Climate change and maize production in the Vaal catchment of South Africa: assessment of farmers’ awareness, perceptions and adaptation strategies

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ABSTRACT: In recent years, maize production in South Africa has faced challenges related to climate change which have prompted farmers to adapt their production activities. We assessed factors informing the adaptive decision-making of maize farmers in the Vaal catchment by examining linkages between farmers’ experiences, their perceptions of climate change and the adaptation strategies they use. Data were collected through semi-structured household-level interviews, key informant interviews and focus group discussions. Catchment climate data were also collected to determine key 30 yr trends (1989−2018) and the farmers’ level of awareness about these trends. Data were analysed using descriptive statistics, Mann-Kendall (MK) test, Sen’s slope test, climate anomalies and multinomial logit modelling. Results suggest that maize farmers in the catchment are aware of climate change (95%), with many of them referring to it as ‘a shift in climate’. This perceived ‘shift’ is supported by meteorological data, as the MK test confirmed a decreasing inter-annual precipitation trend (−0.149) and a decreasing trend at the onset of the maize planting season (−0.167), with temperature showing an increasing trend (0.470). These trends have inspired the adoption of a range of timing-related responses and other farming and off-farm adaptations. Modelling results revealed farmer perception, farmer typology and the nature of maize production (rainfed) as some of the variables with a deciding influence on the nature of the adaptation employed. The study confirms the importance of understanding intersections between qualitative and quantitative variables in triggering adaptive responses. Current strategies need to be expanded and supplemented to improve resilience and prevent maladaptation.

KEY WORDS: Maize farmers · Climate change · Perception · Adaptation · Vaal · South Africa

1. INTRODUCTION

Climate change threatens sustainable development in Africa by placing additional burdens on the environmental and social resources required for sustenance. In many African countries and regions, agricultural production and access to food are projected to be severely compromised by climate variability and change (IPCC 2007). The detrimental consequences of these changes are expected to profoundly impact those involved in agriculture, due to agriculture's direct dependence on climate-sensitive parameters such as temperature, rainfall and soil fertility (Bedeke et al. 2018, Khanal et al. 2018, Shoko et al. 2019, Soglo & Nonvide 2019, Thinda et al. 2020). Climate change adds considerable dynamics of uncertainty to agricultural production by increasing the frequency of floods, drought, temperature extremes and soil degradation. Current changes in climate are affecting crop yields differently in many regions. The adverse impacts of these changes are experienced most severely in regions where rainfed food production is the dominant source of staple food (Ndhleve et al. 2017), therefore threatening food security.

Responses to climate variation differ between regions and are dictated by histories, perception of change and viability of available options (IPCC 2007). Historical discourses on climate change, however, have generally not been people-orientated (Bonewit & Shreeves 2015). The introduction of socio-economic paradigms into these discussions has thus been slow and only recently gained some momentum. With this momentum there is a growing consensus that the vulnerability of agricultural populations to climatic conditions cannot solely be understood through the quantification of biophysical impacts. There is also a need to understand the nature of intersections between climate change, local contextual challenges, farmers' perceptions, current coping mechanisms and farmers' decisions to adapt (Tucker et al. 2010). Studies that explore the social aspects of vulnerability to climate change with in-depth examination of the underlying socio-economic and institutional factors are therefore needed (Wehbe et al. 2005) to inform the development of suitable and context-driven adaptation processes for vulnerable populations.

Climate change has contributed to global agricultural decline by about 1−5% per decade over the last 3 decades (Mashizha 2019). Bannayan et al. (2016) predicted a decline in crop production by as much as 82% due to climate change within the next century. African countries and regions are projected to be severely compromised by the negative relationship between agriculture and climate change (IPCC 2014a, Soglo & Nonvide 2019). The IPCC (2007) predicted that this negative relationship would lead to losses in yield by as much as 50% in 2020 relative to food production levels at that time. This trend was expected to further entrench food insecurity and malnutrition concerns.

South Africa is a water-stressed country (Nhamo et al. 2020), which is further predisposed to the impacts of climate change due to its location in a semi-arid region. The country's agricultural sector is mostly rainfed, which renders it particularly vulnerable to climatic variability (Dabrowski et al. 2008, Ndhleve et al. 2017). Agriculture in South Africa sustains more than 70% of southern Africa's food, employment and livelihood needs (Cammarano et al. 2020). Added to climate-related concerns, farmers in South Africa are also subjected to limitations such as insufficient access to arable land, high production costs, weak technological support and poorly implemented policy initiatives, which all tend to exacerbate the challenges experienced by farmers trying to adequately respond to climatic threats (Mapfumo et al. 2014).

Maize Zea mays L. is the most important field and food crop in South Africa (Ambrosino et al. 2014, Mangani et al. 2019) and the largest locally produced field crop (Ambrosino et al. 2014). South Africa is one of the largest producers and exporters of maize in the Southern African Development Community (SADC) (Dabrowski et al. 2008), with more than 11 Mt produced in the 2018/2019 maize planting season (Department of Agriculture, Forestry and Fisheries; DAFF 2018). This field crop is predominantly produced in the Highveld region of South Africa, which constitutes the whole of Gauteng, almost the whole of the Free State, and portions of the Northern Cape, Mpumalanga, North West and Limpopo (Walker & Schulze 2008). A decline in the rate of maize production is already evident in South Africa.

This declining trend is expected to continue as temperature increases and an intensification and increase in the frequency of dry spells are anticipated in the future (Oduniyi et al. 2019). In 2019, the decline in total maize production in South Africa was also attributed to delayed rainfall in some parts of the maize production areas at the start of the planting season, which rendered farmers unable to complete the planting process due to lower soil moisture (DAFF 2019).

Mangani et al. (2019) projected a yield reduction by 1% associated with each degree day above 30^0C under optimal rainfed conditions in the key maize production regions of South Africa. This is expected to increase to 1.7% when drought conditions are experienced at around 21 d before anthesis (Mangani et al. 2019). They further reported that yield variations due to extreme events such as low or high temperatures or water deficit are the result of flower death and failure in pollination (high or low temperatures), while water stress reduces seed sets. A 24.3% reduction in maize yield was reported by Mangani et al. (2019) for the planting season 2014/ 2015, due to drought and heat waves. Maize production also dropped by another 21.4% in the 2017/2018 season compared to the previous seasons (DAFF 2019). These decreasing trends were attributed to delayed rainfall in some parts of the maize production areas at the start of the planting season, which resulted in a decline in the area planted for maize production (DAFF 2019).

In response to the declining trends in terms of maize production due to climatic conditions, adaptation is increasingly seen as an absolute necessity. However, the IPCC (2014b) cautions that adaptation can reduce the impacts of climate change, but its effectiveness is constrained by increasing rates and magnitude of climatic changes. Adaptation should therefore be proactive, dynamic, viable and constantly revisited to ensure that the interventions provide adequate resilience towards sustainable crop production, food security and livelihoods.

Khanal et al. (2018) suggested that farmers are aware of climate change and have been adjusting agricultural management practices to deal with climatic and non-climatic stresses. South Africa has a dual agricultural economy, comprising a well-developed commercial farming sector and an evolving subsistence farming sector (Greyling & Pardey 2019, Cammarano et al. 2020), creating a diverse maize production system in this country. The impacts of climate change and responses are expected to be unique for different sectors and regions, hence a homogeneous climate change policy and adaptation plan may be inadequate. There is therefore a need to not only understand the range of perceptions and nature of adaptation responses, but to also understand the varying levels of exposure to climate risk by farmers involved in different scales of maize farming in the maize production areas. The kind of assessment which seeks to examine the differential range of adaptation responses and its level of alignment to good adaptation could help inform the understanding of current adaptation approaches and challenges related to this.

The impacts of climate change on agriculture in South Africa are well documented (Walker & Schulze 2008, Wilk et al. 2015, Elum et al. 2017, Oduniyi et al. 2019, Shoko et al. 2019). Furthermore, several studies have examined farmers' perceptions of climate change on maize production and adaptation approaches deployed to improve resilience within these contexts (Chikosi et al. 2019, Ndhleve et al. 2017, Oduniyi et al. 2019, Oduniyi & Tekana 2019). However, most of these studies focused on the impact and perception of climate change by either smallholder farmers or commercial farmers in isolation, with the smallholder farmers receiving more attention as they are perceived to be more vulnerable. The differential observation of climate change by different farmer typologies within the same region and the appraisal of their different responses is an area that has not received much attention. To our knowledge, perceptions of climate change held by the different maize producer typologies in the Vaal catchment of South Africa have not been examined to date. The level of alignment between farmers’ perceptions and actual meteorological evidence has also remained mostly underexplored.

Against this background, we assessed farmers’ awareness and perceptions of climate change and how it impacts their maize production in the Vaal catchment. We then appraised the level of congruence between farmers’ perceptions of the changes in climate and actual meteorological trends. We also evaluated the nature of adaptations deployed by the farmers, against questions about the appropriateness of these adaptive strategies, i.e. ‘good practice’ as applicable in the context of the Vaal catchment. We furthermore attempted to understand factors that would have a bearing on the nature of the adaptation strategies implemented by the farmers. We hypothesized that maize farmers in the Vaal catchment are aware of and are perceiving changes in climate. We also hypothesized that farmers’ perceptions are consistent with meteorological evidence which informs their adaptive responses. In addition, we hypothesized that underlying factors could be limiting the adaptive responses of farmers, which may manifest as a form of maladaptation.

The study seeks to contribute to a better contextual understanding of the level of awareness and perception of climate change amongst maize farmers in the Vaal catchment and the nature of their adaptive responses. It highlights the potential for maladaptation if adaptations deployed are not implemented correctly, or where factors limit the farmers’ ability to efficiently apply the strategies. Our findings could inform the development of a suitable adaptation strategy or guidelines to stabilize or prevent the decline in maize production in the Vaal catchment area.

