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Nexus between summer climate variability and household food security in rural Mpumalanga Province, South Africa

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A B S T R A C T

Ongoing climate changes are likely to impact household food security in rural households that depend on rainfed subsistence agriculture. This paper investigates the relationship between summer climate variability and household food security in rural Mpumalanga, South Africa. We used a household panel data set nested in the Agincourt Health and Socio-Demographic Surveillance System, together with rainfall and temperature data for the summer periods 2006-07 to 2018-19 from three weather stations that surround the study area. We quantified the variability of rainfall using coefficient of variation and the standardised rainfall anomaly index, while temperature variability was reflected by the standardised temperature anomaly. In addition, the Mann-Kendall analysis was applied to detect temporal trends in rainfall and temperature. Longitudinal models accounting for socioeconomic and climate factors were used to estimate the relationship between weather and climate. The results reveal significant impact on food security from high inter-annual rainfall variability through fluctuations in food consumption, dietary diversity, and the experience of hunger. This study offers significant insights on how dietary diversity, food availability and overall food security are positively associated with greater average rainfall through subsistence agriculture as a livelihood strategy. These insights have important implications by suggesting seasonal forecasts to predict periods of potential food insecurity in local communities and can guide government policy and interventions to lessen food insecurity in rural areas.

1. Introduction

Food insecurity persists as a serious development challenge (Prosekov and Ivanova, 2018) and, as such continues to be an important topic in both scientific and development communities (Conceição et al., 2016). As an example, food insecurity has remained on the international development agenda through the United Nations' Sustainable Development Goal # 2 (SDG) on zero hunger (Gil et al., 2019). A complex, dynamic phenomenon, food security has many dimensions including biophysical, climatic, economic, and

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infrastructural. On climate, the Intergovernmental Panel on Climate Change (IPCC) projections strengthen the view that climate change and variability will challenge livelihoods and dramatically impact impoverished households (Birkmann et al., 2022). Food insecurity represents one of those challenges as demonstrated by being implicated in the first two United Nations Sustainable Development Goal to eradicate both extreme poverty and hunger (Al-Amin and Ahmed, 2016).

Sub Saharan Africa (SSA) is an especially vulnerable region that will be negatively affected by the effects of climate change because of its geographical location and socioeconomic context of inequality, extensive poverty, slow pace of development and high levels of food insecurity (Han et al., 2019; Shackleton et al., 2015). This is especially the case for communities facing high levels of poverty, malnutrition and lack of employment opportunities (Adeyeye et al., 2023; Azzarri and Signorelli, 2020). Such communities often lack the ability to respond to changing and highly variable climate conditions such as shifts in seasonal weather patterns (Ebi and Bowen, 2016; Myers et al., 2017). Indeed, rural populations in SSA, highly dependent on rainfall for subsistence agriculture are largely already food insecure (Giller et al., 2021) and therefore, especially vulnerable (FAO, 2018).

Studies on climate-related impacts on food security tend to be at regional, national or global scale. The focus is typically on agricultural production as a key element of food availability and ultimately food security. For example, studies by Schlenker and Lobell (2010) and Zinyengere et al. (2013) estimate climate-related yield losses of major food crops to be approximately 18% for southern Africa and to approximately 22% for the whole of SSA. Of particular interest were maize yield losses for two agro-based countries, South Africa and Zimbabwe, which were estimated to be above 30%. Even so, while there are many such studies examining climate change, environmental variability, and food production, few studies have evaluated the direct and indirect impacts of seasonal temperature and rainfall variability and extremes on livelihoods and food security to which rural subsistence are particularly sensitive (Miller et al., 2016; Savo et al., 2016). A few recent studies have examined the association between recent climatic events and household food security (e.g., Islam et al., 2022; Randell et al., 2021; Randell et al., 2022). While this research contributes useful insights on the relationship between climate and food security, the cross-sectional nature of these studies has limitations highlighting the need for longitudinal data. Longitudinal insights are also rare although Randell et al. (2022) point out that climatic impacts and effects vary by timing of exposure. We combine understanding of these gaps to argue that any prospects for enhancing food security and rural livelihoods in SSA within a changing climate requires an improved understanding of the impact of changing weather seasonality patterns, across time on household food security.

1.1. Climate change and rural food security in southern Africa

Climate change predictions point to decreased rainfall and increased temperatures in southern Africa (Archer et al., 2018; Pohl et al., 2017). This has caused increased concern about food insecurity in this southern part of the SSA region (Shukla et al., 2020). Any variation in inter-annual rainfall and temperature in southern Africa tends to exerts significant influence on agricultural production and ultimately food security across the region (Thomas et al., 2022). A report by the World Food Programme (WFP) in 2019 estimated that 41 million people in southern Africa were food insecure. Specific to South Africa, our study site, Stats SA (2022) reported that about 14 million South Africans were estimated to be food insecure in 2019, largely due to recurrent droughts as a consequence of climate change (WFP, 2019). A variety of significant changes in climate have been observed (Kruger and Sekele, 2013; MacKellar et al., 2014; van Wilgen et al., 2016) such as rising temperatures. Average annual temperature trends between 1960 and 2000 show an increase of about 0.13 °C per every 10 years. Average rainfall trends are less defined, but with an inclination towards decline in the number of rainy days combined with an increase of inter-annual rainfall variability. Climate projections point to an increased variable rainfall pattern (Mastrorillo et al., 2016) and this trends are projected intensification by the end of 2100 (DEA, 2013).

In South Africa, nearly 21% of households are involved in agriculture with 65% of these using subsistence agriculture to meet or supplement household food needs (Stats SA, 2022; Tibesigwa and Visser, 2016). It is foreseen that climate change, experienced through changing rainfall patterns and rising temperatures, will negatively affect both subsistence and commercial agriculture in South Africa (Cammarano et al., 2020; Mpandeli et al., 2019). Already climate change has been implicated as drivers for abandonment of subsistence agriculture in rural areas by smallholder farmers in the communal areas of South Africa (Shackleton et al., 2019).

Most research on climate and food security in rural South Africa specifically examines local agricultural production as an important mechanism linking the two (Elum et al., 2017; Maponya and Mpandeli, 2013; Tibesigwa et al., 2016; Andersson et al., 2020; Mpandeli et al., 2019). While a logical focus gap remains in terms of examining how production ultimately shapes food availability, hunger, and dietary diversity – the outputs of production (Ickowitz et al., 2019). The seasonality of such impacts also remains underexplored.

Another gap relates to the temporal dimensions of existing studies which are predominantly cross-sectional (for examples: Drysdale et al., 2019, 2020; Tibesigwa and Visser, 2015; Musemwa et al., 2015; Walsh & van Rooyen (2015). As an example, Tibesigwa et al. (2015) assessed the impact of climate change on income and food sufficiency on South African rural households. Their cross sectional examination found that climate change will be initially mildly harmful but will grow over time and lead to a 151 per cent loss in net revenue by the year 2080. Another cross sectional study in Kwazulu Natal South Africa investigated the relationship between rainfall and food security (Drysdale et al., 2020). They identified an anticipated negative relationship between amount of rainfall and food security which was attributed to intra and inter seasonal droughts duration. This study highlighted need for conducting a longitudinal analysis to further assess the impact of high rainfall variability on household food insecurity.

While important, cross sectional studies neglect consideration of both food security and environmental conditions and, therefore, their complex, nuanced association across time. This calls for new approaches to expand our current understanding of climate impacts on food security. Even so, data limitations inhibit such analysis. (Fawcett et al., 2017; Thiede and Strube, 2020).

In response to this gap, we use longitudinal data from the Sustainability in Communal Socio-Ecological Systems (SUCSES) study nested within the Agincourt Demographic and Health Surveillance System (ADHSS), combined with historical climate records to examine three core questions: (i) What are the patterns in inter-annual and intra seasonal summer rainfall and temperature over the last decade in Bushbuckridge, Mpumalanga Province South Africa? (ii) What is the relationship between household crop production and inter-seasonal variability in summer rainfall and temperature? (iii) How does summer rainfall and temperature variability in Bushbuckridge relate to or affect household food security?

2. Materials and methods

2.1. Conceptual framework

This study is based on a simple conceptual framework that illustrates how climate can affect household food security in a rural setting in South Africa (Fig. 1). Specifically, rural food security in South Africa depends on both subsistence and commercial agriculture. Subsistence agriculture supplements household food needs through production of field crops and vegetables in home gardens during the summer rainfall season. On the other hand, commercial agriculture, that produces most the food for the nation primarily relies on rainfall but also has irrigation. In this study we utilize the framework in Fig. 1 below to explore how climate can affect subsistence agriculture and ultimately household food security given the vulnerability of home production to weather variability.

2.2. Study site

The study was carried out in the Agincourt Health and Socio-Demographic Surveillance System (AHDSS) site of the Medical Research Council/-Wits University Rural Health and Health Transitions Research Unit, in Bushbuckridge, Mpumalanga Province, South Africa. The study site lies between 24.8279°S and 31.2197°E. The Bushbuckridge Local Municipality includes 67 villages that have high human population densities with more than 400 households per village. Each village is generally arranged in a grid pattern along a network of roads/tracks (Kahn et al., 2012). Since 1992 the University of the Witwatersrand has been collecting data on household sociodemographic, crop and livestock production, harvesting of natural resources and food security in this study area on an ongoing basis since 1992. The Agincourt HDSS site encompasses 31 villages hence, the study site was conducive for such a longitudinal study.

