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Integrating Maize Yield and Agricultural Drought Analysis for Sustainable Food Security: A Provincial Study in South Africa (1993–2022)

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ABSTRACT

Extreme climatic events, such as droughts, hinder progress toward achieving the sustainable development goal of food security. South Africa is vulnerable to drought-related agricultural losses, which have led to food insecurity. However, few studies have focused on the long-term impacts of drought on crop production at a regional scale. Therefore, we aimed to examine the intensity, magnitude, and trend of rainfall-based short-term agricultural drought at the provincial scale in South Africa based on the Standardized Precipitation Index (SPI). Additionally, we analyzed the impact of agricultural drought on maize yield by calculating the Standardized Yield Residual Series (SYRS) and Crop Drought-Resilience Factor (CDRF). To this end, we collected rainfall data from 29 stations across nine provinces along with maize yield data for the period of 1993–2022. Agricultural drought analyses based on the three-month (SPI-3) and six-month (SPI-6) SPIs demonstrated dynamic variations in occurrence, with Sen's slope indicating that 10 stations exhibited a significant increase in drought events across South Africa. Notably, SPI-6 analysis showed that Gauteng, Free State, and North West provinces experienced the highest percentages of severe to extreme drought events during the study period, at 4.17%, 3.89%, and 3.61%, respectively. Furthermore, the majority of provinces in South Africa experienced an extreme SPI-6 magnitude ranging from −46.03 in Western Cape Province to −61.6 in Free State Province. The dynamic effects of agricultural drought on maize yield revealed that the maximum yield loss of 13% occurred in 1993 in Eastern Cape Province, while some provinces experienced no yield loss during certain years. However, CDRF analyses identified Western Cape (CDRF [SPI-3] = 0.52, CDRF [SPI-6] = 0.62) and Mpumalanga (CDRF [SPI-6] = 0.7) provinces as the most vulnerable to food insecurity due to the severe non-resilience of maize to drought in these regions. This study reveals the complex interplay between climatic extremes and maize yield variability, providing valuable insights for managing regional food production systems and ensuring future food security in South Africa.

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1 | Introduction

Climate change poses considerable challenges for agricultural production systems, potentially triggering food insecurity globally (Hasegawa et al. 2018; Ocwa et al. 2023). For example, climate change and weather extremes threaten agricultural productivity by increasing plant stress and lowering crop yield (Hasegawa et al. 2018; Rezaei et al. 2023). Meanwhile, the agricultural sector contributes to climate change through fertilization, enteric fermentation, and agronomic procedures that release greenhouse gases from the soil (Lynch et al. 2021; Zuma et al. 2023). The interplay between the main climatic factors, such as temperature and rainfall, largely influences crop growth and food production (Simanjuntak et al. 2023). For example, elevated temperatures and insufficient rainfall increase the water demand, potentially leading to crop failure (Nyambariga et al. 2023). In this context, the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change projected that approximately 10% of cropland would be affected by climatic extremes under high emission scenarios by mid-century (Lee et al. 2023). Anthropogenic warming and drought events lowered crop yields and aggravated crop pests and diseases as well as weeds, increasing the risk of global food insecurity (Ju-Qi et al. 2022). Previous studies have reported that future climatic projections under the sixth phase of the Coupled Model Intercomparison Project scenarios involve an increased frequency of agricultural drought, which will likely impact crop production worldwide (Arshad et al. 2023; Mohammed et al. 2024; Nyambariga et al. 2023). A protracted deficiency in precipitation, coupled with high surface temperatures, is likely to exert a catastrophic influence on agricultural productivity in both rainfed and irrigated regions (Ray, Fares, and Risch 2018). Consequently, such climate alterations are likely to have a negative impact on food security, especially considering the growing human population (Hall et al. 2017).

Climatic extremes such as droughts, floods, and heatwaves are likely to affect global, regional, and local food production systems (Lesk, Rowhani, and Ramankutty 2016). Extremely low and high rainfall tends to increase the occurrence of droughts and floods over both small and large regions (Shao and Kam 2020). However, low precipitation plays a crucial role in increasing the frequency and intensity of drought events (Nxumalo et al. 2022). Drought is characterized by insufficient water at the interface between the land and atmosphere, which has a substantial impact on human activities and ecosystems (Epule et al. 2023; Mishra and Singh 2010). Meteorological drought is initiated by a reduction in rainfall, which decreases soil moisture, and it may lead to hydrological drought, which is characterized by reduced streamflow. Meanwhile, agricultural drought is characterized by precipitation shortages and soil moisture deficits that affect crop yield (Zhu et al. 2019). Moreover, the consequences of drought involve other setbacks, such as agricultural impairment, water constraints, and land subsidence (Berg and Sheffield 2018; Liu, Cao, and Li 2024). Particularly in the developing regions of the world, drought can prompt severe outcomes, including famine, migration, and potential conflict (Miyan 2015). Therefore, droughts have a profound impact on human livelihoods in terms of agricultural and economic losses (Fernández et al. 2023; Venkatappa et al. 2021). Agricultural droughts have substantial economic impacts in terms of reduced industrial output and GDP loss (Song et al. 2024). For instance, historical agricultural drought impacts assessments in North and sub-Saharan Africa showed economic losses from 1997 to 1999 and from 2004 to 2007 (Bhaga et al. 2020; Tanarhte et al. 2024). Agricultural droughts cause severe damage to crop production systems, decreasing yields and potentially leading to famine (Brüntrup and Tsegai 2017; Venkatappa et al. 2021). During the past decade, several prolonged and intense droughts have been experienced in Europe, Africa, Asia, and Australia, and such droughts are projected to occur more frequently in the future owing to population growth and climatic changes (Freire-González, Decker, and Hall 2017). The drought history of Africa provides strong evidence of severe to extreme drought events in the past 50 years, with varied agroeconomic impacts (Masih et al. 2014). Furthermore, climate models have projected a 20% decrease in precipitation by the 2080s in South Africa, which would lead to reduced water availability and decreased crop yields (Conway et al. 2015; Serdeczny et al. 2017).

South Africa is a semi-arid country that is susceptible to frequent droughts because of its high average summer temperatures and low winter precipitation (Meza et al. 2021; Simanjuntak et al. 2023; Wolski et al. 2021). Several extreme drought events categorized by their duration, severity, and extent have been reported in past decades, with profound impacts on crop production (Adisa, Masinde, and Botai 2021; Nxumalo et al. 2022). By the year 2020, more than 40% of productive lands in South Africa were cultivated for maize, which is considered an important staple food and poultry feed (Gouse et al. 2016; Nkhuoa 2017). However, maize production has been substantially affected by climate change in the form of rainfall deficits and frequent droughts over the years. For example, in the 1990s, droughts caused considerable agricultural losses, such as approximately 70% crop failure and livestock loss, which led to malnutrition (Rouault and Richard 2003). Declining rainfall and rising temperatures are expected to cause frequent droughts, increasing stress in plants, especially during germination (Kim, Lee, and Kim 2024).

Maize production in South Africa ranges from large-scale commercial production systems to smallholder farms that sustain local livelihoods (Fischer and Hajdu 2015). The North West, Free State, KwaZulu-Natal, and Mpumalanga provinces accounted for 16%, 43%, 4.5%, and 24% of the country's maize production in 2021 (Simanjuntak et al. 2023). However, the vulnerability of maize crops to agricultural drought has caused a notable decline in crop yield, similar to that reported in other regions of the world (Mohammed et al. 2022; Széles et al. 2024). For instance, Bradshaw et al. (2022) reported a high risk of maize yield decline associated with extreme drought events in South Africa. Meanwhile, Adisa et al. (2018) found that several agroclimatic variables, such as minimum and maximum temperature, precipitation, and potential evapotranspiration, explained the variability in maize yield in South Africa. Recently, Makuya et al. (2024) investigated the impact of agricultural drought on maize yield in Free State Province, South Africa and reported an 88% yield loss associated with severe droughts. However, there is a need for detailed agricultural drought assessments at the regional level to support efforts toward achieving the United Nations Sustainable Development Goal of zero

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hunger. Moreover, previous research on agricultural drought assessment in South Africa has mainly focused on the local level, ignoring the wider impact.

Considering the importance of agricultural production in South Africa and its vulnerability to climatic extremes, we aimed to assess agricultural drought and its impact on maize yield at the provincial level based on the Standardized Precipitation Index (SPI) and Standardized Yield Residual Series (SYRS), respectively. The main objectives of this study were to: (1) evaluate rainfall-based short-term agricultural drought in terms of frequency, magnitude, and trends across 29 stations in nine provinces over three decades (1993–2022); (2) examine the impact of agricultural drought on maize crop yield loss through SYRS followed by calculating the Crop Drought-Resilience Factor (CDRF) (3) analyze the statistical relationships between the SYRS and SPI through Pearson Correlation.

2 | Materials and Methods

2.1 | Study Area

We selected South Africa (22°–35° S; 17°–33° E), located at the tip of southern Africa, as the study area (Knight and Rogerson 2019). The elevation of South Africa ranges from −252 to 3375 m (Figure 1). It consists of nine provinces: Northern Cape, North West, Western Cape, Eastern Cape, Gauteng, Limpopo, Mpumalanga, Free State, and KwaZulu-Natal (Nxumalo et al. 2022) (Figure 1). The country completely encloses Lesotho and partially envelops Swaziland.

South Africa is a semi-arid region with annual rainfall of approximately 500 mm (Dennis and Dennis 2012). Most parts of the country receive rainfall in summer, while other parts such as the Cape Peninsula receive rainfall in winter owing to their Mediterranean climate (Mahlalela, Blamey, and Reason 2019). South Africa experiences winter in the middle of the year, while summer occurs in December and January. The mean annual temperature is approximately 17.5°C, and monthly temperatures range from 11°C during the winter months to 22°C during the summer months. The highest levels of precipitation typically occur in November and March, whereas the lowest occur in June and August (Reason 2017).

2.2 | Data Collection

The main datasets used in this study included rainfall and maize crop yield. Monthly rainfall data for 29 stations (Figure 1, Table 1) were obtained from the South African Weather Service for the period from 1993 to 2022 (https://www.weathersa.co.

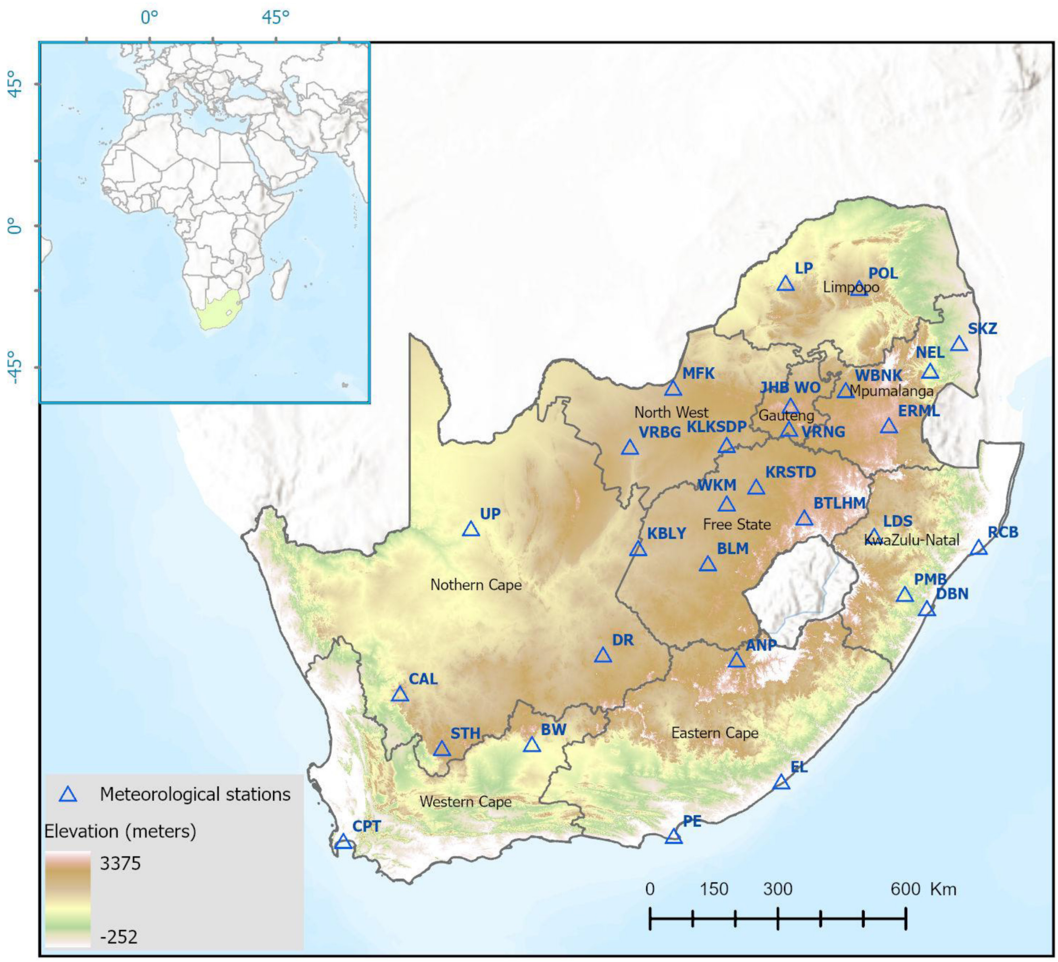

FIGURE 1 | Map of South Africa showing provincial divisions and locations of studied meteorological stations.