2. LITERATURE REVIEW

This section provides a review of literature on climate change adaptation strategies implemented by farmers globally, including in South Africa, to provide a contextual background to the study. The section details what are deemed to be ‘good adaptation practices’ that have been used elsewhere in the world to improve resilience of farmers to the threats associated with climate change. This brief literature review also emphasizes the importance of achieving alignment between the adaptation strategies deployed in a certain region and actual climatic conditions in order to avoid current or future maladaptation.

Variation in climate is the principal cause of changes in food production, i.e. periods of surplus or deficits in grain production (Oduniyi et al. 2019). Changes in the onset of the rainy season directly influence farm management practices, from planting and crop development to harvesting, because it could lead to insufficient soil water content during the developmental stages of the crop, which will affect yields (Sadiq et al. 2019, Roffe et al. 2020). This view is supported by Moeletsi et al. (2011), who contended that rainfall in semi-arid parts of southern Africa is among the most important elements affecting agriculture, as soil water availability substantially influences crop growth, development and yield. Farmers across the world have therefore been deploying coping mechanisms in the form of adaptation to improve their resilience.

In Bangladesh, hazard-prone rural households recognised the impacts of climate change on their livelihoods and adopted a range of farming and non-farming strategies, which varied significantly amongst farming groups. Strategies such as using new crop varieties, changing planting dates and migrating were the key strategies used (Alam et al. 2017). In Nepal, Khanal et al. (2018) concluded that the adoption of appropriate adaptation strategies has significantly increased food productivity. They found that adaptation strategies such as soil and water management have had the most significant influence on food productivity, followed by the timing of farm operations and crop variety adjustments (Khanal et al. 2018). In Iran, the introduction of new, late-maturing cultivars, irrigation, a slight increase in fertilizer application, change in planting dates and the introduction of heat-tolerant varieties showed a positive impact on maize yield in cooler parts of Iran (Rezaei & Lashkari 2019). In China, 3 adaptation measures, namely changing planting dates, switching to a later maturing cultivar with a longer growth period and breeding cultivars with high thermal temperature requirements, were found to increase maize yield to varying degrees (Lin et al. 2017). Amongst these introduced measures, the study concluded that switching to the later-maturing cultivar was the most effective for coping with the adverse impacts of a future warming climate (Lin et al. 2017).

Several studies have also been conducted in South Africa to assess the impact of change in climate on maize production. Mangani et al. (2019) modelled the impact of climate change and quantified the response of maize yield to projected climate in the Highveld area of South Africa. Using 6 general circulation models and 3-time horizons, representing the baseline (1990−2020), near future (2021− 2050) and far future (2051−2080) time periods, the impact of extreme heat and drought on maize production was simulated with climate data generated from 2 radiative forcing scenarios. Reduced future maize yields were projected especially for the far future time period. A simulated maize yield reduction of between 18 and 30% is predicted for different locations of the Highveld (Mangani et al. 2019). In another study, Oduniyi et al. (2019) reported that climate change has led to a drastic decline in the production of maize in South Africa. It was also implied that this will lead to substantial negative impacts on the maize economy and a major shift in area and production of maize in South Africa. Findings and predictions from studies like these thus illustrate the need to develop effective adaptation strategies for maize farmers, especially in the epicenter of maize production in South Africa.

These findings also emphasize the need for maize producers in South Africa to adapt to climate change in a manner that would ensure current and future sustainable production of maize in the country. Some progress towards achieving these goals have already been noted according to Ndhleve et al (2017), Oduniyi & Tekana (2019) and Cammararo et al. (2020). Maize farmers in South Africa are aware of climate change (Ndhleve et al. 2017, Mangani et al. 2019, Oduniyi et al. 2019, Oduniyi & Tekana 2019) and they are already responding to the associated risks by deploying a number of adaptation strategies. The studies highlighted below describe some of the adaptation approaches that are being used by maize farmers to avert the threats associated with climate change.

In their assessment of the potential role of supplemental irrigation and its differential impact on maize yield in the Eastern Cape Province of South Africa, Ndhleve et al. (2017) concluded that surveyed farmers were in fact adapting. These Eastern Cape farmers also ranked irrigation and the change in planting dates as their most important strategies towards combatting the impacts of climate change. Strategies related to the use of improved seed varieties, following the weather forecast, land preparation timing and others were ranked lower in terms of importance. Ndhleve et al. (2017) therefore proposed that the use of supplementary irrigation could be instrumental in reducing the impact of drought or delayed onset of rainfall on maize yield. Oduniyi & Tekana (2019) investigated the perceptions and adaptation strategies of maize producers in the North West province of South Africa. Outcomes from the study illustrated the impacts of climate variability in that province, with evidence of farmers deploying strategies such as minimum or zero tillage, diversifying crops, planting different crops, switching to drought tolerant crops, rotating crops, changing planting dates, reducing planting area and shortening growing periods.

Calzadilla et al. (2014) evaluated the efficacy of the development of irrigation and improvements in agricultural yield as adaptation options to cope with climate change in South Africa. They suggested that for South Africa to adapt to the adverse consequences of global climate change, it would require yield improvements of >20% over baseline investments in agricultural research and development. They reported that an increase in agricultural productivity achieves better outcomes than an expansion of irrigated areas, due to the overall low initial level of irrigated areas in the region and that improvements in agricultural productivity are an effective strategy that could offset the negative impacts of climate change (Calzadilla et al. 2014). Suggested crop improvement measures include crop breeding, enhanced agronomic practices and improved farmers' extension services, particularly for emerging smallholder farmers who are gradually expanding their crop production, and evolving from just subsistence production to selling their produce (Pienaar & Traub 2015).

Information about the diverse range of adaptation strategies towards reducing the associated threats of climate change on maize production is becoming widely available to the farmers, but insights into potentially maladaptive responses remain somewhat limited. Educating farmers about the benefits of adaptation is therefore essential, but there is also a need to ensure that the farmers correctly understand and interpret their local climatic contexts to make appropriately informed decisions about the adaptation approach they choose to use.

According to Work et al. (2019), based on research into multiple types of climate change mitigation and adaptation projects and policies in Cambodia, adaptation initiatives are seen to be intertwined in both policy and adaptation project creation, and this confluence creates potential for maladaptive outcomes. According to Holzkämper (2017), adaptation decisions made under the wrong assumptions may result in undesirable outcomes, especially when short-term benefits outweigh long-term social, economic and environmental costs. Holzkämper (2017) therefore warned that the risk of maladaptation is a key challenge in adaptation planning that requires attention. Making adaptive choices with insufficient information and choosing cultivars and planting dates in relation to the onset and availability of rainfall are examples of adaptive responses which are sensitive to external factors that may affect the vulnerability of farmers and could result in maladaptation. Certain adaptation practices which may be necessary and useful in averting immediate impacts may limit current and future adaptation efforts of others.

The combination of all of the factors highlighted in this study, thus far, suggests that adaptation has become a necessity and not an option in the sustainable production of maize. The literature also highlights the need to recognise potential opportunities for maladaptation, especially where adaptive responses do not align with context-specific climatic conditions or where adaptive responses are limited due to underlying factors that prohibit the application of these strategies to its fullest extent. The next section details the methods we used during our inquiry to understand the dominant perceptions about climate change held by maize farmers in the Vaal area and their adaptive responses.

3. MATERIALS AND METHODS

The study employed a mixed-method approach wherein quantitative and qualitative data were collected and analysed. The unit of assessment was maize farming households in the area. A combination of structured questionnaires (n = 105) and semi structured open-ended key informant interviews (n = 5) and focus group discussions (n = 5) were used. Climate data were also analysed to verify the level of congruence between actual climatic trends and the farmers' perceptions of changes in climate in their area. Data generated from the perception studies were collated and statistically analysed using Statistical Package for the Social Sciences (SPSS 26). Quantitative climate data were analysed using XLSTAT 2020.3.1 The farmers' perceptions were then compared to empirical climate and maize yield data for the catchment, to assess the level of interdependence between these variables. A multinomial logit model was used to estimate the factors that influence adaptive responses to climate change. In addition, the alignment of the array of adaptations utilized by the farmers to global maize adaptation good practices was also explored to identify areas of possible maladaptation.

3.1. Study area

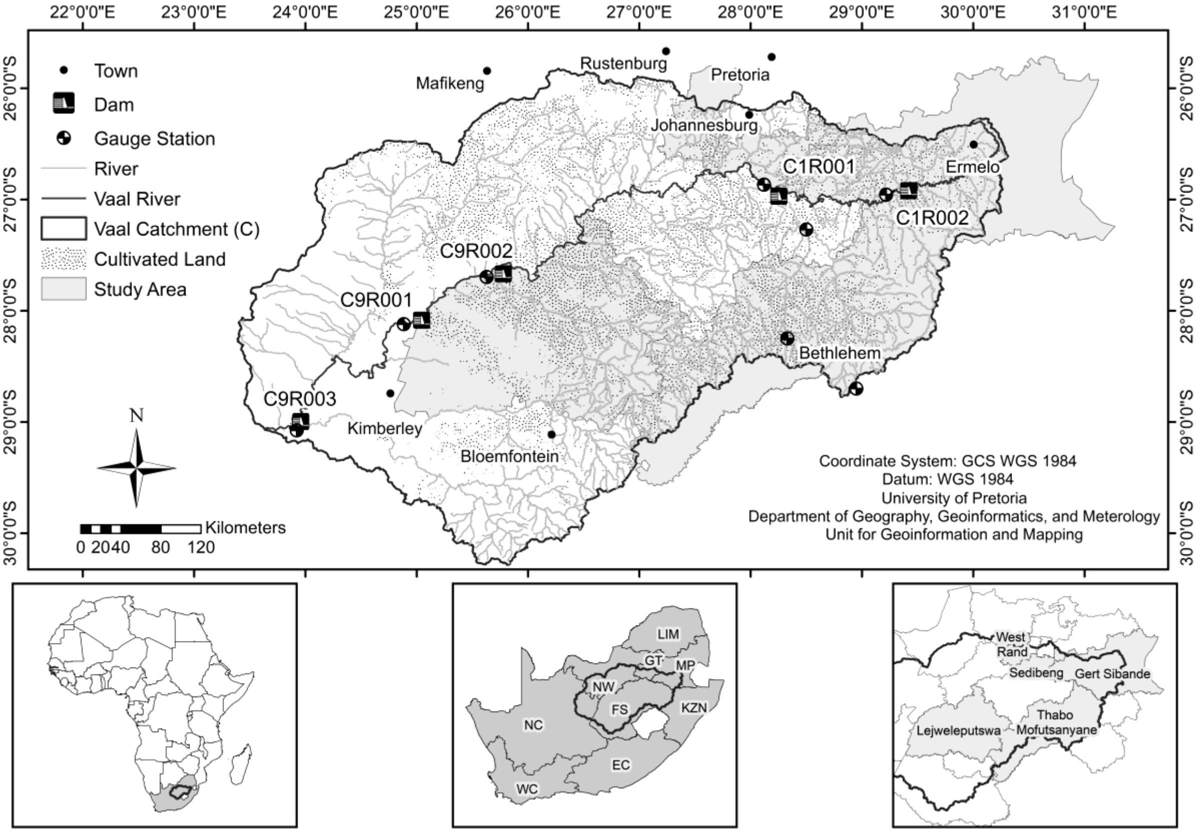

Fig. 1. Vaal river catchment, showing the provinces and districts where the study was conducted. Adapted from the South African Weather Services. LIM: Limpopo; GT: Gauteng; MP: Mpumalanga; NW: North West; FS: Free State; KZN: Kwazulu Natal; NC: Northern Cape; EC: Eastern Cape; WC: Western Cape

