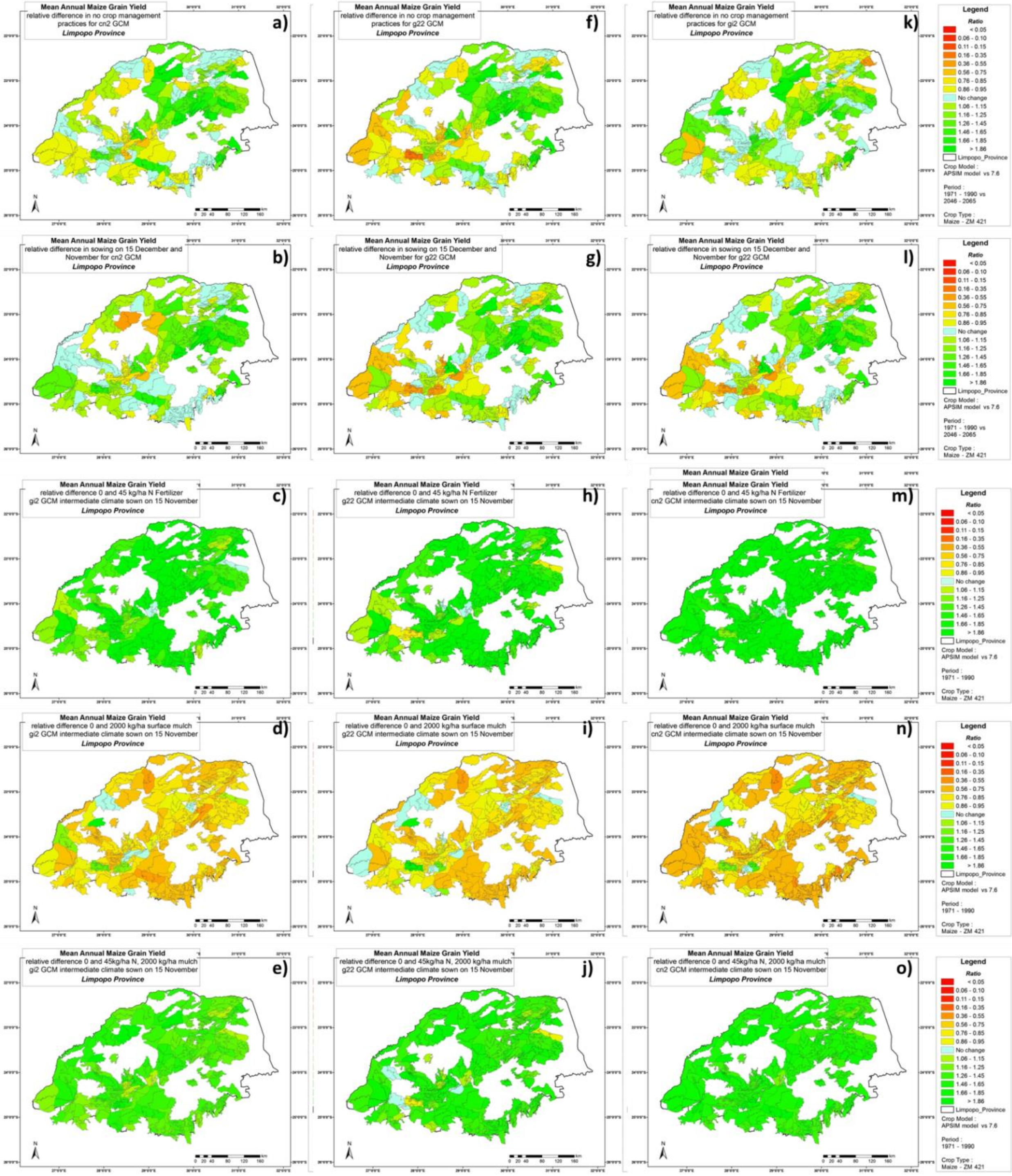

Figure 4.10 Ratio change in GCMs present and future maize yield productivity projections between no surface mulch, N fertilizer, sowing dates and no surface mulch, N fertilizer, sowing dates (a); on 15 November and gi2 GCM sowing dates (b); gi2 GCM N fertilizer (c); gi2 GCM surface mulch (d); gi2 GCM N fertilizer, surface mulch (e); no surface mulch, N fertilizer, sowing dates (f); g22 GCM sowing dates (g); g22 GCM N fertilizer (h); g22 GCM surface mulch (i); g22 GCM N fertilizer, surface mulch (j); no surface mulch, N fertilizer, sowing dates (k); cn2 GCM sowing dates (l); cn2 GCM N fertilizer (m); cn2 GCM surface mulch (n); and cn2 GCM N fertilizer, surface mulch (o)

In Table 4.10, the percentiles of changes in projected mean annual maize grain yields under different crop management practices across the Limpopo Quinaries over the 20 year time periods between present and projected future climate scenarios. The climate change impacts for mean annual maize yield productivity across the Limpopo Province under no crop management between two time periods is likely to result in a range, from 7 percent decline to an increase of 29 %. Planting earlier than present conditions is suggested to increase mean annual yield productivity by 48 % and decrease of 7 %, less in other management practices.

Further analysis, shown in Table 4.11, on spatiotemporal percentage change in projected of maize growing areas between present and projected future climate scenarios suggest a 46 % mean increase and 27 % decline across GCMs in all management practices. The remaining difference between projected increases and decreases are areas that will not experience any significant changes (with the acceptance range of 0.95 to 1.05 ratio change). The spatiotemporal mean changes across GCMs projected between present and future climate without management practices effects suggest a likely decline in mean annual maize grain yields of 27 %, while for changes in sowing dates a likely 16 % decline, followed by 30 % in surface mulch application, and then 32 % for N fertilizer application.

Table 4.10 Percentiles of projected changes in maize grain yield production changes across the climate models, negative values denoting decrease and positive denoting increase, over the Limpopo Province, between present and projected future climate scenario

Crop Management Practice	Percentiles	CN2 GCM	G22 GCM	GI2 GCM	**Mean**
N/A	25th	-5	-12	-5	**-7**
	50th	4	2	4	**3**
	75th	30	37	21	**29**
Sowing dates – 15 Dec / November	25th	1	-7	0	**-3**
	50th	7	8	20	**12**
	75th	32	24	89	**48**
Nitrogen fertilizer	25th	-6	-27	-2	**-12**
	50th	3	-6	10	**2**
	75th	35	19	30	**28**
Surface Mulch	25th	-6	-4	-9	**-6**
	50th	5	9	0.8	**5**
	75th	31	37	17	**28**
N fertilizer, surface mulch	25th	-5	-15	-14	**-8**
	50th	4	-0.13	7	**4**
	75th	32	28	22	**27**

Table 4.11 Percentage change in spatiotemporal in projected under maize grain yield productivity across the sub-catchments over the Limpopo Province, between present and projected future climate scenario

Crop Management Practice	Direction of change*	CN2 GCM	G22 GCM	GI2 GCM	**Mean**
N/A	↑	47	44	47	**46**
	↓	24	33	23	**27**
Sowing dates – 15 Dec / November	↑	60	52	63	**58**
	↓	12	25	9	**16**
Nitrogen fertilizer	↑	45	36	59	**47**
	↓	28	53	15	**32**
Surface Mulch	↑	50	55	41	**48**
	↓	30	23	36	**30**
N fertilizer, surface mulch	↑	46	45	54	**48**
	↓	24	41	22	**29**

* decrease↓, increase↑

4.3.4. Adaptation pathways

The median GCM was selected for the purpose of determining the likely adaptation pathways for the Limpopo Smallholder Farming systems. Three adaptation modes were identified from literature and consultation with experts, which are and likely to be implemented within the region. For each of the modes, a representative adaptation strategy was selected to demonstrate the effects of the pathways and likely effectiveness of the different modes. It is stressed that there are more possible adaptation strategies, which address specific risk and vulnerabilities, and hence not limited to those presented here. The selected strategies in this study address effects of dry spells and/or drought event and heat stress on smallholder farming systems within the Limpopo Province.

4.3.4.1. Incremental Adaptation

Projections of future early maturing maize cultivar suggest an increase in yields over larger area (Appendix: Figure 6.19), covering 70 % of the area, compared to late maturing cultivar. The comparison of late and early maturity cultivars of maize grain yields, under future climate condition, indicated in Appendix: Figure 6.20 by ratio changes point to late maturing cultivar been more suitable, over most of the sub-catchments. The inter-annual variability of maps of early and late maturing maize cultivar yields, shown in Appendix: Figure 6.21, indicate variation in simulated yields over a 20 year period in the mid- century climate projection. Assuming variation less than 30 % indicate less risk, early maturing cultivar would be better option in 63.7 % of the areas, as opposed to late maturing indicating in 53.9 % of the area to have less variability when it is planted.

4.3.4.2. Systemic Adaptation

Supplementary irrigation only when there is soil water deficit, as Appendix: Figure 6.22, difference between present and future projected will likely result in increased maize grain yield over central interior areas and reduction in other parts. The inter-annual variation in maize crop production under supplementary irrigation, shown in Appendix: Figure 6.23, suggests that there will be less variability over most part of the Province.

4.3.4.3. Transformational Adaptation

The assessed adaptation option under transformative adaption, is a shift from cereal crop farming to grass production and hence livestock ranching. In Appendix: Figure 6.24, mean annual total standing dry matter (grass, kg per hectare) at the end of the growing season for present climate scenario indicates over 10 tons per ha of grass production along the north-south interior belt. These areas of high grass production correspond with areas high potential stocking rates of over 350 beasts per ha (Appendix: Figure 6.27). A comparison of future relative to present climate scenario, in Appendix: Figure 6.25 and Figure 6.28 of grass production and stocking rates (respectively), indicate similar trends of increasing over most parts and decrease mainly along central interior in areas of high yields during present climate conditions. The map of inter-annual variability indicates low risk in highly productive areas and greater variability towards low productive areas (Appendix: Figure 6.26).

4.4. Discussion

In this study, empirically downscaled daily GCMs climate scenarios for the A2 emission storyline forcing were used to assess the climate impacts on the Limpopo smallholder farming practices. Guidelines for selecting most representative ensemble of GCMs were adapted from Lutz *et al.* (2016), which take into account the strengths from both the envelope- and past performance-based selection. Additions made to the selection guidelines were the uncertainty analysis in GCMs projection future climate conditions, and use of mean square error and skill score, as well as projection envelopes' final selection heavily reliant on precipitation.

The inclusion of an uncertainty analysis in the selection of representative GCM projections was in part an attempt to quantify the extent of plausible change in the downscaled daily precipitation and temperature patterns, caused by climate model biases and possible downscaling. The reduction in number of GCMs was conducted to reduce computing power and resources of running multiple scenarios, to few most representative GCMs of the ensemble. It is worth noting the likely uncertainties that might arise from this approach may include averaging projected changes over an area and hence diluting or adding an additional uncertain to spatial variation in projected changes. Similarly, performing this analysis over multiple parts, to avoid diluting the effect especially of extreme events, would introduce physical inconsistencies (Lutz *et al.,* 2016).

The climate projections used, as shown in Table 4.8, indicate that there is a high level of certainty in both change and increase in future temperatures, however, future precipitation projections point to moderate certainty in both increase and decrease, but the certainty of there been a change in rainfall is high. This observation is similar to that found in literature on climate change and uncertainty studies, such as IPCC, 2007; IPCC 2014. This observation supports the final selection of representative GCM ensemble process been heavily weighed on projected range of change in precipitation.

Three downscaled daily GCMs climate projections representing minimum, median and maximum mean annual precipitation envelope for projections of 'warm, dry' and 'hotter, wet' climate, were selected for climate impact analyses. The final selection process weighted more on precipitation envelope, as it was more highly variable compared to temperature regimes. Two climate projection time periods were selected for this analysis, i.e. the present (1971 – 1990) and future climate (2046 – 2065).

The reader is reminded of the inherent uncertainty in GCMs (for example, uncertainties emerging from emission storylines, the physics upon which climate models are based on, and projection time period) used and additional to that is the uncertainty introduced by processes involved in climate impacts analyses such as this study. These uncertainties were not covered by this study; however, we find it is important for the reader to consider them and can find more information on them from a study by Cox and Stephenson (2007) to appreciate some of the process and associated uncertainties. Further, uncertainty in crop models is captured in the Agricultural Model Intercomparison and Improvement Project (Rosenzweig *et al*., 2013).

As with the use of ensemble of GCMs, Rötter *et al*. (2011) suggested a similar approach with agrohydrological models used in impact assessment studies owing to a numerous inherent limitations, some of which might be improved with newly acquired field based knowledge of processes and responses. This approach would enable capture or accounting for uncertainty introduced by the impact assessment models.

What are the Limpopo smallholder farmer's crop management practices?

The reliance of smallholder farmers on climate makes them more vulnerable compared to their counterparts (i.e. commercial farmers), owing to limited resources (such as fertilizers, markets and financing, climate insurance, knowledge and technology, etc.) which reduces their resilience to direct and indirect (i.e. altered impacts due to yield limiting and reducing factors) climatic impacts (Wilk *et al.,*2013).

The crop management practices were based on structured survey questionnaires conducted across six villages that targeted at both crop and mixed Limpopo smallholder farming systems. The findings suggest that majority of the farmers were not using any fertilizers and incorporated maize crop residue back in the soil, these were termed poor-resourced farmers. The better-resourced farmers, in the surveyed villages represented the minority smallholder farmers, who had an access to resources such as fertilizer, and an understanding and use of conservation agriculture practices. Both farmers left their cropping land during the fallow period.

There is a huge reliance on past experiences (such as sowing on same period regardless of the weather conditions, re-use of previous seasons seed) and/or use of indigenous knowledge amongst the farmers about planting dates and crop management practices. This is more pronounced amongst resource poor farmers. An inherit contribution to low productivity, amongst small-scale farmers in the region, stems from their recycling or reuse of seed cultivar (instead of selection of seed cultivars based on seasonal forecasts) and clearing of farmlands during fallow period (result in soil loss at start of next season rains).

This observed grouping of smallholder farmers, is similar to that reported by Ziervogel *et al.*(2006) amongst farmers in the Vhembe District (in Limpopo Province) wherein the use of mulch and nitrogen was reported amongst average to better-off farmers and less so in poor farmer group. The dominant sowing dates were in November and December, with a few exceptions in January owing to late onset of rain or logistic related challenges (such as access to resources and tractability).

Do their crop management practices affect likely productivity?

Two crop management practice categories were identified, in this study, in relation to application of fertilizer, planting date and surface mulch cover on potential maize yields. Their management practices were used to develop scenarios, assessed their responses to historical, and projected future climate conditions. A similar climate impact approach was employed in the study by Waha *et al.* (2013), highlights the importance of farmers' crop management practices inclusion in climate impact studies, as it forms the basis to developing climate adaptation strategies.

A validation analysis was conducted to determine if there are correlations between simulations of yield for historical climate and GCM climate projections for the same time period, i.e. 1971 to 1990. The findings suggest that there were areas with similar predictions, within an acceptance range of ± 10 %, however most catchment showed both overestimations and underestimation of prevailing conditions of which spatially varied between the GCMs. The Pearson's correlation and regression analysis indicated a positive moderate correlation across all the sub-catchments in the Limpopo Province. Thus suggesting even though there might not be an overall agreement in the GCMs, however, it gives some confidence in their projection of present climate.

The distribution of maize grain yield over the Province planted on the 15 November over the period 1971 - 1990, without fertilizer and surface mulch cover, is influenced by a combination of rainfall patterns (Figure 6.14b) with high rainfall along the central west parts (corresponding with high altitude areas) and soil properties (Figure 3.3a).

The effect of early planting was observed to have a significantly positive effect on yields over most quinary catchments and less so in a few scattered across the Province. This suggests that planting dates are area specific, with early planting seeming to be more favoured across most maize farms. The site specific effects of planting date effect are supported by Rurinda *et al*. (2015) findings that there is no linear effect of delayed planting, thus suggesting that for some areas delayed planting might be of benefit while others not.

The incorporation of surface mulch only, was simulated on average year to result in up to 55 % reduction in potential yield mostly in high rainfall and temperature areas and less than 5 % in lower rainfall areas central interior of the Province or along the central escarpment. This reduced effect is due to mulch is likely to be site-specific, depended on rainfall amounts with high rainfall areas experiencing greater potential yield losses (Rusinamhodzi *et al*., 2011). Additionally, Qin *et al.* (2015) found that the effects of organic mulch to increase yields tended to decrease with an increase in the availability of water, and high temperatures.

Similar increase in yields, as documented in study by Qin *et al.* (2015), were observed from the interaction effects applying both organic mulch and nitrogen. The simulation of early planted maize showed higher increase in yields compared to late planting, with some areas likely to experience slight reduced potential yields. As expected the application of only N fertilizer, result in general increase in potential yields.

What types of future climates are projected to impact the Limpopo Province?

Postulated future comparison, based on ratio change, between g22 and gi2 with cn2 GCM visually indicate correlation in certain areas, excluding ratio change in g22 with gi2. Areas of agreement between the ratio changes, suggest that there is likely to be less uncertainty in climate projections in those regions from the climate models note (Mastrandrea *et al.*, 2010). The g22 GCM suggest that farmers in the south western areas of the Province would experience lower maize grain yields compared to present conditions and opposite is suggested by the gi2 GCM. There is an agreement amongst the GCMs of potential increase in maize yield in the central interior, based on visual analyses. The central interior of the Province corresponds with historical high rainfall areas and regards as more fertility areas. Even with GCMs projections suggesting slightly wetter future conditions than present, maize yields are projected to decrease over 27 % of the study area on average across GCMs. This decrease in maize yields is attributed to increased temperatures, as found in study by Tibesigwa *et al*. (2016), that it is a main contributor regardless of changes in precipitation.

Early planting was found to have up to 48 % increase in potential mean annual yields and spatiotemporally an increase of 58 %. Similar findings were cited by Myoung *et al.* (2015), wherein optimizing sowing dates using APSIM model in the USA resulted in over 50 % increase in yields. Further, the effects of early sowing are supported by findings in Olesen and Bindi (2002) study that suggest likely extension on the growing season owing to higher temperatures allowing for crops to be planted earlier in spring, to mature more rapidly and to be harvested earlier. This observation based on traditional smallholder farmer practices, suggest that if the LSFs were to adopt climate forecasts for planning their sowing dates, they could reduce loses in potential yields.

Better-resources farmer scenario, application of N fertilizer projected future climate compared to present scenario shows up to 12 % decline in mean annual maize yields over 32 % of the Limpopo maize growing areas. Whereas, 47 percent of the area will experience a likely increase up to 28 % in maize yields. Projected response of mean annual maize yield to application of surface mulch, suggest up to 6 percent reduction over 30 % of the Province and a 28 % increase.

The spatiotemporal changes between projected present and future climate scenario due to interaction effects of crop management practices and climate change impacts suggests that 48 % of the sub-catchment are likely to captialise from the impacts with increase of up to 27 %. The future implications, as suggested by the GCMs, for the Limpopo Province indicates up to 8 % reduction in plausible future maize yields of 29 % across the maize growing farms.

The direction of change from study by Schlenker and Lobell (2010), i.e. projected losses in maize yield, is similar to the findings of this study. However, a direct comparison could not be made owing to different GCM projections, modelling approaches, and spatiotemporal scales. The analyses suggests that better-resourced farmer are likely to benefit from improving soil fertility management, through N fertilizer and surface mulch, however planting early seemed to benefit both farmers over a larger proportion of the Limpopo Province.

The APISM Model, may have underestimated the impact of temperature sensitivity, specifically at flowering stage, and owing to low fertilizer parameters. Lobell *et al*. (2013) found that the effects of temperature (particularly extreme heat) regimes in the APSIM model are accounted for through vapour pressure deficit and soil moisture stress, rather than direct effect of heat stress on reproductive organs. The responds of the model to application of N fertilizer by increase in maize yields suggest that it may be sensitivity to rainfall, particularly with high rainfall areas simulated to have high potential maize yields.

Even though there are likely future benefits as suggest over most sub-catchments compared to projected decline, these effects or the APSIM model simulations do not account for indirect effects emerging from competition for nutrients and water (e.g. weeds), pest and disease damage, etc. (Morin and Thuiller, 2009), which might negate the positive effects. Comparison of farmers practices across the Province, indicate that farmers can lower their likely yield loses owing to climate change impacts by adapting sowing dates, soil-water and fertility management, and crop varieties to change climate conditions, which is already been done in most areas.

Adaptation Pathways

Three adaptation modes, i.e. incremental, systemic and transformational adaptation, were identified from literature in which they were shown to have different temporal, spatial and climate impact application stages. There is a general agreement in terms of sequence in which these adaptation modes, based on study by Rippke *et al.* (2016) and Smith *et al.* (2011), might be needed as adaptive responses or implemented based on presently available GCM climate projections and adaptation pathways thinking by various scholars (Pelling, 2011; Wise *et al*., 2014). Incremental adaptation is thought be a current coping and adaptation efforts applicable leading towards early mid-century, and systemic adaptation being more like a transitional over the mid-century and then followed by transformational adaptation towards end of mi-century. This phased adaptation pathways approach is said to occur over time and with progression in climate impacts. However, it is likely not to be as uniform or progressive, as mentioned above, owing to the variability in risks and vulnerabilities of different systems and/or regions. In some systems and/or places, incremental adaptation might not be sufficient, due to sizeable vulnerabilities and risks requiring more drastically enlarged or transformative adaptation for reorganising vulnerable systems (Kates *et al*., 2012). Similarly, Smith *et al*. (2011) describes transformation adaptation, as a response to climate change and an expansion of underdeveloped incremental adaptation, likely to emerge from gaps in adaptive capability of incremental adaptation.

