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Identifying climatic risks and relevant adaptation strategies for selected smallholder farming regions, Limpopo Province, South Africa

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ABSTRACT

Due to low adaptive capacities and high reliance on weather-sensitive natural ecosystems for their livelihoods and food production, smallholder farmers are highly vulnerable to risks associated with climate change and variability. Such risks are location-specific; thus, to cope with them, smallholder farmers require tailored adaptation strategies. To support these farmers, this study aimed to identify climatic risks threatening sustainable smallholder farming in the Limpopo Province regions of Gavaza, Ga-Makanye and Giyani. Weather station records spanning up to 1980–2021 were used to identify climatic risks, for the October–April dryland maize growing season. Risks were identified based on temporal trends and/or interannual variability patterns for reference evapotranspiration and a suite of agriculturally relevant rainfall and temperature indices. Based on the identified risks, tailor-made adaptation strategies were devised for application by farmers within the study region. The results revealed the specific risks of growing seasons becoming shorter and increasingly hotter with highly irregular rainfall patterns. To adapt and improve agricultural productivity despite these prevailing climatic risks, farmers within the study region will benefit if they plant drought tolerant, early maturing and higher yielding crop varieties, apply soil water conservation techniques and make use of seasonal and daily weather forecasts to guide their decision-making.

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1. Introduction

Across Southern Africa (SA), many climatic changes are already emerging. Among these, temperatures and extreme hot temperature characteristics are increasing (F. Engelbrecht et al., 2015; van der Walt & Fitchett, 2021), rainfall amounts and onset dates are becoming increasingly irregular, and increases are evident for the frequency and magnitude of severe wet (floods) and dry (droughts and dry spells) events/periods (Kruger & Nxumalo, 2017a; Masson-Delmotte et al., 2021; Roffe et al., 2021). Negative impacts associated with these changes are exacerbated across SA because much of the population is vulnerable to climate change and variability impacts, and many also have restricted adaptive capacities (F. A. Engelbrecht & Monteiro, 2021; Mpandeli et al., 2019). Smallholder farmers, who rely on rainfed agriculture for their livelihoods, food security and economic development, are among those who are highly vulnerable and have restricted adaptive capacities (Myeni et al., 2019). This is due to a range of factors, including low incomes; inadequate farm equipment, technologies and resources; lack of basic agronomic knowledge; restricted access to and understanding of climate and weather information; and limited awareness of adaptation strategies to cope with climatic variability and changes (Calzadilla et al., 2014; Kom et al., 2022; Mpandeli et al., 2019; Myeni & Moeletsi, 2020; Pretty et al., 2011; Shikwambana et al., 2022).

Evidence of poor quantity yields and low-quality crops (and crop failure), livestock losses, and pest and disease outbreaks highlight that smallholder farmers are already witnessing climate change impacts, which in most instances, occur together with degrading of soils and inefficient farming practices (Calzadilla et al., 2014; Lobell et al., 2011; Myeni et al., 2019; Pereira, 2017; Pörtner et al., 2022; Stuch et al., 2021). Furthermore, climate changes impact their economic development and stability, which in turn threatens their water and food security. Thus, there is an urgent need to build their climate resilience and improve their agricultural productivity using potentially limited or even deteriorating natural resources (Calzadilla et al., 2014; Myeni & Moeletsi, 2020; Pretty et al., 2011; Shikwambana et al., 2021, 2022). One way to do this is to equip smallholder farmers with agrometeorological knowledge on relevant adaptation strategies to aid them to cope with and mitigate climatic risks, occurring due to human-induced climate change and natural patterns of climatic variability (Kom et al., 2022; Myeni, 2021; Myeni et al., 2019; Shikwambana et al., 2022). Although many broad strategies have been proposed in a global context (Pörtner et al., 2022), these are not always relevant at a local level, because climatic changes and natural patterns of variability are location-specific (Mpandeli et al., 2019; Myeni, 2021). Thus, tailor-made adaptation strategies accounting for location-specific climatic risks are urgently needed for smallholder farmers within SA.

The Agricultural Research Council (ARC) in South Africa is mandated to conduct research to develop such tailored information for smallholder farmers. Therefore, as part of the ARC Development of Resilient E-farming for agro-climate risk management in African Multi-environments (DREAM) project, this study aimed to identify suitable adaptation strategies recommended for application by smallholder farmers to cope with and build resilience against the prevailing climate-related risks. For this, we focused on selected locations within the Limpopo Province (i.e. Gavaza, Ga-Makanye and Giyani; Figure 1) and identified local climate-related risks, based on temporal trends and/or interannual variability patterns, derived from weather station records spanning up to

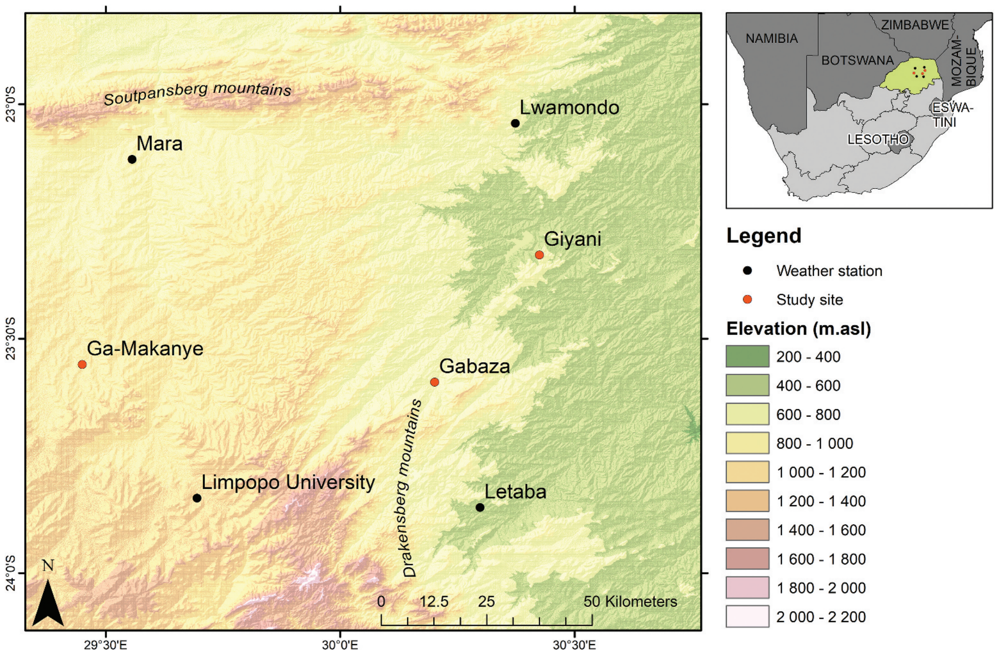

Figure 1. Study region map depicting the smallholder farming region study sites, weather stations and topography within the Limpopo Province (light green) within Southern Africa.