Bushbuckridge Local Municipality is in a semi-arid region with mean annual rainfall following an altitudinal descent from 650 m above sea level in the west to <400 m above sea level in the east (Vågen et al., 2018). Average rainfall in Bushbuckridge ranges from >700 mm in the west to 550 mm in the east. Seasonal rainfall period (summer rainfall) occurs from October to April. The area experiences mean annual temperatures of approximately 22 °C which increases from southwest to northeast and is characterised by hot, humid summers and mild winters.

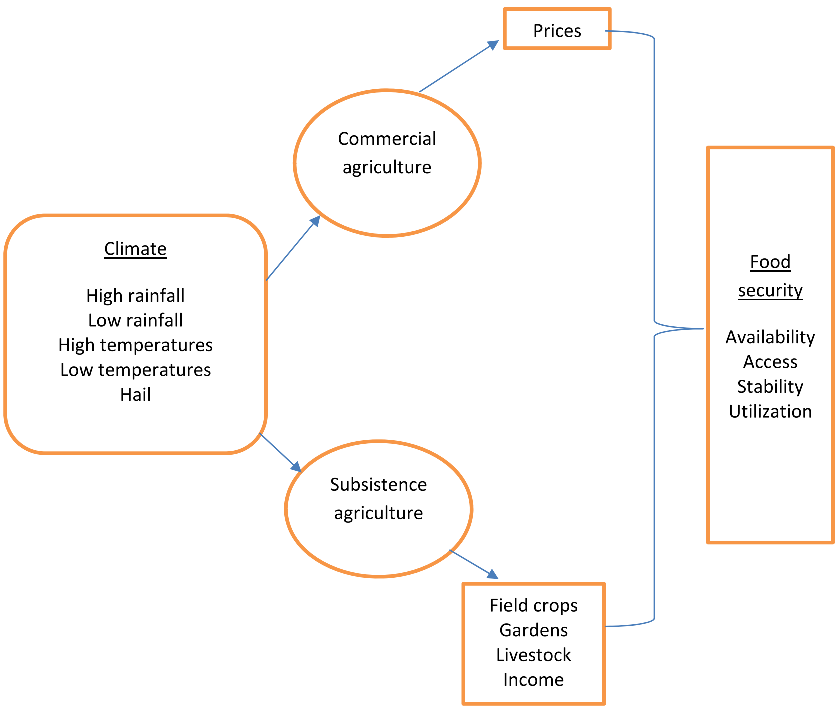

Fig. 1. Conceptual framework for climate effects on rural household food security in South Africa: authors drawn and adapted from Turner et al. (2018).

2.3. Data sources

2.3.1. Climate data

We use rainfall data from Thulamahashe, Hazyview and Shaws Gate meteorological stations. We obtained data for Thulamahashe and Hazyview from the Agricultural Research Council while data for Shaws Gate was obtained from Sabie-Sand Game Reserve. Thulamahashe lies between 24.7237°S and 31.1823°E and is to the north of Agincourt study area, Hazyview lies between 25.0488°S and 31.1395°E and lies to the south west of and Shaws Gate lies between 24.9282°S and 31.4792° E to the south east of the study area. The SRZ wet-season occurs mainly between October and March. Hence seasonal monthly rainfall data from October to April from 2006/7 to 2018/19 was used for data analysis in this study. The study also uses seasonal temperature data for the same period from stations located in Thulamahashe and Hazyview.

2.3.2. Household socioeconomic, livelihood, crop production and food security data

We also use panel data from the 2010–2014 and 2019 rounds of the Sustainability in Communal Socio-Ecological Systems (SUCSES) research project. SUCSES used a detailed questionnaire was used to gather household data on livelihood activities such as subsistence agriculture, cropping in external fields, ownership of livestock, off farm employment, migrant employment, access to social grants, among household demographics and other attributes. In addition to the above, SUCSES project collected household information on magnitude of crop losses and household food security. Specifically, households were asked (i) whether they had planted any crops in the previous 12 months, (ii) if yes, how many crops they planted and (iii) if they had experienced any losses due to shortage of rainfall or hail and (iv) how much crop loss did they experience as a result of shortage of rainfall. In addition, the questionnaire included queries on frequency of food consumption, dietary diversity, experience of hunger and behavioural responses in situations of food unavailability at household level. The SUCSES panel consisted of 587 households in 2010 and by 2019 the households stood at 505 due to attrition from migration, dissolution, and refusals.

2.4. Data analysis

2.4.1. Climate data analysis

The following analytical techniques were applied to the climate data.

(i) Mann-Kendall (MK) test as described by Sneyers (1990) was performed on inter-seasonal and intra-seasonal rainfall and temperature data. This test reveals the presence of either a monotonic increasing or decreasing trend in the dataset over the time.
(ii) The coefficient of variation (CV) was used to compute the variability of inter-seasonal and intra-seasonal rainfall pattern. A higher CV value signifies high variability and a low CV value signifies low variability. The CV is calculated as follows:

$$CV = \frac{\delta}{\mu} \times 100$$

where CV is the coefficient of variation; σ is standard deviation and μ is the mean precipitation. Hare (2003) using the CV classified the magnitude rainfall variability as follows: less variability (CV < 20), moderate variability (20 < CV < 30), and high variability (CV > 30).

(iii) Standardised rainfall anomalies (RAI) and standardised temperature anomalies (TAI) were computed to quantify each summer season in relation to the long-term rainfall and temperature means respectively. This enabled determination of whether the seasons were wet in terms of rainfall, high (+ve values), low (−ve values). We also determined whether the seasons were hot in terms of temperature, high (+ve values), low (−ve values).

The anomalies where calculated as follows for rainfall and temperature

$$Z = \frac{(X_i - \overline{X}_i)}{s}$$

where, Z is standardised rainfall or temperature anomaly; X_i is the seasonal rainfall or seasonal mean temperature of a particular year; $\overline{X}_i$ is long term mean seasonal rainfall or temperature over a period of observation and 's' is the standard deviation of seasonal rainfall or temperature over the period of observation. We used the rainfall anomaly index (RAI) classification designed by van Rooy (1965) to classify the summer seasons wetness or dryness.

2.4.2. Assessment of household crop production and crop loss

SUCSES data on crop production and crop loss were converted into both a dichotomous score (0/1 if a household had/had not grown and crops) and a continuous score (number of crops). Regarding crop loss, a scale of 0–4 represented the level of crop loss from no loss to total loss. Our descriptive analysis has three steps outlining 1) cropping activities; 2) crops grown; and 3) magnitude of crop loss.

2.4.3. Assessment of household food security

Six different measures of food security are used in the analyses representing various dimensions of food access and availability. First, two Household Meal Consumption Frequency Scores (HMFS) were calculated: HMFSa which quantified the number of main meals consumed by a household in a typical day (range 0–3). HMFSb which quantified the number of snack meals consumed by a household in a typical day (range 0–4).

The third indicator was the Household Dietary Diversity Score (HDDS) which quantified food groups consumed by household members and reflected the diversity of food availability and access. The HDDS was a summation of consumption of any of the food in the 13 food groups recommended the Food and Agriculture Organization (FAO), World Health Organization (WHO), and the Food and Nutrition Technical Assistance (FANTA) (0–13).

The fourth indicator was the adapted Household Food Insecurity and Access Scale (HFIAS) which quantified a household access to food in the past 30 days. The adapted Household Food Insecurity Access Scale (HFIAS) used three questions to assess food shortage for the past 30 days and assigned a quantitative measure of 0 for non-occurrence of food shortage, 1 for 1–2 times (rarely) occurrence of food shortage, 2 for 3–10 (sometimes) occurrence of food shortage and 3 for more than 10 times (often) occurrence for each question. The scores ranged from 0 to 9 and score of 9 stood for the highest level of food insecurity.

The fifth indicator was the Coping Strategy Index (CSI) which quantified food shortage in a household The CSI consisted of four questions on strategies which assessed use of the four coping strategies when there is shortage of food. The scores ranged from 0 to 4 and a score of 4 stood for the highest level of food insecurity.

The sixth indicator was the composite Household Food Security Index (HFSI) which quantified a household's overall food security. This indicator was calculated by aggregating the five indicator variables together namely HMFSa, HMFSb, HDDS, HFIAS and CSI, thereby yielding a composite indicator for food insecurity. This composite food insecurity indicator which we denoted household food security index (HFSI) in this study would be more useful in revealing and understanding simultaneously the various dimensions of household food security during the harvesting period The five indicators mentioned above were rescaled such that a score of 1 represented the maximum possible of food security for the metric while a score of 0 represented the highest level of household food insecurity.

Descriptive statistical analysis for the above mentioned food security indicators of the households surveyed for the period 2010–2014 and year 2019 were carried out to get the mean and the standard deviation (SD) for each year. Analysis of variance compared mean values between years and the Tukey test was used to determine the significant differences between years. The food security indicator anomalies for each indicator were calculated as the difference of the yearly mean from the overall mean of the six study rounds of survey and was scaled by dividing by the overall standard deviation of the six study rounds. The results are provided in the supplementary material.