Rurinda *et al.* (2015) suggested that incremental adaptation strategies, such as delayed planting dates, improved crop and soil fertility management, are likely to continue to enhance maize yields in southern Africa in the near future (2040 – 2069). However, might not be sufficient towards the end of the 21 century to curb progressive effects of climate change. However, Leclère *et al.* (2014) found that agricultural systems in most regions might require transformation adaptations much earlier than thought, i.e. by year 2050, for them to cope with climate impacts. This might be due to 2 ^{o}C surface temperature thresholds likely to be reached by most areas earlier than thought, and thus requiring transformative adaptive responses.

In this study, we use the APSIM-GIS coupled modelling approach to investigate the three adaptation modes within each a single adaptation options was selected for purpose of this analysis, based on literature.

- the adaptation option for incremental adaptation was on shifting from long to short duration maize varieties in response to increase in temperature and changes in rainfall patterns,
- systemic adaptation option assessed was supplementary irrigation when there is soil-water deficit during growing season with a 75 % efficiency, and
- the transformational adaptation was large scale shift from cropping to ranching or livestock production indicated by adoption of grass production and stocking rates.

Climate change projections from present to in the mid-century, from A2 emission storyline representing median of all empirically downscaled GCMs over the Limpopo Province, were used to assess the above adaptation options. The emission storyline used in this study assumes no change in terms of mitigation efforts, and its climate projections suggested a greater likely in temperature regimes would exceed 2°C set threshold, in mid-century. The storyline was selected as it is mainly used for impact studies and enables for realistic planning in the likelihood of the mitigation targets not been met. The impacts of climate have been demonstrated in this study on smallholder farmers, and other climate impact studies to be site specific, depended on prevailing environmental conditions, and hence adaptation efforts are hypothesized to spatially as likely climate impacts vary based on particular area's prevailing conditions.

Incremental adaptation: The early maturity maize cultivar performed better than the late maturing cultivar under present climate conditions, over most maize growing areas in the Limpopo Province. This is due to less rainy day and rainfall amounts over the growing season. Whereas, towards the mid-century the maize crop cultivars projections, showed wetter conditions during the rainfall season and the long duration maize crop (PAN 6479) on average performed better compared to short duration (ZM 421), however, the long duration maize variety showed high risk (i.e. year to year variability) compared to shorter duration variety. Therefore, to ensure sustained yield throughout the different growing seasons, the early maturing cultivar was better off. However, if future climate conditions were drier than those projected from median of GCM, the early maturing and drought tolerant cultivar is likely to be more suitable. Challinor *et al*. (2016) found that there is likely shortening in duration of maize crop outside the current variability, and reduction in period from emergence to end of development, in response to temperature, thus resulting in reduced yields.

Systemic adaptation: Supplementary irrigation, in this study was used to represent systemic adaptation phase it was assumed that more sources of water for irrigation, such as further ground water exploration both for extraction and artificial recharge, and reservoir transfers nationally or internationally, will be sort to meet the irrigation demands. The advancement in irrigation water use and efficiency will make it possible for further expansion to current dryland farming systems. The use of supplementary irrigation has been shown to be of benefit to certain areas and not all areas when compared between future relative to present climate. This might be due to findings by Leclère *et al*. (2014) suggesting that irrigation as an adaptation measure might be needed as early as 2020 and hence might be insufficient in responding to impacts of higher temperatures and associated high atmospheric water demand in the mid-century, for low mitigation plausible future. for Further, (ref. Figure 3.3a), areas of low yields or high variability correspond with low organic matter content and sand textured (Figure 3.2b; i.e. sand and loamy sand soils) soil areas. Nath (2014) found that soil total organic content and texture had impact on soil-water holding capacity, wherein he found a negative relationship with water holding capability in sand content and low organic matter.

Transformation adaptation: There is strong agreement amongst recent climate impact studies, indicating a significant decline in major cereal crop yields by 2050 been found across most of the current croplands. These areas are said to have greatly reduced opportunity for agricultural intensification (Pugh *et al*., 2016). On this basis an alternative transformative adaptation, i.e. grass production and hence livestock ranching, was selected as an adaptation option future shifts in landuse from cereal crops.

Changes in grass and livestock production from future relative to present climate indicated an increase in productivity, over most of the Province. This suggests that farmers over most parts are likely to benefit from shift to both grassland and livestock production. The inter-annual variation in productivity of grassland suggests likely less variability that corresponded with high productivity areas.

Otieno and Muchapondwa (2016) study on role of wildlife in climate adaptation in South African areas used for livestock production, suggest that mixed livestock and wildlife are less vulnerable to climate change. Further, wildlife ranching is more robust in face of increase temperatures (Otieno and Muchapondwa, 2016) as they are well adpted to harsh conditions compare to livestock which is said to be impacted by heat stress (Nesamvuni *et al.* 2012). Thus, this will likely prompt changes in landuse to wildlife or other alternative. This shift in landuse has been observed along the western parts of the Limpopo and North West Province, wherein commercial farmers are moving from cereal crops and/or livestock farming to game farming. Limitations in model based climate adaptation assessments are on the lack or inability to take into account the policy changes, farm level decision making triggers and social networks (i.e. human behaviour), roles in influencing direction of landuse change in response to climate change.

4.5. Conclusion

The empirically downscaled daily GCM projections, similar to those documented in the 4th IPCC report, were used in the process selecting from a wide range GCMs more computationally manageable and climatically representative of the projection envelope based on past performance and uncertainty in future projections, and changes in climatic means. Two categories of farmers were identified from the surveyed questionnaire of six rural villages across the Limpopo Province, based on the crop management practices (i.e. application of N fertilizer and surface organic mulch), *viz*. poor and better-resourced farmers. The extent of maize suitability area or growing areas, were restricted to presently maize growing farmers found in each of the quinary catchments in the Limpopo Province. The basis of this assumption is that current landuse and environmental protection policies would not change significantly, the growing urban areas and conservation areas (such as wetlands, national parks, etc.) would limit potential expansions owing to any shifts in farmland suitability.

The overall outcomes of the simulation and climate impact assessment indicated that different soils, climate conditions and management practices across the Province had varying level of influences on potential maize yields. The findings suggests that poor-resourced farmers practicing farming without application N fertilizer and surface mulch are likely to experience lower yields. They might however benefit from selecting optimum planting dates or in this case earlier planting in the growing season. Further, better-resourced farmers seemed to benefit from use of N fertilizer as well as both N fertilizer and mulch. Further, the better-resourced farmers are expected to make use of climate forecasts in the farming activities, as they might be more educated. The uncertainty analysis of the GCM projections used in this study, of which were found to be in agreement with uncertain analysis literature, suggest that there is a high certainty in future temperatures likely to increase as well as change in precipitation which will either increase or decrease. Even though there is still uncertainty in the direction of change in projected precipitation, the impact analyses suggest that temperature will have significant yield reduction impact on agricultural production, regardless of direction of change in precipitation.

For the LSFs to capitalise and sustain their maize yields under plausible wet or dry climates for prevailing and future climate conditions, they would need to adopt climate-smart practices. This climate-smart practices need to be able to address issues of soil fertility, planting dates (i.e. use of climate forecasts for their farming practices), and rainwater management (including soil conservation) amongst others. This is proposed based on the comparison of farmer types crop management practices as some of the likely future conditions suggest highly variable rainfall (of which its distribution is unknown) and increased temperature likely to increase water demands. The spatiotemporal variation in projected potential maize yields highlights the importance of site specific climate change impact assessments and hence adaptation.

Both incremental and systemic adaptation effects decreased in some parts of the maize growing areas in the Limpopo Province, at varying degrees, when comparing relative changes from future to present climate scenario. Conversely, the transformational adaptation showed an increase in grass productivity and livestock stocking rates over part of the Province, in particular, in areas where there was decrease in productivity from other adaptation modes. Therefore, suggesting that transformational adaptation might be of benefit to most of the Province during the mid-century period, compared to other modes. An inter-annual variation was used to test robustness of the adaptation options, which indicated spatial variation in areas of risk across all options. A visual assessment conducted to determine which of the adaptation modes were more robust, and hence the incremental adaption seems to be more robust owing to lesser areas of high year to year variability compared to the other two modes.

Even though, in this study, we evaluated climate adaptation options modes sequentially from incremental to transformational adaptation, Rippke *et al.* (2016) suggested that there might be an overlap in the modes to enable projected transformational changes. The types of possible transformational adaptation options might not only include famers substituting crops, but also changing their livelihood strategies and relocating to other areas. Agroforestry was not considered as a transformational adaptation strategy in this analysis and is recommended for future studies, with emphasis on evaluating indigenous tree species that do not impact the already limited water resources, and are adapted to the high evapotranspiration rates and harsh temperature regimes. Monitoring capacities for tracking both biotic and abiotic factors (including a network of climate stations) impacting the farming systems, in the region, need to be improved for the development of well suited and targeted policies, and adaptive responses. More so, in light of recent studies which suggest transformation in agriculture might be required earlier than thought.

CHAPTER 5. GENERAL DISCUSSION AND CONCLUSION

5.1. General Discussion

The Limpopo Province links South Africa to the rest of the southern African Democratic Community (SADC) through shared borders with Botswana, Zimbabwe and Mozambique. The Province serves as first port of entry into the country and a corridor to the economic hub, based in Gauteng Province, for trade. Further linkage to the SADC region, is through shared natural resources, such as environmental protected areas (joint national parks along the countries border) and water resources (river tributaries flow into the Limpopo River, of which it shares with Botswana, Zimbabwe and Mozambique). These linkages make the activities in the study area (and South Africa), particularly climate change impacts and adaptation responses, to have direct and indirect influence on SADC region and vice versa. The projected climate impacts over the region are likely to include changes in droughts, floods, environmental impacts, pests and diseases, and trade. The impacts of floods and droughts, for example, will influence on the availability of already limited water resources and productivity of agricultural sector (including other economic sectors).

In the Limpopo Province, agricultural farming systems consist of commercial and small-scale agricultural sector, with the commercial sector being large scale farms, well organized and integrated into the agricultural value chain. The small-scale sectors, in contrast, are generally low-input, low-output rainfed farms, often on poor soil with low capital investment. The sector is generally disconnected from commercial production and operates in rural areas with contributions mainly in local informal markets and underpinning food security and rural livelihoods. The Province is characterized by low and highly variable rainfall patterns making it to be prone to climate-related risks, such as dry spells, drought and flood events, upon which the agricultural sector depends on. The lack of adequate water resources threatens agriculture and hence development of their economic activities (ref. Chapter 1).

Maize production in the region is an important grain crop, which contributions to the gross domestic product and it is staple food source for most rural communities (du Plessis, 2003; DAFF, 2013). According to the Intergovernmental Panel on Climate Change 5th Assessment Report there is a growing body of scientific observational evidence pointing to irreversible and irrefutable changes in climate conditions (mainly, increase in surface temperatures), which are associated with anthropogenic activities resulting from emissions of greenhouse gases (IPCC, 2014). Further, these observed changes in prevailing climate conditions have been found to be in agreement with the output from global climate models (GCMs). The GCMs outputs are used in impact modelling to project the likely impacts of climate change on agro-ecosystems. The impacts related to climate change have been observed in several regions across the global on agricultural systems, natural biodiversity ecosystems, etc. (Porter *et al*., 2014).

Climate change will impact all aspects of human well-being from household livelihoods security to climate-related hazards (i.e. storms, floods and droughts) through changes in the current climate regimes, such as increase frequency and occurrence of extreme climate events. Climate impacts would be more pronounced in southern Africa owing to prevailing conditions, such as the high spatiotemporal variability in rainfall, water resource scarcity, poverty levels and low adaptive capacity. Furthermore, vulnerability to climate change will be increased by farmers prevailing conditions and access to resources, such as lack of access to technology, capital and farmland (Morton, 2007). Future projected increases in temperatures, over South Africa, were found to be main contributor to the negative effects of climate change on agricultural productivity compared to either the addition or exclusion of projected decline in precipitation. This was the case for both commercial and small-scale farmers, and hence both their vulnerabilities were equal for specialised crop farming systems. Mixed farming systems, however, were found to be least vulnerable (Tibesigwa *et al*., 2016). With climate impacts equal, amongst the farming community in South Africa, the difference between these agricultural sectors is determined by their resilience and ability to adapt to climate change.

In general, small-scale farmers in the past have struggled to cope with climate variability, owing to their reliance on rainfed systems as there is limited access to irrigation, low use of technology and lack of resources. Small-scale farmers, as individuals or collective, have coped with climate variability with some level of success. Some of the successful coping strategies include are the use of indigenous knowledge for forecasting planting times or as early warning systems or intercropping systems (Mapanda *et al*., 2016). Findings from a review of small-scale farmers' vulnerability and adaptation to climate change suggests that even though this sector might be more vulnerable to change climate, compared to their counterparts, there have developed various coping strategies that are at times undermined, but are effective in making them more resilient. These are access to family labour, diversification patterns away from agriculture, and use of indigenous knowledge. Recent climate adaptation studies suggest that these increment adaptation strategies might not be sufficient to cope with the projected large scale climate vulnerabilities and severe risks that threats resilience of systems (IPCC, 2014; Kates *et al*., 2012). The ineffectiveness of these strategies are projected to be experience over most regions as early as the mid-century, owing to projected increase temperature regimes over 4 ^{o}C, wherein a transformational adaptation might be required (Leclère *et al*., 2014).

Four important concepts emerged from the research presented and discussed in detail below in relation to smallholder farming systems agrohydrological responses and management in changing environmental conditions, each with their key findings. The first of concept is the **effectiveness and advantage of up-scaling daily time-step biophysical farming systems model** to understand the impacts and complex interactions of on-farm (soil, water and crop) management practices and climate change on agricultural and water resource responses at different spatial and temporal scales. The key findings related to this concept were:

- that the daily time-step, biophysical and mechanistic APSIM model is suitable for use in simulation of complex integrated crop, soil and water management practices, and climate change impact studies as shown;
- that the scaling up of successful farming systems to catchment scale was achievable through coupling geographical information system (ArcGIS 10.1) with daily time-step APSIM model, with each sub-catchment (approximate size of 10^1 to 10^2 km^2) making up a catchment assigned a unique driver climate station and spatially dominate soil properties; and
- that it allowed for farmer management practices to be assessed at other locations and over a long period of time with different soil properties and climate conditions, of which can be effective in determining site-specific coping and adaptation strategies from successful management practices and development of new ones; and

The second concept was on the **climate influences on farmers' decision making behaviour**, which occur owing to their psychological distance of past experiences and management responses to changes in environmental conditions. The key findings related to this concept included:

- that the past climate experiences, such as temperature, drought, flood, rainfall season duration and on-set of rainfall season, have a direct impact on farmers willingness to adopt climate-smart adaptation practices; and
- that the psychological distance related to the farmers concerns on future extreme events, and physical and socio-economic constraints are likely to influence their behaviour;

The third concept was on the **complexity of interactions**, which occur between integrated soil, water and crop management practices and climate change. This concept's key findings were:

- that the climatic variable which maize cereal crop is most sensitive to is rainfall (and soil moisture);
- that the practice for attaining optimal crop productivity are areas specific, based on prevailing soil properties (soil water holding capabilities and nutrient status) and available soil water status (i.e. rainfall amount); and
- that each sub-catchment has unique complexities, owning to soil dynamics and local climate conditions, thus each sub-catchment will have unique responses to crop type, farm management practices and climate change effects.

The final fourth concept is the **adaptation being transformative of landscape** to adopt to the adverse effects climate-related risks and vulnerabilities. The key findings of this concept were:

- that the present perceived incremental adaptation might not be sufficient to alleviate projected impacts of climate change and hence will require new or transformative adaptation, when future climate change influenced temperatures shifts beyond the historical variability;
- that the prevailing agricultural landscape might be transformed or development of completely new productions systems, such as transitions from cropland to extensive livestock systems; and
- that the transformational adaptation will influence and/or also require changes in current policies, institutional arrangements, and funding mechanisms, this will be dependent on whether the transformative adaptation is anticipatory or autonomous, to foster broad-scale adoption of climate-smart approaches in agricultural landscapes (Harvey *et al*., 2014).

5.1.1. The Influence of Limpopo smallholder farmers perceptions of climate variability and change impacts, and their belief systems on adaptation strategies

Farmers' understanding and/or past experiences of climate influences their decision making and choice of technology, therefore, contributing to their agricultural productivity, and cropping area and intensity. This is will be of importance to increasing their resilience and development of climate specific adaptation strategies to uncertain future climate change (Lizumi and Ramankutty, 2015). A growing body of evidence suggests that farmers past climate experiences to the effects of the changing climate, and psychological distance related to their concerns and constraints of the impacts are likely to influence their behaviour. Our study (Chapter 2) found that that the Limpopo Smallholder Farmers (LSF) had an understanding of both prevailing and likely future climate conditions, of which corresponded to scientific evidence (i.e. historical climate and climate change projections). The majority of the surveyed LSF indicated having experienced an increase in temperature (about 59 % of the respondents) and perceived a rise in future temperature regimes, and 76 % of LSF said they experienced decrease in precipitation and similarly perceived this to continue into the future (cf. Chapter 2).

Numerous studies, *viz*. Coulibaly *et al*. (2015); Ndamani *et al.* (2015); Ziervogel *et al.* (2006), suggests that farmers do not directly relate climate (such as precipitation) as stressors to their farming system, but the impact of precipitation on water availability, as well as, extreme events such as floods and droughts. For example, farmers find changes in amount of available water owing to climate and water management practices as a stressor that they need to response to. Their findings supports the view by studies, such as that of Adger *et al*., 2005, that climate change adaptation is a response to multifaceted climate impacts with a range of interactions and dynamic stresses. Similarly, LSF found the on-set of rainfall season, length of rainy season, and flood and drought frequency as triggers for adopting climate-smart practice, whereas, precipitation was found not to have a significant impact on their decision making. For example, flood and drought frequency (and intensity) have a negative effect on crop production, and hence household livelihoods and income; therefore, their recurrence might deter farmers from investing in on-farm management activities and/or opt for alternative off-farm activities.

Furthermore, the analysis on the effects of mediating factors of past climate experiences influenced farmers willingness to adopt climate-smart practices. Concerns about extreme climate events had a statistically significant mediating influence on the adaptation behaviour of LSF. The influence of water resources related concerns were also found to influence farmers decision making and adaptation behaviour, in climatically (semi-arid climate) similar areas such as California and New Zealand by Haden *et al*. (2012) and Niles *et al.* (2015), respectively. Further, the economic and physical constraints were also found to have a significant mediating effect on LSF selection of climate-smart practices; in particular, physical constraints had an effect on selection of alternative adaptation measures, and economic constraints on farm management strategies. The effect of economic constraints to farm management strategies, are related to the costs of inputs used to improve plant nutrient availability and those for reducing the effects of yield reducing factors, such as pesticide and herbicides.

Past climate experience of floods and physical constraints, influence them to opt for alternative adaptation measures, whereas, concerns of extreme events triggered them to retreat or abandon farming, and some adopted farm management and agricultural water management strategies. The past experiences of LSF on changes in the onset of the rainfall season and economic constraints influenced the LSF to adopt farm management strategies, while concerns of extreme climate events lead to adoption of cropping patterns (such as planting early maturing and/or drought tolerant crops), farm management and agriculture water management strategies. LSF past experience on changes in the length of rainfall season and physical constraints lead to adoption of alternative adaptation measures, whereas concerns of extreme climate events triggered adoption of cropping pattern, farm management and agriculture water management as adaptation strategies.

Studies by Arbuckle Jr. *et al*. (2013); Haden *et al*. (2012); Niles (2015) had similar finding that suggests, farmers past climate experiences and influencing factors within their farming system may impact their adaptation responses. The findings from this study indicates that that LSF, firstly, have an understanding of past climate conditions and their perceptions of likely future climate are correlate with scientific evidence, and lastly showed how LSF personal experiences with climate change are translated through their concerns of extreme climate events, and physical and economic constraints affect their behaviour.

The success of using the psychological distance theory to explanation of how LSF past experiences, concerns and constraints influence their decision making, indicate that information on farmers past experiences on climate-related risks, even with possible increase severity of climate-related risks owing to climate change, should be integrated with forecasting data to help farmers plan more effective adaptation strategies. LSF past experiences and mediating beliefs (concerns and constraints) influencing their behaviours based on statistical significance were captured in this study, however this was not indicated based on social properties, such as effect of gender roles, culture, and location (local environmental conditions). Such social properties were however inputs as control variables (i.e. location) in the multiple mediation analysis.

5.1.2. Effects of climate-smart practices and technologies on soil-water and agricultural productivity

Climate-smart practices and/or technologies for integrated soil, crop and water management in the agricultural farming systems were identified from literature (Chapter 1) based on their positive effects on agricultural production and soil water conservation effects. These practices were used in this study to assess their effects on improving agricultural production, soil-water and water productivity. Further, these practices have been used in similar climate conditions to alleviate climate-related risks, such as dry spells, climate variability, etc. on smallholder farmer production (ref. Chapter 3). In this study, the climate-smart practices that were assessed included insitu rainwater harvesting (IRWH), no tillage (NT) and conservation tillage (CT) with 0, 3, 6 and 12 ton per ha surface mulch straw mulch. Such practices have been shown to improve soil-water retention, soil conservation (reduce erosion), crop production, and water use efficiency (Mupangwa *et al*., 2016; Yosef and Asmamaw, 2015).