1980–2021; variables considered included reference evapotranspiration (ET_0) and a suite of agriculturally relevant rainfall and temperature indices. We focused on Limpopo because it is the study region for the DREAM project, but also because studies demonstrate that since ~1960, much of the province has been characterized by declining water availability and increasing temperatures during the summer growing season months (Mpandeli et al., 2019; Mupangwa et al., 2023; Shikwambana et al., 2021). Considering this and the high proportion of small-holder farmers within the province, it is necessary to explore climate-related risks for smaller regions within the province, especially since these larger scale trends can favour pest and disease occurrences, increase crop heat and water stress and they even influence livestock health, all of which negatively impacts smallholder famers (Myeni et al., 2019). Therefore, we explore location-specific climatic risk findings to inform the identification of tailor-made adaptation strategies (relevant for dryland maize production) that can be applied by multiple stakeholders (i.e. smallholder farmers, traditional leaders, agricultural cooperatives and extension officers) within the study region.

2. Materials and methods

2.1. Study region

This study focused on the Gavaza, Ga-Makanye and Giyani regions within the Limpopo Province (Figure 1); these locations are considered as they represent study regions for the DREAM project, aiming to advance climatic risk management by smallholder farmers. Home to many smallholder farmers, within these regions, farm sizes average <2 ha, and although agricultural production is somewhat diverse, maize is predominantly grown (along with various vegetables and fruits) during October–April months, while some farmers also keep livestock (Kephe et al., 2022; Shikwambana et al., 2021). Farmers typically have low incomes and limited access to agricultural technologies or equipment (Kephe et al., 2022). Their cropping activities are almost entirely rainfed; thus, rainfall and soil characteristics, and availability of technological resources are major agricultural productivity determinants (Mpandeli et al., 2019; Shikwambana et al., 2021).

Topographically, Gavaza and Giyani are on the windward, eastern side of the Drakensberg Mountains at ~690 and ~680 m.asl, respectively, while Ga-Makanye is on the leeward, western side at ~1100 m.asl (Figure 1). Climatically, based on data described under section 2.2, Gavaza and Giyani (Ga-Makanye) have (has) annual average daily temperatures of ~21-22 (~17–20) °C, annual average rainfall totals of ~700–900 (~400–450) mm, and annual average ET_0 totals ~1000–1200 (~1300–1400) mm (Figure S1-S2). Seasonally, rainfall, temperature and ET_0 vary, such that most annual rainfall occurs during warmer October–April months characterized by higher ET_0 levels (Figure S1-S2). During these months, at Gavaza and Giyani (Ga-Makanye) the average rainfall is ~739–796 (~415–418) mm, while the average ET_0 is ~726–764 (~887–896) mm, and daily mean, maximum and minimum temperatures are ~23–24 (~20–22) °C, ~29–30 (~27–29) °C, and ~ 17–18 (~14–16) °C, respectively (Figure S1–S2). Conversely, very little rain occurs during cooler May–September months characterized by lower ET_0 (Figure S1-S2). Interannually, seasonal rainfall, ET_0 and temperatures vary considerably (Mpandeli et al., 2019). The El Niño-Southern Oscillation (ENSO) is among the variability drivers during the growing season months (Hao et al., 2020; Lakhraj-Govender & Grab, 2019). During El Niño (La Niña) phases, where an ENSO influence is detectable, temperatures are typically above (below) average (Lakhraj-Govender & Grab, 2019), while rainfall totals are typically below (above) average with a heightened drought (flood) risk (Mazibuko et al., 2021), and evaporation levels are typically above (below) average (Hao et al., 2020).

2.2. Data

To investigate historical climatic changes and natural interannual variability patterns, data from four ARC weather stations within 50 km of the study locations were utilized (Figure 1). After an extensive search for weather stations, these were the only stations with continuous datasets, with ≥90% data availability, of daily rainfall and maximum and minimum temperatures for 1980–2021 (Table S1). We also utilized daily ET_0 records, starting during 2005 (2008) for Mara (Letaba, Lwamondo and Polokwane; Table S1).

Although ARC meteorological data are quality-controlled (Moeletsi et al., 2022), data quality was explored, following procedures undertaken by previous studies (e.g. Kruger & Nxumalo, 2017b,; Lakhraj-Govender et al., 2017; Roffe et al., 2021; Wolski et al., 2021). Outliers were identified using boxplots, while many errors were considered, including when daily rainfall or ET_0 were negative, daily minimum temperature ≥ daily maximum temperature, and daily values were repeated over consecutive days. Surrounding station records with shorter/discontinuous records were used to verify errors/outliers, and if confirmed, errors/outliers were deleted. Missing/deleted values were interpolated, using an inverse distance weighting method utilizing nearby (<50 km) station records (Moeletsi et al., 2016; Shabalala et al., 2019). Subsequently, we explored data homogeneity to determine whether non-climatic inhomogeneities existed (Lakhraj-Govender et al., 2017; Moeletsi et al., 2022; Wolski et al., 2021); the methods thereof are presented in the supplementary material.

2.3. Statistical analysis

To provide agriculturally relevant climatic information, our analyses focused on the maize growing season, representing when climate change and natural climate variability pose the greatest risk to smallholder farming (Moeletsi et al., 2011; Myeni & Moeletsi, 2020). Starting annually in July, an onset date was defined as the last day of a 10-day period with ≥25 mm accumulated, and ≥20 mm accumulated in the subsequent 20 days (Moeletsi & Walker, 2012; Moeletsi et al., 2011; Tadross et al., 2007). A cessation date was defined as the last day of a 10-day period accumulating ≥25 mm (Moeletsi & Walker, 2012; Moeletsi et al., 2011; Tadross et al., 2007). Average onset and cessation dates spanned October/November and April/May, respectively; thus, for subsequent analyses, the defined agriculturally relevant growing season was October–April, representing the wet (i.e. rainy) season months typically studied over Limpopo (Rapolaki et al., 2020; Roffe et al., 2020), and the typically reported timing for maize sowing (October–November/December) and harvesting (April; Food and Agriculture Organization of the United Nations (FAO), 2022). To further study the maize growing season, we defined its length following Moeletsi et al. (2011).

