

Article

Assessing the Impact of Agricultural Drought on Yield over Maize Growing Areas, Free State Province, South Africa, Using the SPI and SPEI

Vuwani Makuya ^{1,2,*} , Weldemichael Tesfahuney ¹ , Mokhele E. Moeletsi ^{2,3}  and Zaid Bello ^{3,4} 

¹ Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences, University of the Free State, P.O. Box 339, Bloemfontein 9300, South Africa; tesfahuneyw@ufs.ac.za

² Agricultural Research Council—Natural Resources and Engineering, Private Bag X79, Pretoria 0001, South Africa; moeletsim@arc.agric.za

³ Risk and Vulnerability Assessment Centre, University of Limpopo, Private Bag X1106, Sovenga 0727, South Africa; belloz@arc.agric.za

⁴ Agricultural Research Council—Grain Crops, Private Bag X1251, Potchefstroom 2520, South Africa

* Correspondence: vuwani.makuya19@gmail.com

Abstract: Maize (*Zea mays* L.) is an essential crop in South Africa serving as a staple food; however, agricultural drought threatens its production, resulting in lower yields. This study aimed to assess the impact of agricultural drought on maize yield in the major areas (Bethlehem, Bloemfontein, and Bothaville) that produce maize in the Free State Province from 1990 to 2020. The study used the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) to examine drought occurrences and severity during the maize growing season (October–March). The Standardized Yield Residuals Series (SYRS), Crop Drought Resilient Factor (CDRF), Spearman’s Rank Correlation (r_s), and yield loss rate were employed to emphasize agricultural drought impact on maize yield. The results based on the SPI and SPEI show that drought frequently occurred in Bethlehem, followed by Bloemfontein and Bothaville. Drought severity indicated that moderate droughts were prevalent in Bethlehem, while severe droughts were in all areas (Bethlehem, Bloemfontein, and Bothaville) and extreme droughts in Bloemfontein. The agricultural drought’s impact on maize varied across growth seasons and areas. Notably, the lowest SYRS value of -2.38 (1991/92) was observed in Bethlehem. An extremely strong significant correlation ($r_{\text{SPEI-6 vs SYRS}} = 0.83$, $p = 1.07 \times 10^{-8}$) was observed between the SPEI and SYRS in Bloemfontein during the October–November–December–January–February–March (ONDJFM) season. The CDRF indicated that maize yield was severely non-resilient ($\text{CDRF} < 0.8$) to drought in Bethlehem ($\text{CDRF} = 0.27$) and Bloemfontein ($\text{CDRF} = 0.33$) and resilient ($\text{CDRF} = 1.16$) in Bothaville. The highest maize yield loss of -88.62% was observed in Bethlehem due to extreme agricultural drought. The results suggest that, historically, agricultural drought was a threat to maize production in the studied areas, particularly in Bethlehem and Bloemfontein. This underscores the implementation of sustainable agricultural practices, such as drought-resistant varieties in these areas, to mitigate the impacts of climate change, especially drought, and ensure food security. This is a step toward achieving Sustainable Development Goal 2 (Zero Hunger).

Keywords: drought; SPI; SPEI; SYRS; CDRF; crop resilience; Spearman’s rank correlation; yield loss



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1. Introduction

Drought, an increasingly prevalent consequence of climate change, has become a sinister force wreaking havoc on agricultural systems worldwide [1,2]. Among the numerous crops affected by this climatic phenomenon, maize stands out as one of the most vulnerable in terms of its economic importance as a staple food crop [3]. Drought causes physiological and biochemical changes in maize crops, including reduced photosynthesis, decreased water uptake, and impaired nutrient uptake. These changes can result in

stunted growth, reduced plant height, fewer tillers, and crop failures, ultimately reducing yields [4,5] and affecting food security, livelihoods, and the global economy. For instance, Zimbabwe imported approximately 50% of maize into the country between the 2011 and 2012 growing seasons due to extreme droughts, which affected their production and resulted in vast crop failures [6]. Drought impacts are far-reaching and can cause widespread socio-economic and environmental damage [7]. The impacts of drought are categorized as direct or indirect [8]. Direct impacts include loss of crop [9], livestock production, income, employment, and loss of grazing land and vegetation [7]. Indirect impacts include food price inflation, intensified due to the influence of market dynamics in the agricultural sector [9]. The severity of these impacts depends on the severity of drought and vulnerability of the area. Amongst many countries in the African continent, South Africa is one of the countries affected by droughts particularly the agricultural sector.