The field experiments, coincided with season of above (Year I) and below (Year 2) normal rainfall providing a good opportunity to test the effects of IRWH, NT and CT tillage practices on soil-water and agricultural production (Chapter 3). There was no significant difference in maize grain and biomass yields between the different tillage practices with varying levels of mulch cover (averaging 5 and 10 tons per hectare, respectively) for first growing season which coincided with above normal rainfall. The increase in mulch levels, lead to an increase in available soil-water (Qin *et al*., 2015) and had negative effects on yields during the wet season. The findings of this field experiment and review by Qin *et al.* (2015) present contrasting views on the effects of surface mulch on maize yields that are be dependent on the site-specific prevailing climatic conditions, soil characteristics, water availability and nitrogen (N) input levels. Therefore, this suggests that farmers in low rainfall areas might benefit from application of surface mulch cover, should soil physical (be well drained) and nitrogen status not be limiting. Further, the choice of tillage practice seems not to have significant effect on yields during wet season. Soil-water content (SWC) measured throughout the whole soil profile (0 – 60cm depth) had no statistical significant difference, however, there were significant differences in the top soils (0 – 30 cm depth) across the treatments at specific times during growing stages, particularly at harvesting stage, with IRWH having resulted in high SWC and plant available water (PAW) followed by to NT and then CT.

Conversely, for the second growing season with below normal rainfall the effects of treatments were more apparent with both maize grain and biomass yields increase from CT to IRWH and NT. Similar to first growing season there was no statistical significant differences throughout the whole soil profile were observed in SWC and PAW over the second growing season. In growing seasons, a general increasing trend in SWC and hence PAW was observed with increments in surface straw mulch residue application rates. In the below normal season, CT had more SWC and PAW followed by IRWH and then NT. Maize grain and biomass yields were found to increase with increments in surface straw mulch residue, with more distinct increases, during the below normal rainfall. Similar to yields the water use efficiency (WUE) increase with increments in surface residue mulch, and the surface residue mulch application rates at 12 tons per ha, had highest WUE in year 2. The high WUE is due to improved SWC, of which improved PAW and thus yields.

Botha *et al*. (2014) study on the assessment of IRWH and soil conservation for improving cropland productivity indicate that the tillage practice (i.e. IRWH, NT or minimum tillage and CT) effects varied between different soils and climate conditions. The variation in the effects of IRWH, NT and CT optimal performance across different climate conditions and soils highlights their effects on yield responses according to site-specific conditions. The use of biophysical models, such as the APSIM model, enables for the assessment of soil-water-crop management interaction effects in different environmental conditions (such as soil properties, climate, etc.), and therefore contributes to the developed of site-specific climate smart practices.

In this study, the APSIM model was parameterised, calibrated and validated using field experimental datasets from this study and secondary sources. The calibrated model was used to assess the effects of tillage practices at different soils and climates across the Limpopo Province maize growing sub-catchments. The simulations indicated areas in the Limpopo Province that would benefit from each specific tillage practices, i.e. IWRH, CT and NT, were found to be yielding responses based on specific precipitation and soil texture (indicative of soil properties) classes. Similarly, application of surface straw mulch cover on maize grain yields were found to vary depending on amount of rainfall and soil properties (such as drainage) typically low rainfall areas experiencing positive effects and high rainfall areas reduction in yields (Rusinamhodzi *et al*., 2011). Increasing mulch level application resulted in higher yield over most of the sub-catchments and further yield reduction in a few areas.

Furthermore, the simulations of the interactions effects of the tillage practices with mulch cover were found to further increase the yield potential of most sub-catchments over the Limpopo Province. IRWH with mulch cover significantly outperformed the other practices in yield, whereas, for NT with mulch cover more areas were simulated to experience low yields. The areas of lowered and/or reduced yields were dominantly under NT with mulch cover treatments. This lowered and/or reduced yields, according to Scopel *et al*. (2004), may be due to the positive effects of surface residues been counteracted by an increase in drainage losses. Surface mulch was found to have positive effects on soil-water availability, over most sub-catchment in the Limpopo Province, with low rainfall areas (receiving less than 600 mm) benefitting more mulch cover application (Rusinamhodzi *et al*., 2011).

The recommendation for future studies is to explore the effects of surface and subsurface flows from upstream sub-catchment contribution to downstream sub-catchment, as this affects runoff and soil-water available downstream and hence agricultural productivity. In this study, only runoff generating zero tillage area to capturing basin area within each catchment were assessed, with each catchment simulated at lumped mode (assuming that there were not downstream effects of which is not representative of the real world. This was done to asses effects per catchment and reduces computation, as at this stage the model is not automated or programmed to perform such complex interaction analysis.

5.1.3. Climate change impacts in the Limpopo agricultural smallholder farming systems

Climate change threatens agricultural productivity through changes in frequency and severity of extreme events, variability in rainfall, occurrence and distribution in yield reduction factors (pests and diseases), and suitability of agricultural crops (Lamanna *et al*., 2016). The climate change related risks and vulnerabilities are said to already been felt in sub-tropical developing countries, wherein, most of the poor smallholder farming communities are found (Tibesigwa and Visser, 2015). These farming communities even though are highly vulnerable climate and other stressors, and not are well organized and producing at commercial scales, they play a crucial role through contributions to household livelihoods and local economy (Baiphethi and Jacobs, 2009; Patel *et al*., 2015). The smallholder farmers’ lack of capital, low technology, marginalization from mainstream agricultural value chain (such as markets and policies), poor soil condition and their reliance on natural resources and on climate-sensitive livelihood strategies contributes to their risk and vulnerabilities to climate change (Frank and Buckely, 2012; Mpandeli, 2014).

Waha *et al*. (2013) highlighted the importance of incorporating farmers past decision making regarding the choice of crops, cropping systems, sowing dates, etc. in climate change impact studies to develop adaptation strategies geared towards addressing gaps in on-farm management practices to alleviate climate-related risks and vulnerabilities. Climate change impact assessment on smallholder farmers, in this study, was carried out by characterising the smallholder crop farming systems into poor- and better-resourced farmers based on survey. Further, the crop management practices profile of the characterised poor-resourced smallholder crop farming systems is that for farmers tend to have small farms that are not effectively used (less than 50 % of the farms cultivated), do not sell any access produce and have to some extent mixed farming systems. Whereas, the better-resourced farmers tends to have small individual farm sizes which are used effectively (cultivated the whole farm), practices more mixed crop farming, and sell their access produce (ref. Chapter 4).

It is worth noting that majority of the respondents or LSF from the survey were female, with 63 % been better-off and 13 % accounting for poor-resourced farmers, this finding from the characterisation of smallholder farming systems, even though in this study, the effects of gender roles were not consciously assessed. The high proportion of female in the better-resource farmers group might be an indication that female farmers produce better compared to their male counterparts, if so, this would be in agreement with findings by Tibesigwa and Visser (2015). Their findings suggest that contributions of agriculture to food security were higher in rural female-headed small-scale farm households of South Africa, compared to male-headed households. However, food security was higher in male-headed households owing to contributions from off-farm activities, such as employment (Tibesigwa and Visser, 2015). Further, the better-resourced farmers were found to be practicing more mixed farming, crops such as maize, groundnuts, cowpeas/ beans and sorghum, compared to their counterparts. More diverse farming systems are said to be the least vulnerable to climate change, amongst the subsistence farming sector in South Africa (Tibesigwa *et al*., 2014).

A representative set of global climate models (GCMs) ensemble under the A2 (a low mitigation) scenario were selected from 10 empirically downscaled daily GCMs to point scale to reduce computational costs related to climate impact modelling and time. The approach for selecting the most representative GCMs was adopted from Lutz *et al.* (2016), contributions made in this study towards the approach, was the addition of assessing GCMs confidence levels in predicting historical or observed climate (1971 - 1990). The GCMs prediction confidence analyses gives confidences in the selected GCMs to represent past and location climate conditions. It is worth noting that this does not indicate the GCMs projection ability to project future climate, as the emission scenarios determine this, but its ability to capture local weather systems and patterns, such as frontal rainfall associated with cold fronts (Chapter 4). Three GCMs were selected based on their outputs which represented the 10 GCM ensembles (Low – g22 GCM, Middle – gi2 GCM and High – cn2 GCM) for two likely future climate projections, i.e. ‘warm’, ‘dry’ and ‘hotter’,’wet’. The final selection process heavily weighed on precipitation, the reasoning for this was because of GCMs indicating highly variable projections of future precipitation trends (IPCC, 2014).

Even though sources of uncertainty were not the foci of this study, the reader is alerted to the uncertainty emerging from using models (i.e. mechanistic and deterministic models to name a few), and in GCMs projections illustrated to some extent, which adds to the uncertainty in the assessment climate impacts and adaptation measures. There are a number of initiatives, such as AgMIP Project, which are working on incorporating some of these uncertainties in the climate impact and adaptation studies using multiple models (Rötter *et al*., 2011; Rosenzweig *et al*., 2016) and GCMs to account for this uncertainty and attempted to quantify it. Understanding and /or quantifying uncertainty, from models, is likely to give confidence in the assessments outputs and enables for better planning process and development of policy that accounts for it. The uncertainty analysis performed this study, as part of the selection of the representative GCMs, were found to be in agreement with uncertain analysis literature (IPCC, 2014), of which suggests there is a high certainty in future temperatures likelihood to increase, and for precipitation to change with moderate certainty in the direction of change (to either increase or decrease). Even though there is still uncertainty in the direction of change in projected precipitation, the impact analyses suggest that temperature will have significant yield reduction impact on agricultural production, regardless of direction of change in precipitation.

Two smallholder farming typologies were used to assess the climate change impacts on agricultural crop production in the Limpopo Province, i.e. poor and better-resourced farmers. The main management difference between these farm types was that poor-resourced farmers did not use fertilizers and only a small number incorporated surface mulch cover during tillage. Maize stover, a common by product of the maize dominated cropping system in the region, are used for both ex- and insitu livestock grazing as supplementary feed during dry season, and hence contributing to their household food security and income by selling to livestock famers (Hellin *et* al., 2013; Masikati, 2010). Ziervogel *et al.* (2006) also found that use of mulch and nitrogen was reported amongst average to better-off farmers and less so in poor farmer group, in Vhembe District of the Limpopo Province. Due to different planting times across the Province, two most dominant, i.e. November and December, were used in the assessment. The simulation of climate conditions indicated that the effect of planting date varied across the sub-catchment in the Limpopo Province, with early planting been more favoured over large area. Rurinda *et al*. (2015) found that is no linear effect of delayed planting, thus suggesting that for some areas might benefit from delayed planting while others will not. Furthermore, the incorporation of mulch cover along was found to significantly reduce maize yield more so in high rainfall areas by up to 55 %. Qin *et al.* (2015) also found that the effect of surface organic tends to decrease with an increase in the availability of water, and high temperatures.

A validation analysis of selected GCMs ensemble to predict maize grain yields under present climate spatially indicated areas of concurrence relative to those of observed climate at the same period (1971 – 1990), thus suggesting that there is less uncertainty in GCM climate projections (Mastrandrea *et al.*, 2010) of which was found to be spatially variable. Early planting is projected to result in about 58 % of the Province experiencing up to 48 % increase in maize grain yield, of which are in agreement with findings by Myoung *et al.* (2015) who found early planting to result in over 50 % increase. Olesen and Bindi (2002) attributed this increase to high temperature regimes and early planting leading to rapid crop maturity and earlier harvesting. However, fertilizer application associated with better off farmers resulted in 28 % increase over 47 % of the Province, and only 12 % decrease over 32 % of the area. The application of surface mulch had a negative effect over most of the area, with a few areas projected to have an increase in yields. The use of fertilizers by better off resourced farmers lessened the negative effect of mulch application on maize yields. The combination of early planting and nitrogen fertilizer application, in better-resourced farmer crop management practices, had far greater maize yields responses compared to their counterpart who only made us of planting dates.

Limitations of this study include the lack of integrated climate change impact assessments within the agricultural value chain and with other sectors. The assessment of climate impacts with the inclusion of other stressors, such as pests and weeds, and competition for water resources in the landscape with other water users (for example, industry, domestic users), on crop production would give more realistic yields and economic impacts, as well as policy implications and restrictions. Furthermore, the resetting of initial nitrogen and organic matter conditions in crop model to field experimental conditions might lead to an underestimation of long term cumulative effects of crop management practices to climate change.

5.1.4. Plausible climate change adaptation pathways for the Limpopo agricultural sector

Adaptation pathways provide a logical process to which a set of plausible actions are explored and sequenced based on alternative external changes over time (Haasnoot *et al*., 2013), and assists in developing robust decision making under uncertainty (Wise *et al*., 2014). In this study, adaptation pathways for smallholder farming systems based on psychological factors affecting their behaviour through triggers, such as past climate experiences, concerns for future climate extremes, and physical and socio-economic constraints, influencing their decision making when selecting adaptation strategies presented in Chapter 2. Furthermore, based on the biophysical factors affecting their farming systems through assessment of climate change on present crop management practices and adaptation option modes based on likely severity of future climate-related risks and vulnerabilities.

Numerous studies have identified constraints to climate change adaptation, *viz.* biophysical, economic, policy, institutional arrangement, technology, and social and cultural factors (IPCC, 2014). These factors constrain the effectiveness to plan and implement climate change adaptation options, as these constraints do not occur in isolation from each other, the multiple interactions in constraints are said to significantly reduce adaptation options and thus may lead to maladaptation in response efforts. Adaptation limits are said to occur owing to interactions in climate change, biophysical and socioeconomic constraints (Klein *et al*., 2014). The smallholder farmers, in this study, from across six villages identified constraints that they thought limited their coping and/ or adaptation strategies which were analysed through a factor analysis (cf. Chapter 2) and grouped into social (including knowledge and technology), economic and physical constraints. The constraints were found to be significantly different across all the villages, thus suggesting that farmers perceived certain constraints to be more of a factor than others. The spatial variation in constraints to adaptation adds another level of complexity as climate change is also perceived to be site-specific. The physical and economic constraints, indicated in Chapter 2, were found to have significant indirect (through mediating farmers' past climate experiences) effects on farmers' adaptation behaviours, i.e. their choice of adaptation strategies.

In the past, farmers have responded to changes in climate with varying levels of successes by developing wide range of coping and adaptation strategies (Zievorgel *et al*., 2006), for example, they developed indigenous indicators for early warning to determine the on-set of rainfall season (Mpandeli, 2014). Their response strategies are influenced by a range of factors of which climate-related risk was one. For example, in the case of Sekhukhune Village, decisions were influenced a need to generate income and sustain their livelihoods through food securities (Ziervogel *et al*. 2006). Traditionally, the climate adaptation process has been viewed as one of gradual adjustments in response to climate variability and change, with the objective of sustaining present productivity (Klein *et al*., 2014). Analysis of current LSF, presented in Chapter 4, under near future climate impacts projections suggest that some of the crop management practices will sustain and in some areas increase their current yields. The pathways that are likely to trigger LSF responds to climate change, presented in Chapter 2, based on their understanding of changes in climate, of which were qualified through visual correlation of observed historical and GCM projected future climate, and incremental adaptation strategies, and constraints and concerns their face.

This gradual or incremental adaptation has been found in recent studies not to be effective in responding to climate change impacts, as a result of projected climates suggesting that risks and vulnerabilities will exceed the success of the adaptation responses (Kates *et al*., 2012; Leclère *et al*., 2014; Smith *et al*., 2011). When the thresholds of incremental adaptation are reached, current research proposes transformational adaptation to bridge the gaps associated with adaptation limits. Transformational adaptation is said to be an adaptation that leads to changes in the fundamental attributes of a systems in areas where climate responses and effects may be far greater, abrupt and wide spread, therefore, rendering incremental adaptation obsolete (IPCC, 2014). Leclère *et al*. (2014) found that agriculture systems to adapt to climate change in most regions likely to require transformational adaptations as early as mid-century than thought before. Furthermore, the transformational developments in irrigation were found to be needed in southern Africa, as early as 2020s (Leclère *et al*., 2014). Major concern is that the LSF might not be able to cope with projected future risks and vulnerabilities requiring transformative adaptation, of which it is expected to occur in South Africa in the near future between 2020 and 2050 (Leclère *et al*., 2014), since these farmers have not yet built robust measures to cope with prevailing extreme weather patterns.

Studies by Pelling (2011), Leclère *et al*., 2014, Rickards and Howden, 2012 Smith *et al.* (2011) and others have presented discussions on potential interactions and pathways in which systems can transition from incremental to transformational adaptation, depending on the impending risks and vulnerabilities, the transition pathway to transformative adaptation could be with or without an intermediate phase, called systemic adaptation. In this study, we attempted to illustrate the likely adaptation pathways, shown in Leclère *et al*., 2014, Rickards and Howden, 2012, for the smallholder farming systems in the Limpopo Province, from incremental (cultivars) to systemic (supplementary irrigation) and then transformational adaptation (a shift from croplands to rangeland and stocking rate, in Chapter 4). The adoption of early maturing maize crop as an incremental adaptation option performed better in terms of sustain and increase grain yields over most sub-catchments and show less risk in productivity. Similarly, supplementary irrigation, as a systemic adaptation, was found to benefit most sub-catchment over the Province by increasing future climate maize grain yields and hence reduced year to year variability in projected yields. However, transformative adaptation was found to capitalise from projected future climate, with over 80 % of the study area been projected to experience increase in pasture productivity and hence stocking rates. Even though some sub-catchments in the Province are project to still viable for cereal crop production, the shift in landuse to rangeland will be of benefit to majority of study area. Weindl *et al*. (2015) study shows the resource- and cost-efficiency of transition to livestock, wherein a 50 % shift (mixed farming system) would lower agricultural adaptation costs to 0.8 %.

5.2. Conclusion

Findings from the smallholder farmers' survey in the Limpopo Province indicate that they have an understanding of past climate and likely future climate conditions on their activities. The LSFs perceived past and future climates were found to be in agreement with scientific evidence, based on comparative analysis. Perceived increase in temperature was found to have a clear correlation with observed climate and GCM projections, whereas, the decrease precipitation had moderate correlation as direction of change from observations and more so projections suggests both increase and decrease depending on the GCM. Further the findings suggest that the LSF willingness to adopt climate-smart agriculture practices are directly influenced by changes in temperature and drought, with some swayed by the length of rainfall season and start of the rainfall season. The indirect factors influencing the LSF willingness to adopt were found to be by their local future extreme climate event concerns, and economic and physical adaptation constraints. The study showed that farmers understanding of climate and coping technologies, empowered them and or influenced their response to climate-related risks and vulnerabilities through selection of suitable and specific climate-smart practices. Farmers concerns of extreme climate events and constraints (i.e. social, economic and physical) were found to indirectly mediate how they translate their past climate experiences into future behaviours towards adaptation (Chapter 2). These findings suggest that adaptation amongst the LSFs is motivated primarily by their local future concerns and adaptation constraints, in addition to changes in climate. The LSF physical and socio-economic constraints were found to have a significant effect and hence are limiting factors to adaptation.

The start of El Nino during the second growing season and the above normal rainfall season experienced in the first season, offered an opportunities for the comparison of field experimental treatments (IRWH, NT, CT with surface straw mulch cover). The first season yields had no significant difference with maize grain and biomass yields average 5 and 10 ton per ha, respectively, while in second season the yields were half that of the first and treatment effects were found with high yields from NT tillage practice, followed by IRWH and then CT. Furthermore, maize productivity increased with increments in surface mulch levels. The soil-water and plant available water in the first season were high for NT followed by CT and then IRWH, whereas, for the second season were high for CT followed by IRWH and then NT. In the field experiment, during below normal rainfall, NT performed slightly better than IRWH. This observation suggests that these practices are likely to be more of benefit during dry spells and/or below average rainfall years.

Up scaling and long term climate simulation effects of treatments, across varied soil properties and climate in the Limpopo Province, indicated that the yields and soil-water improvement effects of NT, IRWH and surface straw mulch were strongly associated with site-specific biophysical conditions. Soil-water content and maize grain yields was simulated to increase with increments in surface straw mulch cover levels; with low rainfall areas found to have significant higher maize yields and vice versa. The IRWH and surface straw mulch cover had a significantly greater improvement effect on maize grain yields compared to that of NT and surface straw mulch cover (Chapter 3).

Increased application of surface straw mulch residue was found to improve soil water content, and hence maize yield in low rainfall areas, as long as there is sufficient N levels in the soil and that, they are well drained. This finding leads us to accept the hypothesis that increasing surface residue application leads to higher soil water retention, and hence improved maize crop yields. The opposite was found to be true for high rainfall areas, with poor drainage soils. Further, the combination of IRWH and surface straw mulch was found to perform better than that of NT and CT over most of the sub-catchment in the Limpopo Province, with diverse soil and climate. The findings support the hypothesis that IRWH in combination with conservation agriculture leads to higher yields than CT.

Poor-resourced farmers' potential maize yields under projected future climate will be negative impacted, with some gains arising from those who plant early and do not apply surface mulch. Better-resourced farmers were projected to be better off compared to their counterparts mainly due to their ability to access and use N fertilizer. Even though climate change will affect all farmers equally, the impacts will be felt differently owing to access to resources (such as farming inputs and technology). Therefore, the poor-resourced farmers were found to be more vulnerable to project climate change owing to not using fertilisers as a crop management practice. The traditional cropping systems assessed in this study indicated spatially varied potential gains and losses in yields, if farmers adopted better cropping practices and sowing dates will capitalise from change climate (Chapter 4).

The LSF choice of climate-smart practices, such as tillage, fertilization, climate-ready crops and selection of sowing dates based on climate forecasts, might be adequate adaptation strategies for near future climate change. The direct impacts of climate change on productivity were shown to bring about challenges and opportunities for the LSF, even though the indirect impacts were not assessed in this study (such as pests, diseases and weeds infestation and reoccurrence), they are most likely to present challenges by reducing productivity.