2.4.4. Analysis of the relationship between summer seasonal climate variability, crop production and household food security

To identify the relationship between summer seasonal variability crop production and household food security in the study area, the Pearson correlation and longitudinal mixed effects models were applied, with significance tested at 95% confidence level. To estimate change over time within households, a longitudinal mixed effect regression model is appropriate for representing the change each household is expected to experience from 2010 to 2019. Longitudinal mixed effects modelling conceptualizes repeated observations as being nested within years, allowing clustering of food security scores by household. The full slope-intercept models analysed average household change across time from 2010 to 2014 and 2019 ('within-household variation'), while also allowing households to vary in both initial food security scores and rates of change in food security scores over time ('between-household variation'). The process first involved correlation of independent variables to enable variable reduction to avoid over-representation of a single factor. We performed a correlation test with aim of excluding independent variables with correlations of more than 0.7 to avoid over-representation of related factors. Based on this correlation analysis (see supplementary material) we considered the 10 independent variables of theoretical importance for the modelling process. Two multivariate models were fitted to each food security outcome and crop production variable. In model 1 we controlled for time, socioeconomic and livelihood profiles. In model 2 we introduced local climate parameters to model 1. We subjected the results of our primary models to robustness checks. We compared our results to the correlation test to see if our results were also consistent.

Akaike information criterion (AIC) and Bayesian information criterion (BIC) values were used to compare competing nested models. AIC estimates the distance between the fitted likelihood function and the 'true' likelihood model, whereas BIC estimates the probability of a fitted model being 'true' so lower values indicate better fitting models (Brewer et al., 2016). Fit was assessed using marginal and conditional R^2 values to account for clustering in the sample (Nakagawa and Schielzeth, 2013; Schielzeth and Nakagawa, 2013). Linear mixed effects models tested the impact of summer climate variability and socioeconomic factors on household food security time. Beginning with a 'null model' (no predictors), an iterative model-building process tested a robust set of both fixed and random effects to capture within- and between-household variation in food security scores from 2010 to 2014 and 2019.

3. Results

3.1. What are the patterns in inter-annual and intra seasonal summer rainfall and temperature over the last decade in Bushbuckridge

The summarised summer rainfall results are presented in Table 1 and Fig. 2 below. In Bushbuckridge, Hazyview had a high summer seasonal mean rainfall of 878 mm followed by Thulamahashe (642 mm). The Shaws Gate area tends to receive low summer seasonal rainfall with a mean of 567 mm. All three stations in Bushbuckridge showed high CV values which indicated high variability of rainfall in the study area. This is further supported by the standardised rainfall anomaly index (RAI) (Fig. 2), that showed the presence of high inter-seasonal variability. Using the van Rooy (1965) classification technique, the RAI shows that seasons 2009-10, 2010-11 and 2011-12 were slightly wet, seasons 2012-13, 2013-14 were moderately wet and the 2018-19 season was slightly dry in Hazyview. Thulamahashe and Shaws Gate demonstrate a similar trend of being near normal and slightly wet in 2009-10 and 2010-11 season respectively. Seasons 2011-12, 2012-13 and 2013-14 were near normal for the former and moderately wet for the latter seasons in Thulamahashe while for Shaws Gate the former season was moderately wet and the latter seasons were slightly wet. During the 2018-19 season Thulamahashe and Shaws Gate were both near normal.

The intra-seasonal rainfall variability analysis also showed that the months November, December and January tend to receive most the rainfall while October and April tend to receive the least (Table 2). The monthly CV values were on the higher side, confirming the high variability of rainfall in the study area. As presented in Table 2, the Mann–Kendall (MK) test result revealed non-significant rainfall trends for Hazyview, Thulamahashe and Shaws Gate. With regards to intra-seasonal MK trend analysis, a significant decreasing trend of rainfall in November was observed for the period under observation for Thulamahashe and Shaws Gate (Table 2).

3.1.1. Temperature

The summarised summer seasonal mean temperature results are presented in Table 3 below. Thulamahashe had a high seasonal mean temperature of 24.59 °C while Hazyview had a seasonal mean temperature of 23.32 °C. The standardised temperature anomaly index (TAI) showed the presence of high inter-seasonal temperature variability. The seasons 2012-13 and 2013-14 were generally cool season while the 2015-16 season was generally a hot season (Fig. 3). Intra-seasonal temperature variability analysis also showed that the months January, February and March tend to experience high temperature while in April marks the onset of autumn with a temperature decline (Table 4). As presented in Table 4, significant decreasing trends were observed in the monthly minimum temperatures for October and November in Hazyview (Table 4). Thulamahashe had a significant mean temperature trend observed for April which showed an increase (Table 4).

3.1.2. Relationship between seasonal rainfall and seasonal mean temperature

Table 5 shows the results of the correlation analysis between the three stations for seasonal rainfall. The analysis showed that a significant positive correlation ($p < 0.05$) was observed between rainfall anomalies for Hazyview and Thulamahashe (0.77) and between Hazyview and Shaws Gate (0.72). Table 6 shows the correlation analysis results between temperature anomalies of the two stations and with a significant positive correlation ($p < 0.05$) was observed for Hazyview and Thulamahashe (0.93).

3.2. Household characteristics, crop production and food security

Demographic and socioeconomic data from the surveyed households are shown in Table 7. The average household included 7.96 members, and the average dependency ratio of a household was 0.71, defined as a measure of the number of dependents aged zero to 16 and over the age of 65, compared with the total population aged 17 to 64. Most households are male headed and livelihoods encompass a variety of formal and informal income sources including off farm income and migrant labour. The ratio of off farm employment averaged 0.17 per active adults at household level and migrant employment is a major source of household income. Indeed, a large proportion of men, and increasing numbers of women, are labour migrants. The ratio of migrant employment averaged 0.22 per active adults at household level while such migration facilitates important strong rural-urban linkages.

Rain fed subsistence agriculture is a widespread livelihood strategy employed by households in the study area, with average of 96% of households involved in cropping activities over the study period. (Table 7). The prevalence of cropping varied little between the 2009-10 and 2013-14 seasons when households growing crops cultivated an average of 8 different types of crops. However, households grew significantly fewer crops (roughly half) the number of crops in 2018-19 compared to previous seasons (Table 7). As to crop loss, an average of 45.6% of households experienced zero crop loss, with 15.1%, 16.2% and 21.5% experiencing little, moderate and severe crop losses respectively (Fig. 4). About 1.5% of the households lost 100% of their crops due to extreme weather events (Fig. 4).

The mean household food frequency score for consumption of main meals (HMFSa) was 2.83 ± 0.45 SD and for the consumption of snack meals (HMFSb) was 0.83 ± 1.05 SD for the six study rounds (Table 7). The mean number of main and snack meals differed significantly ($p < 0.05$) across the study years. Notable significant differences were observed in the mean scores for the main meals for the years 2010 and 2019 which were lower than in the years between 2011 and 2014. Snacking (HMFSb) differed in 2011 and 2012, showing more snacking in households across time. Out of the 13 food groups, the study found the yearly mean household dietary diversity score (HDDS) was 7.1 ± 2.11 SD (Table 7). The mean household dietary diversity scores for the year 2013 and 2019 were significantly ($p < 0.05$) lower from the others (Table 7).

The experience of food insecurity in the last 30 days (HFIAS) was 0.45 ± 2.11 SD and this measure fluctuated significantly ($p < 0.05$) across the six study rounds. The yearly mean were significantly higher in 2010, 2012 and 2019. The mean value of the coping

Table 1
Characteristics, variability and trend analysis of rainfall.

Station Name	Latitude	Longitude	Altitude	Period	Mean	SD	CV	MK
Hazyview	25.0488°S	31.1395°E	506	2006-07 to 2018-19	878	320.68	35.02	0.05
Thulumahashe	24.7237°S	31.1823°E	479	2006-07 to 2018-19	642	254.64	39.65	−0.05
Shaws Gate	24.9282°S	31.4792°E	307	2006-07 to 2018-19	567	567.24	37.01	−0.26

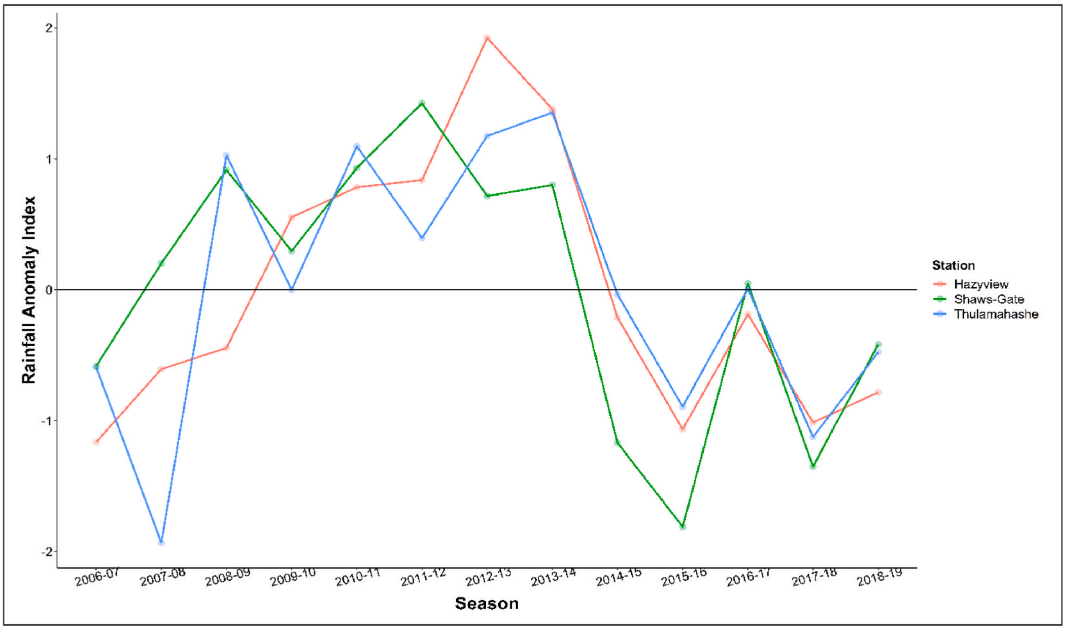

Fig. 2. Standardised summer season rainfall anomaly from 2007 to 08 to 2018-19 seasons.