Based on literature, numerous agriculturally relevant rainfall and temperature indices were calculated annually for the growing season months (Masupha et al., 2016, Herold & McComb, 2021; Roffe et al., 2021; Thoithi et al., 2021). Rainfall indices included: 1) total seasonal rainfall, 2) rain days count (a rain day is classified by ≥1 mm), 3) average daily rainfall intensity (total seasonal rainfall/rain days count), 4) moderate (10–30 mm) and heavy (>30 mm) rain day counts, 5) maximum one-day and five-day rainfall amount and 6) dry-spell period counts (≥5 consecutive dry days). Temperature indices included: 1) average daily mean (average daily maximum and minimum temperature), maximum and minimum temperatures, 2) percentage of very hot days and nights (temperature ≥90^{th} percentile of daily maximum and minimum temperature, respectively), 3) percentage of very cold days and nights (temperature ≤10^{th} percentile of daily maximum and minimum temperature, respectively) and 4) magnitude of hottest (coldest) daily maximum (minimum) day- and night-time temperature. Total ET_0, representing the maximum atmospheric water demand from a crop field (Mzezewa et al., 2010), was also calculated.

Annual values for the variables were used to explore natural interannual variability patterns. The degree of variability was quantified using the coefficient of variation (CV), classified as low (CV < 20%), moderate (20% < CV < 30%) and high (CV > 30%). We also explored ENSO influences on the variables because SA seasonal forecasts consider ENSO as a predominant driver of interannual variability during the summer growing season months (Landman et al., 2019). For this, Spearman's correlation coefficient was used to calculate the strength and directional influence of ENSO using monthly Oceanic Niño Index (ONI) anomalies averaged annually for October–April (Hao et al., 2020; Mazibuko et al., 2021). Thereafter, temporal trends were calculated for the rainfall and temperatures indices using the nonparametric Mann-Kendall trend test and Sen's slope estimator (Lakhraj-Govender et al., 2017). Statistical significance was assessed at the 5% alpha level for all analyses.

3. Results and discussion

3.1. Identifying climate-related risks

Before discussing the climatic risks (based on temporal trends and natural variability patterns), it is noteworthy that few statistically significant results were evident (Table 1). Accounting for this, climatic risks were identified based on spatial consistency (with greater confidence where results were statistically significant) of the trend and variability results across the stations. Therefore, risks were identified if results for at least three stations were indicative of a specific risk despite the statistical significance level (Table 1). Subsequently, based on literature and general knowledge of the study region, identified risks were used to devise a list of adaptation strategies for the region's farmers.

3.1.1. Maize growing season risks

A prominent risk for the maize growing season characteristics was a long-term shift towards shorter growing seasons, up to 17.5 days.decade^{-1} ($p = 0.001$; Polokwane; Table 1). This is driven by later onset (i.e. planting) dates, up to 6.7 days.decade^{-1} ($p = 0.018$; Polokwane) and earlier cessation (i.e. harvesting) dates, up to 10.6 days.decade^{-1} ($p = 0.009$; Polokwane; Table 1). Corroborating these risks, several studies, considering our study region, have detected similar trends using historical records (Kabanda & Nenwiini, 2016; Roffe et al., 2021), while projected trends, until 2099, suggest continuation of these trends (Dunning et al., 2018). Focusing on a larger region within the Limpopo Province and including our study region, Mpandeli et al. (2019) highlight that these trends are shifting and shortening regional growing seasons towards December–March, which in turn impacts crop suitability and is likely decreasing rainfed crop (maize) production, primarily due to a shorter production period. This, and particularly the need to plant later, raises the risk of low yields and poor-quality harvests, and possible crop failure, while increasing food insecurity and potentially even water scarcity (Shikwambana et al., 2021; Tadross et al., 2007).

Due to challenges regarding predictability on the ground, a further risk is that of natural year-to-year variation in the growing season characteristics. While there was a relatively low degree of variation for annual onset dates, up to 13% (Lwamondo), there was a moderate-to-high degree for the annual cessation dates, up to 35% (Mara), and growing season length, up to 33% (Mara; Table 1). This highlights some uncertainty and limited predictability in the region's growing season characteristics, which can add difficulty to decision-making for smallholder farmers to determine the appropriate timing of planting and harvesting as natural variation means that these dates can differ substantially from year-to-year (Moeletsi et al., 2011). Despite a relatively lower variation level (Table 1), variation in onset dates poses a notable challenge for these smallholder

Table 1. Results for the coefficient of variation (CV), temporal trends and Spearman correlations for rainfall- and temperature-based indices, and reference evapotranspiration (ET_0) for the growing season for 1980/81–2020/21.