Recent rethinking on climate adaptation is required in light of the projected changes in climate said to exceed the historical variability thresholds and hence resulting in related risks and vulnerabilities that would to overwhelm the incremental adaptation. Such drastic changes in climate-related risks and vulnerabilities are said to require transformative adaptation measures. The analysis of transformational adaptation for the Limpopo Province smallholder farming systems for the near future climate was prompted by recent studies indicating that incremental adaptation measure might not be sufficient to address the projected risks and vulnerabilities. The current vulnerabilities of smallholder farming system, owing low technologies, poor soil fertility and degraded landscapes attributed to past exploitative practices and poor management, and climate-related risks, such as high variability in rainfall and increasing temperatures, will render their coping strategies ineffective within coming years. Commercial farmers, predominantly along the west parts of the Limpopo Province, have in the recent past switched to game farming, as this were more profitable through tourism and safari hunting (Low and Rebelo, 1996), while other to more intensive livestock ranching.

Recent studies, such as of Rippke *et al.* (2016), suggest that specialised crop farming systems (for example, maize and beans production areas) are already at risk, and will need to undergo transformational adaptation within the next 10 years. Observed temperature, from the past 20 to 50 years, detection study conducted over national parks in South Africa were found to have increased to same levels as those projected from GCMs for 2035 (van Wilgen *et al*., 2015). In southern Africa, transformational developments in irrigation are projected to occur as early as 2020s (Leclère *et al*., 2014), much earlier than most regions which are expected nearer to the 2050s. The transformational adaptation, in terms of landuse shifts has been observed in the region with traditional crop farmers opting for ranching and game farming, and large scale adoptions of irrigation. In the long run in some areas, more drastic transformative measures are said to needed, such as transition to livestock ranching, as cropping might not be a viable livelihood strategy (Rippke *et al*., 2016).

Incremental and systemic adaptation options were found to sustain and increase agricultural productivity, and decrease in other parts of the Province. The shift from cereal cropland to rangelands as a transformative adaptation strategy was shown to capitalise on future climate and hence increase pasture productivity and stocking rates over majority of the Province (ref. Chapter 4). Even though incremental and systemic adaptation were still relevant to specific areas, transformative adaptation will be of benefit most of the farming areas by 2050.

Apart from the ripple effects of climate change on agricultural productions and water resources, the selection of adaptation strategies, will not only affect the Limpopo Province, but also to rest of SADC region. The likely ripple effects of climate change and response activities in the Limpopo Province to the rest of the region will include but not limited to food insecurity, and impact on trade and downstream surface water resources availability, etc. Changes in climate adaptation policies and future planning to mainstream anticipated transformational adaptation, across the SADC region, to avoid the entire regional economies from been paralysed by projected future reoccurrence and intensification of extreme climate events.

5.3. Policy Implications of Climate Change and Response Strategies on Smallholder Agriculture Sector

In South Africa, at the national level great strides have been made in the development and implementation of climate change mitigation and adaptation policies into five sectors, which are agriculture, forestry and other landuses, energy, industry, transport, biodiversity and conservation, and waste. Some of these policies are the National Climate Change Response Policy, climate-compatible sectoral plans and its National Sustainable Development Strategy (such as the Green Economy Policy). There is still a need to translate this policies and associated response frameworks at local scale. Further this should be geared towards sector specific and vulnerable groups, such as rural farming communities’ and their local economic activities, and need to be mainstreamed into current implementation policies and future planning that can be driven at political decision-making level.

In the Limpopo Province, a Provincial Climate Change Strategy 2016 - 2020 has recently been develop, builds on the Limpopo Development Plan and the Green Economy Plan. The strategy identifies key provincial priorities and layout a provincial response plan. The short comings of this strategy is that the planning does not take into account transformational adaptation, of which literature indicates is already needed in South Africa for the agricultural sector, of which is much earlier than mid-century projected timescale to cope with climate change, such as mainstreaming irrigation as an adaptation option. However, the strategy does proposed one adaptation measure that can be classed as transformational when its upscaled and transforming current cereal production system, i.e. support for cattle ranching.

More transformational adaptation measures need to be included in provincial and local response strategies, such as irrigation systems (for example, from efficient alternative water storage (groundwater recharge to use) and develop inter-catchment water resource transfers. The inclusion of transformational adaptation measures, either as anticipatory or autonomous responses, into policy and national development planning will be important, in order to avoid maladaptation when climate-related risks and vulnerabilities overwhelm the incremental adaptive strategies. This does not discount the incremental adaptation strategies, of which could act as bridging strategies while transformational adaptation capacities are developed. Numerous studies have recommended that policy makers and institutional planning should develop and pilot anticipatory transformational adaptation (such as Kates *et al*., 2012; Rippke *et al*., 2016).

In this study indicated the importance of developing site-specific climate adaptation strategies, for addressing climate change impacts on the LSF. Further, the anticipated responses that would be required with the implementation of transformational adaptation involving scaling up of successful practices to a large scale, adoption of new technologies, and leading to transform the landscape would require significant investment in research and financing in the rollout of adaptation efforts. This will require financing from government and private sector, supported by policy, similar to the current climate adaptation funding models, such as the Adaptation Fund, the Green Fund, etc. The funding for climate adaptation can be derived from carbon taxes and trading in carbon credits by supporting LSF to adopt climate smart practices, contributing to both climate mitigation and adaptation, of which will enable them to accumulate carbon credits.

The provincial government needs to fund on the ground projects that address climate adaptation, which might be scaled up. The climate change efforts should be coordinated at Premier Office level to ensure cross-sectoral cooperation or joint response efforts. Further, the private sector needs to be engaged throughout the process (from drafting through to implementation stage) to ensure cohesive and cost-effective policies that are aligned with current and future markets' needs. The development of innovative mixed financing from different sources on climate change response efforts, together with capacity building and access to technologies, knowledge, and information on climate forecasts and best practices will enable smallholder farming systems to be more resilient.

5.4. Contributions of this Study to Knowledge

The contributions of this thesis to existing knowledge are laid out for each research chapter, as follows,

Chapter 2: Determination of factors, including their magnitude and direction, which influence LSF decision making and their chose of climate-smart practices. New contributions to such studies were the evaluation of social, economic and physical constraints effects on farmers' adaptation behaviour, which found that the social constraints did not yield any significant effects, expect for economic and physical constraints to certain adaptation practices.

Chapter 3: The main contributions to new knowledge, in this chapter, were on calibration of maize varieties for use in and configuration of soil-water module to simulate insitu rainwater harvesting with basins in APSIM Model. Further, scaling up successful on-farm climate-smart practices for alleviating climate-related risks to sub-catchment scale, using approaches used in hydrological modelling effects of landuse and landtype.

Chapter 4: Characterisation of the LSF crop management practices for use in climate impact assessment, as this helps in developing specific adaptation strategies taking into consideration the soil-water-crop management practices used.

SUMMARY

The Limpopo Province is one of the nine Provinces in South Africa, located in the far north of the country, bordered by Gauteng (south), Mpumalanga (south-east) and North West (south-west) Provinces along its southern border. It links the country to the southern African Democratic Countries, via Botswana, Zimbabwe and Mozambique, along its northern borders both economically and hydrological. The Province is characterised by insufficient and highly variable rainfall patterns upon which the agricultural sector depends on, prone to extreme climate events (such as drought and flood), high concentration of rural poor and socioeconomic inequalities. Water scarcity and inefficient available water use are some principle constraints evident from low agricultural productivity. Limpopo smallholder farmers (LSF) are faced with numerous challenges, ranging from resource access to agriculturally marginal farmlands located in the former demarcated homelands in agro-ecologies characterized by erratic rainfall, poor soil fertility, low crop productivity, degraded landscapes, and lack of irrigation and limited land for expansion. Climate change is projected to be an additional stressor, threatening small-scale agricultural farmers' productivity and livelihoods. A primary concern addressed by this thesis is to generate scientifically based information that can help to enhance the farmers' ability to respond effectively to current and future climate regimes.

The overall aim of this study was to develop and evaluate climate smart agriculture (CSA) strategies for attaining resilience and adaptation pathways in smallholder farming system to climate variability and change. CSA is an approach that transforms and changes the direction of agricultural development under human-induced climate change. This aim was addressed through the following specific objectives:

- to carry out field survey- and desktop-analysis to investigate whether the LSF perceived past and future climates are in agreement with scientific evidence, and how farmers' inclination to adopt climate smart adaptation practices is influenced by past climate experiences, as well as their constraints and future climate concerns.
- to conduct field experimental trails to evaluate effects of climate smart practices on soil moisture and maize yields, then used to parameterise, calibrate and validate the daily time-step APSIM model, and lastly upscale them to sub-catchment level to test their effects across different soils, climates and locations by coupling the APSIM model with geographical information system. This was done to test if increasing surface residue application leads to higher soil-water retention, and thus maize yield; and if insitu rainwater harvesting (IRWH) in combination with conservation agriculture leads to higher yields than conventional practice.
- to assess the likely impacts and opportunities of LSF's crop management practices under changing environmental conditions, and
- to determine when incremental adaptation is not an option and transformational adaptation might be suitable or needed to address risk and vulnerability of Limpopo Small-scale agriculture under climate future projections.

CSA practices aimed at reducing small-scale farmers' exposure to climate-related risks and increasing their productivity, while improving their resilience and adaptive capacity to climate variability and change were identified. The practices were selected on bases of incorporating an integrated soil, water and crop management strategies approach, to increase and sustain crop productivity by increasing water availability, crop access to soil-water and soil-water holding capacity.

A structured survey questionnaire was used to collate data on across 6 villages (n = 201) to better understand the LSFs practices, experiences and perceptions, with emphasis on climate variability and change. The data was initially used to determine if the LSFs understood impact of climate variability and change, thereafter, utilized the collected information to determine what influences the LSFs willingness to adopt climate-smart adaptation practices. This was archived through a multiple-mediation analysis of farmers past climate experiences, adoption of climate-smart adaptation practices, their future concerns regarding extreme climate, and physical and socio-economic adaptation constraints, presented in **Chapter 2**. The LSF indicated that they have noticed changes in climate (citing hotter conditions and shifts in rainfall onsets) and perceived that temperature are more likely to continue to increase in far distant future while the rainfall will decline. Their observations and perceptions were found to be consistent with historical climate records, and climate model projections, particularly temperature regimes. The multiple-mediation analysis suggests that past climate experiences of LSF directly influenced willingness to adopt climate-smart practices, and indirectly by concerns about future extreme conditions, economic and physical adaptation constraints.

In the third chapter, field experiments data were conducted over two seasons (i.e. 2013/14 and 2014/15) at University of Limpopo Syferkuil Research Farm in Limpopo Province, on effects of tillage practices on maize crop production are presented. The practices considered were (i) tillage practices (i.e. IRWH, no-till (NT) and conservation tillage (CT) practices), (ii) surface organic mulch cover, (iii) planting dates and (iv) maize cultivars. IRWH is documented in literature as mitigating dry spells by increasing soil-water storage and improving crop production. Application of mulch cover is linked with reducing unproductive water loss via evaporation. Integration of both tillage practices and surface mulch cover improves infiltration and hence increases soil-water storage required particularly during critical maize crop growing periods, such as vegetative and reproductive growth stages.

The two seasons offered an opportunity for the comparison of field experimental treatments, with the start of El Nino during the second growing season and the above normal rainfall in the first season. In the first season yields there were no treatment differences, with average maize grain and biomass yields of 5 and 10 ton per ha, respectively, while in second season the yields were half that of the first and treatment effects were found with high yields from NT tillage practice, followed by IRWH and then CT. Further, maize productivity increased with increments in surface mulch levels. The soil-water and plant available water in the first season were high for NT followed by CT and then IRWH, whereas, for the second season were high for CT followed by IRWH and then NT. In the field experiment, during below normal rainfall, NT performed slightly better than IRWH. This observation suggests that these practices are likely to be more of benefit during dry spells and/or below average rainfall years.

The data from the field experiment and secondary data were used to parameterize, calibrate and validate a daily process-based farming systems model, APSIM - Agricultural Production Systems sIMulator. The model calibration indicated a positive strong relationship between predicted and observed maize grain yields and biomass. The validation analysis suggests that the model is capable of simulating soil-water, biomass (r = 0.82 and RMSE of 572 kg.ha^{-1}) and grain yields (r =0.76 and RMSE = 2 577 kg.ha^{-1}). In order to simulate the effects of IRWH on hydrological processes and crop productivity APSIM was configured with a runoff generation area and a basin collection along a soil profile. This concept was adopted from the PARCHED-Thirst model and yielded a strong correlation with observed data. The strong correlation between model simulations and observed were also found in validation analysis of effects of CT and NT tillage practices.

The calibrated model was used for climate impact and adaptation strategies analysis. To perform the analysis over the Limpopo Province, in unmeasured or tested locations and environmental conditions - an APSIM-GIS coupling approach commonly used in hydrological modelling, was adopted in this research for scaling up the validated model's farming systems to sub-catchment scale, for simulating the tillage practices effects on agro-hydrological responses across varying climate and soils over different locations and time period. Findings from the simulations based on APSIM-GIS coupling over maize producing areas in the Province on effects of tillage practices with different surface mulch levels on agrohydrological responses, suggested the available soil-water content increased with increments in surface residue, but these positive effects were negated in some sub-catchments with high rainfall and/or through drainage losses. A similar trend as soil-water content was observed for maize grain yield, but with even more sub-catchments experiencing higher yields, and some decrease with increments in residue application levels mostly in high rainfall areas. The combination of both tillage and surface residue yielded higher maize grain yields in IRWH combination and less so in NT.

In order to select an ensemble of representative General Circulation Model (GCM) suitable for assessing future climate scenarios, GCM's similar to those presented in Intergovernmental Panel on Climate Change 4th Assessment report were used, and only those available at daily time-step and empirically downscaled (to climate station level) were selected for inclusion in the **fourth chapter**. Further, the GCMs scenarios values used were from the A2 emission (low mitigation) storylines forcing over the Limpopo Province. Then, a set of these GCMs scenario values representing four random locations assumed to representative of the Province were selected. The selection process was based the GCMs performance in predicting past climate conditions, followed by their representation of a range of future climate projections, with precipitation as dominant determinant factor owing to all GCM projections suggesting a similar direction in temperature regimes. Crop management scenarios, developed from LSF survey data, were surface mulch application only for poor-resourced farmers, whereas, for better-resourced farmers both nitrogen fertiliser and surface mulch application, both farmer groups with early and late sowing dates. The practices identified were different sowing dates, N fertilizer and surface mulch application, and interaction effects of the

practices. These were used for climate change impacts assessment of LSF system across maize growing sub-catchments over the Province, using the calibrated coupled APSIM-GIS modelling system.

Two climate projections periods, i.e. 1971-1990 and 2046-2065, were used and findings from the assessment indicated that an increased fertiliser use leading to higher soil fertility would increase yields for present and future projections. The incorporation of surface mulch effect lead to significant declines in simulated grain yields (over 90 %) mainly in high rainfall areas. Early sowing dates had significant effect on potential maize yields with 48 % increase, over 58 % of the Province. The interaction effects of the management scenarios are likely to result in up to 17 % higher yields. Therefore, N fertilization should be part of the practices that allow higher productivity even under less favourable climate. Poor-resourced farmers' potential maize yields under projected future climate will be negatively impacted, with some gains arising from those who plant early and do not apply surface mulch. Better-resourced farmers were shown to have an opportunity to capitalise on climate change impacts, compared to their counterparts mainly due to application of N fertilizer. The current poor farmer management practices are not resilient to prevailing climates and are postulated in climate futures leading to significant low crop productivity. Soil fertility, planting dates and soil-water availability, in particular, were identified as factors influencing productivity in the Province. Projected increase in temperature was found to be the main contributors to low or reduce productivity, even with wetter future projections from the GCMs.

The incremental, systemic and transformational adaptation modes, identified from literature as likely climate adaptation pathways, represented by adopt of short duration cultivars, mainstreaming supplementary irrigation and shifting from cereal crop to livestock ranching as adaptation measures (respectively). These adaptation modes were used to assessing plausible optimal adaptation phase for LSF by mid-century, using median GCM and coupled APSIM-GIS modelling approach. The findings indicate that transformational adaptation might be required much earlier than suggested from literature to be towards end of the century, as some areas are already experiencing extreme climate risks and vulnerabilities that might not be alleviated by incremental adaptation measures, as a result of increase temperatures exceeding the historical variability thresholds.

Further, the results suggest that for the beneficial effects of climate-smart practices to optimize agricultural productivity, they would need to be targeted and adapted to a specific biophysical condition. The traditional cropping systems assessed in this study indicated spatially varied potential gains and losses in yields, however, farmers can capitalise on change climate by adopting better cropping practices and using seasonal forecast linked sowing dates. Incremental adaptation measures, such as farm management, are suggested not to be sufficient for addressing projected climate impacts at mid-century. This is expected to occur in certain areas and/or systems, particularly specialised cropping systems, when the climate-related risks and vulnerabilities far outweighs the adaptive response, and thus requiring transformational adaptation. Such transformational adaptation, in terms of landuse change has already observed in the region with traditional crop farmers opting for ranching and game farming, and large scale adoptions of irrigation.

Keywords: *Adaptation, agricultural productivity, climate change, climate smart agriculture, Limpopo smallholder farmers*

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CHAPTER 6. APPENDIX

A. Study Area

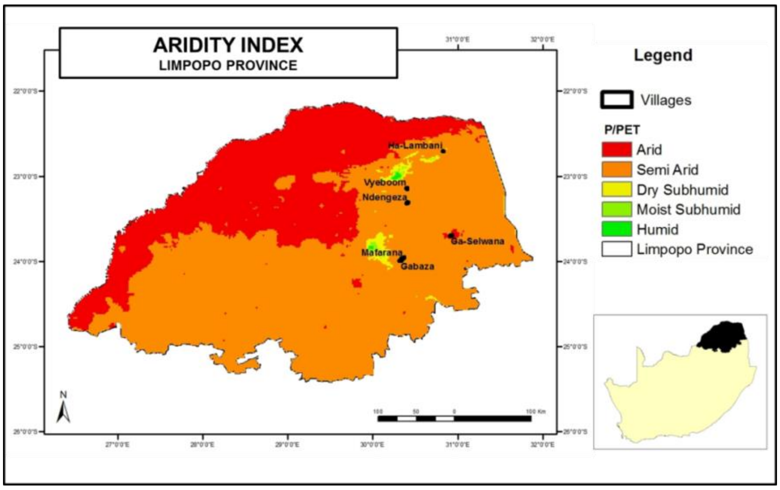

Figure 6.1 Aridity Index in the Limpopo Province, South Africa

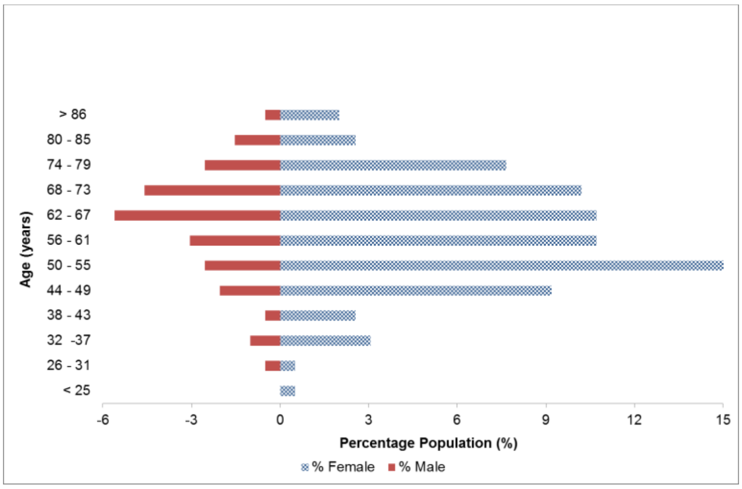

Figure 6.2 Distribution of smallholder agricultural household head by age and sex

B. Precipitation and Temperature Anamolies

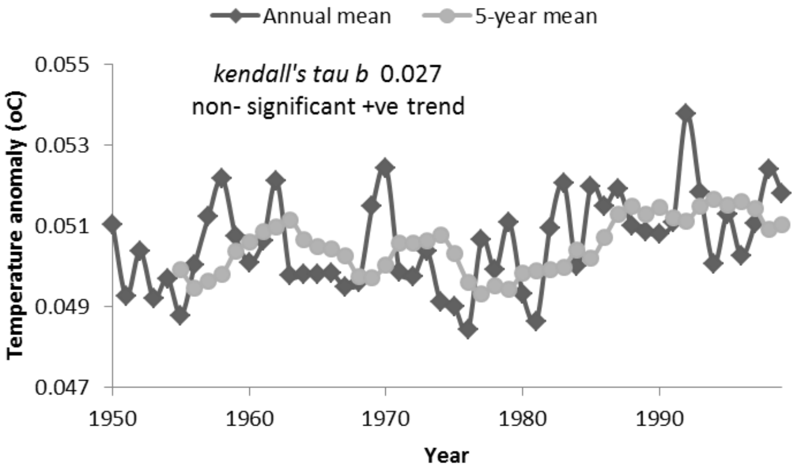

Figure 6.3 Temperature anomaly for Mafarana and Gabaza villages from 1950 to 1999, with 5-year running averages and annual averages