South Africa is recognized for its semi-arid climate and frequent hydro-climatic extreme events such as droughts and floods [10]. Droughts in South Africa are distinguished by fluctuations in rainfall patterns, which are influenced by the atmospheric circulation configurations and the interplay between westerly and easterly circulations [10,11]. The interplay can cause shifts in weather patterns, leading to periods of reduced rainfall and, subsequently, drought conditions. Drought is a primary environmental peril over the entire South African landscape that intermittently results in crop failures and low yields [12]. Crop production in the country is mainly rainfed. Due to its heavy reliance on consistent and adequate rainfall, it is particularly affected by periods of drought because of decreased rainfall (source of water for crop growth) and increased temperatures. One of many crops that are produced in South Africa that are affected by drought is maize. Maize production holds a critical position in South African agriculture, serving as a source of food and employment for most people [13,14]. However, ongoing changes in climate patterns, including increased frequency and severity of drought events, pose significant threats to maize production [15,16]. This is because it causes water stress during critical growth stages of maize, consequent to yield reduction. The Free State, Mpumalanga, and the North West provinces are the leading areas producing maize in South Africa, accounting for approximately 85% of the national output [17].

To be specific, the Free State Province is the leading maize producing region in South Africa. It accounts for approximately 35% of maize production yearly [18]. However, the recurring droughts have led to substantial reductions in maize in the province. This province is characterized by low rainfall and high evaporation rates, making the region susceptible to droughts [19]. Over the years, the province has experienced severe droughts that have negatively impacted its agricultural sector, particularly maize production [20,21]. For instance, the Free State Province produced 7.3 million tons of maize in 2016/17; it declined to 5.2 million tons in 2017/18 and to 4 million tons in 2018/19 because of drought [22]. Droughts in the Free State Province are due to its climate and the unpredictable and often erratic rainfall patterns [21]. These rainfall patterns are influenced by a variety of factors, including atmospheric pressure systems, ocean currents, and global phenomena like El Niño and Southern Oscillation (ENSO) [23]. The unpredictability of these patterns poses a significant challenge to crop production, as sufficient and steady rainfall is crucial for crop growth and yield. The decline in maize production not only affects the province's economy but also threatens food security at regional and national levels. Therefore, monitoring drought conditions is essential as it aids in detecting changes in rainfall levels and soil moisture content.

Drought is a complex and recurring natural phenomenon marked by a prolonged period of insufficient and abnormal temperature patterns [24]. Predicting and assessing droughts are challenging due to their multifaceted causes including hydro-meteorological factors and anomalies in sea surface temperatures [24]. Drought indicators, such as rainfall, temperature, streamflow, groundwater and reservoir levels, soil moisture, and snowpack, play a pivotal role in these assessments, providing a quantitative measure of drought

conditions and helping to track their progression [25]. Therefore, the use of drought measures, such as indices for drought assessment, becomes crucial.