Weather station	Variable (trend units)	CV (%)	Correlation		Trend	
			r	p	s	p
Letaba	Onset date (days.decade^{-1})	11	0.25	0.120	2.4	0.448
Lwamondo		13	0.19	0.227	4.7	0.269
Mara		10	0.35	0.026*	−1.5	0.522
Polokwane		9	0.25	0.119	6.7	0.018*
Letaba	Cessation date (days.decade^{-1})	25	−0.16	0.242	1.1	0.786
Lwamondo		29	0.08	0.614	−7.0	0.197
Mara		35	0.04	0.811	−2.9	0.626
Polokwane		34	−0.07	0.644	−10.6	0.009*
Letaba	Growing season length (days.decade^{-1})	25	−0.38	0.015*	0.0	0.965
Lwamondo		26	0.06	0.715	−10.6	0.140
Mara		32	−0.20	0.213	−0.4	0.940
Polokwane		32	−0.17	0.281	−17.5	0.001*
Letaba	Total seasonal rainfall (mm.decade^{-1})	41	−0.51	0.001*	67.5	0.059
Lwamondo		46	−0.42	0.007*	17.7	0.779
Mara		38	−0.28	0.087	26.6	0.181
Polokwane		32	−0.27	0.089	−17.4	0.351
Letaba	Rain days (days.decade^{-1})	27	−0.53	0.0003*	2.5	0.163
Lwamondo		25	−0.47	0.002*	−1.8	0.265
Mara		25	−0.45	0.003*	1.5	0.216
Polokwane		22	−0.22	0.160	0.0	0.901
Letaba	Daily rainfall rate (mm.decade^{-1})	23	−0.24	0.127	0.8	0.058
Lwamondo		26	−0.22	0.174	0.3	0.567
Mara		24	−0.16	0.524	0.3	0.387
Polokwane		22	−0.16	0.506	−0.3	0.229
Letaba	Moderate rain days (days.decade^{-1})	39	−0.41	0.008*	0.0	0.587
Lwamondo		34	−0.42	0.006*	0.8	0.247
Mara		35	−0.12	0.454	0.0	0.991
Polokwane		34	−0.17	0.264	−0.5	0.173
Letaba	Heavy rain days (days.decade^{-1})	36	−0.35	0.024*	0.8	0.172
Lwamondo		38	−0.31	0.052	0.1	0.592
Mara		39	−0.20	0.212	0.1	0.446
Polokwane		34	−0.14	0.577	0.1	0.560
Letaba	Maximum one-day rainfall (mm.decade^{-1})	37	−0.45	0.003*	2.4	0.247
Lwamondo		29	−0.26	0.104	−0.9	0.552
Mara		29	−0.11	0.479	1.6	0.154
Polokwane		33	−0.17	0.281	−0.8	0.363
Letaba	Maximum five-day rainfall (mm.decade^{-1})	38	−0.51	0.001*	5.2	0.113
Lwamondo		34	−0.28	0.082	−1.7	0.678
Mara		36	−0.23	0.156	−0.2	0.902
Polokwane		40	−0.19	0.485	−1.8	0.181
Letaba	Dry spells (number.decade^{-1})	20	0.10	0.522	0.3	0.560
Lwamondo		20	0.15	0.377	0.1	0.784
Mara		18	0.11	0.547	0.3	0.216
Polokwane		18	0.11	0.497	0.2	0.767
Letaba	Average temperature (°C.decade^{-1})	3	0.46	0.002*	0.3	0.0002*
Lwamondo		3	0.51	0.001*	0.3	0.003*
Mara		3	0.52	0.0005*	0.1	0.412
Polokwane		3	0.54	0.0003*	0.2	0.012*
Letaba	Average maximum temperature (°C.decade^{-1})	4	0.36	0.021*	0.6	0.0001*
Lwamondo		5	0.35	0.023*	0.8	<0.0001*
Mara		4	0.58	0.0001*	0.2	0.160
Polokwane		4	0.50	0.001*	0.3	0.052
Letaba	Average minimum temperature (°C.decade^{-1})	3	0.24	0.021*	0.01	0.937
Lwamondo		4	0.39	0.011*	0.1	0.059
Mara		2	0.29	0.063	0.1	0.400
Polokwane		4	0.27	0.083	0.2	0.032*

(*Continued*)

Table 1. (Continued).

Weather station	Variable (trend units)	CV (%)	Correlation		Trend	
			r	p	s	p
Letaba	Very hot days (%.decade^{-1})	8	0.28	0.080	3.9	<0.0001*
Lwamondo		9	0.35	0.025*	4.2	0.0001*
Mara		7	0.47	0.002*	1.2	0.154
Polokwane		8	0.48	0.001*	2.7	0.006*
Letaba	Very hot nights (%.decade^{-1})	7	0.39	0.012*	0.1	0.919
Lwamondo		7	0.56	0.0001*	1.2	0.141
Mara		6	0.32	0.042*	0.5	0.582
Polokwane		7	0.13	0.417	2.6	0.002*
Letaba	Very cold days (%.decade^{-1})	4	−0.34	0.028*	−1.1	0.029*
Lwamondo		4	−0.33	0.036*	−2.0	0.0001*
Mara		3	−0.46	0.003*	−0.2	0.493
Polokwane		5	−0.47	0.002*	−1.0	0.189
Letaba	Very cold nights (%.decade^{-1})	5	−0.20	0.206	0.3	0.711
Lwamondo		5	−0.17	0.298	1.1	0.074
Mara		5	−0.27	0.082	0.8	0.212
Polokwane		4	−0.20	0.221	0.1	0.831
Letaba	Hottest day-time temperature (°C.decade^{-1})	4	0.39	0.012*	0.9	<0.0001*
Lwamondo		5	0.34	0.028*	0.9	0.0001*
Mara		4	0.47	0.002*	0.3	0.061
Polokwane		5	0.39	0.011*	0.6	0.017*
Letaba	Hottest night-time temperature (°C.decade^{-1})	3	0.24	0.129	0.1	0.522
Lwamondo		4	0.17	0.247	0.3	0.021*
Mara		4	0.22	0.161	0.1	0.458
Polokwane		4	0.44	0.004*	0.3	0.005*
Letaba	Coldest day-time temperature (°C.decade^{-1})	4	0.54	0.0003*	0.3	0.004*
Lwamondo		5	0.55	0.0002*	0.5	0.0002*
Mara		5	0.44	0.004*	0.1	0.452
Polokwane		6	0.29	0.062	0.2	0.171
Letaba	Coldest night-time temperature (°C.decade^{-1})	5	0.08	0.628	0.1	0.363
Lwamondo		6	0.17	0.293	−0.2	0.290
Mara		8	0.03	0.830	−0.04	0.796
Polokwane		8	0.03	0.861	0.1	0.605
Letaba	Reference evapotranspiration	6	0.28	0.454	-	-
Lwamondo		8	0.60	0.032*	-	-
Mara		10	0.45	0.084	-	-
Polokwane		8	0.42	0.152	-	-

Note: *The Sen's slope (s) value presents the trend rate of change per decade which are units presented in brackets for each variable, while the *r* values represent the Spearman correlation coefficient. Statistically significant *p* values (<0.05) are denoted with an asterisk*. Note the shorter ET_0 analysis periods of 2009/10–2020/21 for Letaba and Polokwane, 2008/09–2020/21 for Lwamondo and 2005/06–2021 for Mara.