The Vaal catchment, which is located at 26−28^0 S, 25−29.5^0 E in the north-central and eastern parts of South Africa. Has an approximate size of 192 000 km2 (Fig. 1) The elevation range for the catchment is between 1250 and 2220 m. The mean annual temperature is 15^0 C, with peak temperatures experienced in January and minimum temperatures experienced in July. Rainfall occurs in the spring/summer months of October to April, with highest rainfall experienced in December and January. The catchment's mean annual precipitation is 650 mm. Maize production is the predominant agricultural activity in this area, which is located within the Highveld region of South Africa, an important region responsible for most of the food and feed production for the nation; 70% of the country's cereal crops and 90% of the commercially cultivated maize are grown here (Walker & Schulze 2008, Dabrowski et al. 2008). Data were collected in 3 provinces in the catchment: Free State, Gauteng and Mpumalanga. The choice of the 3 provinces was based on the fact that Free State and Mpumalanga are the top 2 maize-producing provinces, while Gauteng is the top maize exporter (DAFF 2019).

The maize-planting season, which is about 90% rainfed, begins in October and runs to January, and harvesting occurs between May and August of the following year (DAFF 2019). From a methodological perspective, it is important to note that South Africa has a farming typology characterized by a well-developed commercial farming system, typified by large economic investments on the farms, modern crop management techniques, high inputs, extensive use of labour and market-oriented products, in contrast to the smallholder farms, which usually have low use of inputs and minimal labour, with production oriented to local markets and self-consumption (Cammarano et al. 2020). Kirsten & van Zyl (1998) submitted that the South African farmer classification is unique and has mainly 2 categories: (1) the smallscale (smallholder), predominantly black farmers mostly in South Africa's former homeland, and (2) the large-scale commercial farmers, who are mainly white. Kirsten & van Zyl (1998) were of the opinion that the South African farmer typology is in contrast with the situation in many other countries in the world, where the typology would be based on a range of farm sizes. They therefore redefined South Africa’s farmer classification with the notion that farmer typology does not only relate to farm size but also to its viability.

In the Vaal catchment, the farmer typology is unique; for the purpose of this research, we take into account the definitions of farmer typology provided by Cammarano et al. (2020) and Kirsten & van Zyl (1998). We classified the diversity of maize farmer types in the Vaal catchment into 2 categories, i.e., smallholder (also referred to as small-scale) and commercial maize farmers. We define smallholder farmers as maize producers who cultivate maize, both for local market and subsistence use, on either owned, leased, rented or communal land, and where the majority of labour comes from family members. They are considered as having low market participation and inputs and are constrained by finances and land. Production systems can be either rainfed or irrigated. In contrast, commercial farmers are typified by large farming enterprises and investments on owned land, modern crop management techniques, high inputs, rainfed or irrigated crops, use of hired labour and profit and market-oriented.

Maize in South Africa is produced by an estimated 9000 commercial farmers, who produce about 98% of total maize annually, while the numbers of the smallholder farmers are unknown (DAFF 2017, Grey ling & Pardey 2019). Gouse (2016) posited that some 46 500 small holder farmers across the country purchase hybrid maize seed annually; of these, about 70% are located in the Eastern Cape and Kwazulu Natal provinces (DAFF 2018) (which are outside of the Vaal catchment). The other 30% are spread across the country.

3.2. Data collection

3.2.1. Sampling

In this study, the unit of data collection was the maize farming household, with the head of the household as the informant. A 3-stage sampling technique was utilized. In the first stage, the Vaal catchment and the 3 provinces were purposively selected due to their location in the key maize-production region of South Africa (the Highveld) and because they are among the largest maize-producing provinces, with high vulnerability to adverse impacts of climate change (Akanbi et al. 2020). In the second stage, we also purposively selected the Gert Sibande, Letjwele putsa, Sedibeng, Thabo Mofutsanyane and West Rand districts of Free State, Gauteng and Mpumalanga provinces because they are the highest maize producing districts with homogeneous climate. For the purpose of this exploratory study, the full population of commercial maize farmers (n = 9000) (DAFF 2018) was adopted as the total population, with the number of commercial maize producers in the 3 provinces estimated as 6165 (43.6% from Free state, 19.6% from Mpumalanga and 4.1% from Gauteng; Statistics South Africa 2017) and the remaining as small holders. In the third stage, a database of household heads was accessed through extension services and farmer associations, and informants were selected using simple random sampling. The sample size was determined using the sample size calculator of Yamane (1967), which is given by:

$$\frac{\mathrm{N}}{1+\mathrm{N}(\mathrm{e})^{2}} \tag{1}$$

where N is the sample size (N = 9000 is the estimated population of the maize farming households in the selected districts), e = margin of error (estimated at 0.0968), at a 95% confidence interval. This yielded a sample size of 105. Structured questionnaires consisting of both open and closed-ended questions were administered to the farmers through face-to-face interviews. The questionnaire data were captured under the following main sections; demographics, socio economics, farming history/models, plot size, yield, production and marketing challenges, perception of climatic changes, adaptation strategies, and current and future requirements for sustainability. Household surveys were followed by de tailed interviews with key informants, who were knowledgeable individuals with in-depth understanding of maize production dynamics and the interplay between stakeholders in the study area. Key informants were selected using a convenience sampling approach, which entailed interviews with industry specialists and extension officers based on their availability. They were also able to assist with the triangulation and verification of data collected during field visits conducted between June 2019 and January 2020.

3.2.2. Maize production and climate data

The primary quantitative and qualitative data collected from the household survey were complemented with secondary data about historical and current maize production per annum obtained from DAFF[1] and from the South African Grain Information Service (SAGIS)[2] online database. We then obtained 30 yr temperature and precipitation data from the South African Weather Services (SAWS) for the period 1989−2018.

3.3. Data analysis

Survey data were processed, coded and recorded using SPSS 26. Responses were subjected to thematic analysis, descriptive statistics, including percentages, mean and frequency analysis. To assess, categorise and compare demographic/socioeconomic information of the maize-farming households, awareness and perceptions of climate variation, adaptations employed and the barriers to adaptation. In addition, changes in climate and maize yield patterns in the catchment were explored to evaluate their agreement with the farmers' perceptions. To assess what determines adoption of different adaptive measures, we used a multinomial logistic (MNL) regression model. This model is regularly used in decision studies involving multiple choices (Alhassan et al. 2019). According to Alhassan et al. (2019), the advantage of this model over other models such as binary probit or logit is its ability to analyse several adaptation decisions across more than one category. The dependent variables used for this assessment are the 4 main adaptation strategies used by the farmers. Following Ahmed & Ahmed (2019), the multinomial logit regression model utilized in this study is expressed as:

$$Yi = F\ (X1, X2, \ldots, X9) \tag{2}$$

where Yi, the dependent variable, is polychotomous and is the method of choice among other alternatives, i.e. changing planting dates, use of improved seeds, early soil preparation and irrigation.

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[1] https://www.dalrrd.gov.za/Home/Crop-Estimates

[2] https://www.sagis.org.za/historic%20hectares%20&%20production%20info.html

The independent/ explanatory variable X denotes the socioeconomic factors, i.e. farmer typology and gender; type of maize production, i.e. rain-fed or irrigation; education; years of experience; land/tenure type of ownership; farm management option; and perception.

To analyse the climate data, 30 yr monthly precipitation and temperature data were processed to assess monthly and inter-annual variation and trends. Non-parametric Mann-Kendall test and Sen slope estimator were used to determine the climate trends, slope magnitudes and standardized precipitation anomalies. Mann-Kendall test is used to detect the presence of monotonic (increasing or decreasing) trends in the study area and to determine if the trends are statistically significant (Asfaw et al. 2018).

According Asfaw et al. (2018), the Mann-Kendall test S is given as:

$$S = \sum_{i=1}^{n-1} \sum_{j=k=1}^{n} sign\left(X_j - X_i\right) \tag{3}$$

The application of the trend test is done to a time series Xi that is ranked from i = 1, 2…n − 1 and Xj, which is ranked from j = i + 1, 2…. n. Each of the data points Xi is taken as a reference point which is compared with the rest of the data points, i.e. Xj. Detailed calculations of the Mann-Kendall test and the Sen slope are available in the study by Asamoah & Ansah-Mensah (2020). The null hypothesis of the Mann-Kendall test is that there is no trend in the time series, while the alternative hypothesis is that there is trend. A positive Mann-Kendall value indicates an increasing trend, while a negative value indicates a decreasing trend.