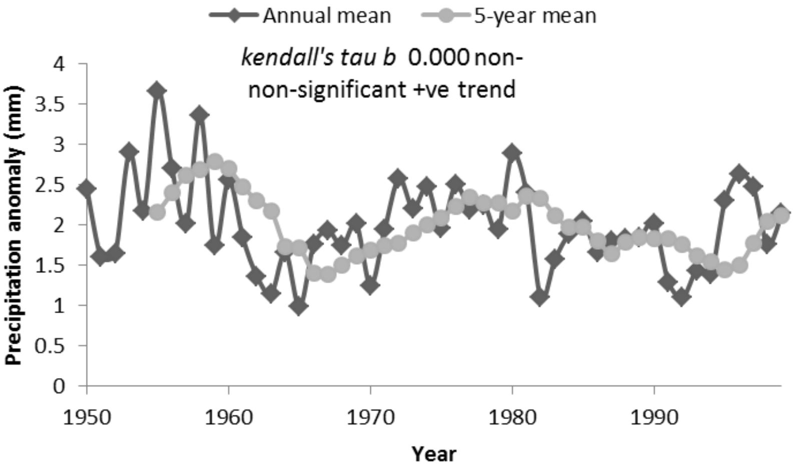

Figure 6.4 Precipitation anomaly for Mafarana and Gabaza villages from 1950 to 1999, with red line representing 5-year running averages and blue line an annual averages

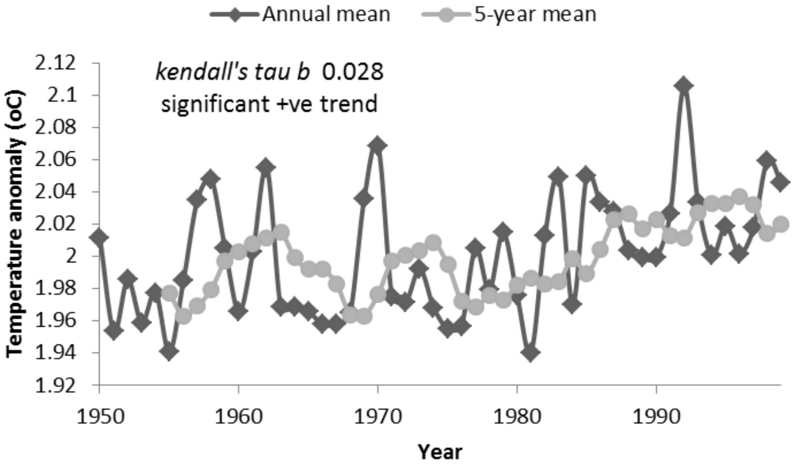

Figure 6.5 Temperature anomaly for Selwane village from 1950 to 1999, with red line representing 5-year running averages and blue line an annual averages

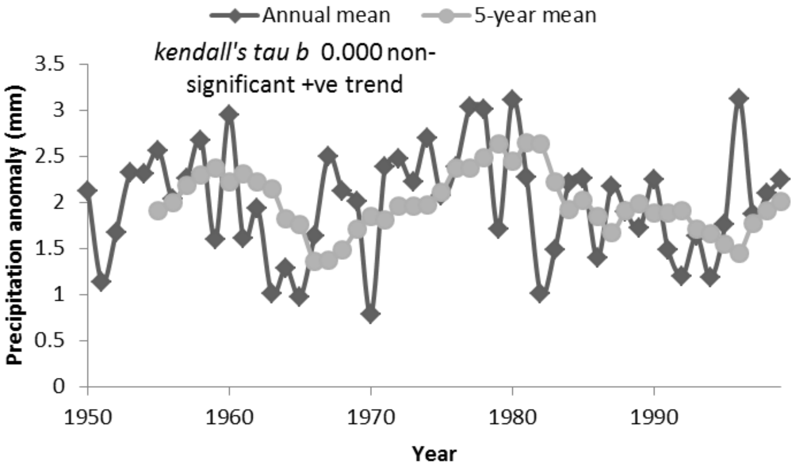

Figure 6.6 Precipitation anomaly for Selwane village from 1950 to 1999, with red line representing 5-year running averages and blue line an annual averages

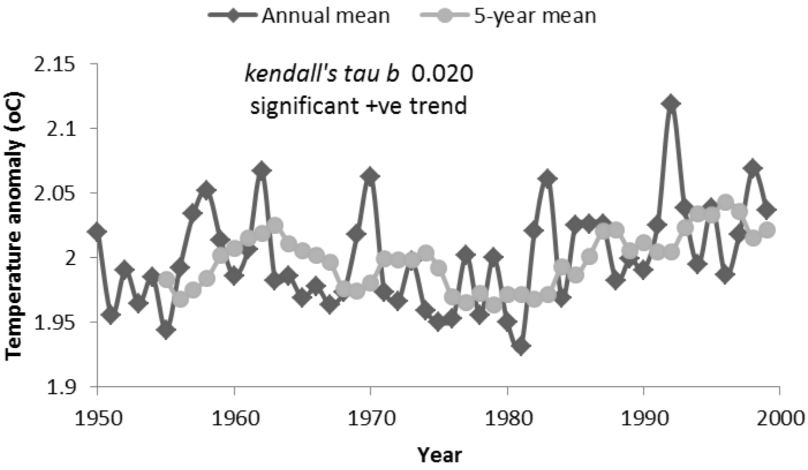

Figure 6.7 Temperature anomaly for Ha-Lambani village from 1950 to 1999, with red line representing 5-year running averages and blue line an annual averages

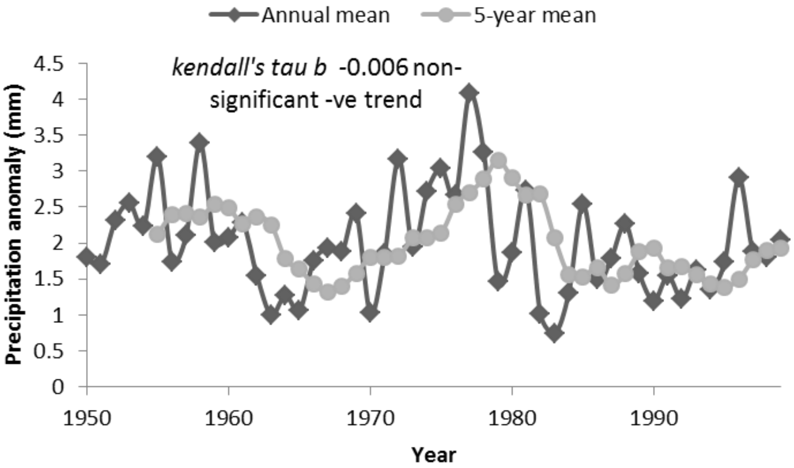

Figure 6.8 Precipitation anomaly for Ha-Lambani village from 1950 to 1999, with red line representing 5-year running averages and blue line an annual averages

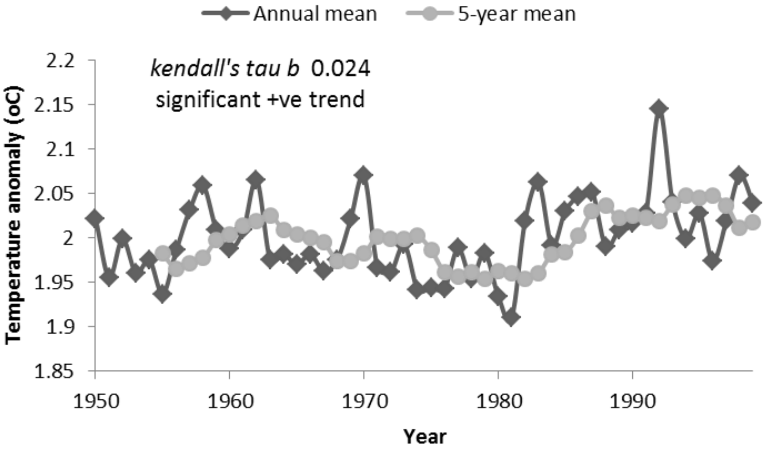

Figure 6.9 Temperature anomaly for Vyeboom and Ndegenza villages from 1950 to 1999, with red line representing 5-year running averages and blue line an annual averages

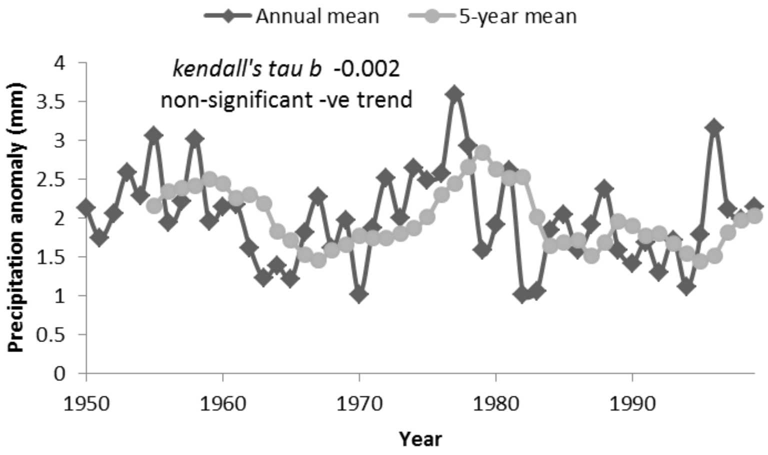

Figure 6.10 Precipitation anomaly for Vyeboom and Ndegenza villages from 1950 to 1999, with red line representing 5-year running averages and blue line an annual averages

Table 6.1 Heat waves, as defined by occurrences per year of more than 30 ^{o}C of daily maximum temperature on ≥ 3 consecutive days, for the period 1950 - 1999

					Exceedance Probability		
Village / study site	Mean value	Coefficient of variation	Maximum value	Minimum value	20 %	50 %	80 %
Gabaza/ Mafarana	30.16	46.38	75.00	7.00	19.20	26.00	39.00
Selwane	127.48	15.88	178.00	95.00	107.00	125.50	145.80
Ha-Lambani	106.56	20.70	165.00	67.00	87.20	105.00	125.80
Ndegenza/ Vyeboom	69.98	29.37	132.00	37.00	51.60	65.50	87.00

Table 6.2 Dry spells, as defined by occurrences per year of more than 0 mm of daily mean precipitation on ≥ 3 consecutive days, for the period 1950 - 1999

					Exceedance Probability		
Village / study site	Mean value	Coefficient of variation	Maximum value	Minimum value	20 %	50 %	80 %
Gabaza/ Mafarana	242.50	8.19	289.00	203.00	226.00	243.00	260.00
Selwane	280.22	6.10	318.00	243.00	264.20	279.00	298.60
Ha-Lambani	264.76	7.73	299.00	228.00	241.60	265.50	284.60
Ndegenza/ Vyeboom	242.20	8.38	282.00	198.00	225.60	242.50	265.00

Table 6.3 Annual occurrences of more than 10 mm of daily mean precipitation on ≥ 3 consecutive days, for the period 1950 - 1999

					Exceedance Probability		
Village / study site	Mean value	Coefficient of variation	Maximum value	Minimum value	20 %	50 %	80 %
Gabaza/ Mafarana	25.50	31.70	46.00	10.00	18.00	26.00	31.8
Selwane	14.80	38.84	29.00	3.00	9.20	15.00	18.80
Ha-Lambani	20.86	85.23	44.00	5.00	13.40	20.00	28.00
Ndegenza/ Vyeboom	30.06	30.09	52.00	13.00	21.20	30.00	38.00

C. Multiple-mediation models results

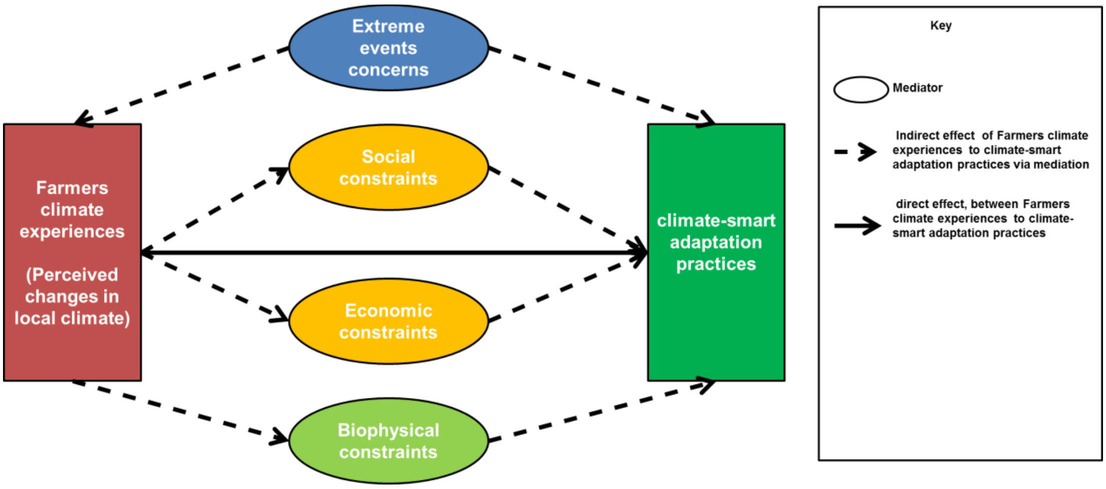

Figure 6.11 A schematic multiple mediation model, indicating indirect effects and direct effects of the farmers’ climate experiences on the farmers’ willingness to adopt climate-smart adaptation practices

Table 6.4 A table of multiple-mediation models results indicating the direct and indirect effects coefficients of the farmers' climate experiences on their willingness to adopt climate-smart adaptation practices

Local Farmer Constraints and Concerns	Model Type	Farmers climate experiences [coefficients ± bootstrap standard error in parentheses]						Model Effects	
	Climate-smart adaptation practices	**Precipitation**	**Temperature**	**Drought Frequency**	**Flood Frequency**	**Length of rainfall season**	**Start of rainfall season**	**Total indirect effects**	**Total significant indirect effects**
Social constraints	Cropping patterns	-0.0004 ± 0.013	0.0006 ± 0.017	-0.019 ± 0.019	0.017 ± 0.020	-0.0021 ± 0.010	0.048 ± 0.012	0.044	0.000
	Retreat or abandon	0.0001 ± 0.0078	-0.006 ± 0.0132	0.0017 ± 0.012	-0.0073 ± 0.015	0.0011 ± 0.0074	-0.0019 ± 0.0077	-0.0104	0.000
	Farm management	0.0004 ± 0.013	-0.019 ± 0.020	0.069 ± 0.017	-0.011 ± 0.020	0.0054 ± 0.013	-0.0058 ± 0.012	0.039	0.000
	Agricultural water management	-0.0004 ± 0.011	-0.002 ± 0.015	-0.014 ± 0.017	0.011 ± 0.020	-0.0017 ± 0.0098	0.0045 ± 0.036	-0.0071	0.000
	Alternative adaptation measures	0.0066 ± 0.015	0.0062 ± 0.014	-0.025 ± 0.021	0.026 ± 0.022	-0.0050 ± 0.012	0.0089 ± 0.014	0.018	0.000
Economic constraints	Cropping patterns	0.003 ± 0.014	-0.002 ± 0.0086	-0.0001 ± 0.0171	-0.0031 ± 0.014	-0.0026 ± 0.014	0.006 ± 0.020	-0.0015	0.000
	Retreat or abandon	-0.0027 ± 0.011	-0.0004 ± 0.0078	-0.0079 ± 0.013	0.0037 ± 0.011	0.0027± 0.012	0.004 ± 0.017	-0.0006	0.000
	Farm management	-0.014 ± 0.019	-0.0018 ± 0.018	-0.029 ± 0.022	0.015 ±0.019	0.021 ± 0.020	**0.035 ± 0.025***	0.026	**-0.035**
	Agricultural water management	-0.0069 ± 0.014	-0.002 ± 0.014	-0.016 ± 0.018	0.0088 ± 0.014	0.014 ± 0.017	0.0017 ± 0.020	-0.013	0.000
	Alternative adaptation measures	-0.022 ± 0.018	0.0002 ± 0.0076	0.0096 ± 0.018	-0.0079 ± 0.015	-0.0031 ± 0.014	-0.0079 ± 0.019	-0.040	0.000
Physical constraints	Cropping patterns	0.001 ± 0.013	-0.013 ± 0.018	0.000 ± 0.0069	0.0020 ± 0.019	0.0064 ± 0.017	0.0002 ± 0.0078	-0.0034	0.000
	Retreat or abandon	-0.002 ± 0.0083	0.0015 ± 0.011	0.0002 ± 0.0051	0.0027 ± 0.012	0.0053 ± 0.012	0.0007 ± 0.0054	0.016	0.000
	Farm management	0.012 ± 0.016	-0.032 ± 0.023	-0.0012 ±0.012	-0.021 ± 0.019	-0.026 ± 0.018	0.0037 ± 0.013	-0.065	0.000
	Agricultural water management	-0.0098 ± 0.014	0.0036 ± 0.016	0.0009 ± 0.011	0.018 ± 0.019	-0.012 ± 0.017	-0.0029 ± 0.011	-0.0022	0.000
	Alternative adaptation measures	-0.022 ± 0.024	0.023 ± 0.020	0.0021 ± 0.019	**0.044 ± 0.026***	**0.032 ± 0.023 ***	-0.0064 ± 0.019	0.073	**0.076**

Extreme events concerns	Cropping patterns	0.029 ± 0.021	0.013 ± 0.018	0.0079 ± 0.013	-0.032 ± 0.025	**0.042 ± 0.026***	**0.038 ± 0.027***	0.098	**0.042**
	Retreat or abandon	0.024 ± 0.015	0.021 ± 0.015	0.0073 ± 0.010	**-0.032** ± **0.018***	0.025 ± 0.018	0.021 ± 0.017	0.066	**-0.032**
	Farm management	**0.064 ±0.03***	**0.054 ± 0.031***	0.021 ± 0.027	**-0.079 ± 0.034***	**0.083 ± 0.36***	**0.072 ± 0.039***	0.22	**0.076**
	Agricultural water management	**0.053 ± 0.026***	**0.037 ± 0.023***	0.017 ± 0.022	**-0.067 ± 0.030***	**0.069 ± 0.030***	**0.52 ± 0.029***	0.63	**0.612**
	Alternative adaptation measures	0.024 ± 0.018	0.0086 ± 0.017	0.0079 ± 0.013	-0.029 ± 0.023	**0.039 ± 0.024***	0.030 ± 0.028	0.081	**0.039**

The provided values are unstandardised coefficients ± standard error indicating the strength, which exists between variables. * and highlighted denotes a significant effect between the variables in the pathway (P ≤ 0.05.). Length of rainfall season and Start of rainfall season were revised to be consistent with climate risk direction

D. Farmer Survey Questionnaire

This structured survey questionnaire template, below, was developed by the author, with inputs from Prof A. Whitbread, Dr. M. Hoffmann, Prof K. Ayisi, Prof J. Odhiambo, Dr. D. Nthakheni, Mr R Ramugundo, and Dr. A. Sullivian (provided inputs on gender issues). This template was used as a guide for collecting information from the Limpopo smallholder, across six villages. The data was predominantly used in Chapter 2 and Chapter 4 of this thesis.