farmers. The timing of onset dates is important for good quality crops and high yields, whereby variation in onset of the maize growing season can lead to uncertainty regarding optimal planting time and in determining an appropriate cultivar to plant (Moeletsi et al., 2011; Tadross et al., 2007). Thus, to promote the use of seasonal forecast information to guide planting (and harvesting) timing, and selection of maize cultivar(s) by smallholder farmers, climatic risks were also identified based on associations between growing season characteristics and the ENSO (Moeletsi et al., 2011). Positive correlation results, ranging from 0.19 ($p = 0.227$; Lwamondo) to 0.35 ($p = 0.026$; Mara), demonstrate that El Niño (La Niña) phase growing periods were typically associated with later (earlier) onset dates (Table 1), as reported in previous studies considering our study region (Dunning et al., 2016; Tadross et al., 2007). For the cessation dates, no conclusive association was detected (Table 1). For the growing season length, three stations revealed negative correlations, ranging from −0.20 ($p = 0.213$; Mara) to −0.38 ($p = 0.015$) for Letaba (Table 1), indicating a shorter (longer) growing season during El Niño (La Niña) phases.

3.1.2. Rainfall risks

Above the direct impacts on rainfed crop farming, changes and variability in rainfall characteristics can also significantly impact freshwater availability; thus, we considered many rainfall indices to identify rainfall-related risks for the region's smallholder farmers. Considering long-term risks based on calculated trends, we identified risks of an increase in average daily rainfall intensity, by up to 0.8 mm.decade^{-1} ($p = 0.058$; Letaba), and an increase in heavy rain days, by up to 0.8 days.decade^{-1} ($p = 0.172$; Letaba; Table 1). Coupled with increasing seasonal rainfall totals, by up to 67.5 mm.decade^{-1} ($p = 0.059$; Letaba; Table 1), these trends may reflect the occurrence of more frequent wetter years (with above average rainfall). While this may be viewed positively for rainfed crop production, this also represents a risk of more frequent floods (caused by heavier daily rainfall events) and waterlogging (for high clay soils in low-lying areas), increased soil erosion (for sandy soils on steep slopes), and increased weed infestation. In the light of these risks, a decline, by up to 18 mm.decade^{-1} ($p = 0.181$; Polokwane), in the maximum five-day rainfall can be viewed positively (Table 1). Notably, flooding risks were also reported in Mpandeli et al. (2019) and Shikwambana et al. (2021). Above this, a risk of potentially increasing drought frequencies was also identified by the increase, of up to 0.3 number.decade^{-1} ($p = 0.560$ for Letaba and $p = 0.216$ for Mara), detected for the number of dry spells (Table 1). This is because too frequent occurrences of dry spells and intense rain events is unfavourable in terms of crop yields and quality, given that crops prefer consistently distributed rainfall (Thoithi et al., 2021). Collectively, the recorded rainfall risks reflect that the regions seasonal rainfall has become increasingly unevenly distributed, while increased dry spell numbers can also lead to intermittent water stress, leading to reduced crop yields or potentially crop failure (Masupha et al., 2016; Mpandeli et al., 2019; Mzezewa et al., 2010; Roffe et al., 2021). In corroborating these rainfall risks, it is noteworthy that Kruger and Nxumalo (2017a) detected generally similar historical trends over the study region, while projected trends are also indicative of increasing risks of more frequent heavy rainfall events and higher dry spell frequencies (Dosio et al., 2021; Dunning et al., 2018).

Based on moderate-to-high CV levels, ranging from 18% to 46%, the greatest rainfall risks are, however, experienced in terms of growing season rainfall interannual variability patterns (Table 1); it is well known that, interannually, rainfall characteristics vary substantially over the Limpopo region (Mazibuko et al., 2021; Rapolaki et al., 2020; Thoithi et al., 2021). Therefore, relatively high CV levels highlight the limited predictability of the growing season rainfall characteristics, which can present difficulty for decision-making in agriculture (Moeletsi et al., 2011). However, over Limpopo, and compared to the rest of Southern Africa, relatively good seasonal forecast skill exists in relation to ENSO (Landman et al., 2019, 2020); thus, highlighting the importance of farmers consulting seasonal forecasts months ahead of and during the growing season (Moeletsi et al., 2011).

With weak to moderate strength correlations (i.e. r values) all demonstrating consistency in the direction of ENSO influence, results highlight that ENSO is a notable driver of interannual rainfall variations (Table 1). In this regard, both El Niño and La Niño phase growing seasons can present risks for crop farming, and while conditions likely during these seasons can also occur during neutral phase ENSO seasons, normal conditions are more typical (Thoithi et al., 2021). Excluding the dry spells frequency, characterized by positive correlations, all remaining rainfall indices were characterized by negative correlations (Table 1), which are similar results to that found in the literature (Mazibuko et al., 2021; Rapolaki et al., 2020; Thoithi et al., 2021). Interpreted, the dry spell results reveal higher (lower) dry spell frequencies during El Niño (La Niña) phase growing periods (Table 1), highlighting that overall, the region is at risk of dry spells, but during El Niño years their frequencies are likely higher. For the remaining indices, results reflect El Niño (La Niña) phase growing periods are associated with lower (higher) seasonal rainfall totals, less (more) frequent rain days, higher (lower) daily rainfall intensities, higher (lower) frequencies of moderate and heavy rain days, and higher (lower) one-day and five-day rainfall maximums (Table 1). These results reflect that flooding is less (more) likely during El Niño (La Niña) phase growing periods, with the opposite being the case for drought occurrences. Thus, during El Niño years, growing season rainfall characteristics are less favourable for crop production with serious water deficits likely, whilst La Niña years are characterized by enhanced rainfall events mostly associated with good yields in most semi-arid areas in SA (Mazibuko et al., 2021; Moeletsi et al., 2011; Thoithi et al., 2021). Notably, for La Niña years, above-average growing season rainfall totals may only favour higher maize yields if daily rainfall events are generally uniformly distributed, as moderate rain days, with short, infrequent dry spells and few periods of high rainfall leading to flooding, water logging, soil erosion and nutrient leaching (Moeletsi et al., 2011; Tadross et al., 2007; Thoithi et al., 2021).