4. RESULTS

4.1. Socio-economic characteristics of the maize-farming household respondents

Table 1 provides a summary of the socio-economic characteristics of the farming households. Results indicate that roughly one-third of the respondents were female (30%) and two-thirds were male (70%). More than 75% of the respondents were between the ages of 36 and 65 years old and 12.5% were either younger than 35 yr or older than 65 yr.

Table 1. Demographic and socio-economic characteristics of the responding maize farming households (n = 105) by frequency and percentage of respondents from each province in which data were collected. Source: field survey data 2019/2020

Variable	Frequency (%)						
	Gauteng		Mpumalanga		Free State		% of total
	n	%	n	%	n	%	
Gender							
Female	13	12	18	17	1	1	30
Male	32	31	23	22	18	17	70
Age (yr)							
<34	5	5	6	6	2	2	12
35–65	35	33	32	31	12	11	75
>66	5	5	3	3	5	4	12
Farmer typology							
Smallholder	30	29	26	25	0	0	54
Commercial	15	14	15	14	19	18	46
Sources of income							
Farming	22	21	28	27	12	11	59
Other	23	22	13	12	7	7	41
Level of education							
<Matric	12	11	30	29	6	6	45
<Undergraduate	30	28	9	9	11	11	48
<Postgraduate	3	3	2	2	2	2	7
Years of experience							
<5	19	18	18	17	2	2	37
6–10	17	16	15	14	5	5	35
>11	9	9	8	8	12	11	28

This indicates that it is the active labor force cohort of the sample that is most active in maize production in the catchment. The bulk of the farmers (59%) depend on maize production as their main source of income, and 28% of the respondents have been farming for >10 yr, about 35% of the respondents have been farming for between 6 and 10 yr, and the majority (37%) for <5 yr.

4.2. Assessment of the perception of climate change

Of the 105 maize-farming households from the Vaal River catchment who participated in the study, descriptive analysis indicates that 90.5% are aware that the climate is changing based on perceived changes in local indicators, i.e. annual temperature and rainfall. Table 2 indicates that maize farmers in the catchment are observing climatic changes in the form of delayed onset of rainfall (95%) and the early cessation of rainfall, with most of the farmers referring to this as 'climate shift' to explain their observation. Others perceived changes in terms of the occurrence of drought (92%), floods, temperature extremes (91%), hailstorms, early frost, extreme winds and reduced rain. The farmers expressed their perceptions based on their observation of warmer summer and colder winter temperatures and rainfall variation over the years. Using descriptive statistics such as percentages and frequencies, their perceptions were evaluated and are summarized in Table 2.

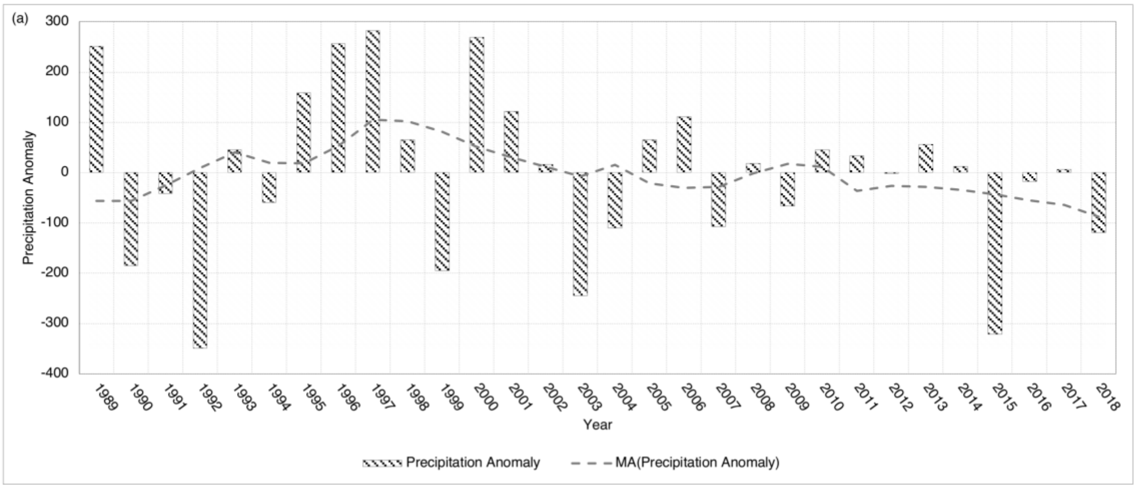
According to the respondents, the media and farmer associations are the main sources of climate change information, as only 26% of the respondents obtain their climate information from extension services while 35 and 39% of the respondents get their information from farmer associations and the media, respectively.

Perceived change in climate	Frequency	Percentage
Change in climate	95	91
Delayed or less rain	100	95
High temperature uncertainty	95	91
Drought/floods	97	92

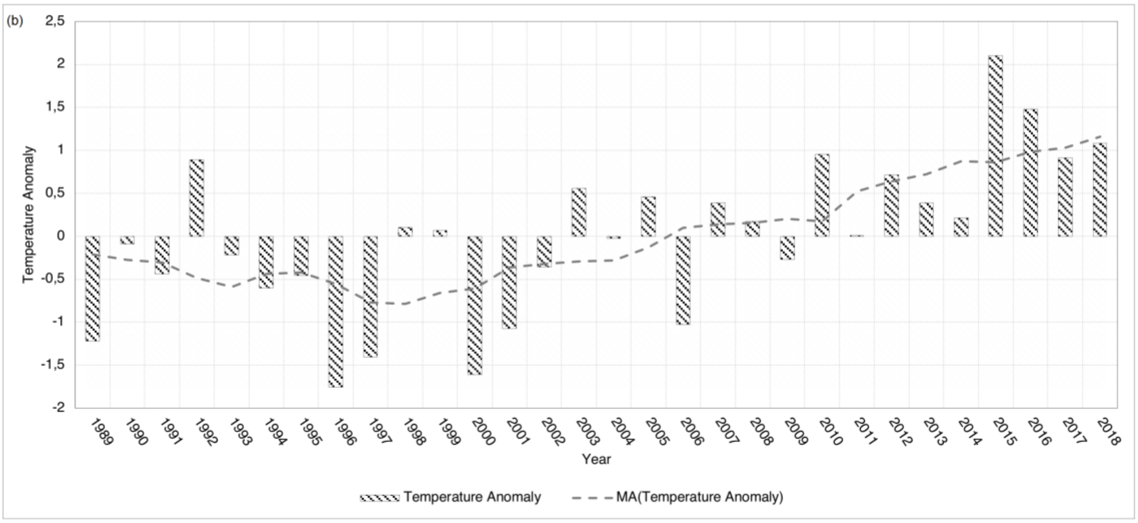
4.3. Correlation between farmers' perceptions and meteorological data

Maize farmers in the catchment have been perceiving warmer summer and colder winter temperatures. They have also perceived a decline in precipitation and a shift in the onset of rainfall during the maize planting season.

Fig. 2a presents the catchment's annual observed precipitation departure from the observed 30 yr average. In the 30 yr period of 1989− 2018, there has been constant variation in catchment's precipitation, with periods of decrease and increase in annual precipitation, with the peak decreases in 1992 and 2015. Highest precipitation occurred between 1994 and 1999, with the peak in 1997. Temperature (Fig. 2b) has been increasing since the early 2000s, peaking in 2015. The lowest deviation from the 30 yr average temperature was observed between 1996 and 2000 and the highest between 2010 and 2018.



Precipitation anomaly and moving average



Temperature anomaly and moving average

Fig. 2. (a) Precipitation (with moving average, MA) and (b) temperature departure from 30 yr inter-annual averages (1989− 2018). The MA for precipitation shows constant variation, whereas the MA for temperature shows a persistent and increasing tendency

To assess if there is a consensus between farmers' perceptions of climate variation in the catchment and meteorological data (empirical historical and current climate), results of the inter-annual precipitation Mann-Kendall trend test shows a decreasing trend of −0.149 and a Sen slope magnitude of −4.333, although there was no statistical significance ($p > 0.05$). The decreasing trend corroborates the farmers perception of decreasing precipitation. Their perception of a shift in precipitation is also confirmed, as the October and November rainfall signifying the beginning of the maize-planting season has also decreased, with rainfall increases only concentrated in December and January (Fig. 3).