Questionnaire

1.1. Questionnaire no.		
	a. Name, Surname	b. Contact details
1.2. Interviewer		
1.3. Translator (if any)		
1.4. GPS Coordinates	S	E

Household characteristics

Location			
2.1. District		2.2. Village	
Household Head Information			
2.4. Name and Surname	____________________	2.5. Sex	a. Male
			b. Female
2.6. Age		2.7. Year born in	
2.8. Ethnic Group	a. Pedi	b. Venda	c. Tsonga
	d. English	d. Ndebele	e. Other (please specify) _________________
2.9. Marital Status	a. Single	b. Married	c. Divorced/ Separated
	d. Widow	e. Polygamous Marriage	
2.10. Education Level in Household	a. None	b. Grade R – 4	c. Grade 5 – 8
	c. Grade 9 - 12	d. Certificate/ Diploma	e. Degree
Household Members			
2.11. No of Household Members			c. Employment Status (Unemployed = 0; Employed = 1, Self-employed = 2)
Age Class	a. Male (total number per age group)	b. Female (total number per age group)	
2.12. < 7 yrs			
2.13. 8 - 15 yrs			

2.14. 17 - 21 yrs				
2.15. 22 - 35 yrs				
2.16. 37 - 64 yrs				
2.17. > 65 yrs				

Gender roles		
	a. decision on*	b. activities on*
2.18. Staple crops, Selection and management		
2.19. Cash crops, selection and management		
2.20. Household work and water collection		
2.21. Land preparations and planting		
2.22. Management of small ruminants		
2.23. Management of large ruminants		
2.24. Selling of produce and animals		
2.25. Buying of inputs		
* male(1),female(2),both(3),hired (4)		

Availability of resources

Assets and Accessibility				
3.1. Own House	Yes (1)	3.2. Telecommunication	a. Landline	a. Mobile
	No (0)		b. Internet	b. None
3.3. Mobility	a. Car	b. Motor bike	c. Bicycle	c. None
3.4. Electricity in Household	Yes (1)	No (0)		
3.5. Farming Equipment	a. Tractor	b. Hand Plough	c. Other (please specify) ______________________	
Access to Water				
3.6. Drinking Water	a. Well	b. River	c. Tape / Piped water	
	d. Borehole	e. Dam	f. Roof rainwater	g. Other (please specify)
3.7. Drinking Water Ownership	a. Own	b. Shared	c. State	
3.8. Irrigation	a. Well	b. River	c. Piped water	

	d. Borehole	e. Dam	f. Other (please specify) ___________________
3.9. Irrigation Water Ownership	a. Own	b. Shared	c. State

Agricultural activities

Land and Ownership					
4.1. Farming Activities	Livestock (1)	Crop (2)	Selling (3)		
4.2. Land	Owned (1)	Shared (2)	Rented (3)		
4.3. Total Size of Land (ha)		4.4. Size Cultivated (ha)			
4.5. Last season production (kg)		4.6. Productivity	Good (1) – Avg. (2)-Poor (3)		
4.7. Slope	flat(1) – mild (2)-steep(3)	4.8. Current use (crop)			
Crop Production					
Planting	a. Summer crop	b. 2010	c. 2011	d. 2012	e. 2013
4.9. Crop name					
4.10. Variety					
4.11. Tillage Implement	Hand (1)- harrow (2) - disk (3) -plough (4)				
4.12. Conventional Tillage	Yes (1) - No (0)				
4.13. Planting Method	Broadcast by hand (1), rows by hand(2), rows by planter (3)				
Planting	a. Summer crop	b. 2010	c. 2011	d. 2012	e. 2013
4.14. Residue visible at sowing	Yes (1) - No (0)				
4.15. Sowing date (dd/mm)					
4.16. Harvested yields (kg)					
4.17. Seeding rate bags per plot (kg)					
4.18. Type of Fertilizer used					
4.19. Fertilizer application	Top (1) - Basal dressing (2) -both (3) – none (0)				
4.20. How often is weeding during growing season	Once (1), Twice (2), Three (3), After weed emerge (4)				

.22. When is weeding?	Pre-planting (1), after emergence (2), flowering (3), kernel (4)				
4.21. Type of Weed control	Chemical (1) –Manual (0)				
4.23. Type of Harvest	Manual (1) – Combine (0)				

Farm management			
Method of	a. Use and/or b. application method	c. when (dd.mm) or d. how often in growing season?	d. have dates change in last 5 yrs
4.24 Land preparation			↑ = ↓
4.25. Planting			↑ = ↓
4.26. Fertilization			↑ = ↓
4.27. Weed control			↑ = ↓
4.28. Pest control			↑ = ↓
4.29. Residue			↑ = ↓
4.30. Soil-water			↑ = ↓
a./b. land preparation : 1 - tractor; 2 - draft cattle; 3 - hand hoes Planting : 1 - row by hand; 2 - broadcasting by hand; 3 - row by planter Fertilization: 1 - fertigation; 2 - foliar nutrition; 3 - by hand Weeding: 1 - chemical; 2 - biological; 3 - by hand Pest: 1 - chemical; 2 – biological			

Market access

Crop Production			
5.1. Access to input markets	Yes (1) – No (0)	5.2. Access to output markets	Yes (1) – No (0)
5.3. Inputs purchased in local markets	a.	b.	c.
5.4. Inputs not available in local markets	a.	b.	c.
5.5. Outputs not available in local markets	a.	b.	c.
main markets for	a. Place name	b. Type market	c. Type transport
5.6. Crop inputs (seeds)		Shop (1) \ Village (2) market (3) \ Auction (4)	Walk (1) \Public (2) \Own transport (3)
5.7. Crop inputs (Fertilizers)		Shop (1) \ Village (2) market (3) \ Auction (4)	Walk (1) \Public (2) \Own transport (3)
5.8. Support from Govt.	a. Seeds	b. Fertilizers	c. Markets for selling
5.9. Other sources of support	a. Seeds ______________	b. Fertilizers ______________	c. Markets for selling ______________

Sources of income

Activity	a.	b. Amount (Monthly (M) or Lump sum (L))	c. Trend in 5 years
Agricultural Income			
6.1. Crops, main product sales	Yes (1) - No (0)		↑ = ↓
6.2. Crop residue	Yes (1) - No (0)		↑ = ↓
6.3. Agricultural Labour (work elsewhere seasonally)	Yes (1) - No (0)		↑ = ↓
6.4. milk sales	Yes (1) - No (0)		↑ = ↓
6.5. Livestock sale	Yes (1) - No (0)		↑ = ↓
< 500 (1); 600-1500 (2); 1600-2500 (3); 2600-3500 (4); 3600-4500 (5); 4600-7500 (6); > 8500 (7) in rand			
Non-Agricultural Income			
6.6. Business or self-employed	Yes (1) - No (0)		↑ = ↓
6.7. Regular employment	Yes (1) - No (0)		↑ = ↓
6.8. Other Agric. Labour (work elsewhere seasonally)	Yes (1) - No (0)		↑ = ↓
6.9. Child grant	Yes (1) - No (0)		↑ = ↓
6.10. Retired	Yes (1) - No (0)		↑ = ↓
6.11. Remittance income (from Family members)	Yes (1) - No (0)		↑ = ↓
6.12. Other income ____________________	Yes (1) - No (0)		↑ = ↓
< 500 (1); 600-1500 (2); 1600-2500 (3); 2600-3500 (4); 3600-4500 (5); 4600-7500 (6); > 8500 (7) in rand			

6.14 Expenditure					
Monthly: 1. (> 35%); 2. (25 to 35%); 3. (15 to 25%); 4. (5 to 15%); 5. (< 5%)					
a. Groceries		b. Clothing		c. Electricity	
d. Water		e. Fertilizers		f. Seeds	
g. Health		h. Education		i. Livestock	
j. Transport		k. Entertainment			

Labour

Labour use for cropping

Activities	a. Labour	b. Crop type and season	c. Gender [male(1) ,female(2),both(3)] and amount
7.1. Is Labour hired (1 - Yes) or Family/Friends (2 - No)?			
7.2. Land preparation	Yes (1) - No (0)		
7.3. Planting	Yes (1) - No (0)		
7.4. Weeding and management	Yes (1) - No (0)		
7.5. Harvesting	Yes (1) - No (0)		
7.6. Crop Residue Collection	Yes (1) - No (0)		
7.7. Other ____________________	Yes (1) - No (0)		
Labour use for livestock			
7.7. Grazing and Watering	Yes (1) - No (0)		
7.8. Fodder Collection	Yes (1) - No (0)		
7.9. Feeding	Yes (1) - No (0)		
7.10. Dung Collection or clearing	Yes (1) - No (0)		
7.11. Other ___________	Yes (1) - No (0)		

Food Security

Food status			
		1. _____ month(s)	2. Reason
8.1. Period of consuming self-produced staple food	a. Average rainfall		
	b. Drought/low or no rainfall		
	c. Flood/ high rainfall		
8.2. Alternative food source	1. Purchase - 2. Grants/donations - 3.other ___________		
8.3. If on food grant, how long have you been receiving it?	a. Yes (1) - No (0)	b. ______ Rand per month	
8.4. How has long the food stores lasted for in past 5 years?	a. ______ months in ave, b. ______ months in wet, c. ______ months in dry yrs	d. ↑ = ↓	

Adaptation to exacerbated Weather Variability owing to Climate Change

Access to Early Warning Systems

9.1. Do you use climate and weather forecasts information for activities?	Yes (1) - No (0)	9.2. Source of information	State (1) – NPO (2) – Self (3) – Purchase (4)
9.3. Do you have access to expect advice on crop and livestock management based on climate/ weather forecast and provide specific management strategies	Extension services (1), Farmer Cooperatives (2), Public media (3), NPOs (4)		
9.4. What is the information used for?	Irrigation schedule (1) -Planning farm activities(2)		
9.5. How is the information used?			
9.6. Are you familiar with water conservation?	Yes (1) - No (0)		
9.7. Which of these water conservation techniques have you used?	1- no tillage	2 – Mulching	3 - infield rainwater harvesting
	4 - crop selection	5 - drip irrigation	6 - conservation tillage (leave residues)
9.8. Why was it adopted and did it impact production?			

Farmer's beliefs about likely response to more extreme weather owing to climate change.

	a. Implement in past 5yrs	b.				
		Very likely (1) >90%	Likely (2) >66%	More likely than not (3) >50%	Unlikely (4) <33%	Extremely unlikely (5) <5%
Climate						
9.9. Use early warning/ climate risk info	Yes (1) - No (0)					
9.10. Use weather forecasts	Yes (1) - No (0)					
Farming based						
9.11. Did Nothing	Yes (1) - No (0					
9.12. Left land fallow	Yes (1) - No (0					
9.13. Sold part of land for alternative	Yes (1) - No (0					
9.14. Leased out part of land for alternative /leased in	Yes (1) - No (0					
9.15. Sold livestock (cattle)	Yes (1) - No (0					
9.16. Maintained poultry, goats	Yes (1) - No (0					
9.19. Change in cropping pattern	Yes (1) - No (0					
9.20. Change planting time	Yes (1) - No (0)					
9.21. Plant early maturing crops	Yes (1) - No (0)					
9.22. Plant drought-tolerant crops	Yes (1) - No (0)					
9.23. Continue with current practices	Yes (1) - No (0)					
9.24. Diversify crops	Yes (1) - No (0)					
9.25. Diversify livelihoods	Yes (1) - No (0)					
9.29. Use of pesticides	Yes (1) - No (0)					

	a. Implement in past 5yrs	b.				
		Very likely (1) >90%	Likely (2) >66%	More likely than not (3) >50%	Unlikely (4) <33%	Extremely unlikely (5) <5%
9.30. Use of fertilizers	Yes (1) - No (0)					
9.31. Use of herbicides	Yes (1) - No (0)					
9.32. Increase farm land	Yes (1) - No (0)					
9.33. Leave farming	Yes (1) - No (0)					
9.34. Followed improved crop production practices	Yes (1) - No (0					
9.35. Additional information gained	Yes (1) - No (0					
9.36. Any other adaptation measure	Yes (1) - No (0					
Agriculture water management						
9.37. Provided supplemental irrigation	Yes (1) - No (0					
9.38. Invested in farm ponds (water harvesting structures)	Yes (1) - No (0					
9.39. Soil-water conservation (mulch, IRWH)	Yes (1) - No (0)					
9.40. Conservation agriculture	Yes (1) - No (0)					
Non-farm based						
9.41. Borrowed money from relatives/others	Yes (1) - No (0					
9.42. Relying on assistance from government/ NGOs	Yes (1) - No (0					
9.43. Less food consumption or changed food habits	Yes (1) - No (0					
9.44. Shifted to non-farm employment	Yes (1) - No (0					
9.45. Reduction in education level of the children	Yes (1) - No (0					
9.46. Out migration to cities	Yes (1) - No (0)					
Diversification beyond the farm						
9.47. Artisan/handcraft	Yes (1) - No (0)					
9.48. Small Business	Yes (1) - No (0)					
4.49. Natural resources (wood, wild fruit, etc.)	Yes (1) - No (0)					
9.50. Resource rent income	Yes (1) - No (0)					
9.51. Salaried/professional employment	Yes (1) - No (0)					
9.53. Wage work	Yes (1) - No (0)					
9.54. Traditional medicine/healing	Yes (1) - No (0)					

Farmer’s perceived barriers to adaption of new technologies or practices

	Yes (1)	Do not (2)	Not (3)
9.55. Uncertainty in proposed technologies			
9.56. Education/ Knowledge			
9.57. Access to weather forecast (short-term)			
9.58. Access to climate projection information (long-term)			
9.59. Access to early warning systems to drought (and/or floods) and climate risk information			
9.60. Financial costs attached to implementation of new strategies			
9.61. Lack of access to market produce			
9.62. Lack of access to credit (loans)			
9.63. Lack of access to crop insurance			
9.64. Expand or implement Irrigation			
9.65. Increase farmed land (acquire more land)			
9.66. Extension support or expert advice			
9.67. Lack of expert advice based on weather forecast			
9.68. Lack of access to more land			

Perception on Climate Variability and Change (↑ -earlier/rise, = -no change, ↓ -delayed/decline)

	In last 5 yrs				In next century	
Changes in	a. Change	b. Trends	c. critical months	d. Seasons	d. change	e. Trends
10.1. Precipitation (rain)	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.2. Short rainfall period	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.3. Variable rainfall seasons	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.4 Temperature	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.5 Runoff (river flow)	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.6. Groundwater (Borehole)	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.7. Flood frequency	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.8. Drought frequency	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.9. Hailstorm	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.10. Planting dates	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.11 Growing season length	Yes (1) – No (2)	↑ = ↓		Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.12. Crop yields	Yes (1) – No (2)	↑ = ↓	reason	Summer – winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓
10.13. Plant disease	Yes (1) – No (2)	↑ = ↓	reason	Summer - winter	Yes (1) – No (2) – Don’t know (3)	↑ = ↓

Assessment of farmer’s perceptions on the effects that possible changes in water resource caused by climate change will have on agricultural production

	Very negative (1)	Negative (2)	No effect or relevant (3)	Positive (5)	Very positive (6)
10.13. Increased precipitation					
10.14. Decreased precipitation					
10.15. Increased variability in precipitation					
10.16. Decreased runoff					

	Very negative (1)	Negative (2)	No effect or relevant (3)	Positive (5)	Very positive (6)
10.17. Increased runoff					
10.18. Increased variability in runoff					
10.19. Decreased groundwater recharge					
10.20. Increased groundwater recharge					
10.21. Declining surface water quality					
10.22. Declining groundwater quality					
10.23. Increased risk of floods					
10.24. Increased risk of droughts					
10.25. Sea level rise					

E. Syferkuil Data

Table 6.5 Maize grain yield responses to tillage practices and mulch levels in the 2013/14 season, Syferkuil Research Farm

Treatment	Grain yield (kg.ha^{-1})	Biomass (t.ha^{-1})	WUE (kg.ha^{-1}.mm^{-1})
Surface mulch (kg.ha^{-1})			
0	5275.0^{a}	10.49^{a}	4.95^{a}
3 000	4875.0^{a}	9.57^{a}	4.56^{a}
6 000	5308.3^{a}	10.28^{a}	4.98^{a}
12 000	5199.2^{a}	11.04^{a}	4.95^{a}
L.S.D (*P*-< 0.05)	0.78	0.45	0.71
Tillage practice			
Conventional	5061.1^{a}	10.72^{a}	4.91^{a}
No-tillage	5262.5^{a}	9.84^{a}	4.94^{a}
Insitu-rainwater harvesting	5169.6^{a}	10.48^{a}	4.75^{a}
L.S.D (*P*-< 0.05)	0.90	0.41	0.90

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Table 6.6 Maize grain yield responses to tillage practices and mulch levels in the 2014/15 season, Syferkuil Research Farm

Treatment	Grain yield (kg.ha^{-1})	Biomass (t.ha^{-1})	WUE (kg.ha^{-1}.mm^{-1})
Surface mulch (kg.ha^{-1})			
0	2339.10^{b}	5.65^{b}	7.50^{b}
3 000	2614.20^{ab}	6.07^{ab}	8.70^{b}
6 000	2692.00^{ab}	5.98^{ab}	8.22^{ab}
12 000	3058.70^{a}	6.70^{a}	9.00^{a}
Tillage practice			
Conventional	2460.70^{b}	5.75^{a}	7.50^{b}
No-tillage	2934.50^{a}	6.65^{a}	9.29^{a}
Insitu-rainwater harvesting	2632.90^{ab}	5.90^{a}	8.28^{ab}

Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Secondary Data

Due to damage by stray animals during the 2010/11 and 2011/12 seasons in the Towoomba/Hutton soil form, maize biomass was taken and the grain yield calculated following the procedure of Bennie *et al.* (1998).

Table 6.7 Biomass and grain yield for the various treatments on the Towoomba/Hutton soil form over four maize growing seasons (2008/09 - 2011/12, source data: Botha *et al.*, 2014)

Parameter	**Season**	**Treatment**		
		CON	*NT*	*IRWH*$_{2.4m}$

Biomass at physiological maturity (kg ha^{-1})	2008/09	3321^{a}	2992^{a}	3587^{a}
	2009/10	4035^{a}	3422^{a}	4317^{a}
	2010/11	3836^{ab}	3501^{a}	3875^{ab}
	2011/12	4627^{b}	1241^{a}	4773^{b}
	Mean	**3955**	**2789**	**4138**
Grain yield (kg ha^{-1})	2008/09	1101^{a}	1060^{a}	1281^{a}
	2009/10	1817^{a}	1490^{a}	1972^{a}
	2010/11	1361^{ab}	1178^{a}	1409^{ab}
	2011/12	1578^{b}	476^{a}	1647^{b}
	Mean	**1464**	**1051**	**1577**

CON = Conventional tillage; *IRWH*$_{2.4m}$ = *IRWH* with a 2.4 m runoff strip; *NT* = No-till. Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Table 6.8 Biomass and grain yield for the various treatments on the Arcadia soil form over four maize growing seasons (2008/09 - 2011/12, source data: Botha *et al*., 2014), Towoomba Research Station

Parameter	Season	Treatment		
		CON	*NT*	*IRWH*$_{2.4m}$
Biomass at physiological maturity (kg ha^{-1})	2009/10	6144^{ab}	4578^{a}	6856^{b}
	2010/11	-	-	-
	2011/12	2965^{a}	2085^{a}	3718^{a}
	Mean	**4555**	**3332**	**5287**
Grain yield (kg ha^{-1})	2009/10	2319^{ab}	1686^{a}	2614^{b}
	2010/11	-	-	-
	2011/12	1113^{a}	793^{a}	1418^{a}
	Mean	**1716**	**1240**	**2016**

CON = Conventional tillage; *IRWH*$_{2.4m}$ = *IRWH* with a 2.4 m runoff strip; *NT* = No-till. Different superscripts within a row indicate a significant difference ($P \leq 0.05$); values with similar superscripts are not significantly different ($P \leq 0.05$).

Table 6.9 Biomass yield and grain yield for various treatments on the Shortlands soil form over three maize growing seasons (2009/10 - 2011/12), Ha-Lambani Cooperative Farm

Parameter	Growing season	Treatment		
		CON	*NT*	*IRWH*$_{2.4m}$
Biomass at physiological maturity (kg ha^{-1})	2009/10	6600^{b}	0^{a}	6946^{b}
	2010/11*	5240^{a}	8946^{b}	7262^{b}
	2011/12	1060^{a}	1040^{a}	1420^{a}
	Mean	**4300**	**3329**	**5209**
Grain (kg ha^{-1})	2009/10	1055^{b}	0^{a}	1250^{b}
	2010/11*	1504^{a}	1248^{a}	1824^{b}
	2011/12	477^{a}	468^{a}	639^{a}
	Mean	**1012**	**572**	**1238**

CON = Conventional tillage; NT = no tillage; IRWH2m = IRWH with a 2 m runoff strip;* Estimated values

Model Calibration

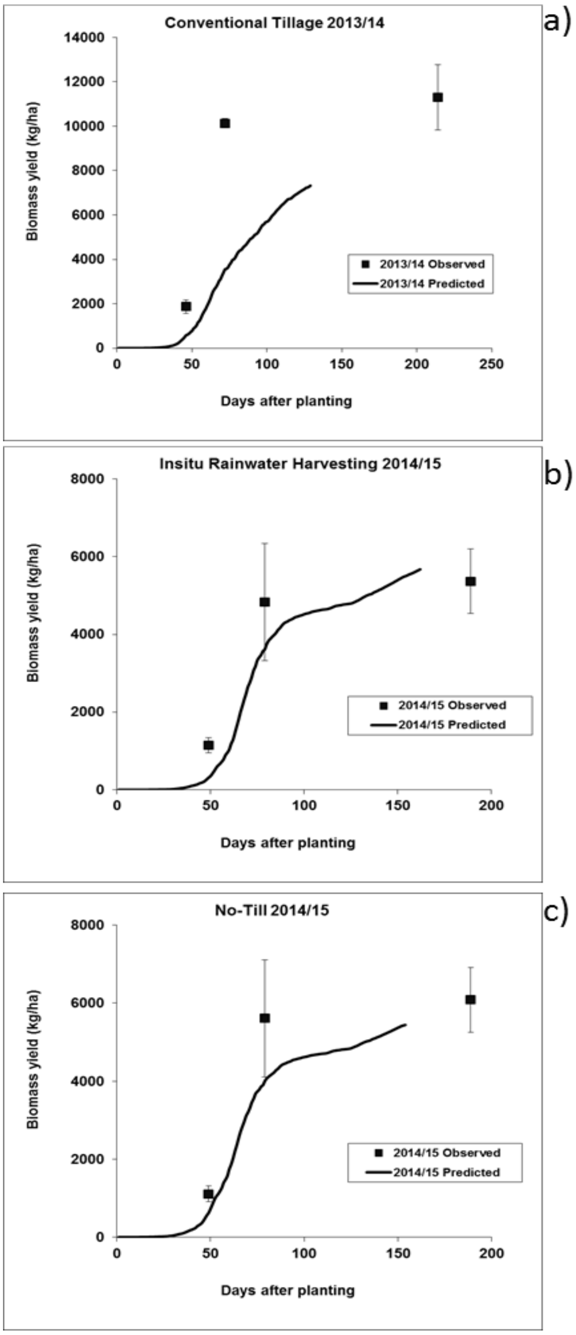

Figure 6.12 Predicted (lines) and observed (symbols) maize biomass of Syferkuil Research Farm for 2013/14 growing season under three tillage practices, i.e. conventional (a), insitu rainwater harvesting (b) and no-till (c)