3.1.3. Temperature risks

A major temperature-based risk is that growing seasons may become too hot for maize cultivation; optimal mean, maximum and minimum temperatures are reported as roughly 20–25 °C, 25–33 °C, and 17–23 °C, respectively (du Plessis, 2003; Waqas et al., 2021). In this regard, we detected increases in mean, maximum and minimum temperatures by up to 0.3 °C.decade^{-1} ($p = 0.0002$ for Lwamondo and $p = 0.003$ for Letaba), 0.8 °C.decade^{-1} ($p < 0.0001$; Lwamondo) and 0.2 °C.decade^{-1} ($p = 0.032$; Polokwane), respectively (Table 1); at these trend rates optimal temperature thresholds could be exceeded by as early as 2051 for Letaba for the average growing season temperatures. Several studies similarly highlight a risk of potentially too hot growing seasons across Limpopo, noting that warmer temperatures exacerbate risks associated with low rainfall and high ET_0 (Mpandeli et al., 2019; Shikwambana et al., 2021). Moreover, increasing temperature trends as detected herein are consistent with historical (Mupangwa et al., 2023; van der Walt & Fitchett, 2021), and projected (F. Engelbrecht et al., 2015) temperature trends reported in the literature. Above this, and despite a low degree of interannual variability with CV < 10%, correlation results reveal that El Niño phase growing seasons also present a risk of too hot growing seasons (Table 1). With trends of increasingly hotter conditions, El Niño events can exacerbate this climate change risk and El Niño growing seasons can become significantly hotter in the future. Positive correlations detected for mean (r of 0.46–0.54 and p of 0.001–0.0003), maximum and minimum temperatures (r of 0.35–058 and 0.24–0.39 and p of 0.021–0.0001 and 0.083–0.011, respectively) reflect that El Niño

(La Niña) phase growing periods were typically associated with higher (lower) temperatures, in accordance with literature (Table 1; Lakhraj-Govender & Grab, 2019).

Regarding extreme temperatures, results reflect that changes in hot extremes (e.g. heatwaves) also pose a risk, whereby their trends reflect an increase in frequency (Table 1). In fact, all hot extreme temperature characteristics were characterized by increasing trends. The number of very hot days increased by up to 4.2 %.decade^{-1} ($p = 0.0001$; Lwamondo), while for the number of very hot nights, increases were up to 2.6 %.decade^{-1} ($p = 0.002$; Polokwane; Table 1). The magnitude of very hot day temperatures increased by up to 0.9 °C.decade^{-1} ($p < 0.0001$ for Letaba and $p = 0.0001$ for Lwamondo), while the magnitude of very hot nights increased by up to 0.3 °C.decade^{-1} ($p = 0.021$ for Lwamondo and $p = 0.005$ for Polokwane; Table 1). In relation to ENSO, correlation results highlight that El Niño phase growing seasons present the greatest risk regarding crop heat stress, as evident from positive correlations ($r > 0.10$) and predominantly statistically significant p values (Table 1). Consistent with findings in the literature (Meque et al., 2022), these correlations reflect that very hot days and nights typically occur more (less) frequently and have higher (lower) magnitudes during El Niño (La Niña) phase growing seasons (Table 1).

Trend and correlation results for cold extremes revealed limited risk, with Mpandeli et al. (2019) highlighting that frost and/or cold temperatures more likely impact winter cropping. However, our results reveal a potential long-term growing season risk, being an increase in cold night occurrences, by up to 1.1 %.decade^{-1} (p 0.074; Lwamondo; Table 1). Above this, correlation results highlight a potential risk for more frequent, colder extreme events during La Niña phase growing seasons (Table 1). For the frequency, negative correlations ($r < -0.17$), which were mostly statistically significant for cold days, reveal more frequent occurrences of very cold days and nights during La Niña phase growing seasons, whereas positive correlations ($r > 0.10$, statistically significant for day-time temperatures) reveal colder magnitudes for very cold day- and night-time extremes (Table 1). Such risks are noteworthy given that cold stress can impact maize grain quality as the maize crop is sensitive to cold conditions during all growth phases (Waqas et al., 2021).

Collectively, the climate change risk of warmer growing seasons with more frequent and hotter extreme temperature events can have significant negative impacts, and during El Niño events, which are associated with above average conditions for the characteristics of hot extremes, these risks will be heightened. While rainfall-related risks may be considered more detrimental to the maize crop, it is important to acknowledge that changing and variable temperatures can also significantly affect crop yield quality (Mupangwa et al., 2023). Increasing minimum temperatures can promote stored sugar loss in plants, ultimately reducing crop yields (Waqas et al., 2021). Conversely, increasing maximum temperatures can introduce crop heat stress, ultimately causing metabolic and/or morphological alterations, leading to irreversible yield reductions (Waqas et al., 2021). Increasing temperatures can also increase pest and disease risks (Mpandeli et al., 2019; Mupangwa et al., 2023). Moreover, warmer conditions in general can translate to increased water requirements for optimum maize growth, and increased crop water stress (Mpandeli et al., 2019). In storage, increasing temperatures can accelerate mould growth, in turn causing grain damage, which can result in loss of stored grains (Mupangwa et al., 2023).

3.1.4. Reference evapotranspiration (ET_0) risks

Although the ET_0 data period was too short for trend calculation, analysis of growing season interannual variability patterns provided key information regarding evapotranspiration/evaporation risks. Interannually, ET_0 was characterized by a lower degree of variation, up to 10% (Mara; Table 1), highlighting some predictability, especially in relation to the ENSO (Mzezewa et al., 2010). In this regard, positive correlations, up to 0.60 ($p = 0.032$; Lwamondo), revealed that El Niño (La Niña) phase growing seasons were associated with higher (lower) ET_0 levels, and essentially higher (lower) evapotranspiration/evaporation risk (Table 1). Higher evaporative demand during El Niño phase growing seasons presents a risk of insufficient soil moisture availability for crop production. In the long term, increasing temperatures and potentially increasing drought frequencies (i.e. increasing dry spell frequencies), as indicated in this study and the literature (Mpandeli et al., 2019; Mupangwa et al., 2023; Shikwambana et al., 2021), may also lead to increased soil water and crop water evaporation (Mzezewa et al., 2010).