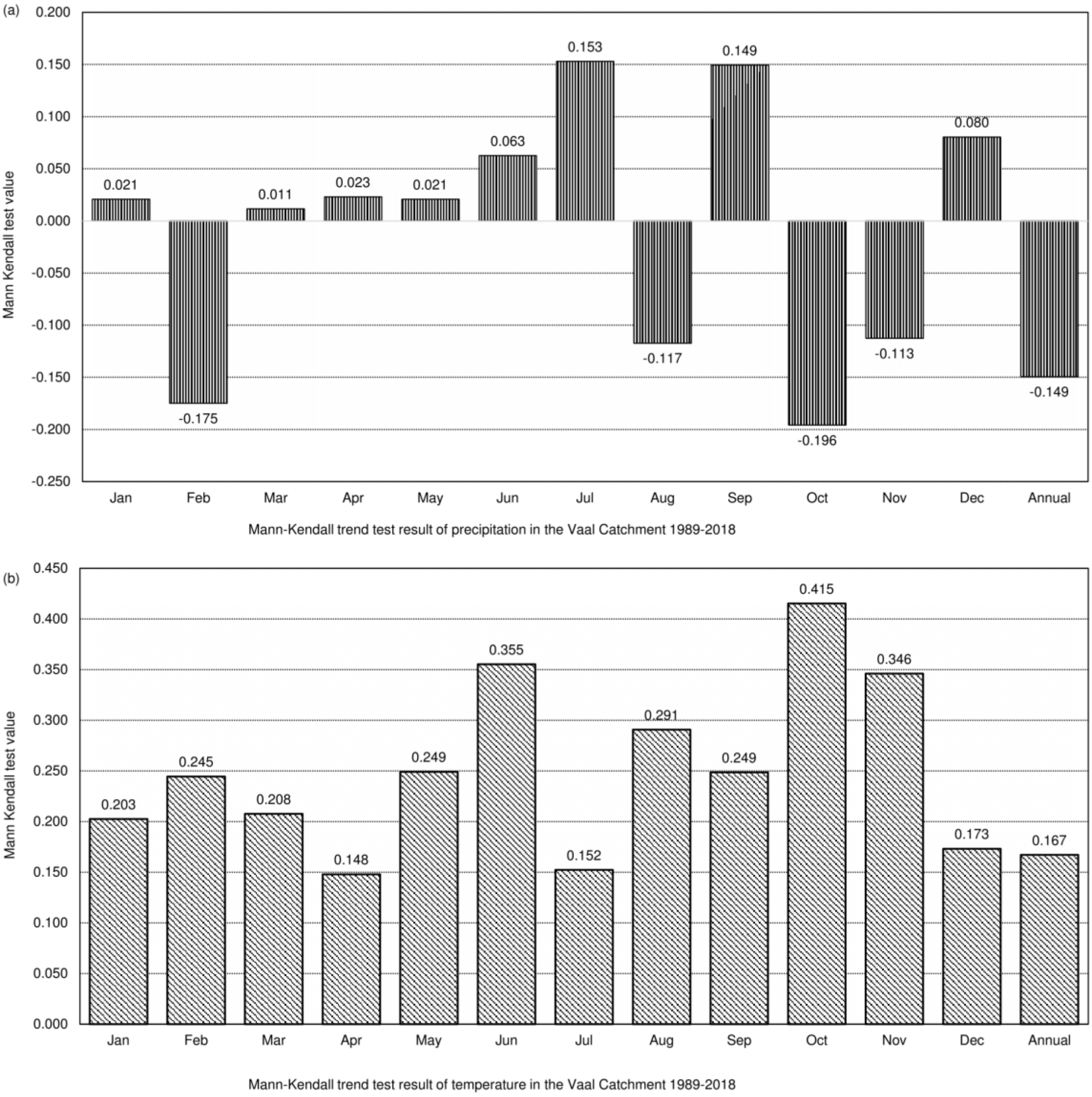


Fig. 3. Results of the Mann-Kendall trend test for (a) precipitation and (b) temperature for the Vaal catchment. (a) An intra-annual precipitation variation trend is evident in some months, with the maize planting season showing the highest decline in precipitation. (b) Temperature shows a constant increasing trend for the catchment. Adapted from South African Weather Service and South African Grain Information Service data. See Appendix Tables A1 & A2 for additional data

The annual temperature Mann-Kendall trend test shows a statistically significant trend (0.470; $p < 0.05$), rejecting the null hypothesis. Intra-annual temperature also shows a significant increasing trend for most of the months, with the onset of the maize planting season (October) showing the highest increasing trend (Fig. 3), confirming the farmers' perception of increasing temperature and decreasing rainfall.

Results of the bivariate correlation to describe the association between the catchment's inter-annual rainfall pattern and maize production (Fig. 4) showed that in the first 10 yr (1989−1998), there was a weak negative correlation of −0.04, indicating that as rainfall increased in the early 1990s after the initial drop, yield continued to decrease. This was as a result of the decline in area planted with maize due to the withdrawal of marginal lands from production (DAFF 2016). In the middle period of 1990−2005, there was a strong negative correlation of −0.5 between yield and change to the farmers. Source: field survey data 2019/2020 rainfall due to a continued declining trend in area planted. The introduction of improved crop varieties and improvement in planting practices resulted in a steady increase in yield and production of maize, despite the decrease in rainfall (1990− 2005). In the last decade (2009−2018), there was a strong positive correlation of 0.5, indicating that the farmers are aware of the changes in the rainfall pattern and have been adjusting maize production to stabilize and improve yield as rainfall fluctuates.

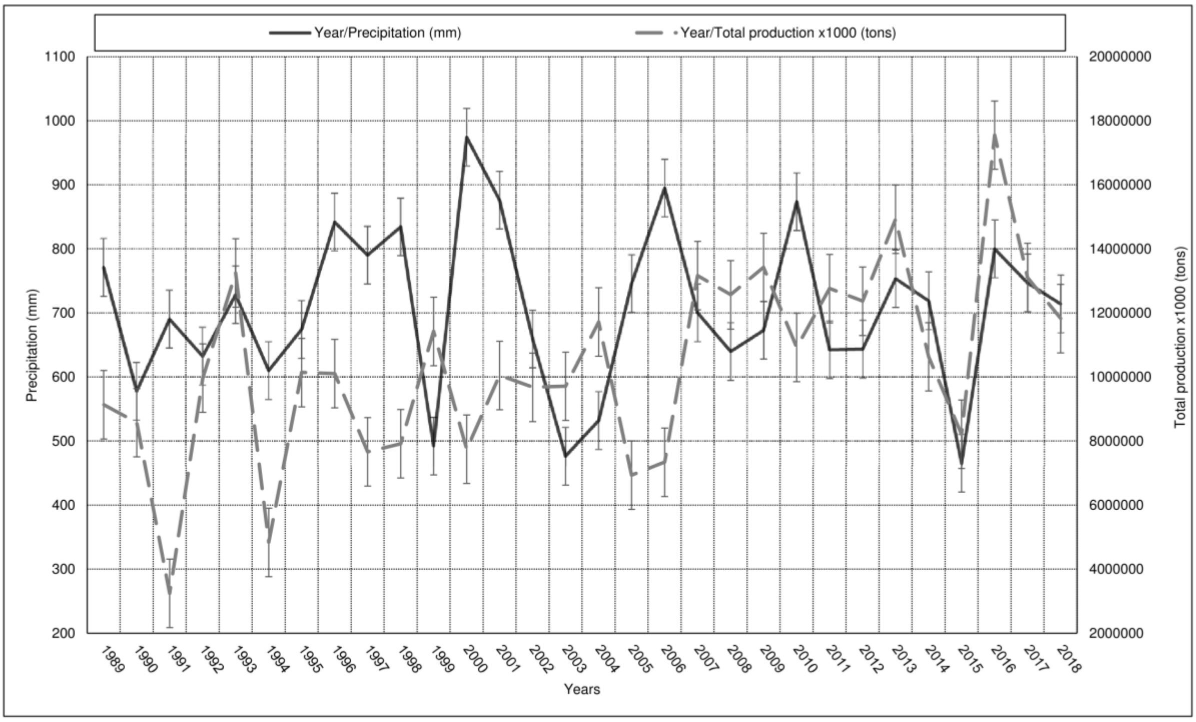
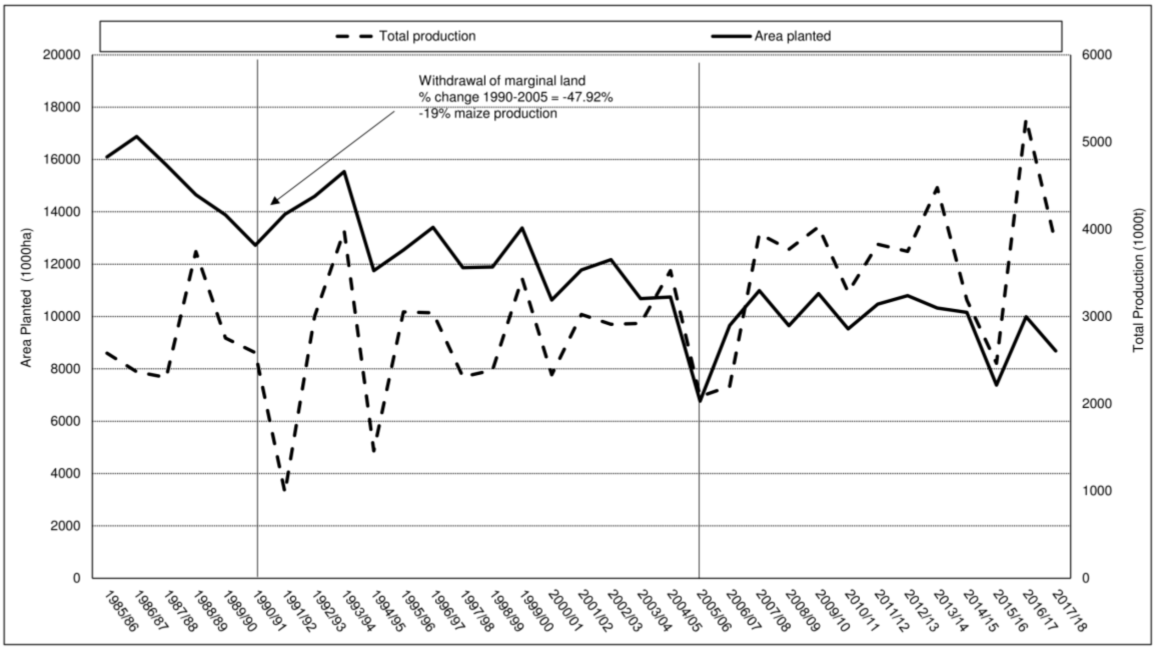


Fig. 4. Average annual rainfall and yield variation (error bars: 95% confidence intervals) with a non-linear association showing some agreement in recent years. The negative correlation in the first 2 decades is a result of land loss. A strong positive correlation is evident in the last decade

Results of our evaluation of the impact of the significant decline in maize production (19%) as a result of the reduction in land area planted to maize (Fig. 5), in the earlier period of the study 1990−2005, shows that 47% of arable land area used for maize production was lost in that period. This led to a reduction in the number of farms, farm employment and food production, and impacted livelihoods (Bernstein 2013).

Maize production became relatively stable after 2005, although the combination of land loss and the impacts of climate variation continue to weigh in on the sector despite the introduction of improved seed and agricultural technologies, which led to initial improvements in yields and production.



Adapted from DAFF 2018- Abstract of Agricultural Statistics

Fig. 5. Variation and association between the land area planted to maize in South Africa and the total maize production. The loss of land area planted to maize from the late 1980s to mid-2000 resulted in the initial substantial reduction in total maize production. This was leveled out with the introduction of improved maize varieties

4.4. Assessment of the local-context-specific adaptation strategies deployed by farmer’s

Results indicate that farmers in the Vaal catchment are adapting to the threats associated with a changing climate. According to the descriptive statistics reported in Table 3, adaptation approaches are not new to the respondents. Results from the study thus suggest that the majority of the farmers are already deploying various forms of adaptation to adjust their maize production to stabilize or increase yield. Some of the key responses are listed in Table 3, summarizing the most common adaptations used by the surveyed respondents.