Table 2
Intra seasonal variability and trend analysis of rainfall (2006-07 to2018-19).

Station	Variable	October	November	December	January	February	March	April
Hazyview	Mean	71.50	125.35	199.12	169.55	110.67	118.24	83.49
	SD	56.59	73.71	86.32	152.66	75.96	102.95	59.92
	CV	79.15	58.80	43.35	90.03	68.64	87.06	71.77
	MK	−0.15	−0.39	−0.154	0	0.31	0.05	−0.03
Thulamahashe	Mean	44.56	83.33	132.19	156.35	87.45	91.19	47.20
	SD	30.02	36.90	87.07	115.96	64.49	74.76	29.37
	CV	67.37	44.28	65.87	74.16	73.75	81.98	62.22
	MK	−0.18	−0.56*	0.10	0.03	0.03	0.13	0
Shaws-Gate	Mean	43.03	90.00	126.07	117.38	75.83	71.32	43.60
	SD	39.77	59.81	51.01	102.36	61.12	72.21	35.95
	CV	92.4	66.45	40.46	87.2	80.6	101.2	82.5
	MK	−0.26	−0.56[a]	−0.39	−0.13	−0.09	−0.03	0.04

*$p < 0.05$.

Table 3
Inter seasonal variability and trend analysis of seasonal mean temperature (2006-07 to 2018-19).

Station	Mean	SD	MK
Hazyview	23.32 °C	0.57	−0.03
Thulamahashe	24.59 °C	0.53	−0.05

strategy index (CSI) was 0.48 ± 1.02 SD and the values showed a decrease over time, as well as significant differences across the years (Table 7). However, it is important to note that levels of food access were particularly poor t in 2010 followed by 2011, indicating higher prevalence of households that engaged in coping strategies in response to food shortages in those years. The mean score for the overall food security index (HFSI) score was 0.71 ± 0.14 SD and these also varied significantly across the period. As might be expected based on the other descriptive results, the household food security index (HFSI) significantly lower in 2010 (0.66) compared to the other years (Table 7).

3.3. The relationship between summer seasonal rainfall, temperature and crop production

We tested the relationship between rainfall anomaly index, temperature anomaly index and household crop production (number of crops grown) across all weather stations (Table 8). Rainfall anomaly index (RAI) showed significant positive correlation with

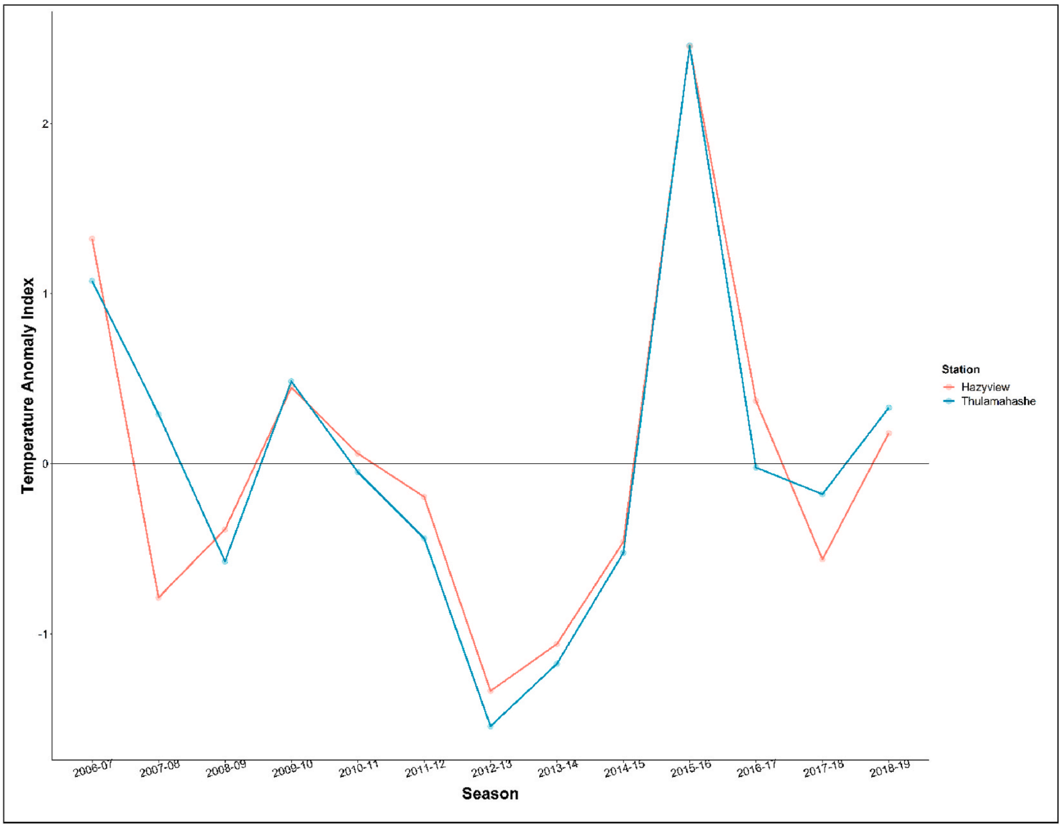

Fig. 3. Standardised seasonal mean temperature anomaly from 2006 to 07 to 2018-19.

Table 4
Intra seasonal variability and trend analysis of mean monthly temperature (2006-07 to 2018-19).

Station	Variable	October	November	December	January	February	March	April
Hazyview	Mean	28.12 ° C	28.12 ° C	29.66 ° C	29.76 ° C	30.44 ° C	30.00 ° C	27.54 ° C
	SD	1.38	1.08	2.06	1.05	1.76	1.05	1.06
	MK	−0.13	0.308	0.13	0.33	0.00	0.05	0.33
Thulamahashe	Mean	29.33 ° C	29.93 ° C	30.90 ° C	30.92 ° C	31.53 ° C	31.09 ° C	28.49 ° C
	SD	1.22	0.79	1.87	1.01	1.11	0.85	0.86
	MK	−0.13	0.28	0.13	0.17	−0.15	−0.15	0.32

*$p < 0.05$.

Table 5
Pearson's correlation coefficients for seasonal rainfall for the stations.

Test		Hazyview	Thulamahashe	Shaws-Gate
Pearson	Hazyview			
	Thulamahashe	0.77*		
	Shaws-Gate	0.72*	0.65*	

*$p<0.05$.

Table 6
Pearson's correlation coefficients for seasonal mean temperature for the stations.

Test		Hazyview	Thulamahashe
Pearson	Hazyview		
	Thulamahashe	0.93*	

*$p<0.05$.

Table 7
Descriptive statistics of key household variables used in regression the analyses.

Variable	2010 Mean (SD)	2011 Mean (SD	2012 Mean (SD)	2013 Mean (SD)	2014 Mean (SD)	2019 Mean (SD
Number of households	587	556	550	516	521	505
Demographic profiles						
Household size	8.11 (4.14)	8.12 (4.19)	7.91 (4.08)	8.59 (4.27)	8.28 (4.08)	6.66 (3.60)
Dependency ratio	0.80 (0.61)	0.76 (0.60)	0.75 (0.66)	0.71 (0.62)	0.66 (0.55)	0.56 (0.49)
Gender of the Household head	0.61 (0.98)	0.57 (0.50)	0.57 (0.50)	0.57 (0.50)	0.55 (0.50)	0.56 (0.50)
Livelihood profiles						
Cropping in external fields	0.57 (0.79)	0.52 (0.75)	0.39 (0.60)	0.50 (0.67)	0.47 (0.66)	0.11 (0.32)
Livestock ownership	0.18 (0.38)	0.18 (0.39)	0.19 (0.39)	0.20 (0.40)	0.20 (0.40)	0.22 (0.41)
Natural resource use intensity	7.10 (2.76)	6.36 (2.31)	5.69 (2.40)	6.06 (2.64)	5.98 (2.72)	5.16 (3.06)
Off farm employment ratio	0.17 (0.23)	0.19 (0.24)	0.15 (0.22)	0.19 (0.24)	0.20 (0.24)	0.19 (0.24)
Migrant employment	0.22 (0.24)	0.22 (0.22)	0.25 (0.25)	0.22 (0.23)	0.22 (0.22)	0.17 (0.24)
Social grants	1024 (905)	1158 (993)	1265 (1103)	1434 (1229)	1484 (1244)	1361 (1130)
Crop production						
Household crop production (%)	97.1	97.8	96.1	99.0	97.2	87.8
Number of crops grown	8.79 (4.9)	9.05 (5.2)	8.40 (4.8)	9.80 (4.9)	9.54 (5.0)	4.71 (4.0)
Food security						
HMFSa	2.78 (0.52)	2.86 (0.45)	2.86 (0.40)	2.86 (0.40)	2.91 (0.32)	2.75 (0.57)
HMFSb	0.81 (1.00)	0.90 (1.13)	0.96 (1.14)	0.80 (1.04)	0.80 (1.05)	0.69 (0.88)
HDDS	7.22 (2.16)	7.45 (2.04)	7.42 (1.92)	6.66 (2.08)	7.68 (1.92)	6.19 (2.20)
HFIAS	0.77 (1.59)	0.36 (0.98)	0.65 (1.58)	0.29 (0.94)	0.19 (0.77)	0.56 (1.06)
CSI	0.76 (1.25)	0.59 (1.10)	0.51 (1.06)	0.42 (0.97)	0.32 (0.85)	0.22 (0.62)
HFSI	0.66 (0.15)	0.71 (0.12)	0.71 (0.12)	0.70 (0.12)	0.74 (0.11)	0.71 (0.14)