3.2. Recommended adaptation strategies

Responding to the identified risks, based on climatic changes and associations with ENSO (i.e. Table 1), we prepared a locally tailored list of adaptation strategies recommended to mitigate risk and build resilience in smallholder farming activities across the study region (Table 2; Makungo & Nkuna, 2023; Mpandeli et al., 2019; Myeni & Moeletsi, 2020; Mzezewa et al., 2010, Mpandeli, 2014; Shikwambana et al., 2021, 2022). It is noteworthy that some risks were identified as indirect effects resulting from other climatic risks (e.g. weed infestation can occur due to more frequent heavy rainfall events or the incidence of pests could occur more frequently due to increasing temperatures; Table 1). To develop these strategies accounting for both the identified climate change and natural variability risks, we considered strategies listed in the literature for the study region (e.g. Mpandeli et al., 2019; Shikwambana et al., 2021) as well as our knowledge of the study region. While most strategies were focused on maize cultivation, we also listed some relevant livestock adaptation strategies as many farmers within the study region also keep livestock. To promote adoption of the recommended strategies, through ongoing activities of the DREAM project, it is important that we present and explain them to all relevant stakeholders (i.e. smallholder farmers, traditional leaders, agricultural cooperatives and extension officers) within the study region, as research reflects that better understanding of recommended adaptation strategies can increase their adoption (Myeni & Moeletsi, 2020).

The listed strategies are proactive (e.g. planting of heat and drought tolerant crop varieties and adoption of mulching in response to a forecast of an El Niño phase growing season) and/or reactive (e.g. prompt weeding following weed sprouting after heavy rainfall events), respectively, representing strategies undertaken prior to a risk occurring or those to cope with a risk (Mpandeli et al., 2019). Overall, the goal was to ensure that strategies require minimum technical expertise and limited external inputs to be viable for rural smallholder farmers that are predominantly elderly with low education levels and limited resources. In this regard, it is important to acknowledge resource challenges that may hinder the application of many strategies listed in Table 2. Among smallholder

Table 2. Prevailing climate-related risks and recommended adaptation strategies.

Climate-related risk	Recommended adaptation strategies
Long-term shifts in onset and cessation dates leading to shorter growing seasons	-Use South African Weather Service (SAWS) seasonal forecasts for long-term planning and short-term daily forecasts for day-to-day decision-making (see: https://www.weathersa.co.za/home/seasonalclimate and https://www.weathersa.co.za/) -Use agrometeorological services, including early warning systems and newsletters (e.g. ARC Umlindi [https://www.arc.agric.za/arc-iscw/Pages/News-Articles.aspx] and National Agrometeorological Committee newsletters) -Plant early maturing cultivars (e.g. fast maturing maize and vegetables) adapted to shorter seasons –Increase crop diversification and intercropping –Delay land preparation -Choose planting dates matching rainfall onset (i.e. delay planting) and use multiple (i.e. staggered) planting dates spread over several weeks to maximize productivity -For optimal seed germination, plant when there is sufficient soil moisture, and avoid planting on cold days -Earlier harvesting (not during rainy conditions)
General high level of interannual variation in seasonal rainfall amount, intensity and distribution	-Check short-term daily weather forecasts often -Use agrometeorological services, including early warning systems and newsletters (e.g. Umlindi and National Agrometeorological Committee newsletters) -Increase crop varieties and/or crops diversification –Incorporate livestock production -Plant early maturing and locally adapted crop varieties -Adjust, and use multiple (i.e. staggered) planting dates spread over several weeks to maximize productivity -In-situ (e.g. run-off directed to crop field) and ex-situ (e.g. borehole, JoJo tank or dam) rainwater harvesting and conservation –Supplementary irrigation where possible
High frequency of heavy rainfall events, increased rainfall intensity, more frequent floods and waterlogging, and increased soil erosion, especially during La Niña phase growing seasons	-Check short-term daily weather forecasts often -Use agrometeorological services, including early warning systems and newsletters (e.g. ARC Umlindi and National Agrometeorological Committee newsletters) –Use crop varieties with higher moisture tolerance –Improve crop area drainage -Prompt weeding, and pest and disease management -Practice erosion control and promotion of infiltration and soil moisture retention (e.g. plant against contours and across hill slopes, and use mulching and/or cover crops), and run-off control (e.g. stone bunds and terracing) -Avoid planting in low-lying lands and heavy clay (waterlogging) soils -In-situ (e.g. run-off directed to crop field) and ex-situ (e.g. borehole, JoJo tank or dam) rainwater harvesting and conservation

(*Continued*)

Table 2. (Continued).

Climate-related risk	Recommended adaptation strategies
Low rainfall amount, reduced soil moisture, and/or frequent occurrence of droughts/dry spells, especially during El Niño phase growing seasons	-Use drought early warning system (e.g. ARC agricultural drought early warning system) -Plant drought (and heat) resistant varieties with lower water requirements –Plant locally adapted cultivars –Crop diversification -Decrease planting density (i.e. plant wide rows) –Prompt weeding –Use mulching and cover cropping to conserve soil moisture –Supplementary irrigation where possible -Improve capturing, storage and efficient water use through farming practices that maximize water infiltration and retention (e.g. contour planting, minimal tillage, intercropping and improved soil organic management) -In-situ (e.g. run-off directed to crop field) and ex-situ (e.g. borehole, JoJo tank or dam) rainwater harvesting and conservation
Long-term increase in temperatures or too hot growing season particularly during El Niño phase growing seasons	-Plant heat (and drought) tolerant crops varieties (e.g. sorghum and millet) –Use mulching and cover cropping to conserve soil moisture and reduce soil temperatures –Prompt weeding –Intercropping -Adopt more heat-tolerant livestock
Long-term trend of more frequent extreme hot temperature events (e.g. heatwaves) and more prolonged dry spells	-Use early warning systems (e.g. ARC agricultural drought early warning system) and short-term weather forecasts –Use mulching and cover cropping to conserve soil moisture and reduce soil temperatures -In-situ (e.g. run-off directed to crop field) and ex-situ (e.g. borehole, JoJo tank or dam) rainwater harvesting and conservation –Supplementary irrigation where possible –Drought and heat tolerant crops and varieties –Crop diversification to spread and reduce risk –Prompt weeding –Reduce herd sizes to save money
Occurrence of extremely cold nights (or days), especially during La Niña phase growing seasons	-Use short-term daily weather forecasts –Avoid planting on cold days -Cover crops (e.g. with nets) for warmth
High evaporation, especially during El Niño phase growing seasons	-Use mulching, intercropping and cover cropping to conserve soil moisture and reduce soil temperatures –Increase soil organic matter to improve water retention
General long-term increased incidence of pests (e.g. locusts, fall armyworms, cutworms and stalk borers) and diseases (e.g. maize leaf necrosis) damaging crops	–Plant crop varieties with improved pest and disease resistance –Use integrated pests and disease management techniques (e.g. push-pull approach where repellent crops, like onion and garlic, are used to keep pests away from the maize crop) –Improve on awareness on when and how to spray to prevent pest and disease infestation –Efficient pesticides use –Intercropping –Crop rotation –Use pest and disease early warning systems

(*Continued*)

Table 2. (Continued).