Table 3. Key adaptation strategies deployed by maize farmers (n = 105) in the Vaal catchment based on their frequency of use. Source: Field survey data 2019/2020

Adaptation	Frequency	Percentage	Rank
Changing planting dates	96	91.4	1
Use of improved seed	90	85.7	2
Crop diversification	79	75.2	3
Early soil preparation	75	71.4	4
Irrigation	30	28.6	5

Changing planting dates, early soil preparation to keep moisture in, irrigation and use of improved seeds to stabilize yield in response to climatic and other non-climatic stressors are some of the adaptation choices. Changing planting dates, which is triggered by the delay in the onset of rainfall, is the most common strategy employed by the farmers (91%), followed by the adoption of improved seed varieties (86%), crop diversification, early soil preparation and irrigation. In most cases, farmers employed more than one of the adaptation strategies.

Table 4 shows the breakdown of the adaptation strategies applied by the different farmer typologies that participated in the study. Results of the chi-squared test shows no significant statistical difference (p = 0.24) in the deployment of the adaptation strategies by the different farmer typologies in response to climate change.

Table 4. Adaptation strategies deployed among the different farmer typologies in the study area by percentage, showing that the adaptation of planting dates is the predominant approach by the responding farmers (n = 105). There was no significant statistical difference in the deployment of the adaptation strategies by the different farmer typologies ($\chi2$ = 8000, p = 0.24). Source: field survey data 2019/2020

Adaptation to climate change	Farmer typology	
	Smallholder	Commercial-scale
Change planting dates	57 (n=32)	38 (n=18)
Early soil preparation	41 (n=23)	34 (n=16)
Irrigation	20 (n=11)	10 (n=5)
Improved seeds/ technology/other	52 (n=29)	38 (n=18)

4.5. Multinomial logistic model result

To examine the factors that influence farmers' choices of adaptation strategies in response to climate change, we used an MNL. The outcome of this assessment is presented in Table 5. The dependent variables are the choices of adaptation mostly deployed in the catchment as shown in Table 3. The reference group assumed there is no adaptation. The explanatory variables centered on the available socioeconomic data. Results displayed in Table 5 show explanatory variables that have significance at 10, 5 and 1% significance levels. MNL analysis shows that independent variables such as age, gender, type of maize production (rainfed) and farm management significantly influenced the use of changing planting dates as an adaptive response. Factors such as age, type of maize production, perception and awareness of climate change as well as farm management were found to influence the choice of improved crop and varieties. Crop diversification was influenced by farmer typology, farm management, perception of climate change and rainfed maize production.

Table 5. Parameter estimates of the multinomial logistic regression model, of the factors that have a deciding influence on maize farmers' adaptive responses to climate change in the Vaal catchment. Bold: significance — ***$p \leq 0.01$; **$p \leq 0.05$; *$p \leq 0.10$. Base category: no adaptation. Number of observations: 105

	Adaptation								
	Improved crop and variety			Changing planting dates			Crop diversification		
	Coef.	SE	Sig	Coef.	SE	Sig	Coef.	SE	Sig
Age	–1.307	0.653	**0.045****	–1.280	0.653	**0.050****	–1.285	0.716	**0.073***
Head of the household	0.291	0.976	0.766	0.465	0.958	0.628	0.436	0.959	0.649
Gender	–1.114	0.875	0.203	–1.125	0.857	**0.189***	–0.894	0.855	0.296
Education level	–0.093	0.893	0.917	–0.191	0.900	0.832	–0.530	0.962	0.582
Farming main source of income	0.335	0.765	0.661	0.251	0.762	0.742	0.352	0.795	0.658
Years of maize farming experience	–0.051	0.609	0.933	–0.151	0.595	0.800	–0.409	0.645	0.526
Farmer typology	–0.687	0.612	0.262	–0.919	0.591	0.120	–1.145	0.634	**0.071***
Farm management–hired labor	2.070	0.790	**0.009*****	2.138	0.802	**0.008*****	2.558	0.908	**0.005*****
Type of ownership	0.095	0.403	0.813	0.125	0.407	0.758	0.125	0.441	0.778
Awareness of climatic changes	1.020	0.686	0.137	0.875	0.668	0.191	0.845	0.696	0.225
Perception of the impact of climate change on livelihood:	–2.307	1.331	**0.083***	–2.798	1.444	**0.053***	–2.826	1.385	**0.041****
Type of maize production: rainfed	–1.878	0.891	**0.035****	–1.969	0.872	**0.024****	–2.247	0.952	**0.018****

4.6. Farmers' exposure and constraints to adaptation

Responses to our survey showed that the farmers can be categorised into 2 different subgroups based on the type of maize production. Outcomes from our study suggest that the effect of climate change impacts on farmers varies across farming scales. Smallholders were found to be more vulnerable, with impacts not only limited to their livelihood strategies but also extending to their level of food security, as some of the farmers consume and sell their proceeds. While the magnitude of the impact in monetary value may be greater for commercial farmers, the impacts are seemingly only limited to their livelihoods. This informs the need for farming type diversity consideration in the development of adaptation policies for the farmers in the catchment. The difference in farming type did not result in differences in their responses to delayed onset of rainfall, as result shows no significant statistical difference ($p = 0.2$) in their response to these threats as seen in Table 4. Another area of similar response is the use of improved seed varieties. The choice of early soil preparation was ranked lower among smallholders in comparison to commercial farmers. This could be attributed to the fact that the smallholders have limited access to farm machinery in the event of a sudden onset of rainfall and need for urgent soil preparation.

More than 85% of the respondents stated that their maize production is rainfed, with only 12% relying on partial or full irrigation. Inputs from key informants suggest that the implementation of irrigation as an adaptation measure is limited by cost of irrigation infrastructures, water and water policies. This limitation is expected to increase farmers' vulnerability.

Farmers that have perceived but are not responding to climatic changes have listed the following barriers as limiting factors to their adjustment to climate change: lack of climate information, financial constraints, lack of institutional support, input challenges, limited capacity to adjust, water policy which constrains irrigation and inadequate land for cultivation. Table 6 provides a list of the areas of adaptation needs as stated by the responding farmers.

Table 6. Areas of adaptation needs identified by the 2 farming typologies in the study area. Farmers listed some of these factors as barriers limiting their ability to efficiently respond to the threats of climate change. Source: field survey data 2019/2020

	Farmer typology		
	Smallholder (n)	Commercial (n)	Total (n)
Access to more land	10	3	13
Extension support	4	0	4
Access to climate forecasts	20	18	38
Machinery and input support	19	4	23

Irrigation support	13	5	18
Marketing	0	9	9
Total	66	39	105

4.7. Alignment of current adaptation strategies to good adaptation practices

Global, regional, and South African good adaptation practices described in the literature are summarized in Table 7. Similar adaptation strategies ap plied by farmers in the Vaal catchment were compared to these practices to assess their alignment. Alignment is considered strong when >80% of respondents are employing the given strategy and partial when >50% but <80% use these strategies. Any adaptation rate below 45% is considered not aligned. The results shown in Table 7 confirm that the adaptation strategies deployed by the respondents are mostly in line with good adaptation practices used by other maize farmers globally to improve resilience to climate change. Areas such as diversification of livelihood, cultivation land limitation and supplementary irrigation/irrigation expansion constraints are seen as problematic areas with the potential for maladaptation.

Table 7. Range of adaptation strategies that have been successfully deployed to limit the impact of climate change in other maize-producing regions and the alignment of respondents' adaptation strategies to such practices. Source: field survey data 2019/2020

Strategy	Alignment of adaptations by maize farmers in the Vaal	Notes
Shifting planting dates (Khanal et al. 2018, Soglo & Nonvide 2019)	Strong alignment	Can extenuate the threat of future climate change on maize production
Planting improved seed varieties (Cairns et al. 2013, Lv et al. 2019)	Strong alignment	
Supplementary irrigation (Sadiq et al. 2019)	Partial alignment	Catchment is water stressed No new irrigation license
Expansion of area under cultivation	Not aligned	Land reform issues in South Africa remain contentious
Agrochemical supplementation (Cairns et al. 2013)	Strong alignment	
Livelihood diversification (Soglo & Nonvide 2019)	Not aligned	Due to financial constraints, most smallholders are unable to implement this adaptation

5. DISCUSSION AND CONCLUSIONS

Our assessment of maize farmers' perceptions of climate change, its impacts, coping mechanisms and adaptations in the Vaal catchment of South Africa suggests that the majority of the maize farmers that participated in the survey were aware that the climate is changing and were already making various adjustments to maize production to stabilize or increase their yields. Evidence of adaptive responses in the Vaal catchment is therefore seen as a promising move in the right direction, especially in the context of the warnings issued by Oduniyi et al. (2019), Adisa et al. (2018) and Shoko et al. (2019) about the future impacts of changes in rainfall and temperature in relation to maize production. The adaptive responses already discernable in the Vaal catchment are therefore in alignment with the call made by Nhamo et al. (2020) for proactive adaptation interventions in a region plagued with increasing aridity, low adaptive capacity, underdevelopment and marginalization.

Respondents' perceptions of climate change in the Vaal catchment area included their observations about decreases and delays in rainfall, increased incidences of temperature extremes, floods, droughts and storms, amongst others. These observations are in agreement with the findings of Elum et al. (2017) in other parts of the current study area. Thinda et al. (2020) recorded a similar trend in their study of climate change adaptation strategies among smallholder farmers, who are beneficiaries of the South African land reform programme. It was also particularly noteworthy that the perceptions of the farmers were informed not just by their own observations of climatic conditions, but also by the information that they are receiving from the media and from farmer associations.