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TABLE 1 | Summary of examined meteorological stations in South Africa (1993–2022).

Province	Stations	Abb	*X*	*Y*	Rainfall[a] (mm)	Elevation (m)
Eastern Cape (EC)	Aliwal North Plaatkop	ANP	26.883	−30.802	46.56	1350
	East London	EL	27.833	−33.033	64.01	124
	Port Elizabeth	PE	25.616	−33.986	49.85	60
Free State (FS)	Betlhelhem	BTLHM	28.334	−28.249	58.25	1689
	Bloemfontein	BLM	26.298	−29.103	43.00	1354
	Kroonstard	KRSTD	27.313	−27.666	37.27	1440
	Welkom	WKM	26.666	−27.994	34.64	1344
Gauteng (GP)	Johannesburg	JHB WO	27.999	−26.156	58.63	1624
	Vereeniging	VRNG	27.958	−26.569	47.63	1481
KwaZulu Natal (KZN)	Durban	DBN	30.946	−29.965	84.12	14
	Lady Smith	LDS	29.75	−28.575	52.19	1069
	Pietermaritzburg	PMB	30.402	−29.627	59.57	673
	Richards Bay	RCB	32.017	−28.783	89.62	7
Limpopo (LP)	Lephalela	LP	27.705	−23.676	31.92	839
	Polokwane	POL	29.451	−23.857	54.29	1226
Mpumalanga (MP)	Ermelo	ERML	29.983	−26.497	58.96	1774
	Nelspruit	NEL	30.911	−25.503	61.00	883
	Skukuza	SKZ	31.588	−24.992	42.98	276
	Witbank	WBNK	29.192	−25.832	55.00	1555
Northern Cape (NC)	Sutherland	STH	20.662	−32.399	17.12	1458
	Upington	UP	21.264	−28.411	19.35	835
	De Aar	DAR	−30.6651	23.9927	26.58	1247
	Kimberley	KMBLY	−28.8061	24.7698	33.52	1198
	Springbok	SPB	−29.6694	17.8788	17.24	1006
North West (NW)	Klerksdorp	KLKSDP	26.62	−26.898	42.00	1329
	Mafikeng	MFK	25.542	−25.803	39.57	1281
	Vryburg	VRBG	24.652	−26.954	37.00	1245
Western Cape (WC)	Beaufort Wes	BW	22.573	−32.347	21.20	899
	Cape town	CPT	18.602	−33.963	38.05	42

[a]Average monthly rainfall.

za/). Maize crop statistics for a 30-year period (1993–2022) were accessed through the open-source Grain SA website (https://www.grainsa.co.za/). The maize data comprised the total cultivated area, total production, and yield for all nine provinces in South Africa.

2.3 | Standardized Precipitation Index

Historically, meteorologists have used a variety of indices to assess the duration, intensity, and severity of droughts, ranging from simple indices, such as the percentage of normal precipitation and precipitation percentiles, to more complicated ones, such as the Palmer Drought Severity Index (Hayes and Lowrey 2007; Wells, Goddard, and Hayes 2004). However, there was a need for an index that is easy to calculate, easy to use, statistically reliable, and based on the understanding that precipitation deficits have varying impacts on land cover, land use, soil moisture, groundwater, and streamflow (Afshar et al. 2022; Arshad et al. 2022; Faheem et al. 2024; Wang, Rogers, and Munroe 2015). Thus, the SPI was introduced by McKee, Doesken, and Kleist (1993). The SPI is user-friendly and easy

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to comprehend, given that the only input parameter required is rainfall data, which is computed using the gamma distribution function $G(x)$ as follows:

$$G(x) = \frac{1}{\beta\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta}, x > \quad (1)$$

$$\text{SPI} = \frac{xi - \overline{x}}{\sigma} \quad (2)$$

where xi is the rainfall for month i, $\overline{x}$ is the mean rainfall, and σ is the standard deviation.

A positive SPI value denotes precipitation that exceeds the mean, indicating humid conditions, and a negative SPI value denotes precipitation that is below the mean, implying dry conditions (Tsakiris et al. 2007) (Table 2). We calculated the three-month SPI (SPI-3) and six-month SPI (SPI-6) to evaluate the intensity and magnitude of agricultural drought and its impact on maize yield across all provinces of South Africa. Drought intensity was classified based on the threshold presented in Table 2.

2.4 | Drought Trend

The non-parametric Mann–Kendall trend test and Sen's slope were employed to capture the monotonic trend in the SPI-3 and SPI-6 time series (Kendall 1948; Sneyers 1991). These tests are unaffected by the actual distribution of the data and are less sensitive to outliers (Reshu et al. 2014). Non-parametric trend tests are appropriate for distinguishing tendencies in hydrological time series that may be distorted or affected by outliers (Hamed 2008). The test interpretation was based on the following two hypotheses: (i) the null hypothesis Ho, which signifies no SPI drought trend in the series and (ii) the alternate hypothesis Ha, which denotes a significant ($p<0.05$) trend. Furthermore, Sen's slope determines the direction of the trend, where positive values show an increasing trend in the SPI (no drought) and negative values show a decreasing trend in the SPI, revealing an increase in drought occurrence over the time series. Moreover, inverse distance weighting (IDW) spatial interpolation technique was employed in ArcGIS pro to spatially analyze the extent of SPI drought across South Africa.

2.5 | Drought Frequency and Magnitude

The frequency of drought events was calculated by dividing the number of drought events n_d with the total number of months N during the time period (1993–2022) as follows:

TABLE 2 | Threshold defining drought intensity based on the Standardized Precipitation Index.

Drought classification	SPI threshold
Near normal	$-1.0 \leq \text{SPI} \leq 1.0$
Moderate drought	$-1.49 < \text{SPI} < -1.0$
Severe drought	$-2.0 < \text{SPI} < -1.5$
Extreme drought	$\text{SPI} \leq -2.0$

$$\text{DF} = \frac{n_d}{N} \times 100 \quad (3)$$

The SPI drought magnitude (DM) was calculated according to the method of Dashtpagerdi et al. (2015) as follows:

$$\text{DM} = -\left(\sum_{j=1}^{x} \text{SPI}_{i,j}\right) \quad (4)$$

where j represents the first month of the drought period, which continues until the end of drought x for timescale i. The *DM* is computed in monthly units, where SPI values are less than −1. Hence, the sum of negative SPI values below a certain threshold defines the SPI DM, which is currently categorized into three classes: moderate, high, and extreme.

2.6 | Impact of Drought on Maize Yield

2.6.1 | Maize Production

Maize is an important summer season rainfed crop in South Africa (Blignaut, Ueckermann, and Aronson 2009). Maize covers approximately 50% of the cultivated area in South Africa, and it is the dominant crop in the northern and northeastern provinces (Omolola et al. 2019). It is recognized as the country's major source of food and contributes more than 9 billion per annum to the country's economy. Climatic variability, such as seasonal rainfall and temperature fluctuations, plays a crucial role in determining maize yield. Water is the main limiting factor of maize yield in the study region due to its high dependence on rainfall (Adisa et al. 2018; Botai et al. 2016). For instance, Blignaut, Ueckermann, and Aronson (2009) reported that a 1% decrease in rainfall is likely to reduce maize yield by 1% in this area. South Africa is known to be a water-scarce country, and with recurring drought events, maize production may be affected, as this crop is highly reliant on rainfall (Lyon 2009). Hence, the vulnerability of maize to drought conditions is a major challenge in this country (Ferreira et al. 2023). Sustainable land use practices are required to cope with the challenges of growing rainfed maize in arid regions of South Africa (Haarhoff, Kotzé, and Swanepoel 2020). The evolution of maize yield since 1993 in all provinces of the country has revealed an increase in yield, illustrating the increasing demand for maize (Figure 2).

2.6.2 | Standardized Yield Residual Series

To offset the effects of non-climatic variables, such as irrigation, fertilization, improved seed varieties, and technological factors (Tessema, Joerin, and Patt 2018), maize yield time series was fitted using polynomial regression to compute the yield residuals series. This method provides a clear understanding of the impacts of climatic phenomena on crop yield (Nxumalo et al. 2022; Wu et al. 2022). The SYRS was calculated as follows:

$$\text{SYRS}_{\text{maize}} = \frac{X_{i\_}\overline{X_i}}{\sigma} \quad (5)$$

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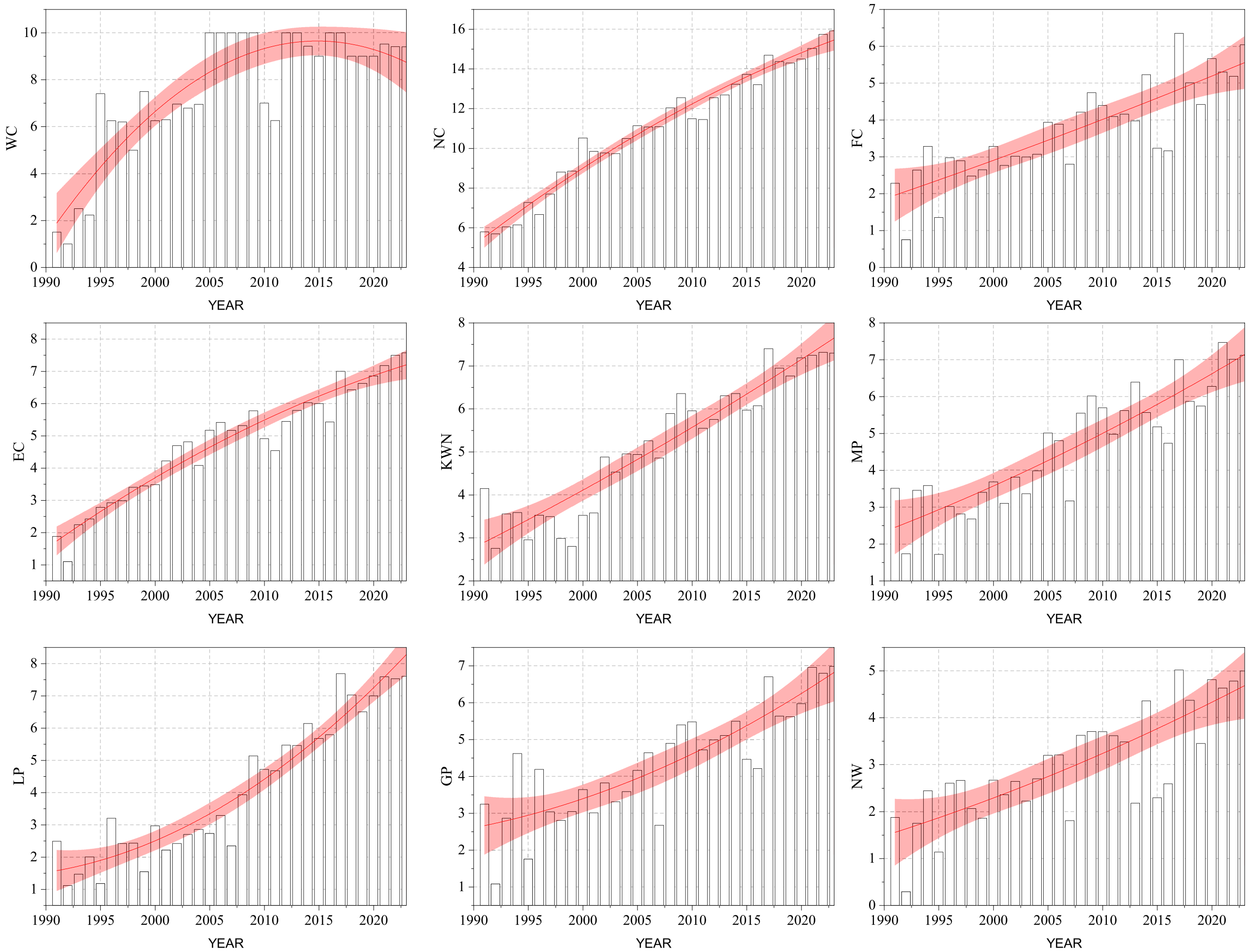

FIGURE 2 | Maize yield evolution in the study area from 1993 to 2023. The black columns represent the yield in the corresponding year, the red line shows the polynomial regression, and the red shaded area indicates the 95% confidence band.

where X_i is the detrended maize yield residual for a particular period, $\overline{X_i}$ is the mean, and σ is the standard deviation. The resulting SYRS values were categorized (Table 3) to classify the intensity of yield loss due to climate-associated SPI droughts.

After calculating the SYRS for maize, Pearson correlation (r) analysis was performed to evaluate the strength of the statistical relationships between SPI-3 and SPI-6 and SYRS as follows:

$$r = \frac{\sum_{i=1}^{n} \left(x_i - \overline{x}\right)\left(y_i - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n} \left(x_i - \overline{x}\right)^2 \left(y_i - \overline{y}\right)^2}} \tag{6}$$

where x_i presents the individual maize yield residual at a certain time and $\overline{x}$ presents its mean, y_i presents the drought (SPI-3 and SPI-6) and $\overline{y}$ presents the mean SPI drought.