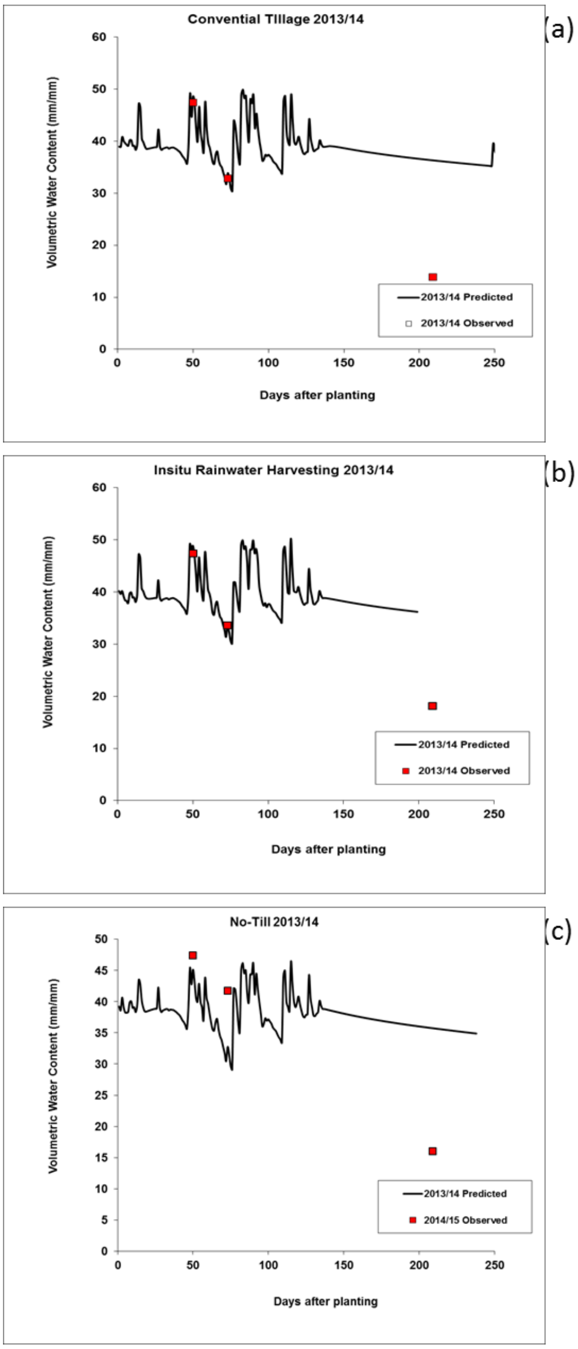

Figure 6.13 Predicted (lines) and observed (symbols) volumetric water content (mm/mm) at 30 cm depth of Syferkuil Research Farm for 2013/14 growing season under three tillage practices, i.e. conventional (a), insitu rainwater harvesting (b) and no-till (c)

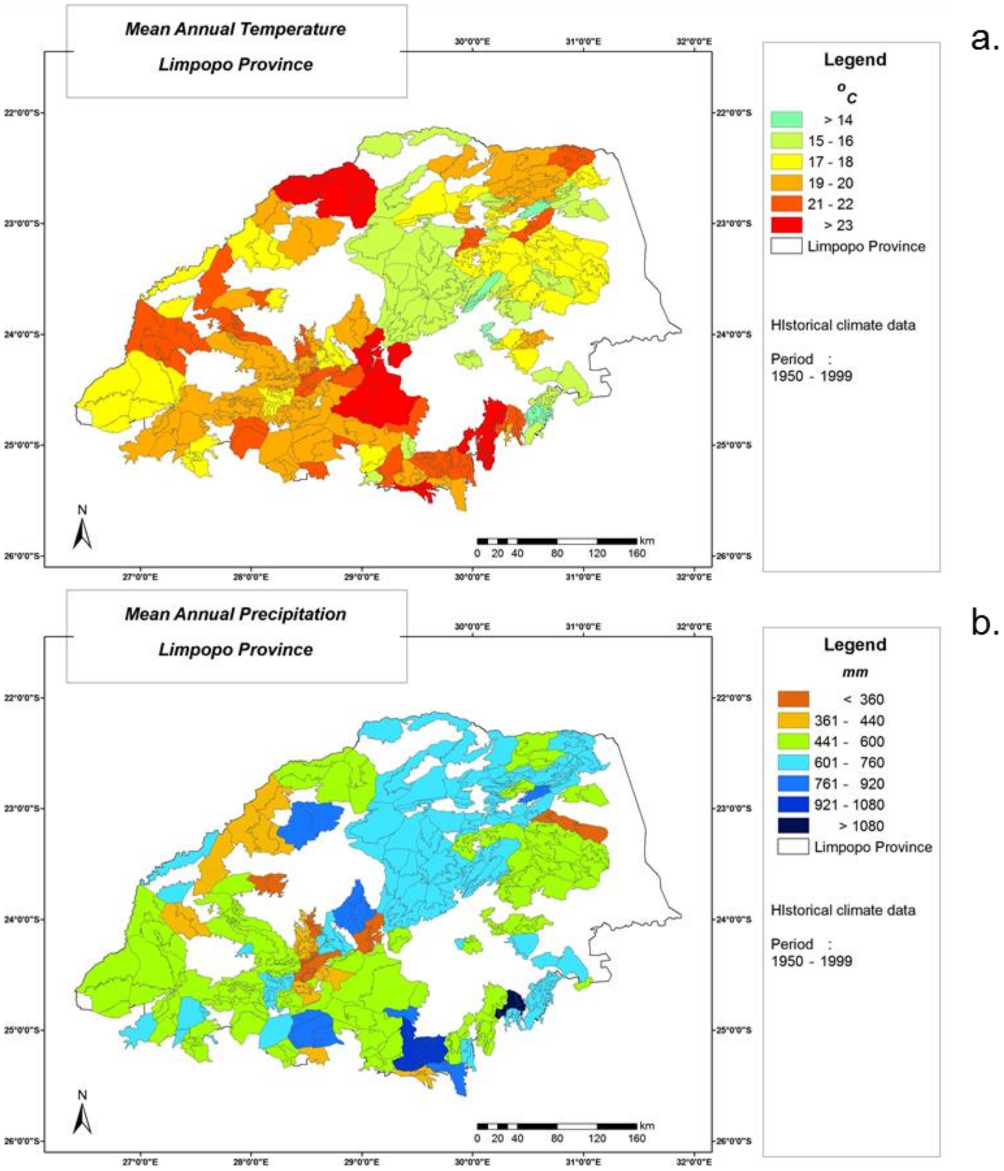

Figure 6.14 Mean annual temperature (a) and precipitation (b) over the Limpopo Province maize growing seasons, over the period 1950 to 1999

F. VBA Code

Visual Basic programme, in Microsoft excels, was to perform climate data extraction from historical climate and global climate model projections database provided by Prof R. Schulze at School of Environmental Hydrology, University of KwaZulu-Natal. The same coding was used to assimilate each data file into a format suitable for converting it into an APSIM model met file. Further, the coding formed the basis for performing query analysis of multiple data file.

Author: Dr Gummadi and Mr R Lekalakala

```
Sub copydata()
Dim Path As String
Dim FileIn As String
Dim FileOut As String
Dim Station As String
Dim SheetName As String
Dim Lon As Double
Dim Lat As Double
Dim Alt As Double
Dim RF As Double
```

```
Dim TMAX As Double
Dim TMIN As Double
Dim SR As Double
Dim X As Integer, Y As Integer, Z As Integer, A As Integer, B As Integer, C As Integer
Path = "E:\Climate\e21\e21pr3\"
    For X = 1 To 11583
        Worksheets("e21pr3").Select
        Lon = Cells((X + 1), 3)
        Lat = Cells((X + 1), 4)
        Alt = Cells((X + 1), 5)
        FileIn = Cells((X + 1), 6)
        Station = Cells((X + 1), 2)
        SheetName = Cells((X + 1), 12)

        Workbooks.OpenText Filename:= _
        Path & FileIn, Origin:=437 _
        , StartRow:=1, DataType:=xlFixedWidth, FieldInfo:=Array(Array(0, 1), Array( _
        8, 1), Array(12, 1), Array(14, 1), Array(16, 1), Array(21, 1), Array(27, 1), Array(34, 1), _
        Array(67, 1), Array(102, 1), Array(108, 1), Array(114, 1)), TrailingMinusNumbers:= _
        True
        Cells.Replace What:="p", Replacement:="", LookAt:=xlPart, SearchOrder:= _
        xlByRows, MatchCase:=False, SearchFormat:=False, ReplaceFormat:=False

        Columns("A:A").Select
        Selection.NumberFormat = "0"

        Workbooks("e21pr3.xlsx").Activate
        Sheets("TEST").Select
        Sheets("TEST").Copy After:=Sheets(X)
        Sheets("TEST (2)").Select
        Sheets("TEST (2)").Name = SheetName

        ' copy rainfall data
        Workbooks(FileIn).Activate
        RF = Range("E1:E18262").Select
        Selection.Copy
        Workbooks("e21pr3.xlsx").Activate
        Sheets(SheetName).Select
        Cells(9, 6).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
       :=False, Transpose:=False

        ' copy TMAX data
        Workbooks(FileIn).Activate
        TMAX = Range("F1:F18262").Select
        Selection.Copy
        Workbooks("e21pr3.xlsx").Activate
        Sheets(SheetName).Select
        Cells(9, 4).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
       :=False, Transpose:=False


        ' copy TMIN data
        Workbooks(FileIn).Activate
        TMIN = Range("G1:G18262").Select
        Selection.Copy
        Workbooks("e21pr3.xlsx").Activate
        Sheets(SheetName).Select
        Cells(9, 5).Select
```

```
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
       :=False, Transpose:=False


        ' copy SR data
        Workbooks(FileIn).Activate
        SR = Range("I1:I18262").Select
        Selection.Copy
        Workbooks("e21pr3.xlsx").Activate
        Sheets(SheetName).Select
        Cells(9, 3).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
       :=False, Transpose:=False

        Cells(4, 2) = Station
        Cells(4, 3) = Lat
        Cells(4, 4) = Lon
        Cells(4, 5) = Alt
        Cells(4, 6) = "BEEH"
    Application.DisplayAlerts = False
    Workbooks(FileIn).Close

  Next X

End Sub
```

G. Surveyed Limpopo Smallholder Farmer Characterisation

SPSS version 23.0 was used determine factors influencing farm characterization and classification.

Factor analysis

1. Initial factor variables used in the analysis,

Descriptive Statistics

	Mean	Std. Deviation	Analysis N
Sex	.766	.4247	192
Age	60.307	13.3849	192
Ethinc Group	2.135	.7466	192
Education	.755	.4311	192
Family Size	5.786	2.5666	192
Land Onwership	.891	.3129	192
LandSize (ha)	8.997161	18.6393592	192
Farming actiivity	.292	.4557	192
Selling	.083	.2771	192
Percentage cultivated	78.895586230000000	41.400338170000000	192
2014 Maize Yield (t/ha)	.515693645000000	.452540781000000	192
Productivity status	.292	.4557	192
Farm Slope	1.229	.5313	192
Cropping patterns	.453	.4991	192
Use of climate information	.661	.4745	192

Soil and water conservation measures	.464	.5000	192
Access to markets	.698	.4604	192
Fertilizer application	.099	.2994	192
Access to extension services	.693	.4626	192
Use Labour	.859	.3485	192

2. After oblimin rotation, selection of variable with factor above 0.4

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.646
Bartlett's Test of Sphericity	Approx. Chi-Square	632.235
	df	91
	Sig.	.000

Structure Matrix

	Factor		
	1	2	3
LandSize (ha)	**-1.997**	-.076	.277
Percentage cultivated	**.775**	.065	-.246
Cropping patterns	-.227	.060	.162
Age	.222	.097	-.180
Farming actiivity	.109	**.982**	.127
Selling	.072	**.368**	.069
Use Labour	-.106	-.302	.276
Ethinc Group	.115	-.229	-.002
Use of climate information	-.331	-.008	**.902**
Access to extension services	-.299	-.110	**.789**
Soil and water conservation measures	-.079	.014	**.442**
Access to markets	-.271	.145	**.414**
Education	-.110	.030	**.348**
Land Onwership	.056	-.018	-.133

Extraction Method: Maximum Likelihood.
Rotation Method: Oblimin with Kaiser Normalization.

3. K-means cluster analysis

Final Cluster Centers

	Cluster	
	1	2
LandSize (ha)	1.4	43.8
Farming actiivity	.3	.1
Selling	.1	.0
Percentage cultivated	93.1	7.1
Soil and water conservation measures	.5	.5
Use of climate information	.6	.9
Access to extension services	.6	.9
Access to markets	.6	.9
Education	.7	.8

ANOVA

	Cluster		Error			
	Mean Square	df	Mean Square	df	F	Sig.
LandSize (ha)	54101.042	1	85.768	199	630.786	.000
Farming actiivity	1.477	1	.200	199	7.385	.007
Selling	.287	1	.073	199	3.960	.048
Percentage cultivated	223241.476	1	248.978	199	896.630	.000
Soil and water conservation measures	.076	1	.251	199	.301	.584
Use of climate information	3.537	1	.207	199	17.113	.000
Access to extension services	2.243	1	.202	199	11.091	.001
Access to markets	2.821	1	.199	199	14.154	.000
Education	.135	1	.186	199	.728	.394

The F tests should be used only for descriptive purposes because the clusters have been chosen to maximize the differences among cases in different clusters. The observed significance levels are not corrected for this and thus cannot be interpreted as tests of the hypothesis that the cluster means are equal.

H. Modified Bristow and Campbell (1984) equation (Solar Radiation)

The Bristow and Campbell (1984) equation

$$R_s = 0.75\, R_a[1 - 1/T_{ra}{}^{a})] \quad 6.1$$

where,

R_s = daily flux of incoming solar radiation,

R_a = extraterrestrial radiation, function of the solar constant, earth's radius vector, latitude and solar declination, i.e. an expression of time of year.

a = clear sky atmospheric transmissivity of Ra
= 0.75 in the Bristow and Campbell equation, and which represents the depletion of Ra due to scattering by atmospheric aerosols (mainly dust) and the pure atmosphere (Rayleigh extinction), as well as absorption by water vapour

while

b, c = empirical constants governing the depletion of the solar beam due to cloudiness and rainfall, and for which daily T_{ra} is used as an estimator on the premise that cloudy/rainy conditions are associated with high atmospheric humidity and hence a low diurnal Tra while under clear skies high temperature ranges prevail.

Modified equation the Bristow and Campbell (1984) equation, for South Africa, accounts for clear sky extinction of R_s by water vapour by utilising temperature range as a surrogate for atmospheric water vapour content; whereas, for cloudy/rainy days regression “constants” have been optimised by region and season to try and account for different meteorological conditions which can prevail (Schulze and Chapman, 2008).

$$R_s = 0.75\, R_a\, [1 - 1/T_{ra}^{a}] \qquad 6.2$$

Using Liu and Scott’s (2001) formulation of daily temperature range, viz.

Tra = Tmxd - (Tmnd + Tmnd+1) / 2

where,

T_{ra} = diurnal temperature range (°C),
T_{mxd} = maximum temperature for the day,
T_{mnd} = minimum temperature for the day, and
T_{mnd+1} = minimum temperature for the following morning

I. Changes in climate means

Projected changes in climate means and likelihood of occurrence, based on agreement between model, over the Limpopo Province

		Mean annual surface temperature (oC)			
		Slightly Warmer < 0.5	**Warmer 0.5 to 1.5**	**Hotter 1.5 to 3.0**	**Much Hotter > 3.0**
Mean annual precipitation (% change)	**Much Drier < -30**		Likelihood: 10 % 2 models	Likelihood: 30 % 6 models	
	Drier - 30 to -10		Likelihood: 5 % 1 model	Likelihood: 5 % 1 model	
	Little Change -10 to 10				
	Wetter 10 to 30				
	Much Wetter > 30				Likelihood: 50 % 10 models

Table 6.10 Minimum data requirements to run APSIM Model

Dataset	Variable name	Spatial reference	Temporal reference	Source
Climate data (observed)	temperature, Precipitation, solar radiation	climate station	minimum and maximum daily mean daily	Schulze (1997)
Soil data	physical and chemical properties	soil profiles		Landtype Survey Staff (2012)
Climate projections	Temperature	point scale downscaled	minimum and maximum daily	GSAG, UKZN

precipitation, solar radiation	mean daily

J. Climate Adaptation Pathways

Materials and methods

Climate projections from ‘middle-of-the-road’ GCM (median of 10 empirically downscaled GCM, i.e. gi2 GCM) for present and mid-century time periods daily climate values were used to derive an exposure index for the Limpopo Province. The Limpopo exposure index was computed using guidelines and protocols obtained from ICRISAT - India. Climate exposure (Table 6.11) indicators were computed and then area weighed, based on weighting derived from literature.

Table 6.11 Exposure indicators used in developing a weighted index

No.	**Exposure Indicators**	**Present Climate**		**Future Climate**	
		mean	*Standard deviation*	*mean*	*Standard deviation*
1.	Mean Annual Maximum Temperature	24.60	3.31	27.33	2.64
2.	Mean Annual Minimum Temperature	11.12	2.81	13.76	3.00
3.	Heat wave Occurrences (days)	0.00	0.00	0.00	0.01
4.	Cold wave Occurrences (days)	141.40	53.59	93.80	52.24
5.	Severe Heat wave Occurrences (days)	0.00	0.00	0.00	0.00
6.	Severe Cold wave Occurrences (days)	106.61	51.59	93.80	52.24
7.	Coefficient of Variability in November rainfall (%)	9.75	1.76	9.88	1.76
8.	Coefficient of Variability in December rainfall (%)	9.65	1.70	9.51	1.69
9.	Mean Annual Precipitation	567.55	140.39	642.15	163.13
10.	Monsoon rainfall	372.79	89.66	409.77	103.66
11.	Coefficient of Variability Monsoon rainfall (%)	10.40	1.72	9.89	1.58
12.	Simple daily Intensity Index(Mm/day)	12.14	2.29	12.40	2.33
13.	Heavy rainfall (days)	0.41	0.36	0.51	0.43
14.	Very heavy rainfall (days)	0.03	0.07	0.05	0.10
15.	Consecutive Dry days	12.00	0.93	11.70	0.90
16.	Number of times more than 14 days of dry in Monsoon (no/time slice)	3.05	1.95	2.55	1.59
17.	Consecutive Wet days	3.13	0.92	3.43	0.90
18.	Number of times more than 14 Days of Wet in Monsoon (no/time slice)	0.00	0.00	0.01	0.09
19.	Number of Annual Rainy Days	4.15	1.27	4.61	1.30
20.	95th percentile rainfall	28.38	7.02	32.11	8.16
21.	Hot day Frequency	0.00	0.00	0.00	0.01

Results

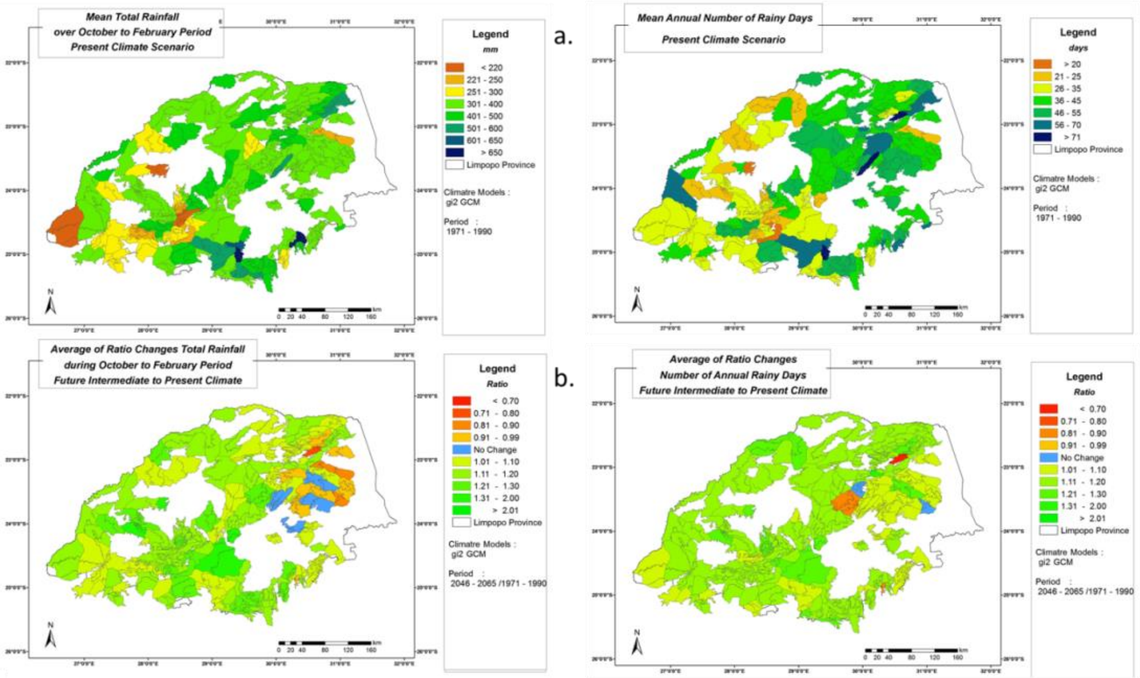

Figure 6.15 Mean total rainfall over October to February period present climate (a), ratio change in total rainfall from future to present climate over October to February period present climate (b), mean annual number of rainy days present climate (c), and ratio change number of annual rainy days from future to present climate

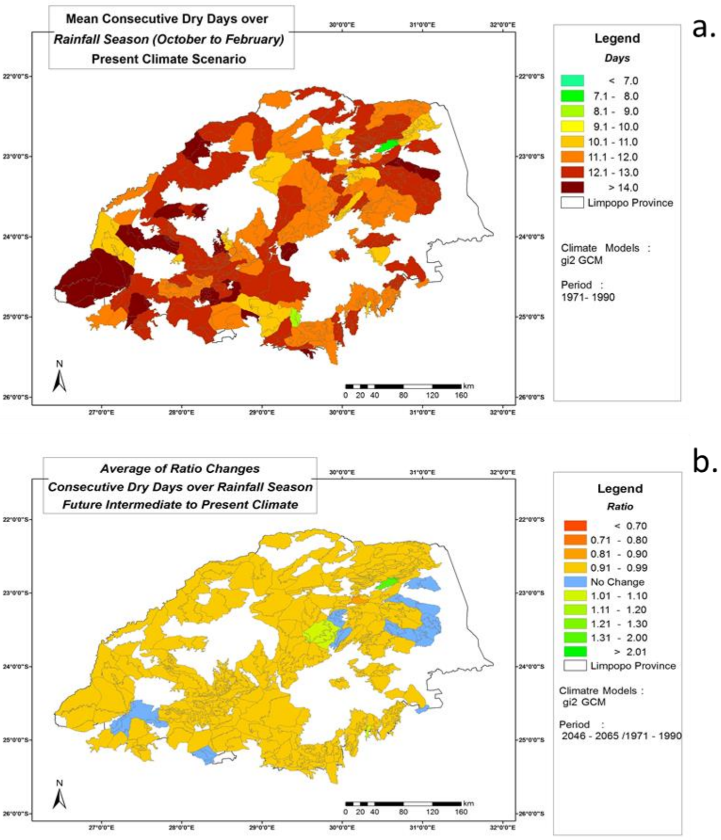

Figure 6.16 Mean of consecuitve dry days over the rainfall season (October - February) present climate (a); and ratio chnages in average consecutive dry days over the rainfall season of future to present climate (b) scenario