Climate-related risk	Recommended adaptation strategies
General weed infestation	-If available, use weed tolerant crop varieties –Increased and prompt weeding –Cover cropping –Intercropping –Crop rotation –Efficient herbicide use
Long-term declining fertility and land degradation	-Use kraal manure, compost and organic fertilizers, applying correct amount at correct time and depth (for easy root access) -Minimal tillage and soil conversation techniques (e.g. contour bunds or planting pits) to reduce run-off, and enhance infiltration and drainage -Farming practices that protect the soil from erosion and reduce water losses, (e.g. mulching and cover cropping), are recommended -Divert nutrient deposition to fields (e.g. planting at bottom of slope) –Timely weed and pest control –Correct spacing of crops –Plant high yielding crop varieties -Crop diversification and intercropping, including maize with vegetables and legumes –Crop rotation

farmers in general and for those in the study region, these challenges can include a lack of knowledge on basic agronomic practices; poor access and use of weather and climate information services; limited equipment for supplementary irrigation; and lack of access to good seed cultivars (leading to poor harvests), fertilizers and pesticides, and harvest storage facilities (to prevent pest and disease infestation, especially when rains are heavy; Mpandeli et al., 2019; Myeni & Moeletsi, 2020; Myeni et al., 2024). Towards addressing these challenges, the ARC Agrometeorology Division conducts workshops to train extension officers, on a range of topics (e.g. how to access and utilize seasonal forecasts to ensure cropping success for an upcoming season), who are tasked to support local smallholder farmers through information dissemination.

To explain how, with guidance from extension officers who work to transfer knowledge and represent the bridge from scientific research to the ground, farmers can adopt the suggested strategies, we refer to 2023/24 season (i.e. October 2023 to April 2024). This season was forecasted as an El Niño phase growing season with high probabilities of above-average minimum and maximum temperatures and low probabilities of near- to above-normal rainfall conditions in the earlier season, with relatively high probabilities of below-normal rainfall for the later season (2024; South African Weather Service SAWS, 2023). Having accessed this forecast via the extension services, as examples from Table 2, farmers could have adopted zero or minimum tillage while also considering drought and heat tolerant crops (e.g. sorghum and cowpea) as a precautionary and in addition to maize. To prepare for planting, farmers could have considered daily rainfall forecasts to determine when it will rain and subsequently when to plant. For a higher chance of success, farmers could have adopted staggered planting dates, while also decreasing their planting densities. Mulching would have been important to account for above average evaporative demands and dry spell frequencies. Adopting as many strategies as possible would have enhanced the chances of successful cropping during the 2023/24 season. Beyond this season, greater chances of success will be facilitated by continued adoption of the recommended adaptation strategies, and particularly those aligning with hotter, drier conditions.

4. Summary and conclusions

Across SA, smallholder farming productivity is adversely impacted by climate change and natural interannual variability, and in the future, this is expected to continue and perhaps worsen. For coping and resilience, smallholder farmers can benefit significantly from agrometeorological advice on relevant adaptation strategies. These are, however, not a 'one size fits all' solution; thus, tailor-made strategies accounting for location-specific climatic changes and seasonal variability patterns are required (Myeni, 2021). Therefore, using selected weather station records spanning up to 1980–2021, we explored temporal trends and/or natural variability patterns for ET_0 and a suite of agriculturally relevant rainfall and temperature indices to identify climate-related risks and devise tailor-made adaptation strategies recommended for application by smallholder farmers residing in the study region. By linking climate data directly with adaptation strategies that are feasible for the study region's smallholder farmers, this study contributes knowledge to bridging the gap between scientific research and practical application.

In terms of risks, results showed that hotter growing seasons coupled with highly irregular rainfall amounts, distribution and seasonal onset and cessation are major climatic risks for smallholder farmers in the Gavaza, Ga-Makanye and Giyani regions. It is important to acknowledge that the selected weather stations are not directly within the study regions; thus, the results must be interpreted with some caution as the study regions climatic characteristics are spatially heterogeneous (Mpandeli et al., 2019). However, to reduce the impact of this limitation we only identified risks based on spatial consistency in the results. Therefore, it must be noted that the reported risks may not be comprehensive. Hence, it is recommended that future studies utilize gridded datasets (e.g. ERA5-Land reanalysis), while also considering additional weather parameters that impact agricultural activities (e.g. relative humidity, wind speed and compound events). Nonetheless, in response to reported risks, farmers need access to appropriate crop varieties that are adapted and resistant to these climatic risks, while their uptake of weather/climate information, facilitated by extension services, is increasingly important for informed decision-making. Above this, many other adaptation strategies were advised, with farmers encouraged to apply as many as possible that are feasible and affordable to them.

Moving forward, for the study region there is still a need for further identification of climate-related risks, and a need for further agrometeorological support (e.g. direct agrometeorological information dissemination with relevant training in terms of application) in dealing with climatic risks. To complement the identification of risks based on historical climate data, it is necessary to identify risks based on high-resolution, bias-corrected climate projections. To better support smallholder farmers, there is a need for improving access to climate/weather information and services, where such information and services need to be agriculturally tailored to inform agricultural decision-making regarding the selection of crop varieties and planting dates, for instance. In this regard, the establishment of an operational numerical weather modelling infrastructure in the context of early warning and agricultural-relevant forecasting represents one ongoing effort at the ARC (by the Agrometeorology Division) that can significantly aid planning and decision-making.

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