2.6.3 | Crop Drought-Resilience Factor

The CDRF represents the potential a crop possesses to endure external pressure without its structure and functions being

TABLE 3 | Standardized Yield Residual Series threshold for classifying maize yield-loss intensity.

Yield loss category	SYRS value
Low yield loss	$-1.0 < \text{SYRS} \leq -0.5$
Moderate yield loss	$-1.5 < \text{SYRS} \leq -1$
High yield loss	$\text{SYRS} \leq -1.5$

altered (Mohammed et al. 2022; Sharma and Goyal 2018). We calculated the CDRF to evaluate the extent of the impact of drought on maize crops on a regional scale using the following equation:

$$CDRF = \frac{D_{\mathrm{dr}}}{D_{\mathrm{dt}}} \tag{7}$$

where D_{dr} is the maize yield in the growing season of the driest year and D_{dt} is the detrended yield for the same year. The threshold of the CDRF (Mohammed et al. 2022) is presented in Table 4.

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3 | Results

3.1 | Frequency and Magnitude of Agricultural Droughts

Agricultural drought (SPI-3 and SPI-6) analysis based on data from 29 stations showed dynamic variations in drought occurrence, magnitude, and trends across the nine provinces of South Africa. The cyclical drought pattern during 1993–2022 revealed several drought years at different stations in the region (Figure 3). The most prominent and common drought years in the maize growing season (November to March), which were identified in all provinces of the region, were 2002, 2003, 2015, 2018, and 2019. Furthermore, the highest number of drought events was recorded from 2012 to 2022 in all provinces of the region. The most intense short-term agricultural drought events were reported in Gauteng, Northern Cape, Eastern Cape, and Western Cape provinces in 2002 and 2019, with SPI-3 values of −6.93, −6.62, and −5.71, respectively. The most intense droughts in 2015 were recorded in KwaZulu-Natal (SPI-3 = −4.48), Free State (SPI-3 = −4.43), and Northern Cape (SPI-3 = −4.09) provinces.

TABLE 4 | Classification of the Crop Drought-Resilience Factor.

Crop yield resilience to drought	CDRF value
Resilient	CDRF > 1
Slightly non-resilient	0.9 < CDRF < 1
Moderately non-resilient	0.8 < CDRF < 0.9
Severely non-resilient	CDRF < 0.8

The percentage distribution of SPI-3 drought intensity revealed severe to extreme drought events in Limpopo (3.3%), with an extreme magnitude of −48, Free State (3%), with an extreme magnitude of −57.8, and Gauteng (2.7%), with an extreme magnitude of −6.5. High percentages of moderate drought events were recorded in Free State (9.1%), followed by Gauteng (8.6%), Northern Cape (7.7%), and Mpumalanga (7.2%). Western Cape had the highest percentage of mild drought events at 48%, followed by Eastern Cape at 46%, Mpumalanga at 44%, and Free State at 36%. Furthermore, Western Cape, North West, Mpumalanga, KwaZulu-Natal, and Eastern Cape experienced moderate to high magnitudes of SPI-3, which ranged from −26.3 in Western Cape to −39.06 in KwaZulu-Natal (Figures 4 and 5).

Similarly, SPI-6 analysis revealed that Gauteng, Free State, and North West provinces experienced the highest percentages of severe to extreme drought events at 4.17%, 3.89%, and 3.61%, respectively. Meanwhile, Eastern Cape, Mpumalanga, and Northern Cape experienced a few drought events over the three decades at 0.56%, 0.83%, and 2.2%, respectively. The highest percentages of moderate drought events were recorded in Free State and Limpopo provinces at 8% each, followed by KwaZulu-Natal and Northern Cape at 7.7% each, Western Cape at 6.9%, and Gauteng and North West at 5.8% each. The highest percentage of mild drought events was recorded in Eastern Cape (50.8%), followed by Mpumalanga (44%), Gauteng (39%), and Limpopo and North West (38% each) (Figure 4). Notably, the majority of provinces in South Africa experienced an extreme SPI-6 magnitude, which ranged from −46.03 in Western Cape to −61.6 in Free State. Meanwhile, Eastern Cape experienced the lowest SPI-6 magnitude of −17.7 (Figure 5).

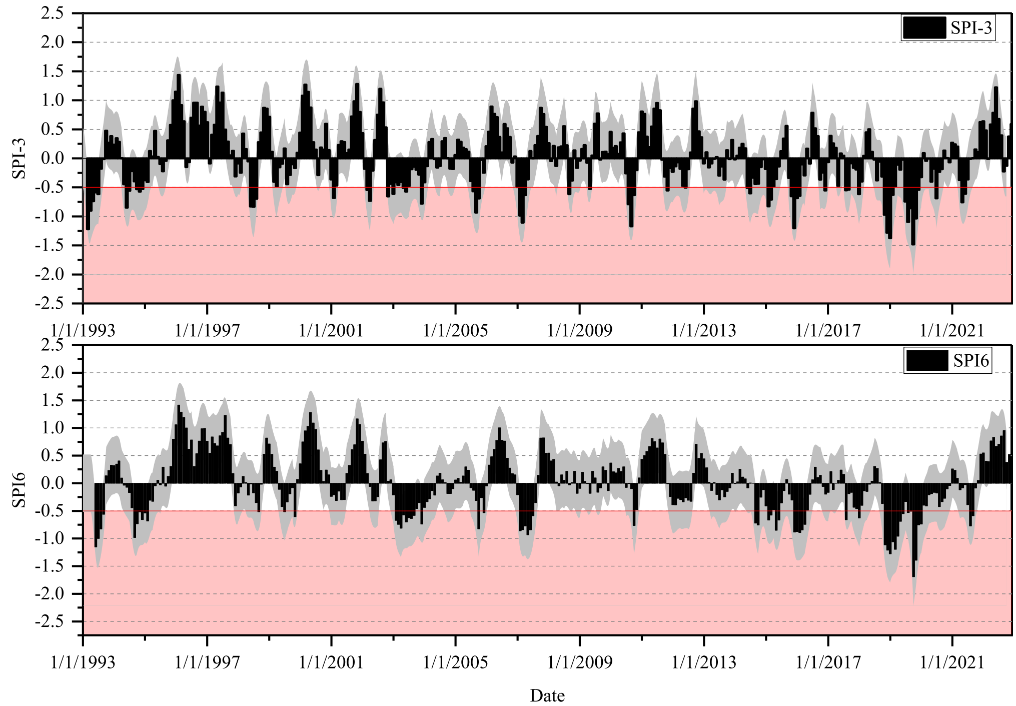

FIGURE 3 | Evolution of drought across South Africa from 1993 to 2022 based on agricultural drought SPI-3 and SPI-6, averaged across all studied stations in the country. The black line represents the values based on SPI-3 and SPI-6, the gray shaded area indicates the standard deviation, and the red line marks the threshold for drought occurrence.

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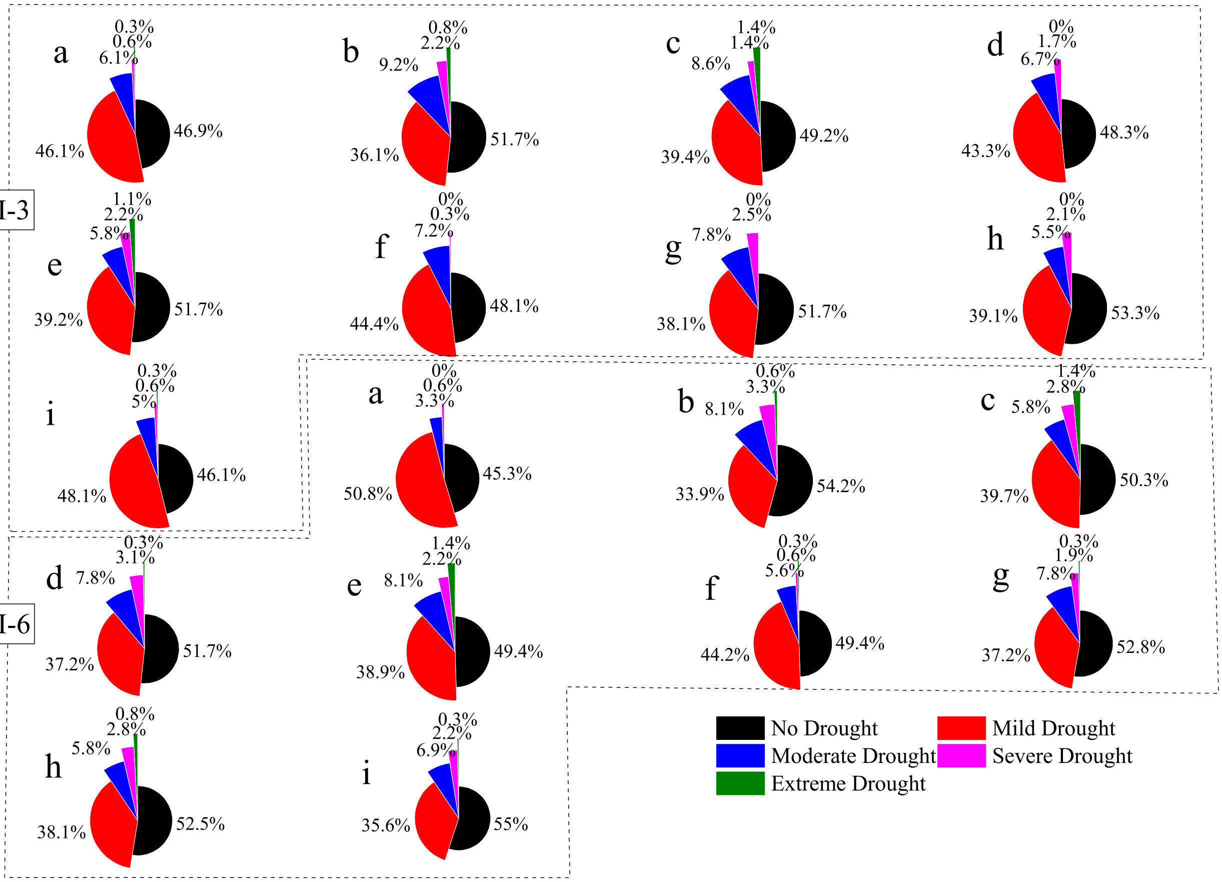

FIGURE 4 | Intensity percentage of SPI-3 and SPI-6 drought events in each province: (a) Eastern Cape, (b) Free State, (c) Gauteng, (d) KwaZulu-Natal, (e) Limpopo, (f) Mpumalanga, (g) Northern Cape, (h) North West, (i) Western Cape.

3.2 | Trend Analysis of Short-Term Agricultural Droughts

The Mann–Kendall trend test and Sen's slope analysis of the SPI-3 and SPI-6 droughts for all 29 stations across the nine provinces of South Africa revealed significant ($p < 0.05$) drought events during the study period. Sen's slope analysis showed that 10 stations in the region exhibited a significant ($p < 0.05$) declining trend in SPI-3, indicating an increase in the occurrence of drought events in the recent decade. These included SKZ station in Mpumalanga Province, PMB and DBN in KwaZulu-Natal Province, and VRBG in North West Province, each with the highest Sen's slope of −0.03, followed by VRNG in Gauteng Province, RCB in KwaZulu-Natal Province, and CAL and STH in Northern Cape Province, each with a significant ($p < 0.05$) Sen's slope of −0.02.

Additionally, EL and PE stations in Eastern Cape Province recorded significant declining trends, each with a Sen's slope of −0.01, whereas MFK in North West Province and BTLHM and WKM in Free State Province showed non-significant declining trends, each with a Sen's slope of −0.01 (Figure 6) (Table A1). Only NEL station in Mpumalanga Province showed a significant increasing trend in SPI-3, indicating a decline in drought occurrence in recent years. Notably, 10 of the 29 stations showed no significant decreasing or increasing trends in drought occurrence (Figure 6) (Table A1).

Similarly, Sen's slope analysis of SPI-6 agricultural drought showed significant ($p < 0.05$) declining trends at the same stations which experienced SPI-3 declining trend, with the highest Sen's slope of −0.05 at PMB station in KwaZulu-Natal Province, followed by a Sen's slope of −0.04 at VRBG station in North West Province. Overall, Sen's slope analysis revealed an increase in drought occurrence in Mpumalanga, Gauteng, and North West in the northern region, KwaZulu-Natal in the eastern region, Northern Cape in the northwest of South Africa and Eastern Cape in the southern region of South Africa (Figure 6) (Table A1). However, a few stations in these regions also revealed significant ($p < 0.05$) rising trends in the SPI-6, with positive Sen's slope values at UP and KMBLY in Northern Cape, KLKSDP in North West, and NEL and ERML in Mpumalanga.

3.3 | Analysis of Maize Yield Losses

We performed SYRS analysis to evaluate the impact of agricultural drought on maize yield at the provincial scale in South Africa. The nine provinces of South Africa exhibited substantial variation in maize yield loss during the period. Eastern Cape Province had high yield losses (SYRS ≤ -1.5) in 1993 (13%) and 1994 (12.5%), followed by moderate yield losses ($-1.5 < \text{SYRS} \leq -1$) from 1995 to 1997 (9%–10%), and a low yield losses ($-1.0 < \text{SYRS} \leq -0.5$) in 1998 (7.5%), 2001 (2.7%), 2004 (6.3%), 2010 (2.8%), and 2011(6.6%) (Table 5; Figures 7 and 8).