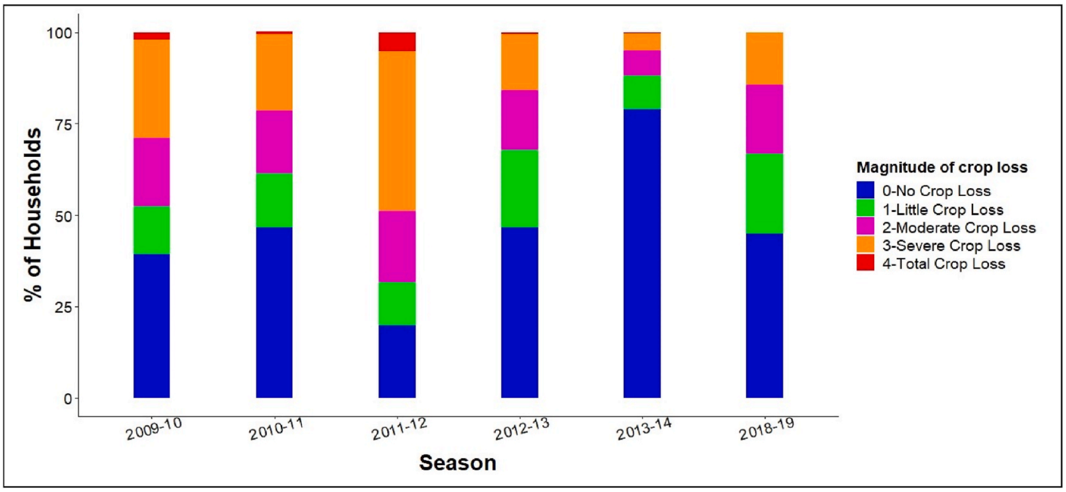

Fig. 4. Percentage of households that experience rainfall related crop loss.

household crop production while the temperature anomaly index (TAI) showed significant negative correlation with household crop production.

3.4. *The relationship of household characteristics, summer seasonal rainfall, temperature and crop production*

Table 9 shows the effects of household characteristics and local climate on household crop production and crop loss scores. Model 1

Table 8
Coefficients for correlation between seasonal climate anomalies and household crop production.

Station	Climate	Number of crop grown
Hazyview	RAI	0.29[a]
	TAI	−0.16[a]
Thulamahashe	RAI	0.26[a]
	TAI	−0.19[a]
Shaws-Gate	RAI	0.23[a]

[a] $p < 0.05$.

tested the relationship between household characteristics and crop production and all the household characteristics, except migrant employment, were significant predictors and positively associated with household crop production ($p < 0.05$). Model 2 added climate conditions indicating that rainfall in Thulamahashe was significantly and positively associated with household crop production (number of crops grown) while temperature was significantly and negatively associated. We also tested the relationships with crop losses. External fields were significantly and positively associated with high crop losses while both temperature and rainfall were significantly and negatively associated with crop losses.

3.5. The relationship of summer seasonal rainfall, temperature, crop production and food security

We tested the relationship between the rainfall anomaly index, temperature anomaly index and our six food security indicators across all stations (Table 10). The rainfall anomaly index (RAI) showed positive correlation with consumption frequency scores for main meals (HMFSa) and snack meals (HMFSb) but was only significant for rainfall values in Shaws Gate stations. A significant positive correlation between the rainfall anomaly index (RAI) and dietary diversity (HDDS) was observed across all stations as was the case for rainfall and food access (HFIAS) as well as overall food security (HFSI). This means that as seasonal rainfall increased the prevalence of experience of hunger decreased, improving overall food security. The temperature anomaly index (TAI) had significant negative correlation with consumption of main meals (HMFSa) and overall food security index (HFSI), meaning that food security was generally lower in years that were warmer relative to the mean (Table 10). We also tested the relationship between household crop production and food security (Table 11), Where a significant positive correlation ($p < 0.05$) was found between household crop production and all the food security indicators except the coping strategy index (CSI).

The effects of household characteristics, summer seasonal climate and crop production on household food security.

Table 12 shows the effects of household characteristics, summer seasonal climate and crop production on food security. Model 1 tested the effects between household characteristics and food security and demonstrated varying impacts. External fields and a household migrants were significant predictors of the number of crops grown ($p < 0.05$) and were also positively associated with main meal consumption (HMFSa). Household size, cropping in external fields, and number of crops grown were significant, positive predictors $p < 0.05$) of snacking (HMFSb) and all the household characteristics except dependency ratio were significant, positive predictors of dietary diversity (HDDS). Off farm employment and migrant employment were significant, positive predictors ($p < 0.05$) of HFIAS and CSI which are indicators of food access. The dependency ratio was also negatively associated with the coping strategies while all household characteristics except the dependency ratio were significant, positive predictors ($p < 0.05$) with overall food

Table 9
Regression models predicting the effects of household characteristics and local climate on household crop production and crop loss scores.

Outcome variable	Independent variable	Model 1		Model 2	
		Coef.	Std.Err	Coef.	Std.Err
Household crop production	Intercept	7.63*	0.12	7.68*	0.25
	Wave	−0.27*	0.04	−0.49*	0.06
	Household size	0.93*	0.11	0.66*	0.11
	Dependency ratio	0.26*	0.10	0.24*	0.10
	External fields	1.93*	0.14	1.60*	0.14
	Off farm employment	1.53*	0.39	1.16*	0.38
	Migrant employment	0.28	0.37	−0.34	0.39
	Thulamahashe TAI			−1.07*	0.19
	Thulamahashe RAI			0.68*	0.30
	Shaws-Gate RAI			0.14	0.19
	Model fit				
	AIC	19013.27		18768.69	
	R^2	0.38		0.44	
	Number of observations	3235		3235	
	Number of groups	587		587	
		Coef	Std Err	Coef	Std Err
Household crop loss score	Intercept	0.58*	0.11	0.59*	0.10
	Wave	−0.04	0.24	−0.04	0.03
	Household size	0.00	0.01	0.00	0.01
	Dependency ratio	0.01	0.01	0.01	0.01
	External Fields	0.09*	0.01	0.09*	0.01
	Off farm employment	−0.02	0.04	−0.02	0.04
	Migrant employment	0.03	0.04	0.03	0.04
	Thulamahashe TAI			−0.10	0.08
	Thulamahashe RAI			−0.33*	0.09
	Shaws-Gate RAI			−0.21*	0.08
	Model fit				
	AIC	4302.01		4299.06	
	R^2	0.05		0.11	
	Number of observations	3235		3235	
	Number of groups	587		587	

*$p<0.05$.

Table 10
Coefficients for correlation between seasonal climate anomalies and food security metrics.

Station	Climate	HMFSa	HMFSb	HDDS	HFIAS	CSI	HFSI
Hazyview	RAI	0.09[a]	0.03	0.11[a]	0.09[a]	−0.03	004[a]
	TAI	−0.09[a]	0.00	−0.01	−0.14[a]	−0.08[a]	−0.10[a]
Thulamahashe	RAI	0.11[a]	0.03	0.13[a]	0.14[a]	0.01	0.08[a]
	TAI	−0.09[a]	−0.01	−0.03	−0.13[a]	0.36	−0.10[a]
Shaws-Gate	RAI	0.09[a]	0.07[a]	0.18[a]	0.04[a]	−0.05[a]	0.04[a]

[a] $p < 0.05$.

Table 11
Coefficients for correlation between household crop production and food security metrics.

Variable	HMFSa	HMFSb	HDDS	HFIAS	CSI	HFSI
Number of crops grown	0.09[a]	0.09[a]	0.16[a]	0.05[a]	−0.02	0.07[a]

[a] $p < 0.05$.

security (HFSI).

Model 2 tested the effects of household characteristics, household crop production and local climatic conditions on food security. Our results for household characteristics were consistent with model 1 results. Household crop production was a significant, positive predictor ($p < 0.05$) with main meal consumption (HMFSa), snacking (HMFSb), and household dietary diversity (HDDS). Local climate conditions indicated that local rainfall was significant predictors and positively associated with main meals (HMFSa), dietary diversity (HDDS), food access (HFIAS), as well as overall food security (HFSI). The results also show that local temperature was significantly and negatively associated with consumption of main meals and overall food security (HFSI). Finally, our results also show that at each round of survey (wave), household dietary diversity (HDDS) decreased while household food access (HFIAS and CSI and overall food security (HFSI) significantly increased.