Counteractive adjustments made by the farmers in response to climate change in the study area include changes in planting dates, use of improved seeds, increased use of irrigation and chemicals, minimum or no tillage and insurance, among others. Results indicate that contrary to outcomes from other similar studies, farmers in the study area do not see livelihood diversification and tillage minimization as the ultimate choice of adaptation. More than 70% of the maize farmers opted for a change in planting dates as the best approach to both the late onset of rainfall/ reduction in rainfall and temperature fluctuations. Their response is based on their perception of the change in climate as a shift in climate. Historically, early rainfall in the catchment commenced in early September (Mangani et al. 2019) and triggered the beginning of the planting season; this has now changed to October–November (Shoko et al. 2019). Roffe et al. (2020) also recorded similar findings, reporting later wet season start dates together with a reduction in summer wet-season rainfall in the study area.

The application of the Mann-Kendall trend test yielded confirmatory statistically significant evidence to support the farmers' perception of warmer temperature and the decline and shift in precipitation during the onset of the rainy and maize-planting seasons. The model has been successfully implemented for similar assessments in different parts of South Africa. Studies by Nyikadzino et al. (2020), Ndlovu & Demlie (2020) and Mengistu et al. (2020) used the model to evaluate climate change trends in different agro-ecological zones of South Africa.

While most of the farmers observed the change in climate, not all of them are able to respond with remedial actions in the form of adaptations, due to barriers including financial constraints, lack of institutional support, limited information on climate change and adaptation options, stringent insurance requirements etc. The extent to which farmers in the catchment can respond to the impacts of climate change is dependent in large part on their ability to effectively deploy available adaptation and coping mechanisms. Given the diversity of constraints faced by the different farmer typologies, the adaptive capacity of the smallholders is considered to be low (Greyling & Pardey 2019).

For the commercial farmers, apart from changes in planting dates due to the delayed onset of rainfall, other farming practices continued as normal, as most responses have been built into the normal production practices, signifying the possible influence of farmer typology in farmers’ vulnerability and need for adaptation. While the current and future needs of smallscale/ smallholder farmers range from input needs and machinery support to irrigation assistance and extension services, the immediate need for the commercial farmers is marketing. Delayed onset of rainfall interpreted as a shift in climate by some of the respondents is one of the key triggers of initial adaptive responses by farmers in the catchment.

Respondents are actively participating in approaches that allow them to adapt to the threats associated with climate change, as signified by the alignment of their adaptation strategies with identified adaptive good practices. However, there is danger in the over or under-application of some of these approaches without the knowledge of either their environmental or agronomic consequences, which could result in increased vulnerability of the farmers. As reported by Work et al. (2019), maladaptation are described as actions or inactions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change or diminished welfare now or in the future. The possibility for maladaptation at present or in the future is particularly noticeable for the smallholders in the study area, which should be a key indicator for future policy interventions.

According to the respondents, in response to the delay in the onset of rainfall and the shortening of the planting season, they have adapted their planting dates. Respondents reported that they will only plant after the first set of rain. However, according to Mangani et al. (2019), maize grain yield is negatively affected by the number of days in the planting season with temperatures above 30°C, while temperatures below 10°C result in the halting of all active development (Walker & Schulze 2008). Planting later means planting when temperatures are higher. With the increase in current and projected temperatures for the study area, this could result in further vulnerability if the adaptive approach is not well supplemented with other approaches such as the use of appropriate maize varieties with shorter growth periods (Moeletsi 2017). The strategy to prepare soil early in time for the first season rains and to keep moisture in, may also be counterproductive, as it exposes the soil if not adequately planned.

The intensification of irrigation was another key adaptation approach by the respondents, in a catchment where water needs already exceed the natural yield of the main source of water, the Vaal River (Akanbi et al. 2020). The catchment is only able to meet its current demand through inter-basin transfers. The water supply limitation informed the restrictions on the issuing of new irrigation licenses as part of the water conservation and demand management strategies in the catchment. Increases in irrigation requirements will therefore exacerbate the already stressed water management authority. Enabling policy that will ensure water conservation and demand management but also allow irrigation water efficiency, should be developed to ensure that increased irrigation in the catchment does not translate into a maladaptive response.

The consistent decline in maize production in the region, which was initially attributed to a significant reduction in maize production land area and more recently to climate variation, is expected to have socio economic and food security implications. Greyling & Pardey (2019) posited that the continued growth in yield due to improved seed varieties enabled maize production to reach an all-time high of 14.92 Mt in 2014, notwithstanding the continued contraction in planted area (by 1.4% yr−1 on average), indicating that the farmers' adjustment of their production in response to both land loss and climate impact were yielding positive outcomes. However, the severe 2015 drought resulted in a significant decrease in maize production of >24% from the previous season. Subsequent seasons continue to observe a decreasing trend in production.

Despite the increasing use of a range of adaptations, some of the farmers who are perceiving the changes in climate are unable to adapt. Limiting factors such as access to credit, lack of information, heavy insurance specifications and insufficient extension support are listed as some of the barriers. These issues are not unique to farmers in the Vaal River area, as similar studies by Oduniyi et al. (2019) in the Northwest province, Chikosi et al. (2019) in Limpopo and Ndhleve et al. (2017) in the Eastern Cape province of South Africa reported similar barriers. Another limitation is the stringent insurance requirement for crops to be planted by certain cut-off dates based on historical understanding of the climate in the study area and to avoid the early frost. These imposed deadlines disadvantage farmers when rainfall is delayed.

Sustainable production of maize in the Vaal catchment area will require farmers to effectively adapt to climate change. The different farming scales in the area indicate the need for a robust adaptation strategy that not only considers the implementation of good adaptation approaches and takes into account the differential vulnerability of the different farmer typologies, but also recognises the possibility of maladaptation if the perceived changes in climate are not well understood. While some of the adjustments made by the farmers in response to climate change may result in an initial increase in productivity, they may also result in increased agricultural vulnerability (Neset et al. 2019). Transformational adaptation plans that are facilitated by policy reforms are required to avoid future unintended outcomes in adaptation and sustainable production of maize in the study area. Providing support in capacity building, awareness, credit access, advance access to meteorological information, cohesive/aligned policies and extension support will be a step in the right direction. Current adaptation strategies therefore need to be expanded and supplemented to improve resilience and prevent maladaptation.

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LITERATURE CITED

Adisa OM, Botai JO, Hassen A, Darkey D and others (2018) Variability of satellite derived phenological parameters across maize producing areas of South Africa. Sustainability 10: 3033

Ahmed MA, Ahmed MA (2019) Farmers' perception and adaptation to climate change: multinomial logistic model evidence. Int J Econ Manag Stud 6: 143−151

Akanbi R, Ndarana T, Davies N, Archer E (2020) Integrated assessment of the influence of climate change on current and future intra-annual water availability in the Vaal River catchment. J Water Clim Change, doi:10. 2166/ wcc.2020.269

Alam G, Alam K, Mushtaq S (2017) Climate change perceptions and local adaptation strategies of hazard-prone rural households in Bangladesh. Clim Risk Manag 17: 52−63

Alhassan H, Kwakwa PA, AdzawlaW(2019) Farmers choice of adaptation strategies to climate change and variability in arid Region of Ghana. Rev Agric Appl Econ 22: 32−40

Ambrosino C, Chandler RE, Todd MC (2014) Rainfall derived growing season characteristics for agricultural impact assessments in South Africa. Theor Appl Climatol 115: 411−426

Asamoah Y, Ansah-Mensah K (2020) Temporal description of annual temperature and rainfall in the Bawku Area of Ghana. Adv Meteorol 2020: 3402178

Asfaw A, Simane B, Hassen A, Bantider A (2018) Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: a case study in Woleka subbasin. Weather Clim Extrem 19: 29−41

Bannayan M, Paymard P, Ashraf B (2016) Vulnerability of maize production under future climate change: possible adaptation strategies. J Sci Food Agric 96: 4465−4474

Bedeke SB, Vanhove W, Wordofa MG, Natarajan K, Van Damme P (2018) Perception of and response to climate change by maize-dependent smallholders. Clim Res 75: 261−275

Bernstein H (2013) Commercial agriculture in South Africa since 1994: ‘natural, simply capitalism’. J Agrar Change 13: 23−46

Bonewit A, Shreeves R (2015) The gender dimension of climate justice. Europarl. https://www.europarl.europa.eu/RegData/etudes/IDAN/2015/536478/IPOL_IDA(2015)536478_EN.pdf (accessed 10 February 2020)

Cairns JE, Hellin J, Sonder K, Araus JL, MacRobert JF, Thierfelder C, Prasanna BM (2013) Adapting maize production to climate change in sub-Saharan Africa. Food Secur 5: 345−360

Calzadilla A, Zhu T, Rehdanz K, Tol RSJ, Ringler C (2014) Climate change and agriculture: impacts and adaptation options in South Africa. Water Resour Econ 5: 24−48

Cammarano D, Valdivia RO, Beletse YG, DurandWand others (2020) Integrated assessment of climate change impacts on crop productivity and income of commercial maize farms in northeast South Africa. Food Secur 12: 659−678

Chikosi ES, Mugambiwa SS, Tirivangasi HM, Rankoana SA (2019) Climate change and variability perceptions in Ga-Dikgale community in Limpopo Province, South Africa. Int J Clim Chang Strategies Manag 11: 392−405

Dabrowski JM, Masekoameng E, Ashton PJ (2008) Analysis of virtual water flows associated with the trade of maize in the SADC region: importance of scale. Hydrol Earth Syst Sci 13: 1967−1977

DAFF (Department of Agriculture, Forestry and Fisheries) (2016) Impact of drought on crop production and the food value chain. https://www.nda.agric.za/doaDev/sideMenu/others/CCDM/docs/Impact%20of%20drought%20on%20crop%20production%20and%20food%20value%20chain%208%20July%202016.pdf (accessed 10 April 2020)

DAFF (2017) A profile of the South African maize market value chain. https://www.nda.agric.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Maize%20Market%20Value%20Chain%20Profile%202017.pdf (accessed 12 April 2020)