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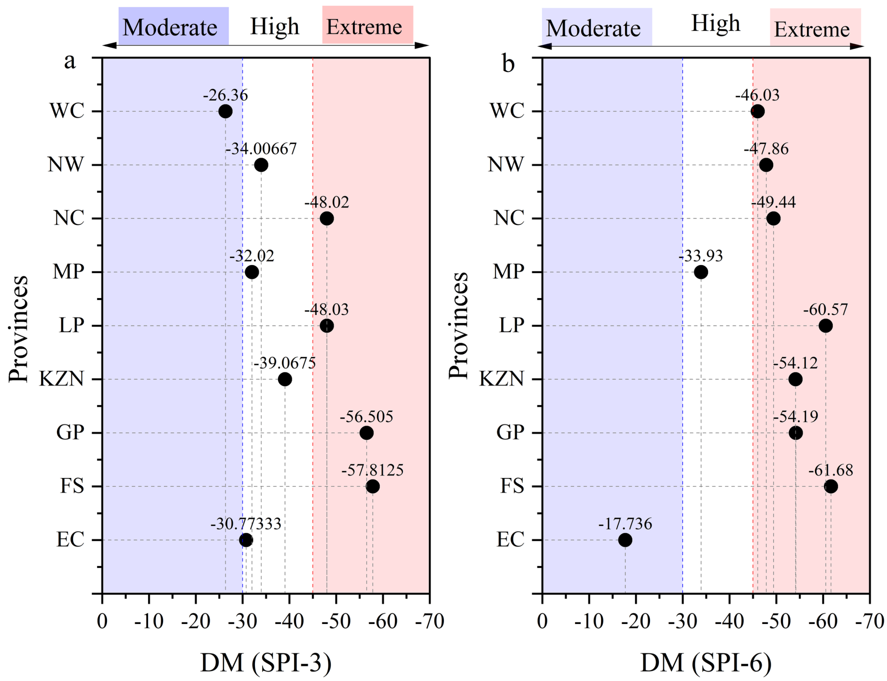

FIGURE 5 | Drought magnitude (DM) based on (a) SPI-3 and (b) SPI-6 drought events in all provinces across South Africa from 1993 to 2022. Blue represents moderate DM values, white represents high DM values, and red represents extreme DM values.

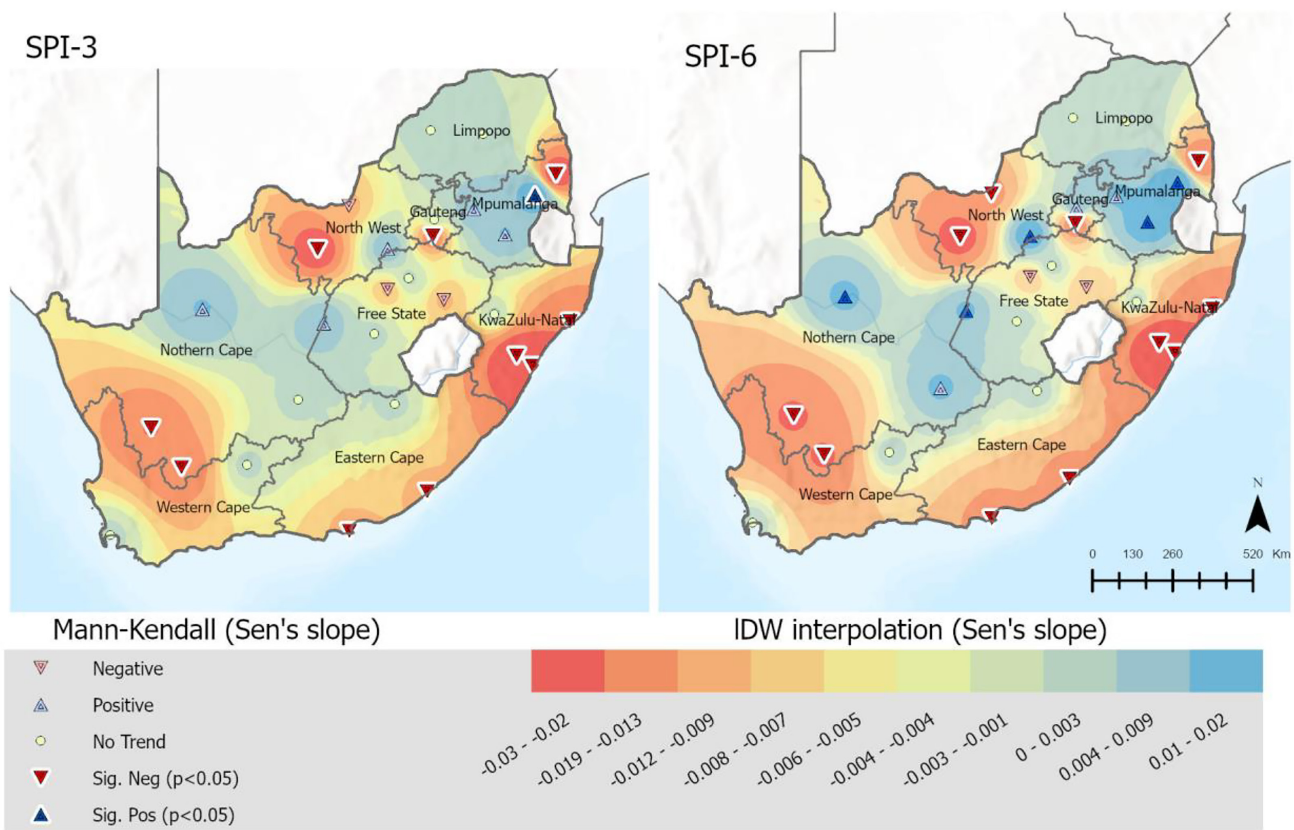

FIGURE 6 | Spatial pattern of Sen's slope showing directional trends in SPI-3 and SPI-6.

Overall, there was a substantial loss in maize yield in 13 out of 30 years during the study period. In Free State Province, the highest maize yield losses were observed in 2015 (SYRS = −2.04, YL = 17.7%) and 2016 (SYSR = −2.2, YL = 19%), followed by that in 1995 (SYRS = −1.81, YL = 15.7%) (Table 5; Figures 7 and 8).

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TABLE 5 | Maize Standardized Yield Residual Series at the provincial scale.

Year	EC	FS	GP	KZN	LP	MP	NC	NW	WC
1993	−1.62 H	0.28	−0.22 L	0.61	−0.17 L	0.835	0.78	−0.70 L	0.68
1994	−1.55 H	1.25	1.11	0.37	0.28	0.831	0.48	−1.97 H	0.42
1995	−1.28 M	−1.81 H	−1.95 H	−1.09 M	−0.65 L	−1.17 M	1.13	−0.54 L	1.87
1996	−1.23 M	0.54	1.38	−0.34 L	1.27	−0.01 L	0.20	−0.49 L	1.34
1997	−1.28 M	0.26	−0.31 L	−0.68 L	0.37	−0.35 L	0.74	−1.07 M	1.16
1998	−0.94 L	−0.49 L	−0.72 L	−1.89 H	0.26	−0.63 L	1.37	−1.27 M	0.61
1999	−1.00 M	−0.47 L	−0.48 L	−2.51 H	−0.77 L	−0.05 L	1.04	−0.48 L	1.23
2000	−1.06 M	0.48	0.24	−1.46 M	0.51	0.09	2.17	−0.78 L	0.67
2001	−0.34 L	−0.44 L	−0.76 L	−1.62 H	−0.40 L	−0.63 L	1.18	−0.51 L	0.52
2002	0.09	−0.27 L	0.25	0.50	−0.35 L	−0.06 L	0.72	−0.91 L	0.56
2003	0.12	−0.41 L	−0.60 L	−0.39 L	−0.25 L	−0.65 L	0.32	−0.45 L	0.34
2004	−0.79 L	−0.40 L	−0.35 L	0.14	−0.28 L	−0.18 L	0.63	0.03	0.23
2005	0.34	0.69	0.30	−0.13 L	−0.60 L	0.703	0.84	0.04	1.02
2006	0.52	0.53	0.81	0.21	−0.23 L	0.352	0.40	−1.32 M	0.86
2007	0.16	−1.32 M	−2.12 H	−0.76 L	−1.40 M	−1.43 M	0.04	0.44	0.70
2008	0.25	0.69	0.81	0.92	−0.03	0.801	0.53	0.52	0.54
2009	0.69	1.30	1.32	1.55	0.94	1.120	0.62	0.52	0.38
2010	−0.35 L	0.67	1.24	0.60	0.29	0.649	−0.72 L	0.43	−0.72 L
2011	−0.83 L	0.04	−0.03	−0.35 L	−0.01 L	−0.21 L	−1.13 M	0.31	−1.11 M
2012	0.11	0.03	0.12	−0.19 L	0.53	0.273	−0.50 L	−0.96 L	−0.10 L
2013	0.44	−0.45 L	0.06	0.63	0.24	0.896	−0.74 L	1.15	−0.25 L
2014	0.64	1.23	0.37	0.52	0.65	−0.08 L	−0.63 L	−0.85 L	−0.59 L
2015	0.57	−2.04 H	−1.32 M	−0.37 L	−0.11 L	−0.62 L	−0.55 L	−0.55 L	−0.88 L
2016	−0.12 L	−2.22 H	−1.93 H	−0.37 L	−0.29 L	−1.22 M	−1.38 M	1.78	−0.72 L
2017	1.58	2.39	1.29	1.90	1.30	0.889	−0.41 L	1.16	−0.87 L
2018	0.90	0.19	−0.47 L	0.89	0.32	−0.39 L	−1.07 M	0.27	−1.34 M
2019	1.08	−0.92 L	−0.77 L	0.39	−0.53 L	−0.67 L	−1.50 M	1.58	−1.49 M
2020	1.30	0.90	−0.58 L	1.00	−0.37 L	−0.30 L	−1.68 H	1.41	−1.64 H
2021	1.63	0.08	0.50	0.96	−0.13 L	0.73	−1.56 M	1.56	−1.63 H
2022	1.96	−0.27 L	−0.03 L	0.94	−0.55 L	0.113	−1.29 M	1.63	−1.82 H

In Gauteng Province, the highest yield losses were recorded in 2007 (SYRS = −2.12, YL = 16.7%), 1995 (SYRS = −1.95, YL = 15.4%), and 2016 (SYRS = −1.93, YL = 15.2%). Additionally, low yield losses were observed in Gauteng in 1997–1999, 2001, 2003, 2004, 2018, and 2020. Meanwhile, KwaZulu-Natal Province experienced a long period of yield loss from 1995 to 2001, with high yield losses (SYRS ≤ −1.5) in 1998 (YL = 15.5%), 1999 (YL = 20.6%), and 2001 (YL = 13.3%) (Figure 8).

Limpopo and Mpumalanga provinces experienced low to moderate yield losses during 1995–2007. Northern Cape and Western Cape experienced the impacts of agricultural droughts (SPI-3 and SPI-6) with high yield loss from 2010 to 2022. Meanwhile, Northwest Province experienced low to moderate yield losses from 1993 to 2003. Additionally, Northwest Province faced climate change impacts in the drought years of 2012–2016, with low yield losses in 2012, 2014, and 2015 (Table 5; Figures 7 and 8).

3.4 | Statistical Relationship Between Drought and Maize Yield

Pearson correlation analysis revealed a dynamic relationship between the SYRS and SPI-3 values. In Free State Province, there