4. Discussion

4.1. Exposure to rainfall and temperature variability

Bushbuckridge has a unimodal summer rainfall pattern (October to April) and our study sought to understand how inter-annual climate variability dynamics during the summer growing season influences subsistence agriculture and ultimately household food security in rural South Africa. Specific attention to seasonal rainfall variability is important since rural subsistence agricultural activities are largely governed by these rainfall periods, especially in areas where dryland farming is the norm. Temporally, the trends for rainfall from 2006 to 07 to 2018-19 show that the region experienced high inter and intra seasonal rainfall variability with CV values above 30%. On an intra seasonal monthly time scale, significant decreasing trends in monthly total rainfall for November was observed, which is especially important since this period coincides with planting of crops, and the observed significant decline and high variability of rainfall in this month makes planting and germination of crops unpredictable. These results concur with Dube and Nhamo (2020) who observed a similar patterns of decline and high inter-annual variability in nearby Kruger National Park (although not statistically significant).

4.2. Relationship between summer climate variability and subsistence agriculture

Despite the fact that most households in this study area are highly reliant on off-farm livelihood sources such as labour migration and social grants (Ragie et al., 2020), subsistence agriculture remains an important component of the livelihoods. Subsistence agriculture is particularly important to food security. This is evidenced by over 90% of surveyed households which engaged in crop production activities each summer rainfall season. The study area is associated with summer seasonal average rainfall ranging from 567 to 878 mm which is suitable for maize production, a staple crop in South Africa (Moeletsi and Walker, 2012). In our study, rainfall pattern for the period 2009-10 to 2013-14 was mostly above normal although the average number of crops grown by households declined significantly over the years, with the most significant decline in 2019. This may be attributed to the continuous drought that occurred between the 2014-15 and the 2018-19 seasons. We then explored the relationship between climate variability and number of crops grown, as seen from this study, temperature and rainfall are significant factors. We find that high rainfall variability has made it difficult for sustainable and stable subsistence rainfed agricultural and food production. This is logical in that because a highly variable rainfall pattern is often associated with extreme weather events that are fatal to crops (Ali et al., 2017). In our case, this is evidenced by the percentage of households (55%) that experienced weather-related crop losses. These losses are attributed to weather related incidences, of which cyclones, floods and intra seasonal droughts are the major causes of crop losses and are directly related to climate change.

Table 12
Regression models predicting the effects of household characteristics and local climate on household food security.

Model	Independent variables	HMFSa Coef (Std Err)	HMFSb Coef (Std Err)	HDDS Coef (Std Err)	HFIAS Coef (Std Err)	CSI Coef (Std Err)	HFSI Coef (Std Err)
Model 1	Intercept	0.93* (0.01)	0.21* (0.01)	0.53* (0.01)	0.90* (0.01)	0.77* (0.01)	0.64* (0.01)
	Wave	0.00 (0.00)	−0.00 (0.00)	−0.01* (0.00)	0.01* (0.00)	0.03* (0.00)	0.01* (0.00)
	Household size	0.01 (0.00)	0.02* (0.01)	0.02* (0.00)	0.00 (0.00)	0.00 (0.01)	0.01* (0.00)
	Dependency ratio	0.01 (0.00)	0.01 (0.00)	−0.01* (0.00)	−0.00 (0.00)	−0.01* (0.01)	−0.01 (0.00)
	External fields	0.01* (0.00)	0.02* (0.01)	0.01* (0.00)	0.01 (0.00)	0.01 (0.01)	0.01* (0.00)
	Off farm employment	0.02 (0.01)	0.03 (0.02)	0.08* (0.01)	0.04* (0.01)	0.06* (0.02)	0.06* (0.01)
	Migrant employment	0.03* (0.01)	−0.02 (0.02)	0.10* (0.01)	0.08* (0.01)	0.16* (0.02)	0.11* (0.01)
	Number of crop grown	0.01* (0.00)	0.01* (0.01)	0.02* (0.00)	0.01 (0.00)	0.00 (0.00)	0.01* (0.00)
	Model 1 fit						
	AIC	−2901.37	477.45	−3004.11	−4005.14	−96.81	−3970.83
	R^2	0.11	0.05	0.28	0.22	0.26	0.29
	Number of observations	3235	3235	3235	3235	3235	3235
	Number of groups	587	587	587	587	587	587
Model 2	Intercept	0.91* (0.01)	0.21* (0.01)	0.50* (0.01)	0.89* (0.01)	0.76* (0.01)	0.62* (0.00)
	Wave	0.00 (0.00)	−0.00 (0.00)	−0.00* (0.00)	0.01* (0.00)	0.03* (0.00)	0.01* (0.00)
	Household size	0.00 (0.00)	0.02* (0.00)	0.02* (0.00)	0.00 (0.00)	0.00 (0.01)	0.01* (0.00)
	Dependency ratio	0.00 (0.00)	0.01 (0.00)	−0.01* (0.00)	−0.00 (0.00)	−0.01* (0.01)	−0.01 (0.00)
	External fields	0.01 (0.00)	0.02* (0.01)	0.01 (0.00)	0.00 (0.00)	0.01 (0.01)	0.01* (0.00)
	Off farm employment	0.02 (0.02)	0.03 (0.02)	0.07* (0.01)	0.03* (0.01)	0.06* (0.02)	0.06* (0.01)
	Migrant employment	0.03* (0.01)	−0.02 (0.02)	0.09* (0.01)	0.07* (0.01)	0.16* (0.02)	0.11* (0.01)
	Number of crops grown	0.01* (0.00)	0.01* (0.01)	0.01* (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
	Thulamahashe TAI	−0.00 (0.01)	−0.00 (0.01)	0.03* (0.01)	0.01 (0.01)	0.01 (0.01)	−0.02* (0.01)
	Thulamahashe RAI	0.02* (0.00)	0.00 (0.01)	0.05* (0.01)	0.04* (0.01)	0.01 (0.01)	0.01* (0.01)
	Shaws-Gate RAI	0.01* (0.01)	0.04* (0.01)	0.05* (0.00)	−0.01 (0.01)	0.00 (0.01)	0.02* (0.01)
	Model 2 fit						
	AIC	−2931.40	470.06	−30100.84	−4077.95	−91.80	−4000.19
	R^2	0.12	0.05	0.32	0.24	0.26	0.30
	Number of observations	3235	3235	3235	3235	3235	3235
	Number of groups	587	587	587	587	587	587

*$p < 0.05$.
RAI denotes Rainfall anomaly index.
TAI denotes Temperature anomaly index.

4.3. Relationship of summer climate variability and food security

We finally explored the relationship between summer climate variability (seasonal rainfall, and temperature) and food security. We see that rainfall variability is a significant predictor of all the food security metrics except the experience of hunger (HFIAS) and coping strategies (CSI). We see that household food consumption and dietary diversity in households typically falls in years with a lower rainfall during the rainy season and increases in years with more rainfall. In order to provide more insight into the last point we also factor in the association between temperature and rainfall. A significant negative correlation between rainfall and temperature was observed in that higher rainfall is associated with cooler temperatures, conditions more suitable for crop production. Our models further confirm this finding by showing temperature to be a significant, negative predictor of overall household food security, while the opposite is true for rainfall.

Subsistence farmers have a tendency to grow a variety of crops in their fields and these diversified agricultural systems are an important factor in boosting dietary diversity and nutritional food security (Jones et al., 2014). In our study, the number of crops grown was positively associated with dietary diversity. Therefore, increased dietary diversity in households can be realised through consumption of own produced foods. Our results confirm important summer seasonal dimensions that in higher rainfall years, most produce tends to reach maturity and more diverse food is available for consumption at household level. However, in lower rainfall years' substantial crops losses may occur, resulting in reduced diversity of food available to households resulting in a decrease in the food groups that they consume at household level. This result concurs with M'Kaibi et al. (2015) who observed significant differences between results of wet seasons and dry seasons; with the dry seasons exhibiting relatively lower levels of dietary diversity compared to wet seasons.

In most rural areas of South Africa, poverty is high and income from on farming activities is limited (Ragie et al., 2020). On this basis our proxy for subsistence agriculture (number of crops grown) was not a significant predictor of food access (HFIAS and CSI) which mainly depends on household income. However, of particular interest is that the rainfall anomaly for Thulamahashe is a significant predictor of food access (HFIAS) which showed that there was a significant positive relationship between rainfall and food access in this study area. This further reveals the impact subsistence agriculture has on food access and ultimately household food security. Through their own production households are able to save income and the savings contribute to purchasing of food needs that they cannot produce. Hence increased rainfall increases household production that either increases household income or enables households to cut costs and purchase other food.

Our results showed a significant negative relationship between temperature and HFSI indicator which captures various dimensions of food security. Our results also showed a significant positive relationship between rainfall and HFSI, further substantiating observed relationship between rainfall and food security in these communities. Drought stress due to decreased rainfall and increased temperatures (hot and dry conditions) can cause a decline in agricultural output and ultimately food insecurity. These results reinforce the notion by Lamb & Steinberger (2017) that climate change will have complex impacts on human well-being. For communities such as the one in Mpumalanga that make use of farming and natural resources for livelihoods, changes in weather and seasonal patterns may cause significant instabilities and fears, especially where changes may be substantial and widespread and include elements of shocks through the occurrence of extreme events.