DAFF (2018) Trends in the agriculture sector 2018. https://www.dalrrd.gov.za/Portals/0/Statistics%20and%20Economic%20Analysis/Statistical%20I nformation/Trends%20in%20the%20Agricultural%20Sector%202018.pdf (accessed 24 January 2020)

DAFF (2019) Trends in the agriculture sector 2018. 2019. https://www.dalrrd.gov.za/Portals/0/Statistics%20and%20Economic%20Analysis/Statistical%20Information/Trends%20in%20the%20Agricultural%20Sector%202019.pdf (accessed 6 February 2020)

Elum ZA, Modise DM, Marr A (2017) Farmer's perception of climate change and responsive strategies in three selected provinces of South Africa. Clim Risk Manag 16: 246−257

Gouse M, Sengupta D, Zambrano P, Zepeda JF (2016) Genetically modified maize: less drudgery for her, more maize for him? Evidence from smallholder maize farmers in South Africa. World Dev 83:27–38

Greyling JC, Pardey PG (2019) Measuring maize in South Africa: the shifting structure of production during the twentieth century, 1904−2015. Agrekon 58: 21−41

Holzkämper A (2017) Adapting agricultural production systems to climate change—What's the use of models? Agriculture 7: 86

IPCC (2007) Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, p 7−22

IPCC (2014a) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, p 151–165

IPCC (2014b) Adaptation planning and implementation. In: Climate change 2014: impacts, adaptation, and vulnerability. A. Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, p 869–898

Khanal U, Wilson C, Lee B, Hoang V (2018) Climate change adaptation strategies and food productivity in Nepal: a counterfactual analysis. Clim Change 148: 575−590

Kirsten JF, van Zyl J (1998) Defining small-scale farmers in the South African context. Agrekon 37: 551−562

Lin Y, Feng Z, Wu W, Yang Y, Zhou Y, Xu C (2017) Potential impacts of climate change and adaption on maize in northeast China. Agron J 109: 1476−1490

Lv Z, Li F, Lu G (2019) Adjusting sowing date and cultivar shift improve maize adaptation to climate change in China. Mitig Adapt Strategies Glob Change 25: 87−106

Mangani R, Tesfamariam EH, Engelbrecht CJ, Bellocchi G, Hassen A, Mangani T (2019) Correction to: Potential impacts of extreme weather events in main maize (Zea mays L.) producing areas of South Africa under rainfed conditions. Reg Environ Change 19: 1453−1454

Mashizha TM (2019) Building adaptive capacity: reducing the climate vulnerability of smallholder farmers in Zimbabwe. Business Strategy Dev 2: 166−172

Mapfumo P, Jalloh A, Hachigonta S (2014) Review of research and policies for climate change adaptation in the agriculture sector in Southern Africa. Future Agricultures

Working Paper 100. Future Agriculture Consortium, Brighton Mengistu AG, Tesfuhuney WA, Woyessa YE, van Rensburg LD (2020) Analysis of the spatio-temporal variability of precipitation and drought intensity in an arid catchmentin South Africa. Climate (Basel) 8: 70

Moeletsi ME (2017) Mapping of maize growing period over the Free State Province of South Africa: heat units approach. Adv Meteorol 2017: 7164068

Moeletsi ME, Walker S, Landman WA (2011) ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa. Phys Chem Earth 36: 715−726

Ndhleve S, Nakin MDV, Longo-Mbenza B (2017) Impacts of supplemental irrigation as a climate change adaptation strategy for maize production: a case of the Eastern Cape Province of South Africa. Water SA 43: 222−228

Ndlovu MS, Demlie M (2020) Assessment of meteorological drought and wet conditions using two drought indices across KwaZulu-Natal Province, South Africa. Atmosphere 11: 623

Neset TS, Wiréhn L, Klein N, Käyhkö J, Juhola S (2019) Maladaptation in Nordic agriculture. Clim Risk Manag 23:78−87

Nhamo L, Ebrahim GY, Mabhaudhi T, Mpandeli S and others (2020) An assessment of groundwater use in irrigated agriculture using multi-spectral remote sensing. Phys Chem Earth 115: 102810

Nyikadzino B, Chitakira M, Muchuru S (2020) Rainfall and runoff trend analysis in the Limpopo river basin using the Mann Kendall statistic. Phys Chem Earth 117:102870

Oduniyi OS, Tekana SS (2019) Establishing the nexus between climate change adaptation strategy and smallholder farmers’ food security status in South Africa: a bicasual [sic] effect using instrumental variable approach. Cogent Soc Sci 5: 1

Oduniyi OO, Antwi MA, Tekana SS (2019) Prioritization on cultivation and climate change adaptation techniques: a potential option in strengthening climate resilience in South Africa. Agron Colomb 37: 62−72

Pienaar L, Traub L (2015) Understanding the smallholder farmer in South Africa: towards a sustainable livelihoods classification. 29th Int Conf on agricultural economics, August 8–14, 2015. International Association of Agricultural Economists, Milan

Rezaei EE, Lashkari A (2019) The consequences of change in management practices on maize yield under climate warming in Iran. Theor Appl Climatol 137: 1001−1013

Roffe SJ, Fitchett JM, Curtis CJ (2020) Investigating changes in rainfall seasonality across South Africa: 1987− 2016. Int J Climatol, doi:10.1002/joc.6830

Sadiq MA, Kuwornu JKM, Al-Hassan RM, Alhassan SI (2019) Assessing maize farmers’ adaptation strategies to climate change and variability in Ghana. Agriculture 9: 90

Shoko RR, Belete A, Chaminuka P (2019) Maize yield sensitivity to climate variability in South Africa: application of the Ardl-Ecm approach. J Agribus Rural Dev 54: 363−371

Soglo YY, Nonvide GMA (2019) Climate change perceptions and responsive strategies in Benin: the case of maize farmers. Clim Change 155: 245−256

Statistics South Africa (2017) Census of commercial agriculture, 2017. Financial and production statistics. http: //www. statssa.gov.za/publications/Report-11-02-01/ Report-11-02-012017.pdf

Thinda KT, Ogundeji AA, Belle JA, Ojo (2020) Understanding the adoption of climate change adaptation strategies among smallholder farmers: evidence from land reform beneficiaries in South Africa. Land Use Pol 99:104858

Tucker CM, Eakin H, Castellanos EJ (2010) Perceptions of risk and adaptation: coffee producers, market shocks, and extreme weather in Central America and Mexico

Global Environ Change 20: 23−32 Walker NJ, Schulze RE (2008) Climate change impacts on agro- ecosystem sustainability across three climate regions in the maize belt of South Africa. Agric Ecosyst Environ 124: 114−124

Wehbe M, Eakin H, Seiler RA, Vinocur MG, Santos C, Civitaresi HM (2005) Social methods for assessing agricultural producers' vulnerability to climate variability and change based on the notion of sustainability. AIACC Working Paper No. 19. www.start.org/Projects/AIACC_Project/working_papers/Working%20Papers/AIACC_WP_No019.pdf

Wilk J, Hjerpe M, YangW, Fan H (2015) Farm-scale adaptation under extreme climate and rapid economic transition. Environ Dev Sustain 17: 393−407

Work C, Rong V, Song D, Scheidel A (2019) Maladaptation and development as usual? Investigating climate change mitigation and adaptation projects in Cambodia. Clim Policy 19: S47−S62

Yamane T (1967) Statistics. An introductory analysis, 2nd edn. Harper & Row, New York, NY

Appendix. Additional data

Table A1. Mean and range of monthly temperature (°C) in the Vaal catchment, based on a 30 yr (1989–2018) data set from the South African Weather Services (SAWS) (see Section 3.2). Mann-Kendall test showing statistically significant increasing temperature trend. Bold indicates significance (*p < 0.1; **p < 0.05; ***p < 0.01)

	Minimum	Maximum	Mean	SD	Kendall's tau	p	Sen's slope
January	23.533	28.967	26.951	1.308	0.203	0.116	0.046
February	24.433	29.667	26.554	1.547	0.318	**0.014*** **	0.080
March	22.533	27.300	25.354	1.231	0.288	**0.026** **	0.055
April	20.467	25.667	22.992	1.438	0.154	0.242	0.040
May	17.467	24.133	20.693	1.528	0.212	0.101	0.057
June	16.433	21.100	18.221	1.147	0.359	**0.005*** **	0.067
July	13.967	21.467	17.910	1.448	0.170	0.187	0.042
August	17.700	24.933	20.747	1.468	0.318	**0.014*** **	0.067
September	21.433	26.933	24.278	1.629	0.200	0.126	0.057
October	21.767	29.333	24.951	1.406	0.357	**0.006*** **	0.072
November	23.300	29.067	25.908	1.553	0.321	**0.013** **	0.093
December	23.500	32.133	26.979	1.663	0.182	0.159	0.050

Table A2. Mean and range of monthly precipitation (mm) in the Vaal catchment, based on a 30 yr (1989–2018) data set from the South African Weather Services (SAWS). Mann-Kendall test showing statistically significant decreasing precipitation trends. Bold indicates significance (*p < 0.1; **p < 0.05; ***p < 0.01)

	Minimum	Maximum	Mean	SD	Kendall's tau	p	Sen's slope
January	73.700	250.700	158.503	49.449	0.167	0.564	44.750
February	51.133	309.433	133.346	61.720	–0.500	**0.083***	–41.283
March	35.933	233.900	107.208	41.249	–0.167	0.564	–16.633
April	2.650	127.867	48.254	27.074	0.167	0.564	22.017
May	0.000	93.500	19.214	22.384	0.000	1.000	0.150
June	0.000	40.600	12.206	13.258	0.667	**0.021** **	8.617
July	0.000	69.767	8.014	14.683	0.000	1.000	–0.417
August	0.200	100.433	17.661	21.275	0.167	0.564	10.967
September	0.667	97.133	24.459	24.222	0.000	1.000	3.500
October	29.400	185.200	77.629	44.798	–0.167	0.564	–6.867
November	22.033	240.267	101.761	54.710	–0.333	0.248	–15.517
December	34.267	296.933	139.498	58.110	0.000	1.000	–13.733