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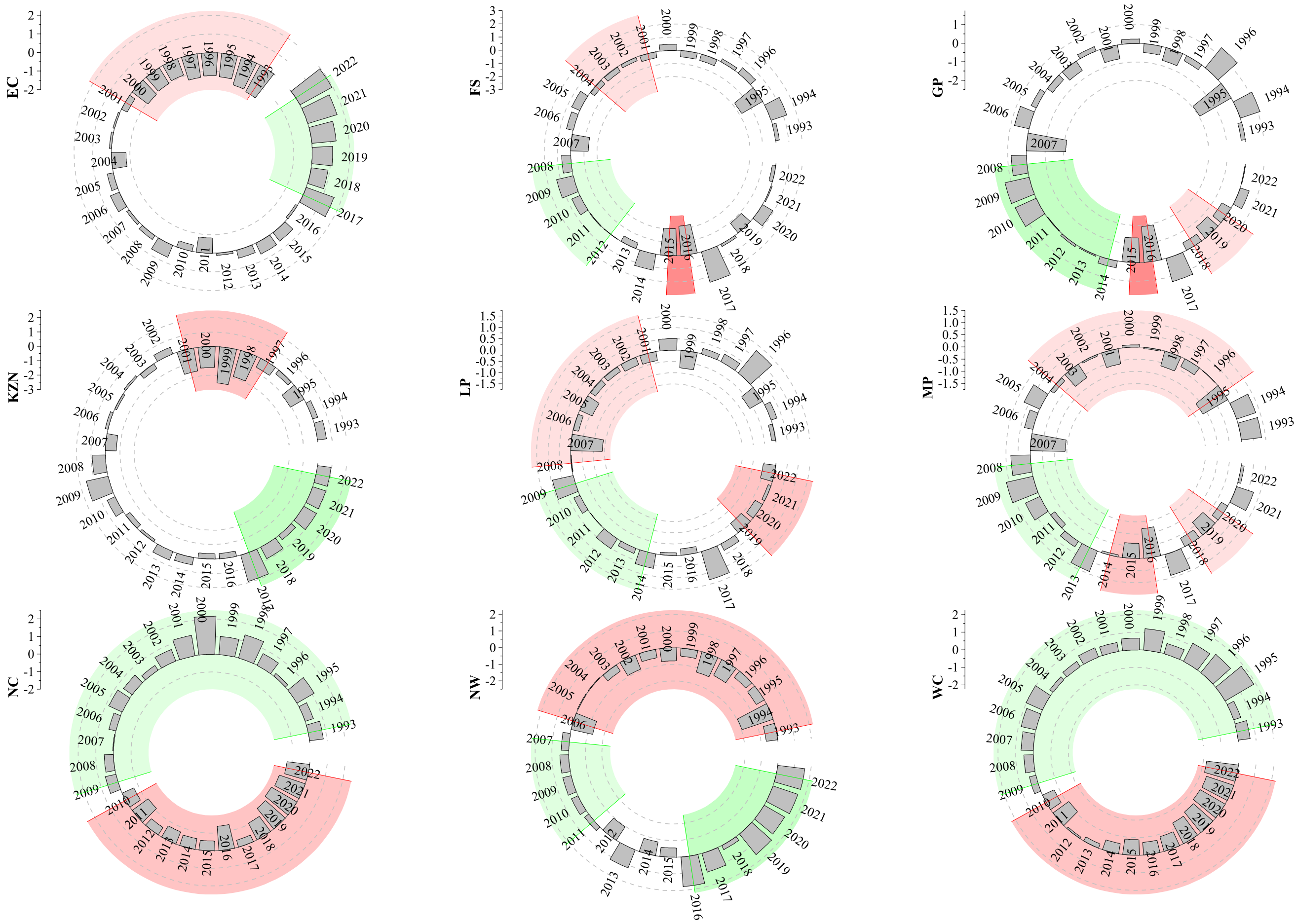

FIGURE 7 | Standardized Yield Residual Series (SYRS) showing maize yield gain (green) and loss (red) during 1993–2022.

were significant and strong positive correlations between the SYRS and SPI-3 values in February ($r=0.64$) and March ($r=0.50$), revealing the significant impact of agricultural drought on maize yield. In Western Cape and Mpumalanga provinces, there were moderate correlations between the SYRS and SPI-3 values in January ($r=0.47$, 0.42, respectively) and February ($r=0.40$). In Gauteng Province, there were positive correlations between the SYRS and SPI-3 values in January ($r=0.30$), February ($r=0.43$), and March ($r=0.36$). Furthermore, there were positive correlations between the SYRS and SPI-3 values from January to March in most provinces of South Africa, including Free State, Gauteng, Limpopo, Mpumalanga, and Western Cape.

In contrast, there were negative correlations between the SYRS and SPI-3 values in Eastern Cape ($r=-0.33$), KwaZulu-Natal ($r=-0.29$), and North West ($r=-0.25$) provinces, indicating no significant impacts of agricultural drought on maize yield. However, positive correlations between the SYRS and SPI-3 values were recorded in the growing season (November–March), with the strongest correlation in Free State ($r=0.44$), followed by those in Western Cape ($r=0.39$), Gauteng ($r=0.29$), Limpopo ($r=0.28$), Mpumalanga ($r=0.28$), and Northern Cape ($r=0.2$) (Table A2) (Figure 9).

Pearson correlation analysis also revealed positive correlations between the SYRS and SPI-6 values in Free State, Gauteng, Limpopo, Mpumalanga, Northern Cape, and Western Cape provinces during the maize growing season. However, negative correlations between the SYRS and SPI-6 values were recorded in the sowing months (November–December), except in Northern Cape and Western Cape provinces. In Northern Cape, there were positive correlations in November ($r=0.19$), December (sowing stage) ($r=0.21$), January ($r=0.19$), February ($r=0.14$), and March ($r=0.13$). The highest correlations between the SYRS and SPI-6 values were recorded in Free State Province in February ($r=0.57$) and March ($r=0.56$), followed by those in Limpopo Province in February ($r=0.51$) and March ($r=0.48$). In Mpumalanga Province, there were moderate positive correlations in January ($r=0.43$), February ($r=0.46$), and March ($r=0.42$). Similarly, Gauteng Province exhibited moderate positive correlations between the SYRS and SPI-6 values in the growing months, including January ($r=0.35$), February ($r=0.45$), and March ($r=0.44$) (Table A3) (Figure 9). Additionally, there were positive correlations between the SYRS and SPI-6 values during the entire maize growing season in Free State ($r=0.37$); Gauteng, Limpopo, and Western Cape ($r=0.3$); Northern Cape ($r=0.24$); and Mpumalanga ($r=0.16$). Similar to the results for SPI-3 droughts, SPI-6 droughts also had negative correlations with the SYRS in Eastern Cape, KwaZulu-Natal, and North West provinces (Table A3) (Figure 9).

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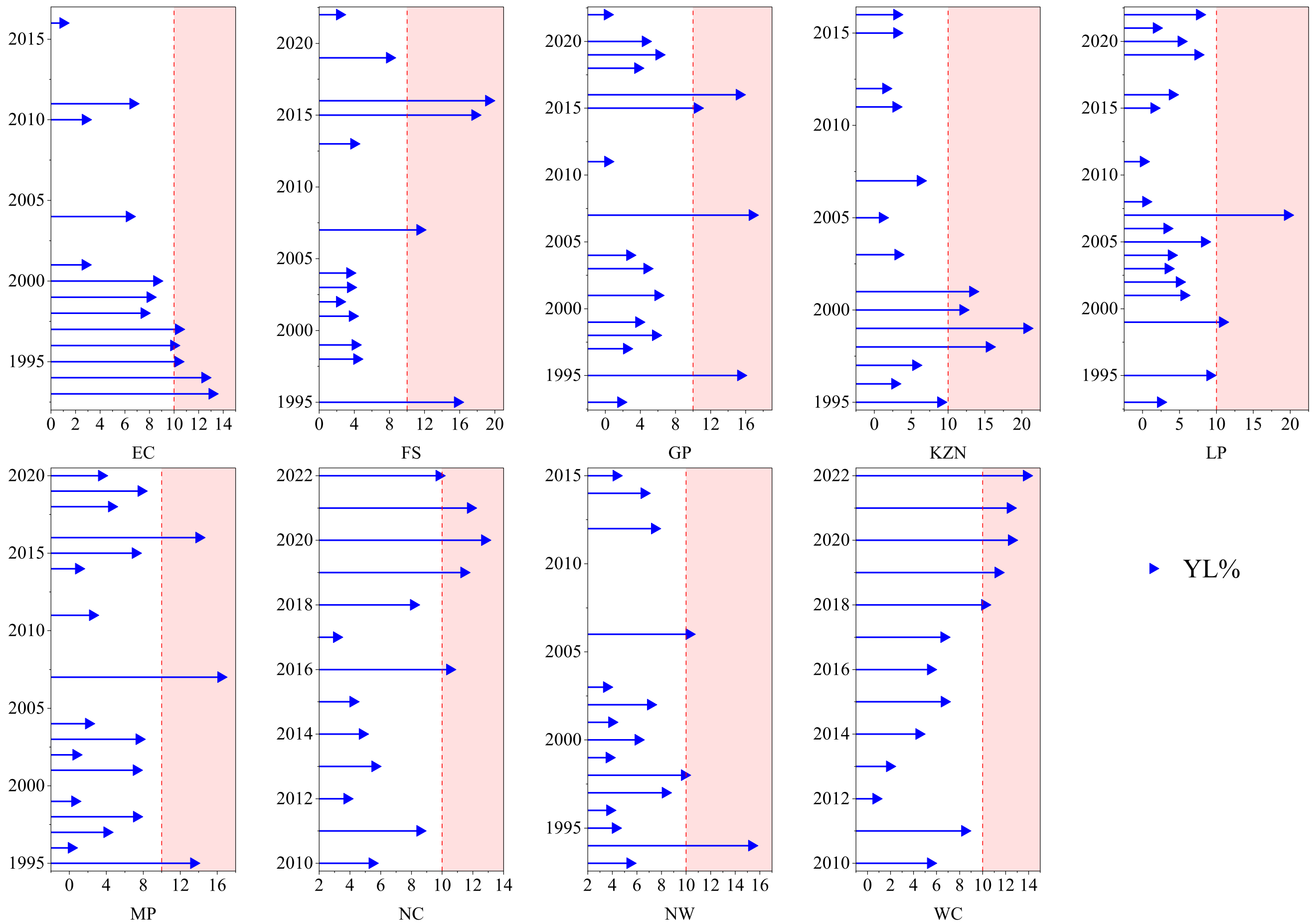

FIGURE 8 | Maize yield loss percentage (YL%) in respective years for all provinces across South Africa from 1993 to 2022. The red line indicates the threshold of a 10% yield loss, while the red shaded area represents the associated risk.

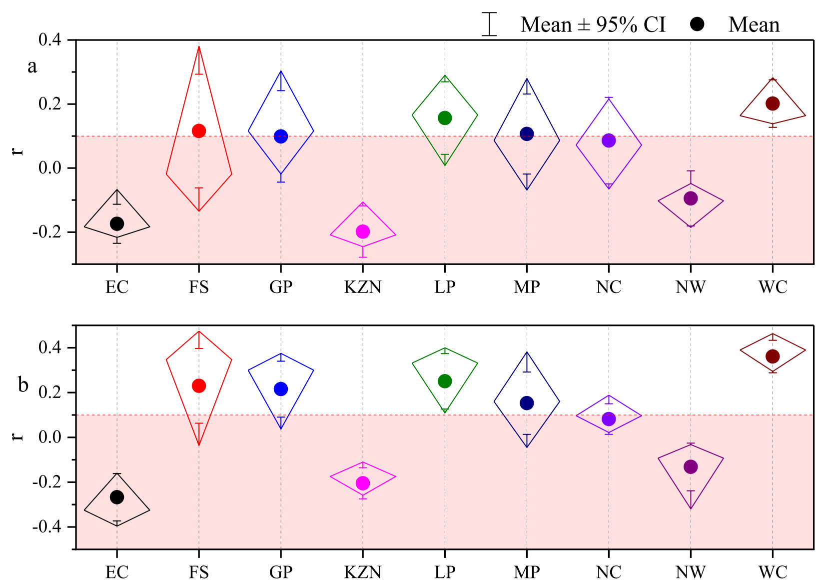

FIGURE 9 | Pearson correlations between maize Standardized Yield Residual Series (SYRS) and three-month and six-month Standard Precipitation Index (SPI-3 and SPI-6, respectively) values: (a) SYRS and SPI-3, (b) SYRS and SPI-6.

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3.5 | Crop Drought-Resilience Factor Analysis for Maize

Maize drought-resilience was analyzed based on a threshold CDRF value of 0.8 in the driest year of the study period for both SPI-3 and SPI-6. We determined that maize was severely non-resilient in Western Cape (CDRF [SPI-3] = 0.52, CDRF [SPI-6] = 0.62) and Mpumalanga (CDRF [SPI-6] = 0.7) provinces. Furthermore, maize was found to be moderately non-resilient in North West (CDRF = 0.83), Northern Cape (CDRF = 0.84), and Free State (CDRF = 0.88) provinces (Figure 10).

In Limpopo Province, maize was found to be slightly non-resilient for SPI-6 (CDRF = 0. 92) but resilient for SPI-3 (CDRF = 1.05). In Gauteng Province, maize was found to be slightly non-resilient, with a CDRF of 0.9 for both SPI-3 and SPI-6. Meanwhile, the CDRF results revealed that maize crops were resilient in Eastern Cape (CDRF = 1.56) and KwaZulu-Natal (CDRF = 1.03) provinces (Figure 10). This aligns with the negative correlation between the SYRS and SPI values in these provinces, confirming that maize was resilient and showed no significant impact from agricultural drought.

4 | Discussion

4.1 | Climate Change and Drought in South Africa

It is important to evaluate the impacts of regional climatic factors on the agricultural sector in South Africa because of agriculture's contributions to the country's GDP and food security (Ala-Kokko et al. 2021). Agrometeorological droughts have profound effects on crop yield at the regional level (Arshad et al. 2023). Additionally, the interannual variability in rainfall and temperature associated with El Niño Southern Oscillation is known to cause meteorological droughts at lower latitudes (Jury 2018). El Nino events disrupt rainfall and temperature patterns in the pacific ocean, leading to drier and warmer conditions in South Africa, which profoundly impact agricultural and water resources in this region (Omolola et al. 2019). Moreover, the movement of the South Atlantic anticyclones causes a more pronounced east–west weather pattern, leading to drier conditions in the southern tip of South Africa, such as in Cape Town (Mupazviriho, Dalton, and Bekker 2022). The rainfall in South Africa revealed a slightly decreasing trend at many stations in the northern and eastern provinces (CAL, DBN, EL, PMB, RCB, SKZ, STH, VRNG, and VRBG), except in the eastern coastal plains (Jury 2019).