4.4. Policy implications

Our findings have important policy implications. First, heightened rainfall and temperature variability highlights the need for climate smart agriculture to buffer agriculture-based households from total crop losses and deagrarianization in communal landscapes. This study shows that the process of deagrarianization observed in some rural areas is not uniform as households in this part of rural South Africa rely, in part, on subsistence agriculture, First, even if no longer the mainstay of livelihoods household crop production is a critical element for food security. Thus these rural communities are vulnerable to climate impacts on food production. Secondly, there is need for rural households to diversify livelihood incomes sources to reduce climate vulnerability. Such diversification could enhance household capacities to invest in agriculture infrastructure such as irrigation and, subsequently, improve crop production and overall income. Thirdly, while our results are able to show the influence of weather patterns on household food production and food security, we were unable to account for changes in food prices, an important aspect of food security and another dimension of food security that is impacted by climate variability.

5. Conclusion

This study examined the relationship between summer climate variability and households' food security in rural households in Mpumalanga, South Africa and we have three primary conclusions. First, climate variability characterizes the study region as we observed significant decline of rainfall and increased temperatures for November, thus making crop production unpredictable. Further, the area of Bushbuckridge is located in a region projected to experience future temperature increases and more rainfall variability. Secondly, over 96% of the surveyed households were involved in rainfed subsistence agriculture to supplement household food requirements, therefore, their food security is vulnerable to climate stressors. Thirdly, rainfall and temperature variability were intricately linked with household food security through significant shifts in consumption patterns. Lastly, we illustrate that summer seasonality is a key component in the livelihood and vulnerability context and must be considered within interventions to improve livelihood outcomes. We contend there is need to synthesize and communicate climate change information to local communities to better inform crop production planning. It is also important to work towards understanding and harnessing the synergistic interactions of climate and weather change, socioeconomics, and subsistence agriculture. Critically, insights from such research must be integrated into planning and policy development in support of food security in rural communities across the Global South.

Author contributions

The study was conceived by Farirai Rusere, Wayne Twine, Lori Hunter and Mark Collinson. Methods were developed by all authors. Analysis was carried out by Farirai Rusere The original manuscript was written by Farirai Rusere, and all the other authors edited subsequent drafts.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envdev.2023.100892.

References

Adeyeye, S.A.O., Ashaolu, T.J., Bolaji, O.T., Abegunde, T.A., Omoyajowo, A.O., 2023. Africa and the Nexus of poverty, malnutrition and diseases. Crit. Rev. Food Sci. Nutr. 63 (5), 641–656. https://doi.org/10.1080/10408398.2021.1952160.

Al-Amin, A.Q., Ahmed, F., 2016. Food security challenge of climate change: an analysis for policy selection. Futures 83, 50–63. https://doi.org/10.1016/j.futures.2016.04.002.

Ali, S., Liu, Y., Ishaq, M., Shah, T., Abdullah, Ilyas, A., Din, I., 2017. Climate change and its impact on the yield of major food crops: evidence from Pakistan. Foods 6 (6), 39. https://doi.org/10.3390/foods6060039.

Andersson, L., Wilk, J., Graham, L.P., Wikner, J., Mokwatlo, S., Petja, B., 2020. Local early warning systems for drought – could they add value to nationally disseminated seasonal climate forecasts? Weather Clim. Extrem. 28, 100241 https://doi.org/10.1016/j.wace.2019.100241.

Archer, E., Engelbrecht, F., Hansler, A., Landman, W., Tadross, M., Helmschrot, J., 2018. Seasonal Prediction and regional climate projections for southern Africa. In: Revermann, R., Krewenka, K., Schmiedel, U., Olwoch, J., Helmschrot, J., Jurgens, N. (Eds.), *Climate Change and Adaptive Land Management in Southern Africa - Assessments, Challenges, and Solutions* (Biodiversi). Klaus Hess Publishers.

Azzarri, C., Signorelli, S., 2020. Climate and poverty in Africa south of the sahara. World Dev. 125, 104691 https://doi.org/10.1016/j.worlddev.2019.104691.

Birkmann, J., Liwenga, E., Pandey, R., Boyd, E., Djalante, R., Gemenne, F., Leal Filho, W., Pinho, P.F., Stringer, L., D W, 2022. Poverty, livelihoods and sustainable development coordinating. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009325844.010.1171.

Brewer, M.J., Butler, A., Cooksley, S.L., 2016. The relative performance of AIC, AICC and BIC in the presence of unobserved heterogeneity. Methods in Ecology and Evolution 7 (6), 679–692. https://doi.org/10.1111/2041-210X.12541.

Cammarano, D., Valdivia, R.O., Beletse, Y.G., Durand, W., Crespo, O., Tesfuhuney, W.A., Jones, M.R., Walker, S., Mpuisang, T.N., Nhemachena, C., Ruane, A.C., Mutter, C., Rosenzweig, C., Antle, J., 2020. Integrated assessment of climate change impacts on crop productivity and income of commercial maize farms in northeast South Africa. Food Secur. 12 (3), 659–678. https://doi.org/10.1007/s12571-020-01023-0.

Conceição, P., Levine, S., Lipton, M., Warren-rodríguez, A., 2016. Toward a food secure future: ensuring food security for sustainable human development in Sub-Saharan Africa. Food Pol. 60, 1–9.

DEA, 2013. Long-term adaptation scenarios flagship research Programme (LTAS) for South Africa. In: Climate Trends and Scenarios for South Africa (Vol. 1, Issue 6).

Drysdale, R.E., Moshabela, M., Bob, U., 2019. Adapting the Coping Strategies Index to measure food insecurity in the rural district of iLembe, South Africa. Food Cult. Soc. 22 (1), 95–110. https://doi.org/10.1080/15528014.2018.1547067.

Drysdale, R.E., Moshabela, M., Bob, U., 2020. ' A creeping phenomenon ': the association between rainfall and household food insecurity in the district of iLembe , KwaZulu-Natal. Clim. Dev. 0 (0), 1–11. https://doi.org/10.1080/17565529.2020.1737795.

Dube, K., Nhamo, G., 2020. Evidence and impact of climate change on South African national parks. Potential implications for tourism in the Kruger National Park. Environ. Develop. 33 (January 2019), 100485 https://doi.org/10.1016/j.envdev.2019.100485.

Ebi, K.L., Bowen, K., 2016. Extreme events as sources of health vulnerability: drought as an example. Weather Clim. Extrem. 11, 95–102. https://doi.org/10.1016/j.wace.2015.10.001.

Elum, Z.A., Modise, D.M., 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. https://doi.org/10.1016/j.crm.2016.11.001.

FAO, 2018. The state of food security and nutrition in the world 2018. Building climate resilience for food security. In: FAO. FAO.

Fawcett, D., Pearce, T., Ford, J.D., Archer, L., 2017. Operationalizing longitudinal approaches to climate change vulnerability assessment. Global Environ. Change 45, 79–88. https://doi.org/10.1016/j.gloenvcha.2017.05.002. May.

Gil, J.D.B., Reidsma, P., Giller, K., Todman, L., Whitmore, A., van Ittersum, M., 2019. Sustainable development goal 2: improved targets and indicators for agriculture and food security. Ambio 48 (7), 685–698.

Giller, K.E., Delaune, T., Silva, J.V., van Wijk, M., Hammond, J., Descheemaeker, K., van de Ven, G., Schut, A.G.T., Taulya, G., Chikowo, R., Andersson, J.A., 2021. Small farms and development in sub-Saharan Africa: farming for food, for income or for lack of better options? Food Secur. 13 (6), 1431–1454. https://doi.org/10.1007/s12571-021-01209-0.

Han, F., Cook, K.H., Vizy, E.K., 2019. Changes in intense rainfall events and dry periods across Africa in the twenty-first century. Clim. Dynam. 53 (5–6), 2757–2777. https://doi.org/10.1007/s00382-019-04653-z.

Hare, W., 2003. Assessment of knowledge on impacts of climate change - contribution to the specification of the Art. 2 of the UNFCCC. In: Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen.

Ickowitz, A., Powell, B., Rowland, D., Jones, A., Sunderland, T., 2019. Agricultural intensi fi cation , dietary diversity , and markets in the global food security narrative. Global Food Secur. 20, 9–16. https://doi.org/10.1016/j.gfs.2018.11.002. November 2018.

Islam, M.S., Islam, A.H.M.S., Sato, M., 2022. Nexus between climatic extremes and household expenditures in rural Bangladesh: a nationally representative panel data analysis. Asia-Pacific Journal of Regional Science 0123456789. https://doi.org/10.1007/s41685-022-00266-3.

Jones, A.D., Shrinivas, A., Bezner-Kerr, R., 2014. Farm production diversity is associated with greater household dietary diversity in Malawi: findings from nationally representative data. Food Pol. 46, 1–12. https://doi.org/10.1016/j.foodpol.2014.02.001.

Kahn, K., Collinson, M.A., Xavier Gómez-olivé, F., Mokoena, O., Twine, R., Mee, P., Afolabi, S.A., Clark, B.D., Kabudula, C.W., Khosa, A., Khoza, S., Shabangu, M.G., Silaule, B., Tibane, J.B., Wagner, R.G., Garenne, M.L., Clark, S.J., Tollman, S.M., 2012. Profile: Agincourt health and socio-demographic surveillance system. Int. J. Epidemiol. 41 (4), 988–1001. https://doi.org/10.1093/ije/dys115.