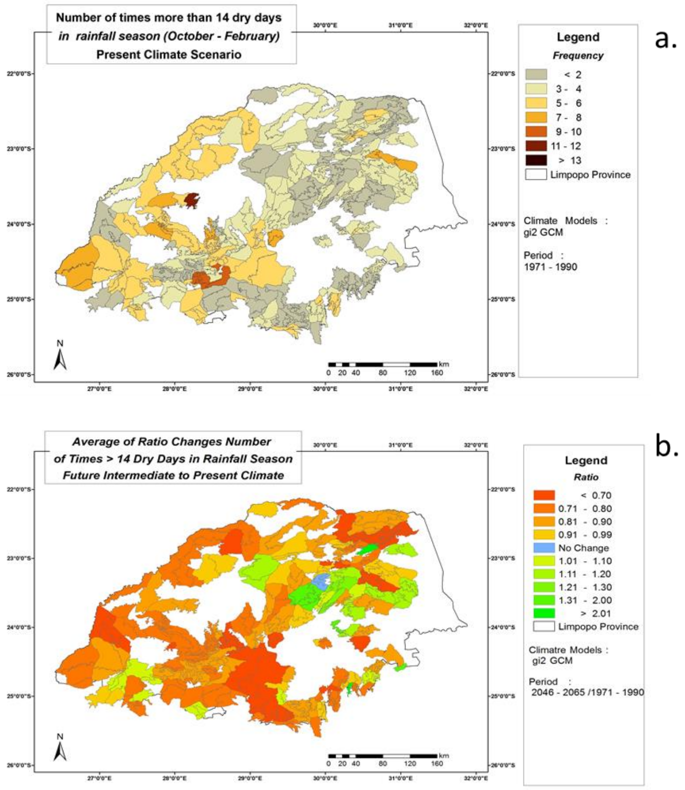

Figure 6.17 Mean of number of times more than 14 dry days over the rainfall seasons' (October - February) present climate (a); and ratio changes in average number of times 14 dry days over the rainfall season of future to present climate (b) scenarios

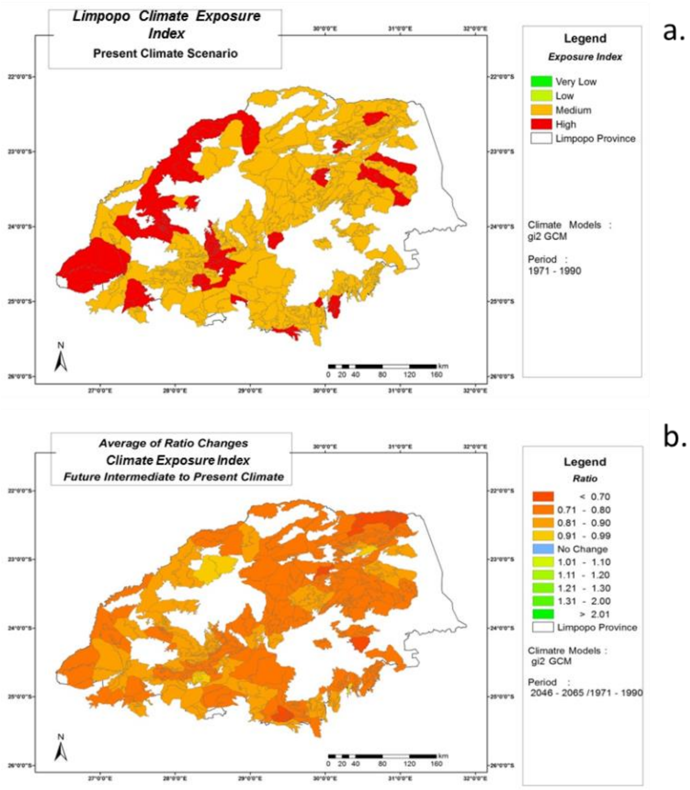

Figure 6.18 Mean of climate exposure index of present climate (a); and ratio changes (b) of future to present climate scenarios over the Limpopo Province

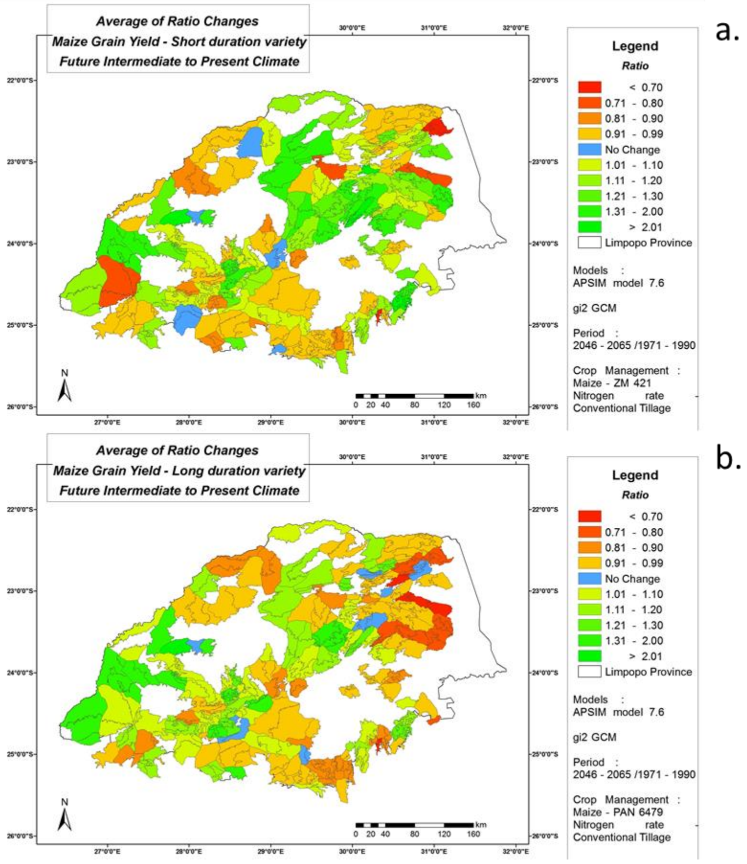

Figure 6.19 Average of ratio changes in maize grain yields in early (a) and Late (b) maturing cultivar for future future relative to present climate scenario, over the Limpopo Province

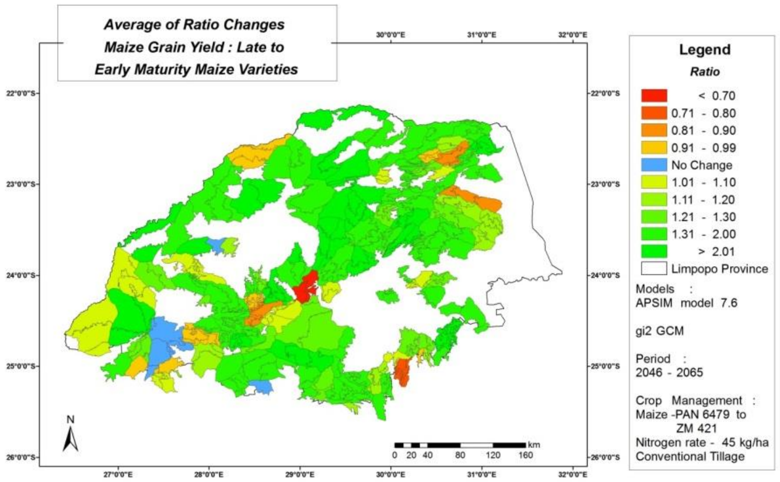

Figure 6.20 Average of ratio changes in maize grain yields from Late (PAN 6479) relative to early (ZM421) maturing cultivars for present climate scenario, over the Limpopo Province

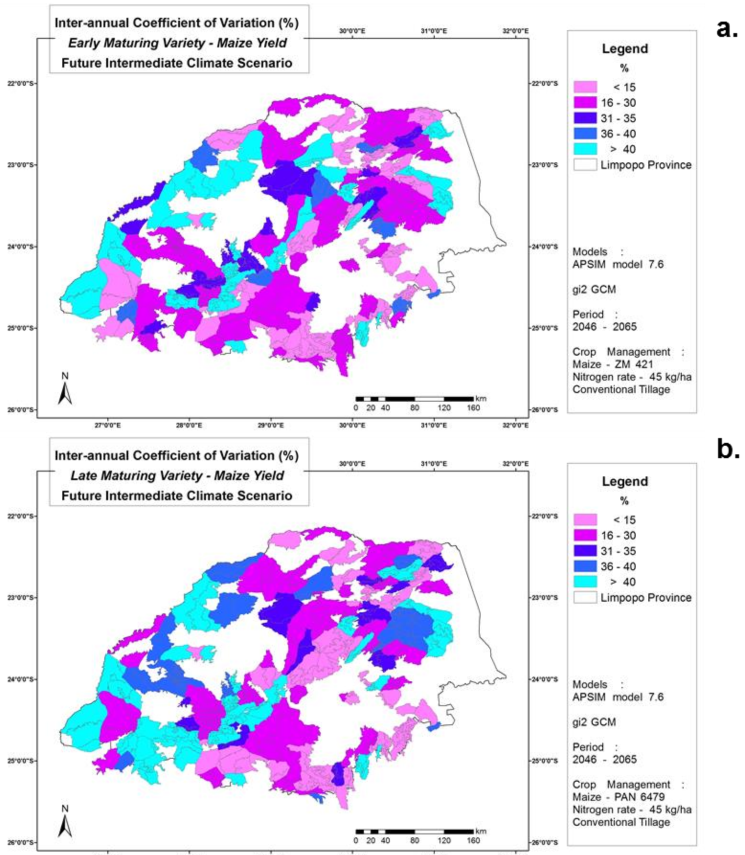

Figure 6.21 inter-annual coefficient of variability (%) for early (a) and late (b) maturing maize cultivars during the projected future climate scenario, over the Limpopo Province

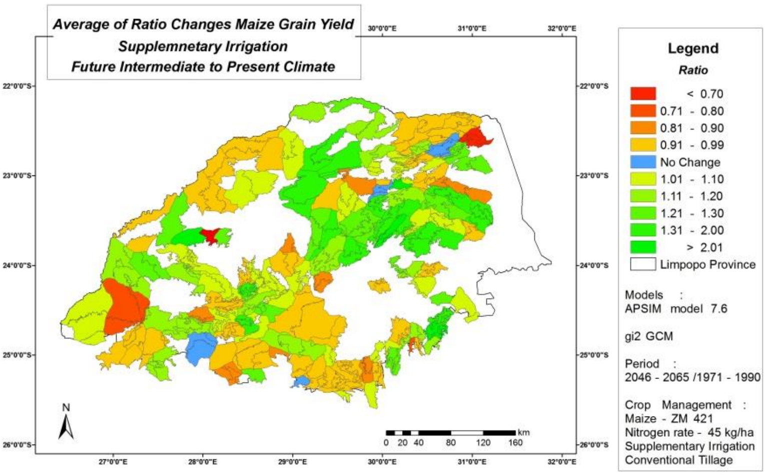

Figure 6.22 Average of ratio changes in maize grain yields under supplementary irrigation for future relative to present climate scenario, over the Limpopo Province

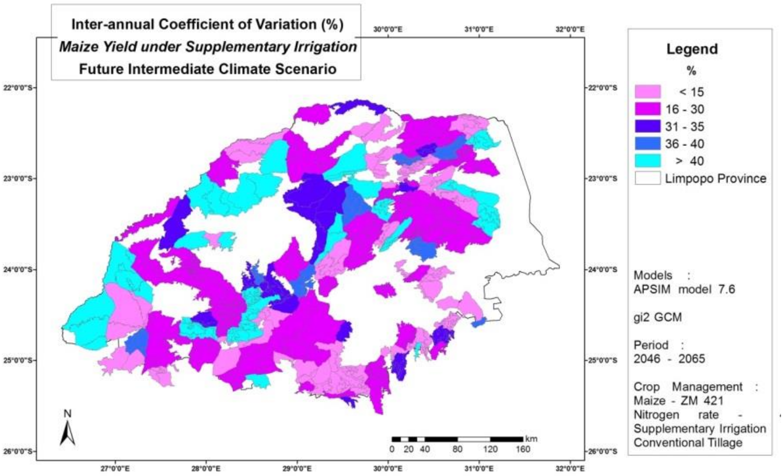

Figure 6.23 Inter-annual coefficient of variation (%) for maize grain yields under supplementary irrigation for future relative to present climate scenario, over the Limpopo Province

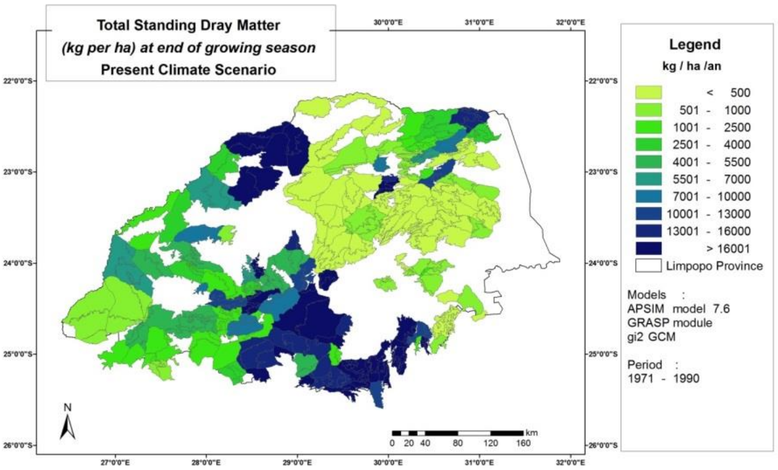

Figure 6.24 Mean total standing dry matter (kg per hectare) at the end of the growing season for present climate scenario, over the Limpopo Province

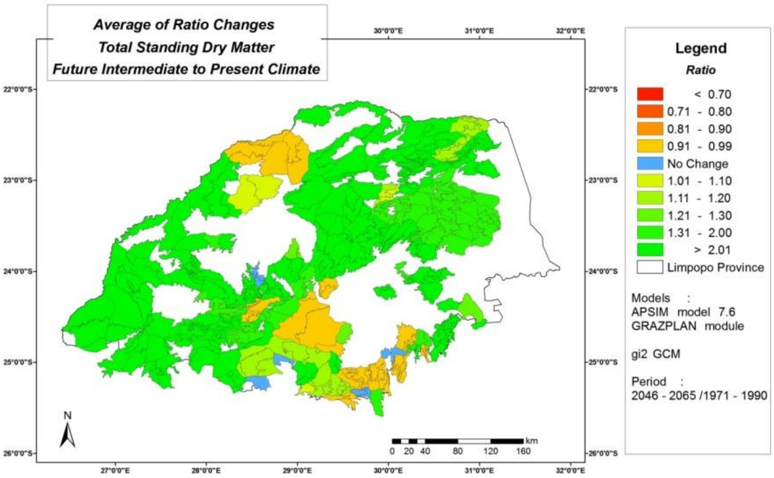

Figure 6.25 Average of ratio changes in total standing dry matter for future relative to present climate scenario, over the Limpopo Province

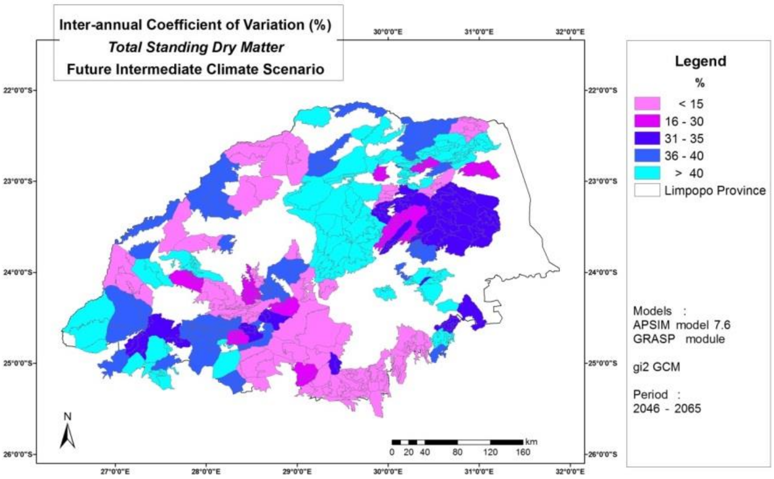

Figure 6.26 Inter-annual coefficient of variation (%) of total standing grass dry matter for future inetermediate climate scenario from gi2 GCM, over the Limpopo Province

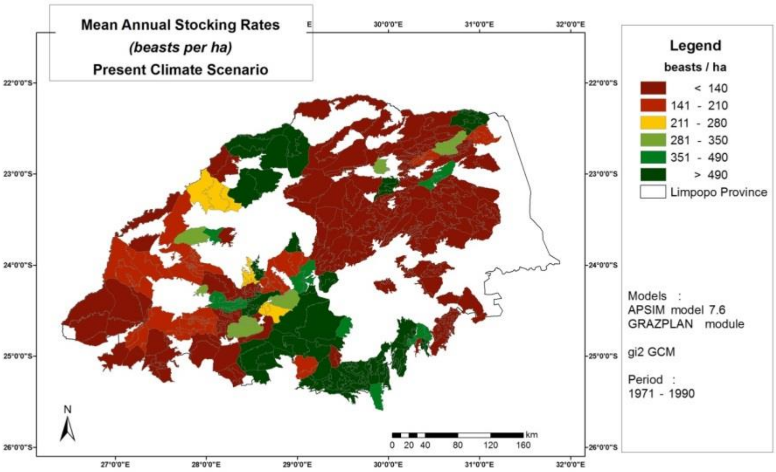

Figure 6.27 Mean annual stocking rate (number of beasts per hectare) for present climate scenario, over the Limpopo Province

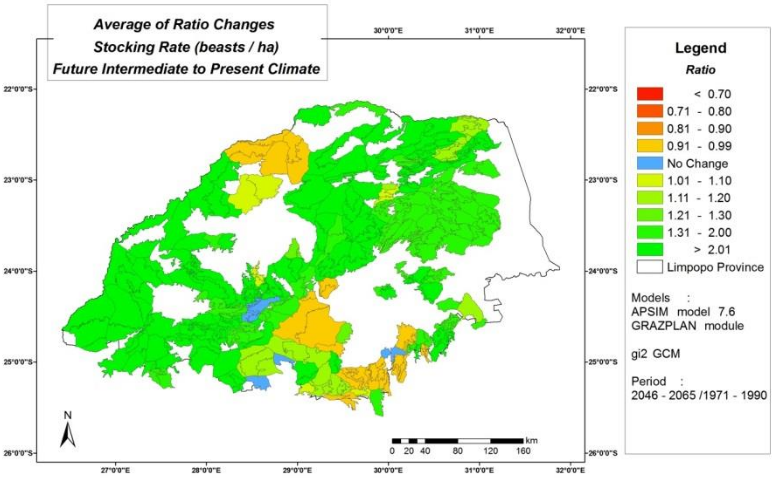

Figure 6.28 Average of ratio changes in stocking rate (number of beasts per hectare) for future climate, over the Limpopo Province

DECLARATIONS

1. I, hereby, declare that this Ph.D. dissertation has not been presented to any other examining body either in its present or a similar form. Furthermore, I also affirm that have not applied for a Ph.D. at any other higher school of education.

Göttingen,

....
(Signature)

....
(Name in block capitals)

2. I, hereby, solemnly declare that this dissertation was undertaken independently and without any unauthorized aid.

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....
(Signature)

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Curriculum Vitae

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02/2002 – 02/2002	Science Foundation Certificate University of the North, Polokwane, South Africa
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PUBLICATIONS

Lekalakala, R.G. and Schulze, R.E. 2010. Climate Change, Pests and Diseases: Background. In: Schulze, R.E. 2010. Atlas of Climate Change and the South Africa Agricultural Sector. Department of Agriculture, Forestry and Fisheries, RSA, Chapter 8.1, 285-288.

Nesamvuni E., **Lekalakala R.,** Norris D. and Ngambi, J.W. 2012. Effects of Climate Change on Dairy, South Africa. African Journal of Agricultural Research Vol. 7(26), 3867 - 3872.

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CONFERENCE PROCEEDINGS

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R.G. Lekalakala and R. E. Schulze. 2009. Projected Hydrological Responses to Land Degradation and Suggested Plausible Adaptation Strategies. Conference on Sustainable Land Management in Drylands of Southern Africa, Namibia

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SKILLS

Soft skills

- Project and people management
- Scientific writing and communication
- Information retrieval skills
- Networking

Research techniques

- Field and soil survey
- Irrigation design; Dam design (i.e. spillway)
- Data collection; Statistical analysis methods
- Measurement and estimation of basic hydrological parameters
- Agrohydrolocal Modelling, Geographical analysis (including mapping) and Remote sensing
- Climate change impact analyses and adaptation strategies analyses

Software:

- Statistical packages: Genestat, stastix, SPSS, Excel (Microsoft Office)
- Agrohydrological Models: *ACRU* Agrohydrological Model, SCS model, APSIM and DSSAT
- Geographical Information Systems and Earth Observation Tools: ArcView 3, Arc GIS,
- Microsoft Office: all
- Programming – Visual Basic

LANGUAGES

Sepedi – Mother Tongue
English – Advance
Afrikaans, German, Sesotho, Ndebele, Zulu – Basic