The availability of and variability in solar and wind resources have also been affected by climate change, with declining trends observed during the summer (Schlosser et al. 2021). Moreover, the climatic pattern in South Africa revealed a projected temperature rise of 0.02°C per annum by 2050 with a declining trend in rainfall (Jury 2019). In the context of insufficient rainfall, Sen's slope analysis showed increasing trends in the number of drought events in Mpumalanga, Gauteng, North West, KwaZulu-Natal, Northern Cape, and Eastern Cape provinces during the study period (Figure 6). Our findings aligned with Botai et al. (2016), confirming the vulnerability of Free State and North West provinces to drought occurrence. The notable drought spells identified in our findings included 2002–2007, which was also reported by Malherbe et al. (2016), and 2002–2003, which was experienced in all provinces of South Africa. The other major drought spell extended from 2013 to 2020, with 2015, 2018, and 2019 as common drought years in all provinces. Previous studies by Archer et al. (2022) in Eastern Cape Province and Kganvago et al. (2021) in Western Cape Province also highlighted multiyear drought events in the same decade, which lead to economic and agricultural losses.

The severe impacts of the rainfall deficit during the 2015–2017 drought, specifically in the southwestern provinces of the country, led to this drought being reported as a one in a hundred years extreme event (Wolski et al. 2021). A study by Ndlovu and Demlie (2020) revealed that 1992–1993 and 2015 were the worst dry years on record in KwaZulu-Natal Province. Several

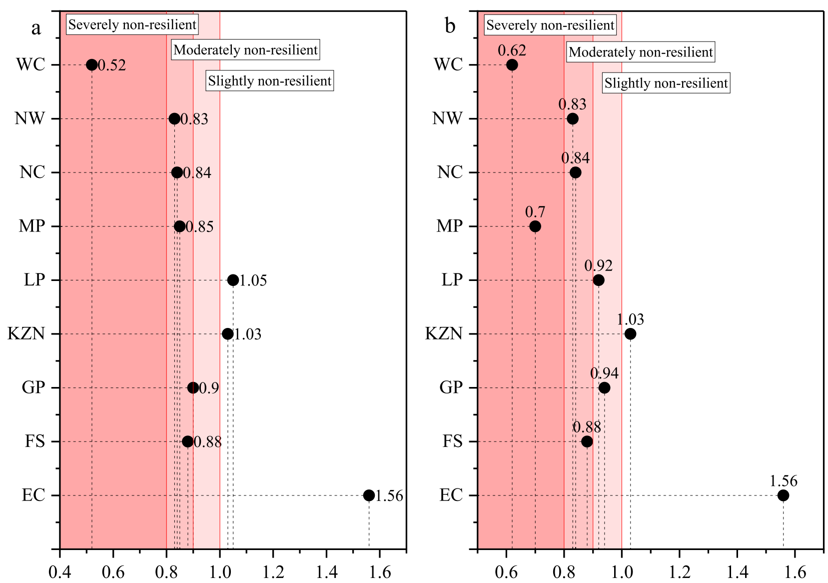

FIGURE 10 | Crop Drought-Resilience Factor (CDRF) for maize in all provinces for SPI-3 and SPI-6.

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key contributors to these drought spells have been reported previously, including the effects of El Niño, poleward shift of the jetstream, and formation of moisture corridors, which led to notable drying, specifically in the southwestern region of South Africa (Sousa et al. 2018).

4.2 | Dynamic Effects of Agricultural Drought on Maize Yield

Climatic extremes have been reported to affect maize yield in different provinces of South Africa (Simanjuntak et al. 2023). The SYRS analysis revealed that in 2015 and 2016, moderate to high yield losses occurred in the majority of provinces, which were linked to the agricultural impacts observed during the 2015–2017 drought spell (Figure 7). Northern Cape and Western Cape provinces have also experienced higher maize yield losses recently, with the highest yield losses in 2020 (SYRS = −1.68 and −1.64, respectively) and positive correlations ($r = 0.2$ and 0.39, respectively) between the SYRS and SPI values throughout the growing season (Figures 7 and 9). Similarly, Eastern Cape and North West provinces experienced substantial climate-related yield losses from 1993 to 2003 and in 2004. Thus, drought has remained the primary driver of considerable maize yield losses over the past three decades (Mangani et al. 2019; Omolola et al. 2019). Moreover, Kim, Iizumi, and Nishimori (2019) found that the frequency and intensity of extreme events, such as droughts and heatwaves, exacerbate their impacts on global crop production. Furthermore, Mangani et al. (2018) modeled the impact of extreme events (droughts and heatwaves) on maize yield and projected a decline in yield under future climate scenarios.

A moderate positive correlation between the SYRS and SPI-3 and SPI-6 values revealed that Free State, Gauteng, Limpopo, and Western Cape experienced direct impacts of agricultural droughts on maize yield, which were evident in the yield losses reported in drought years. Theron et al. (2021) also reported drought-associated wheat yield losses in Western Cape Province during the 2015–2018 drought spell. Our analysis of drought resilience showed that maize was severely non-resilient in Western Cape, with CDRF values of 0.52 for SPI-3 and 0.62 for SPI-6, which were related to the intense drought in 2019. Similarly, the CDRF value for SPI-6 in Mpumalanga Province showed that maize is a severely non-resilient crop (Figure 10). A study by Cammarano et al. (2020) in Free State projected a climate-induced decline in maize production of more than 10%, which could be overcome by implementing adaptation strategies at the local scale. Although maize was found to be non-resilient in many provinces, such as North West, the negative correlations between the SYRS and SPI values in Eastern Cape and KwaZulu-Natal provinces showed that maize is a resilient crop in some regions.

Improvements in smallholder rainfed maize farming through conservation tillage have provided a sustainable approach for coping with the negative impacts of agricultural droughts (Rippke et al. 2016; Walker and Schulze 2006). However, the semi-arid northern and northeastern provinces of South Africa, followed by Western Cape in the southern region, are more susceptible to the severe impacts of agricultural droughts than other provinces. Our study also suggest that technological progress drives the development of crops with increased resilience in a few provinces. In addition to implementing sustainable farming methods and selecting improved cultivars, an early warning drought-monitoring system is required to adapt to future climate change conditions and mitigate drought-associated agricultural yield losses.

4.3 | Study Limitations and Future Directions

In this study, we relied on the SPI as an indicator of drought, omitting consideration of other sophisticated drought indices such as the Standardized Precipitation Evapotranspiration Index, Rainfall Anomaly Index, or Bhalme–Mooley Drought Index. Additionally, satellite-based agricultural drought indices such as the Normalized Difference Vegetation Index and Enhanced Vegetation Index were not incorporated to support our research outcomes. Therefore, future studies should include multiple drought indices.

We utilized data from 29 meteorological stations across South Africa to obtain weather information. Future studies should include more stations for enhanced accuracy. The temporal scope of this study was limited to a 30 year period (1993–2022) due to a lack of available data and considerable data gaps before 1993. Moreover, this study focused solely on maize crops; hence, further research is recommended to extend this analysis to other crops.

5 | Conclusions

In this study, we aimed to investigate the impact of agricultural drought on maize production in South Africa, given that maize is a crucial staple food in this region and South Africa is a major exporter of maize to neighboring countries. Due to the high dependency of South African maize on rainwater, the rainfall-based SPI-3 and SPI-6 were used to evaluate drought characteristics and trends. The SYRS was calculated to determine the actual intensity and percentage of yield loss at the provincial scale. Additionally, we analyzed the correlations between the SYRS and SPI-3 and SPI-6 values to determine the impact of drought on maize yield. We drew the following conclusions:

1. South Africa has experienced frequent droughts over the past three decades, with 2002, 2003, 2015, 2018, and 2019 being common drought years for all provinces. In particular, North West Province, northeastern Mpumalanga Province (SKZ station), eastern KwaZulu-Natal Province, southwestern Northern Cape Province (CAL and STH stations), and Eastern Cape Province (EL and PE stations) experienced significant increasing trends in the number of drought events, with negative Sen's slopes ranging from −0.03 to −0.01.

2. The SYRS analysis revealed that Limpopo, Mpumalanga, and Gauteng provinces experienced the highest yield losses during the 30 year period. Northern Cape and Western Cape provinces experienced high maize yield losses from 2010 to 2022, with the highest yield losses in 2020; the SYRS was positively correlated with the SPI throughout the growing

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season, with frequent droughts from 2013 to 2020. Eastern Cape and North West provinces experienced substantial climate-related yield losses from 1993 to 2003 and in 2004. In 1999, KwaZulu-Natal Province experienced the highest yield loss (SYRS = −2.51), resulting in a 20% loss compared to the cumulative yield loss in all years.

3. Positive correlations between the SYRS and SPI-3 and SPI-6 values revealed that Free State, Gauteng, Limpopo, and Western Cape experienced direct impacts of agricultural droughts, which were manifested as maize yield losses in drought years. The CDRF analysis also showed that maize is a moderately to severely non-resilient crop in these provinces, except for Limpopo, where it is slightly non-resilient.
4. The negative correlations between the SYRS and SPI values during the entire maize-growing season in Eastern Cape, KwaZulu-Natal, and North West provinces showed that there were no significant impacts of agricultural drought on maize in these regions. Furthermore, maize was found to be highly resilient in Eastern Cape and KwaZulu-Natal provinces and moderately non-resilient in North West Province.

Hence, our research findings imply the need for targeted intervention policies with long-term strategic planning to mitigate the impact of agricultural drought on maize production in South Africa. Moreover, regional disparities in maize yield losses suggest the need for tailored support for smallholder farms at a local scale to mitigate varying levels of climate-induced agricultural vulnerability across the region. Furthermore, the crop resilience analysis in this study provides valuable insights for agricultural decision-making.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available upon request.

References

Adisa, O. M., C. M. Botai, J. O. Botai, et al. 2018. "Analysis of Agro-Climatic Parameters and Their Influence on Maize Production in South Africa." *Theoretical and Applied Climatology* 134, no. 3: 991–1004. https://doi.org/10.1007/s00704-017-2327-y.

Adisa, O. M., M. Masinde, and J. O. Botai. 2021. "Assessment of the Dissimilarities of EDI and SPI Measures for Drought Determination in South Africa." *Watermark* 13, no. 1: 82. https://www.mdpi.com/2073-4441/13/1/82.

Afshar, M. H., B. Bulut, E. Duzenli, M. Amjad, and M. T. Yilmaz. 2022. "Global Spatiotemporal Consistency Between Meteorological and Soil Moisture Drought Indices." *Agricultural and Forest Meteorology* 316: 108848. https://doi.org/10.1016/j.agrformet.2022.108848.

Ala-Kokko, K., L. Lanier Nalley, A. M. Shew, et al. 2021. "Economic and Ecosystem Impacts of GM Maize in South Africa." *Global Food Security* 29: 100544. https://doi.org/10.1016/j.gfs.2021.100544.

Archer, E., J. du Toit, C. Engelbrecht, et al. 2022. "The 2015-19 Multi Year Drought in the Eastern Cape, South Africa: It's Evolution and Impacts on Agriculture." *Journal of Arid Environments* 196: 104630. https://doi.org/10.1016/j.jaridenv.2021.104630.

Arshad, S., J. H. Kazmi, F. A. Prodhan, and S. Mohammed. 2023. "Exploring Dynamic Response of Agrometeorological Droughts Towards Winter Wheat Yield Loss Risk Using Machine Learning Approach at a Regional Scale in Pakistan." *Field Crops Research* 302: 109057. https://doi.org/10.1016/j.fcr.2023.109057.

Arshad, S., J. H. Kazmi, S. Shaikh, et al. 2022. "Geospatial Assessment of Early Summer Heatwaves, Droughts, and Their Relationship With Vegetation and Soil Moisture in the Arid Region of Southern Punjab, Pakistan." *Journal of Water and Climate Change* 13, no. 11: 4105–4129. https://doi.org/10.2166/wcc.2022.425.

Berg, A., and J. Sheffield. 2018. "Climate Change and Drought: The Soil Moisture Perspective." *Current Climate Change Reports* 4, no. 2: 180–191. https://doi.org/10.1007/s40641-018-0095-0.

Bhaga, T. D., T. Dube, M. D. Shekede, and C. Shoko. 2020. "Impacts of Climate Variability and Drought on Surface Water Resources in Sub-Saharan Africa Using Remote Sensing: A Review." *Remote Sensing* 12, no. 24: 4184. https://www.mdpi.com/2072-4292/12/24/4184.

Blignaut, J., L. Ueckermann, and J. Aronson. 2009. "Agriculture Production's Sensitivity to Changes in Climate in South Africa: Research Article." *South African Journal of Science* 105, no. 1: 61–68. https://doi.org/10.10520/EJC96874.

Botai, C. M., J. O. Botai, L. C. Dlamini, N. S. Zwane, and E. Phaduli. 2016. "Characteristics of Droughts in South Africa: A Case Study of Free State and North West Provinces." *Watermark* 8, no. 10: 439. https://www.mdpi.com/2073-4441/8/10/439.

Bradshaw, C. D., E. Pope, G. Kay, et al. 2022. "Unprecedented Climate Extremes in South Africa and Implications for Maize Production." *Environmental Research Letters* 17, no. 8: 084028. https://doi.org/10.1088/1748-9326/ac816d.

Brüntrup, M., and D. Tsegai. 2017. "Drought adaptation and resilience in developing countries".