Kruger, A.C., Sekele, S.S., 2013. Trends in extreme temperature indices in South Africa: 1962-2009. Int. J. Climatol. 33 (3), 661–676. https://doi.org/10.1002/joc.3455.

Lamb, W.F., Steinberger, J.K., 2017. Human well-being and climate change mitigation. Wiley Interdiscip. Rev.: Clim. Change 8 (6), 1–16. https://doi.org/10.1002/wcc.485.

M'Kaibi, F.K., Steyn, N.P., Ochola, S., Du Plessis, L., 2015. Effects of agricultural biodiversity and seasonal rain on dietary adequacy and household food security in rural areas of Kenya. BMC Publ. Health 15 (1), 1–11. https://doi.org/10.1186/s12889-015-1755-9.

MacKellar, N., New, M., Jack, C., 2014. Observed and modelled trends in rainfall and temperature for South Africa: 1960-2010. South Afr. J. Sci. 110 (7–8), 51–64. https://doi.org/10.1590/sajs.2014/20130353.

Maponya, P., Mpandeli, S., 2013. Perception of farmers on climate change and adaptation in Limpopo province of South Africa. J. Hum. Ecol. 42 (3), 283–288.

Mastrorillo, M., Licker, R., Bohra-mishra, P., Fagiolo, G., Estes, L.D., Oppenheimer, M., 2016. The influence of climate variability on internal migration flows in South Africa. Global Environ. Change 39, 155–169. https://doi.org/10.1016/j.gloenvcha.2016.04.014.

Miller, V., Yusuf, S., Chow, C.K., Dehghan, M., Corsi, D.J., Lock, K., Popkin, B., Rangarajan, S., Khatib, R., Lear, S.A., Mony, P., Kaur, M., Mohan, V., Vijayakumar, K., Gupta, R., Kruger, A., Tsolekile, L., Mohammadifard, N., Rahman, O., et al., 2016. Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the Prospective Urban Rural Epidemiology (PURE) study. Lancet Global Health 4 (10), e695–e703. https://doi.org/10.1016/S2214-109X(16)30186-3.

Moeletsi, M.E., Walker, S., 2012. A simple agroclimatic index to delineate suitable growing areas for rainfed maize production in the Free State Province of South Africa. Agric. For. Meteorol. 162 (163), 63–70. https://doi.org/10.1016/j.agrformet.2012.04.009.

Mpandeli, S., Nhamo, L., Moeletsi, M., Masupha, T., Magidi, J., Tshikolomo, K., 2019. Assessing climate change and adaptive capacity at local scale using observed and remotely sensed data. Weather Clim. Extrem. 26 (November), 100240 https://doi.org/10.1016/j.wace.2019.100240.

Musemwa, L., Muchenje, V., Mushunje, A., Aghdasi, F., Zhou, L., 2015. Household food insecurity in the poorest province of South Africa: level, causes and coping strategies. Food Secur. 7 (3), 647–655.

Myers, S.S., Smith, M.R., Guth, S., Golden, C.D., Vaitla, B., Mueller, N.D., Dangour, A.D., Huybers, P., 2017. Climate change and global food systems: potential impacts on food security and undernutrition. Annu. Rev. Publ. Health 38, 259–277. https://doi.org/10.1146/annurev-publhealth-031816-044356.

Pohl, B., Macron, C., Monerie, P., 2017. Fewer Rainy Days and More Extreme Rainfall by the End of the Century in Southern Africa. Nature Publishing Group. https://doi.org/10.1038/srep46466. April, 6–12.

Prosekov, A.Y., Ivanova, S.A., 2018. Food security: the challenge of the present. Geoforum 91, 73–77. https://doi.org/10.1016/j.geoforum.2018.02.030. February.

Ragie, F.H., Olivier, D.W., Hunter, L.M., Erasmus, B.F.N., Vogel, C., Collinson, M., Twine, W., 2020. A portfolio perspective of rural livelihoods in. South Afr. J. Sci. 116 (9), 1–8.

Randell, H., Gray, C., Shayo, E.H., 2022. Climatic conditions and household food security: evidence from Tanzania. Food Pol. 112, 102362 https://doi.org/10.1016/j.foodpol.2022.102362. November 2021.

Randell, H., Jiang, C., Liang, X.Z., Murtugudde, R., Sapkota, A., 2021. Food insecurity and compound environmental shocks in Nepal: Implications for a changing climate. World Development 145, 105511. https://doi.org/10.1016/j.worlddev.2021.105511.

Savo, V., Lepofsky, D., Benner, J.P., Kohfeld, K.E., Bailey, J., Lertzman, K., 2016. Observations of climate change among subsistence-oriented communities around the world. Nat. Clim. Change 6, 462–474. https://doi.org/10.1038/nclimate2958.

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5 (1).

Shackleton, C.M., Mograbi, P.J., Drimie, S., Fay, D., Hebinck, P., Hoffman, M.T., Maciejewski, K., Twine, W., 2019. Deactivation of field cultivation in communal areas of South Africa: patterns, drivers and socio-economic and ecological consequences. Land Use Pol. 82, 686–699. https://doi.org/10.1016/j.landusepol.2019.01.009. December 2018.

Shackleton, S., Ziervogel, G., Sallu, S., Gill, T., Tschakert, P., 2015. Why is socially-just climate change adaptation in sub-Saharan Africa so challenging ? A review of barriers identified from empirical cases. WIREs Clim. Change 6, 321–344. https://doi.org/10.1002/wcc.335.

Shukla, S., Arsenault, R., , K, Hazra, A., Peters-Lidard, C., Koster, D., , R, Davenport, F., Magadzire, T., Funk, C., Kumar, S., McNally, A., Getirana, A., Husak, G., Zaitchik, B., Verdin, J., Dieudonne Nsadisa, F., Becker-Reshef, I., 2020. Improving early warning of drought-driven food insecurity in southern Africa using operational hydrological monitoring and forecasting products. Nat. Hazards Earth Syst. Sci. 20 (4), 1187–1201. https://doi.org/10.5194/nhess-20-1187-2020.

Sneyers, R., 1990. On the Statistical Analysis of Series of Observations.

Stats, S.A., 2022. Measuring Food Security in South Africa: Applying the Food Insecurity Experience Scale.

Thiede, B.C., Strube, J., 2020. Climate variability and child nutrition : findings from sub-Saharan Africa. Global Environ. Change 65, 102192. https://doi.org/10.1016/j.gloenvcha.2020.102192. November.

Thomas, T.S., Robertson, R.D., Strzepek, K., Arndt, C., Thomas, T.S., 2022. Extreme Events and Production Shocks for Key Crops in Southern Africa Under Climate Change 4. https://doi.org/10.3389/fclim.2022.787582. May.

Tibesigwa, B., Visser, M., 2015. Small-Scale Subsistence Farming, Food Security, Climate Change and Adaptation in South Africa: Male-Female Headed Households and Urban-Rural Nexus. Economic Research Southern Africa. *June*, 1–33.

Tibesigwa, B., Visser, M., 2016. Assessing gender inequality in food security among small-holder farm households in urban and rural South Africa. World Dev. 88, 33–49.

Tibesigwa, B., Visser, M., Collinson, M., Twine, W., 2016. Investigating the sensitivity of household food security to agriculture-related shocks and the implication of social and natural capital. Sustain. Sci. 11 (2), 193–214. https://doi.org/10.1007/s11625-015-0332-6.

Tibesigwa, B., Visser, M., Turpie, J., 2015. The impact of climate change on net revenue and food adequacy of subsistence farming households in South Africa. Environ. Dev. Econ. 20 (3), 327–353. https://doi.org/10.1017/S1355770X14000540.

Turner, C., Aggarwal, A., Walls, H., Herforth, A., Drewnowski, A., Coates, J., Kalamatianou, S., Kadiyala, S., 2018. Concepts and critical perspectives for food environment research: a global framework with implications for action in low- and middle-income countries. Global Food Secur. 18, 93–101. https://doi.org/10.1016/j.gfs.2018.08.003.

Vågen, T.-G., Winowiecki, L.A., Twine, W., Vaughan, K., 2018. Spatial gradients of ecosystem health indicators across a human-impacted semiarid savanna. J. Environ. Qual. 47 (4), 746–757. https://doi.org/10.2134/jeq2017.07.0300.

van Rooy, M., 1965. A rainfall anomaly index independent of time and space. Notos 14.

van Wilgen, N.J., Goodall, V., Holness, S., Chown, S.L., Mcgeoch, M.A., 2016. Rising temperatures and changing rainfall patterns in South Africa's national parks. Int. J. Climatol. 36 (2), 706–721. https://doi.org/10.1002/joc.4377.

WFP, 2019. End - of - Season Update for 2018/19 and Overview of the Food Security Situation in 2019/20 WFP Regional Bureau for Southern Africa (RBJ) Food Security in Southern Africa in 2019/20 2018/19 Seasonal Performance (Issue 9).

Walsh, C.M., van Rooyen, F.C., 2015. Household food security and hunger in rural and urban communities in the free state province, South Africa. Ecol. Food Nutr. 54 (2), 118–137. https://doi.org/10.1080/03670244.2014.964230.

Zinyengere, N., Crespo, O., Hachigonta, S., 2013. Crop response to climate change in southern Africa: a comprehensive review. Global Planet. Change 111, 118–126.