Cammarano, D., R. O. Valdivia, Y. G. Beletse, et al. 2020. "Integrated Assessment of Climate Change Impacts on Crop Productivity and Income of Commercial Maize Farms in Northeast South Africa." *Food Security* 12, no. 3: 659–678. https://doi.org/10.1007/s12571-020-01023-0.

Conway, D., E. A. van Garderen, D. Deryng, et al. 2015. "Climate and Southern Africa's Water–Energy–Food Nexus." *Nature Climate Change* 5, no. 9: 837–846. https://doi.org/10.1038/nclimate2735.

Dashtpagerdi, M. M., M. R. Kousari, H. Vagharfard, D. Ghonchepour, M. E. Hosseini, and H. Ahani. 2015. "An Investigation of Drought Magnitude Trend During 1975–2005 in Arid and Semi-Arid Regions of Iran." *Environmental Earth Sciences* 73, no. 3: 1231–1244. https://doi.org/10.1007/s12665-014-3477-1.

Dennis, I., and R. Dennis. 2012. "Climate Change Vulnerability Index for South African Aquifers." *Water SA* 38, no. 3: 417–426. https://doi.org/10.10520/EJC121554.

Epule, T. E., A. Chehbouni, D. Dhiba, and E. L. Molua. 2023. "A Regional Stocktake of Maize Yield Vulnerability to Droughts in the Horn of Africa." *Environmental Monitoring and Assessment* 196, no. 1: 76. https://doi.org/10.1007/s10661-023-12229-y.

Faheem, Z., J. H. Kazmi, S. Shaikh, S. Arshad, S. Noreena, and S. Mohammed. 2024. "Random Forest-Based Analysis of Land Cover/

20483694, 2024, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/fes3.70006 by Safwan A. Mohammed - European University Of Cyprus , Wiley Online Library on [09/10/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Land Use LCLU Dynamics Associated With Meteorological Droughts in the Desert Ecosystem of Pakistan." *Ecological Indicators* 159: 111670. https://doi.org/10.1016/j.ecolind.2024.111670.

Fernández, F. J., F. Vásquez-Lavín, R. D. Ponce, et al. 2023. "The Economics Impacts of Long-Run Droughts: Challenges, Gaps, and Way Forward." *Journal of Environmental Management* 344: 118726. https://doi.org/10.1016/j.jenvman.2023.118726.

Ferreira, N. C. R., R. P. Rötter, G. Bracho-Mujica, et al. 2023. "Drought Patterns: Their Spatiotemporal Variability and Impacts on Maize Production in Limpopo Province, South Africa." *International Journal of Biometeorology* 67, no. 1: 133–148. https://doi.org/10.1007/s00484-022-02392-1.

Fischer, K., and F. Hajdu. 2015. "Does Raising Maize Yields Lead to Poverty Reduction? A Case Study of the Massive Food Production Programme in South Africa." *Land Use Policy* 46: 304–313. https://doi.org/10.1016/j.landusepol.2015.03.015.

Freire-González, J., C. Decker, and J. W. Hall. 2017. "The Economic Impacts of Droughts: A Framework for Analysis." *Ecological Economics* 132: 196–204. https://doi.org/10.1016/j.ecolecon.2016.11.005.

Gouse, M., D. Sengupta, P. Zambrano, and J. F. Zepeda. 2016. "Genetically Modified Maize: Less Drudgery for Her, More Maize for Him? Evidence From Smallholder Maize Farmers in South Africa." *World Development* 83: 27–38. https://doi.org/10.1016/j.worlddev.2016.03.008.

Haarhoff, S. J., T. N. Kotzé, and P. A. Swanepoel. 2020. "A Prospectus for Sustainability of Rainfed Maize Production Systems in South Africa." *Crop Science* 60, no. 1: 14–28. https://doi.org/10.1002/csc2.20103.

Hall, C., T. P. Dawson, J. I. Macdiarmid, R. B. Matthews, and P. Smith. 2017. "The Impact of Population Growth and Climate Change on Food Security in Africa: Looking Ahead to 2050." *International Journal of Agricultural Sustainability* 15, no. 2: 124–135. https://doi.org/10.1080/14735903.2017.1293929.

Hamed, K. H. 2008. "Trend Detection in Hydrologic Data: The Mann–Kendall Trend Test Under the Scaling Hypothesis." *Journal of Hydrology* 349, no. 3: 350–363. https://doi.org/10.1016/j.jhydrol.2007.11.009.

Hasegawa, T., S. Fujimori, P. Havlík, et al. 2018. "Risk of Increased Food Insecurity Under Stringent Global Climate Change Mitigation Policy." *Nature Climate Change* 8, no. 8: 699–703. https://doi.org/10.1038/s41558-018-0230-x.

Hayes, M. J., and J. Lowrey. 2007. "Drought Indices." *Intermountain West Climate Summary* 3, no. 6: 2–6.

Ju-Qi, D., Y. Jia-Shuang, X. Xin-Wu, and J. Hui. 2022. "Interpretation of the IPCC AR6 Report on Agricultural Systems (1673-1719)." https://doi.org/10.12006/j.issn.1673-1719.2022.035.

Jury, M. R. 2018. "Climate Trends Across South Africa Since 1980." *Water SA* 44: 297–307. https://doi.org/10.4314/wsa.v44i2.15.

Jury, M. R. 2019. "South Africa's Future Climate: Trends and Projections." In *The Geography of South Africa: Contemporary Changes and New Directions*, edited by J. Knight and C. M. Rogerson, 305–312. Cham: Springer International Publishing.

Kendall, M. G. 1948. *Rank Correlation Methods*. Oxford, England: Griffin.

Kganvago, M., M. B. Mukhawana, M. Mashalane, A. Mgabisa, and S. Moloele. 2021. "Recent Trends of Drought Using Remotely Sensed and In-Situ Indices: Towards an Integrated Drought Monitoring System for South Africa." Paper presented at the 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS.

Kim, J. E., J.-H. Lee, and T.-W. Kim. 2024. "Assessment of Regional Drought Risk Coupled With Drought Response Capacity Considering Water Supply Systems." *Stochastic Environmental Research and Risk Assessment* 38, no. 3: 963–980. https://doi.org/10.1007/s00477-023-02608-9.

Kim, W., T. Iizumi, and M. Nishimori. 2019. "Global Patterns of Crop Production Losses Associated With Droughts From 1983 to 2009." *Journal of Applied Meteorology and Climatology* 58, no. 6: 1233–1244. https://doi.org/10.1175/JAMC-D-18-0174.1.

Knight, J., and C. M. Rogerson. 2019. "The Development and Context of Geography in South Africa." In *The Geography of South Africa: Contemporary Changes and New Directions*, edited by J. Knight and C. M. Rogerson, 1–4. Cham: Springer International Publishing.

Lee, H., K. Calvin, D. Dasgupta, et al. 2023. "IPCC, 2023 Climate Change 2023: Synthesis Report, Summary for Policymakers." In *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Core Writing Team. Geneva, Switzerland: IPCC. https://www.ipcc.ch/report/ar6/syr/.

Lesk, C., P. Rowhani, and N. Ramankutty. 2016. "Influence of Extreme Weather Disasters on Global Crop Production." *Nature* 529, no. 7584: 84–87. https://doi.org/10.1038/nature16467.

Liu, X., K. Cao, and M. Li. 2024. "Assessing the Impact of Meteorological and Agricultural Drought on Maize Yields to Optimize Irrigation in Heilongjiang Province, China." *Journal of Cleaner Production* 434: 139897. https://doi.org/10.1016/j.jclepro.2023.139897.

Lynch, J., M. Cain, D. Frame, and R. Pierrehumbert. 2021. "Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO_2-Emitting Sectors." *Frontiers in Sustainable Food Systems* 4. https://doi.org/10.3389/fsufs.2020.518039.

Lyon, B. 2009. "Southern Africa Summer Drought and Heat Waves: Observations and Coupled Model Behavior." *Journal of Climate* 22, no. 22: 6033–6046. https://doi.org/10.1175/2009JCLI3101.1.

Mahlalela, P. T., R. C. Blamey, and C. J. C. Reason. 2019. "Mechanisms Behind Early Winter Rainfall Variability in the Southwestern Cape, South Africa." *Climate Dynamics* 53, no. 1: 21–39. https://doi.org/10.1007/s00382-018-4571-y.

Makuya, V., W. Tesfuhuney, M. E. Moeletsi, and Z. Bello. 2024. "Assessing the Impact of Agricultural Drought on Yield Over Maize Growing Areas, Free State Province, South Africa, Using the SPI and SPEI." *Sustainability* 16, no. 11: 4703. https://www.mdpi.com/2071-1050/16/11/4703.

Malherbe, J., B. Dieppois, P. Maluleke, M. Van Staden, and D. L. Pillay. 2016. "South African Droughts and Decadal Variability." *Natural Hazards* 80, no. 1: 657–681. https://doi.org/10.1007/s11069-015-1989-y.

Mangani, R., E. Tesfamariam, G. Bellocchi, and A. Hassen. 2018. "Modelled Impacts of Extreme Heat and Drought on Maize Yield in South Africa." *Crop and Pasture Science* 69, no. 7: 703–716. https://doi.org/10.1071/CP18117.

Mangani, R., E. H. Tesfamariam, C. J. Engelbrecht, G. Bellocchi, A. Hassen, and T. Mangani. 2019. "Potential Impacts of Extreme Weather Events in Main Maize (*Zea mays* L.) Producing Areas of South Africa Under Rainfed Conditions." *Regional Environmental Change* 19, no. 5: 1441–1452. https://doi.org/10.1007/s10113-019-01486-8.

Masih, I., S. Maskey, F. E. F. Mussá, and P. Trambauer. 2014. "A Review of Droughts on the African Continent: A Geospatial and Long-Term Perspective." *Hydrology and Earth System Sciences* 18, no. 9: 3635–3649. https://doi.org/10.5194/hess-18-3635-2014.

McKee, T. B., N. J. Doesken, and J. Kleist. 1993. "The Relationship of Drought Frequency and Duration to Time Scales." Paper presented at the Proceedings of the 8th Conference on Applied Climatology.

Meza, I., E. Eyshi Rezaei, S. Siebert, et al. 2021. "Drought Risk for Agricultural Systems in South Africa: Drivers, Spatial Patterns, and Implications for Drought Risk Management." *Science of the Total*

20483694, 2024, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/fes3.70006 by Safwan A. Mohammed - European University Of Cyprus , Wiley Online Library on [09/10/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Environment 799: 149505. https://doi.org/10.1016/j.scitotenv.2021.149505.

Mishra, A. K., and V. P. Singh. 2010. "A Review of Drought Concepts." *Journal of Hydrology* 391, no. 1: 202–216. https://doi.org/10.1016/j.jhydrol.2010.07.012.

Miyan, M. A. 2015. "Droughts in Asian Least Developed Countries: Vulnerability and Sustainability." *Weather and Climate Extremes* 7: 8–23. https://doi.org/10.1016/j.wace.2014.06.003.

Mohammed, S., K. Alsafadi, G. O. Enaruvbe, et al. 2022. "Assessing the Impacts of Agricultural Drought (SPI/SPEI) on Maize and Wheat Yields Across Hungary." *Scientific Reports* 12, no. 1: 8838. https://doi.org/10.1038/s41598-022-12799-w.

Mohammed, S., S. Arshad, F. Alsilibe, et al. 2024. "Utilizing Machine Learning and CMIP6 Projections for Short-Term Agricultural Drought Monitoring in Central Europe (1900–2100)." *Journal of Hydrology* 633: 130968. https://doi.org/10.1016/j.jhydrol.2024.130968.

Mupazviriho, M. K., A. Dalton, and B. Bekker. 2022. "The Effect of Climate Change on Variable Renewable Energy in South Africa: A Trend Analysis." Paper presented at the 2022 57th International Universities Power Engineering Conference (UPEC).

Ndlovu, M. S., and M. Demlie. 2020. "Assessment of Meteorological Drought and Wet Conditions Using Two Drought Indices Across KwaZulu-Natal Province, South Africa." *Atmosphere* 11, no. 6: 623. https://www.mdpi.com/2073-4433/11/6/623.

Nkhuoa, P. G. 2017. *Water Footprint Assessment of Maize and Associated Broiler Production in South Africa*. South Africa: University of the Free State.

Nxumalo, G., B. Bashir, K. Alsafadi, et al. 2022. "Meteorological Drought Variability and Its Impact on Wheat Yields Across South Africa." *International Journal of Environmental Research and Public Health* 19, no. 24: 16469. https://www.mdpi.com/1660-4601/19/24/16469.

Nyambariga, F. K., A. O. Opere, E. Kituyi, and D. A. Amwata. 2023. "Climate Change Scenario Projections and Their Implications on Food Systems in Taita Taveta County, Kenya." *PLOS Climate* 2, no. 6: e0000114. https://doi.org/10.1371/journal.pclm.0000114.

Ocwa, A., E. Harsanyi, A. Széles, et al. 2023. "A Bibliographic Review of Climate Change and Fertilization as the Main Drivers of Maize Yield: Implications for Food Security." *Agriculture & Food Security* 12, no. 1: 14. https://doi.org/10.1186/s40066-023-00419-3.

Omolola, M. A., O. B. Joel, M. A. Abiodun, et al. 2019. "Analysis of Drought Conditions Over Major Maize Producing Provinces of South Africa." *Journal of Agricultural Meteorology* 75, no. 4: 173–182. https://doi.org/10.2480/agrmet.D-18-00049.

Ray, R. L., A. Fares, and E. Risch. 2018. "Effects of Drought on Crop Production and Cropping Areas in Texas." *Agricultural & Environmental Letters* 3, no. 1: 170037. https://doi.org/10.2134/ael2017.11.0037.

Reason, C. J. C. 2017. *Climate of Southern Africa*. Oxford Research Encyclopedia of Climate Science: Oxford University Press. Retrieved September 26, 2024. https://oxfordre.com/climatescience/view/10.1093/acrefore/9780190228620.001.0001/acrefore-9780190228620-e-513.

Reshu, Y., S. K. Tripathi, G. Pranuthi, and S. K. Dubey. 2014. "Trend Analysis by Mann-Kendall Test for Precipitation and Temperature for Thirteen Districts of Uttarakhand." *Journal of Agrometeorology* 16, no. 2: 164–171. https://doi.org/10.54386/jam.v16i2.1507.

Rezaei, E. E., H. Webber, S. Asseng, et al. 2023. "Climate Change Impacts on Crop Yields." *Nature Reviews Earth and Environment* 4, no. 12: 831–846. https://doi.org/10.1038/s43017-023-00491-0.

Rippke, U., J. Ramirez-Villegas, A. Jarvis, et al. 2016. "Timescales of Transformational Climate Change Adaptation in sub-Saharan African Agriculture." *Nature Climate Change* 6, no. 6: 605–609. https://doi.org/10.1038/nclimate2947.

Rouault, M., and Y. Richard. 2003. "Intensity and Spatial Extension of Drought in South Africa at Different Time Scales." *Water SA* 29, no. 4: 489–500. https://doi.org/10.4314/wsa.v29i4.5057.

Schlosser, A., A. Sokolov, K. Strzepek, T. Thomas, X. Gao, and C. Arndt. 2021. "The Changing Nature of Hydroclimatic Risks Across South Africa." *Climatic Change* 168, no. 3: 28. https://doi.org/10.1007/s10584-021-03235-5.

Serdeczny, O., S. Adams, F. Baarsch, et al. 2017. "Climate Change Impacts in sub-Saharan Africa: From Physical Changes to Their Social Repercussions." *Regional Environmental Change* 17, no. 6: 1585–1600. https://doi.org/10.1007/s10113-015-0910-2.

Shao, W., and J. Kam. 2020. "Retrospective and Prospective Evaluations of Drought and Flood." *Science of the Total Environment* 748: 141155. https://doi.org/10.1016/j.scitotenv.2020.141155.

Sharma, A., and M. K. Goyal. 2018. "Assessment of Ecosystem Resilience to Hydroclimatic Disturbances in India." *Global Change Biology* 24, no. 2: e432–e441. https://doi.org/10.1111/gcb.13874.

Simanjuntak, C., T. Gaiser, H. E. Ahrends, et al. 2023. "Impact of Climate Extreme Events and Their Causality on Maize Yield in South Africa." *Scientific Reports* 13, no. 1: 12462. https://doi.org/10.1038/s41598-023-38921-0.

Sneyers, R. 1991. "On the Statistical Analysis of Series of Observations".

Song, Y., J. Joo, H. Kim, and M. Park. 2024. "Development and Applicability Evaluation of Damage Scale Analysis Techniques for Agricultural Drought." *Watermark* 16, no. 10: 1342. https://www.mdpi.com/2073-4441/16/10/1342.

Sousa, P. M., R. C. Blamey, C. J. C. Reason, A. M. Ramos, and R. M. Trigo. 2018. "The 'Day Zero' Cape Town Drought and the Poleward Migration of Moisture Corridors." *Environmental Research Letters* 13, no. 12: 124025. https://doi.org/10.1088/1748-9326/aaebc7.

Széles, A., L. Huzsvai, S. Mohammed, et al. 2024. "Precision Agricultural Technology for Advanced Monitoring of Maize Yield Under Different Fertilization and Irrigation Regimes: A Case Study in Eastern Hungary (Debrecen)." *Journal of Agriculture and Food Research* 15: 100967. https://doi.org/10.1016/j.jafr.2024.100967.

Tanarhte, M., A. J. De Vries, G. Zittis, and T. Chfadi. 2024. "Severe Droughts in North Africa: A Review of Drivers, Impacts and Management." *Earth-Science Reviews* 250: 104701. https://doi.org/10.1016/j.earscirev.2024.104701.

Tessema, Y. A., J. Joerin, and A. Patt. 2018. "Factors Affecting Smallholder Farmers' Adaptation to Climate Change Through Non-Technological Adjustments." *Environmental Development* 25: 33–42. https://doi.org/10.1016/j.envdev.2017.11.001.

Theron, S. N., E. Archer, S. J. E. Midgley, and S. Walker. 2021. "Agricultural Perspectives on the 2015-2018 Western Cape Drought, South Africa: Characteristics and Spatial Variability in the Core Wheat Growing Regions." *Agricultural and Forest Meteorology* 304-305: 108405. https://doi.org/10.1016/j.agrformet.2021.108405.

Tsakiris, G., A. Loukas, D. Pangalou, et al. 2007. "Drought Characterization." *Drought Management Guidelines Technical Annex* 58: 85–102.

Venkatappa, M., N. Sasaki, P. Han, and I. Abe. 2021. "Impacts of Droughts and Floods on Croplands and Crop Production in Southeast Asia–An Application of Google Earth Engine." *Science of the Total Environment* 795: 148829. https://doi.org/10.1016/j.scitotenv.2021.148829.

Walker, N. J., and R. E. Schulze. 2006. "An Assessment of Sustainable Maize Production Under Different Management and Climate Scenarios for Smallholder Agro-Ecosystems in KwaZulu-Natal, South Africa." *Physics and Chemistry of the Earth, Parts A/B/C* 31, no. 15: 995–1002. https://doi.org/10.1016/j.pce.2006.08.012.

Wang, H., J. C. Rogers, and D. K. Munroe. 2015. "Commonly Used Drought Indices as Indicators of Soil Moisture in China." *Journal of*

20483694, 2024, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/fes3.70006 by Safwan A. Mohammed - European University Of Cyprus , Wiley Online Library on [09/10/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Hydrometeorology 16, no. 3: 1397–1408. https://doi.org/10.1175/JHM-D-14-0076.1.

Wells, N., S. Goddard, and M. J. Hayes. 2004. "A Self-Calibrating Palmer Drought Severity Index." *Journal of Climate* 17, no. 12: 2335–2351. https://doi.org/10.1175/1520-0442(2004)017<2335:ASPDSI>2.0.CO;2.

Wolski, P., S. Conradie, C. Jack, and M. Tadross. 2021. "Spatio-Temporal Patterns of Rainfall Trends and the 2015–2017 Drought Over the Winter Rainfall Region of South Africa." *International Journal of Climatology* 41, no. S1: E1303–E1319. https://doi.org/10.1002/joc.6768.

Wu, J., G. Cheng, N. Wang, H. Shen, and X. Ma. 2022. "Spatiotemporal Patterns of Multiscale Drought and Its Impact on Winter Wheat Yield Over North China Plain." *Agronomy* 12, no. 5: 1209. https://www.mdpi.com/2073-4395/12/5/1209.

Zhu, Y., Y. Liu, W. Wang, V. P. Singh, X. Ma, and Z. Yu. 2019. "Three Dimensional Characterization of Meteorological and Hydrological Droughts and Their Probabilistic Links." *Journal of Hydrology* 578: 124016. https://doi.org/10.1016/j.jhydrol.2019.124016.

Zuma, M., G. Arthur, R. Coopoosamy, and K. Naidoo. 2023. "Incorporating Cropping Systems With Eco-Friendly Strategies and Solutions to Mitigate the Effects of Climate Change on Crop Production." *Journal of Agriculture and Food Research* 14: 100722. https://doi.org/10.1016/j.jafr.2023.100722.

20483694, 2024, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/fes3.70006 by Safwan A. Mohammed - European University Of Cyprus , Wiley Online Library on [09/10/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Appendix A

TABLE A1 | An overview of drought trend (1993–2022) based on MK test and Sen's slope estimator.

Station	Abbreviation	SPI-3		SPI-6	
		p value	Sen slope	*p* value	Sen slope
Aliwal North	ANP	0.01	0.00	0.06	0.00
Beautfford-West	BW	0.76	0.00	0.17	0.00
Bloemfontein	BTLHM	0.29	−0.01	0.22	−0.01
Betlhehem	BLM	1.00	0.00	0.54	0.00
Calvinia	CAL	0.00015	−0.02	<0.0001	−0.03
Cape town	CPT	< 0.0001	0.00	<0.0001	0.00
Dearr	DR	0.64	0.00	0.20	0.01
Durban	DBN	<0.0001	−0.03	<0.0001	−0.03
East London	EL	0.04	−0.01	0.000131	−0.02
Ermelo	ERML	0.11	0.01	0.02	0.02
Johannesburg	JHB WO	0.46	0.00	0.11	0.01
Kimberly	KBLY	0.47	0.01	0.05	0.01
Klerksdorp	KLKSDP	0.17	0.01	0.004	0.02
Kroonstad	KRSTD	0.01	0.00	<0.0001	0.00
Lady-Smith	LDS	0.33	0.00	0.18	0.00
Lephalale	LP	0.78	0.00	0.83	0.00
Mafikeng	MFK	0.18	−0.01	0.004	−0.02
Nelspruit	NEL	0.004	0.02	<0.0001	0.02
Pietermaritzburg	PMB	<0.0001	−0.03	<0.0001	−0.05
Polokwane	POL	<0.0001	0.00	<0.0001	0.00
Port-Elizabeth	PE	0.08	−0.01	0.003	−0.02
Richards-Bay	RCB	0.03	−0.02	<0.0001	−0.03
Skukuza	SKZ	<0.0001	−0.03	<0.0001	−0.03
Sutherland	STH	0.001	−0.02	<0.0001	−0.03
Upintong	UP	0.47	0.01	0.05	0.01
Vereeniging	VRNG	0.004	−0.02	<0.0001	−0.03
Vryburg	VRBG	<0.0001	−0.03	<0.0001	−0.04
Welkom	WKM	0.22	−0.01	0.17	−0.01
Witbank	WBNK	0.36	0.01	0.22	0.01

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TABLE A2 | Pearson correlation between SPI-3 and SYRS.

Region	January	February	March	April	May	June	July	August	September	October	November	December	GS
EC	−0.35	−0.20	−0.16	−0.04	−0.06	−0.07	−0.22	−0.17	−0.18	−0.04	−0.21	−0.22	−0.33
FS	0.38	0.64	0.50	0.30	−0.14	−0.08	−0.14	−0.13	−0.22	−0.05	−0.02	0.01	0.44
GP	0.30	0.43	0.36	0.31	0.12	0.05	−0.01	−0.02	−0.36	−0.12	−0.19	0.13	0.29
KZN	−0.25	−0.25	−0.16	−0.17	−0.08	0.04	−0.11	−0.05	−0.21	−0.23	−0.46	−0.36	−0.29
LP	0.29	0.37	0.42	0.32	0.11	0.01	0.26	0.17	0.01	0.04	−0.20	−0.05	0.29
MP	0.42	0.40	0.33	0.22	0.09	0.06	0.10	−0.04	−0.18	−0.09	−0.13	−0.07	0.28
NC	0.04	−0.07	−0.01	0.12	0.07	−0.23	−0.24	−0.13	0.24	0.40	0.49	0.22	0.2
NW	−0.29	−0.19	−0.17	−0.05	−0.07	0.25	0.07	−0.05	−0.13	−0.21	−0.10	−0.05	−0.25
WC	0.47	0.28	0.18	0.11	0.16	0.14	0.16	0.05	0.07	0.14	0.28	0.17	0.39

TABLE A3 | Pearson correlation between SPI-6 and SYRS.

Region	January	February	March	April	May	June	July	August	September	October	November	December	GS
EC	−0.52	−0.33	−0.40	−0.40	−0.16	0.02	0.03	−0.09	−0.16	−0.29	−0.32	−0.34	−0.52
FS	0.35	0.57	0.56	0.47	0.52	0.42	0.23	−0.18	−0.17	−0.10	−0.01	−0.04	0.37
GP	0.35	0.45	0.44	0.38	0.37	0.36	0.28	0.13	−0.05	−0.13	−0.13	0.04	0.3
KZN	−0.17	−0.12	−0.25	−0.26	−0.07	−0.09	−0.13	−0.11	−0.08	−0.22	−0.42	−0.39	−0.34
LP	0.33	0.51	0.48	0.40	0.36	0.43	0.36	0.13	0.05	0.11	−0.17	−0.05	0.33
MP	0.43	0.46	0.42	−0.04	0.38	0.34	0.19	0.09	0.03	−0.05	−0.14	−0.27	0.16
NC	0.19	0.14	0.13	0.10	0.02	−0.13	−0.09	−0.03	0.02	0.06	0.19	0.21	0.24
NW	−0.34	−0.32	−0.42	−0.20	−0.14	−0.05	−0.01	0.02	0.24	−0.09	−0.05	−0.03	−0.33
WC	0.25	0.17	0.12	0.29	0.43	0.34	0.33	0.53	0.48	0.41	0.46	0.48	0.39

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