Numerous indices have been developed to quantify, detect, characterize, and monitor drought occurrences and severity. Among these, the SPI and the SPEI stand out due to their extensive use and proven effectiveness, particularly with long-term data [26–28]. These indices have become practical tools for monitoring drought conditions and are widely adopted in agricultural spaces [29–31]. The SPI and SPEI indices were chosen due to their standardization, adaptability, and simplicity in analyzing drought over various timescales [30]. Moreover, these indices (SPI and SPEI) were selected based on the readily available data for the studied areas. The SPI and SPEI are suitable for the study of agricultural drought [32]. The combined usage of SPI and SPEI provides a more comprehensive understanding of drought conditions [33]. The SPI uses rainfall data only to quantify drought, and the SPEI incorporates additional parameters such as temperature and potential evapotranspiration (PET) [27]. This makes the SPEI particularly useful in dry locations with high temperatures, where evapotranspiration is the predominant type of water loss [34]. The distinctiveness of our study lies in the application and context of these indices. While these indices have been extensively employed in various studies, our approach diverges significantly in its utilization of these indices. Contrary to the conventional use of default timescales in previous studies [19,35], this research strategically categorizes these timescales (3 and 6-month timescales) into specific seasons. This categorization is carefully aligned with the various stages of the maize growing season—computing, identifying, monitoring and characterizing droughts aids in developing and implementing drought management and mitigation strategies.

Drought management is critical to mitigating the impacts of drought and building resilience. It encompasses scientific approaches, such as developing drought indicators, selecting and prioritizing measures to alleviate drought impacts, and characterization of drought episodes [36]. Measures can be short-term or long-term and can encompass a variety of strategies. For instance, they can include national drought policies, climate adaptation strategies, and disaster risk reduction [37]. However, it is essential to note that the effectiveness of these measures is not solely determined by their inherent design or implementation. Instead, it is significantly influenced by the socio-economic environment in which drought occurs [38].

Previous studies in the Free State Province focused on characterizing, assessing, and monitoring drought using the SPI and SPEI [19,29,39]. Moreover, most of these studies have been conducted at the provincial or regional (districts) level, leaving a dearth of knowledge at the local level. Furthermore, the impact of agricultural drought on maize yield during the maize growing season [35,40] has been under-explored. Studying drought at a local level is crucial, as understanding its impacts can lead to more effective strategies for managing drought and maintaining crop yields. Therefore, this study aims to assess the impact of agricultural drought on maize yield at a local level in the maize growing season using the SPI and SPEI. In order to achieve this, the study assessed the following: (a) Seasonal agricultural drought occurrence and severity; (b) Trends; (c) The impact of agricultural drought on maize yield over the maize growing season. Understanding the intricacies of drought on crop production is not only relevant but also timely, considering the increasing frequency and severity of drought events due to climate change. The study's findings will assist farmers, policymakers, researchers, and stakeholders to work collaboratively toward developing mitigation strategies to ensure a sustainable future for maize production in the face of an increasingly unpredictable climate in these areas.

2. Materials and Methods

2.1. Study Area

The Free State Province is situated at the center of South Africa between latitudes of 26.6° S and 30.7° S and longitudes of 24.3° E and 29.8° E [29]. It has five district municipalities: Fesile Dabi, Lejweleputswa, Thabo Mofutsanyane, Mangaung, and Xhariepe

district municipalities. This selected province is the biggest maize producer in South Africa [41,42]. Due to its climate and fertile soil, it has a conducive environment that allows crop production, including maize. The selected areas in this study are Bethlehem, Bloemfontein, and Bothaville, the main areas producing maize. Bethlehem is located in the eastern part of the province, at coordinates of 28.2423° S and 28.3111° E, with an altitude of 1631 m above sea level (m.a.s.l.). Meanwhile, Bloemfontein is located at 29.0852° S, 26.1596° E in the central part of the province, positioned at an elevation of 1304 m.a.s.l. Similarly, Bothaville is located at coordinates 27.3740° S and 26.6200° E, in the northern part of the province, with an altitude of 1280 m.a.s.l. (Figure 1). The annual mean rainfall in these semi-arid areas ranges from 522.78 mm to 788.53 mm (Table 1). The climate of Bethlehem is temperate, with dry winters and warm summers (Cwb), while Bloemfontein has a cold semi-arid steppe climate (BSk) and a hot semi-arid steppe climate (BSh) in Bothaville based on the Köppen–Geiger system by Rohli et al. [43]. The most dominant soil types include sandy loams in Bethlehem and Bothaville and fine sandy loams in Bloemfontein [44] (Table 1).

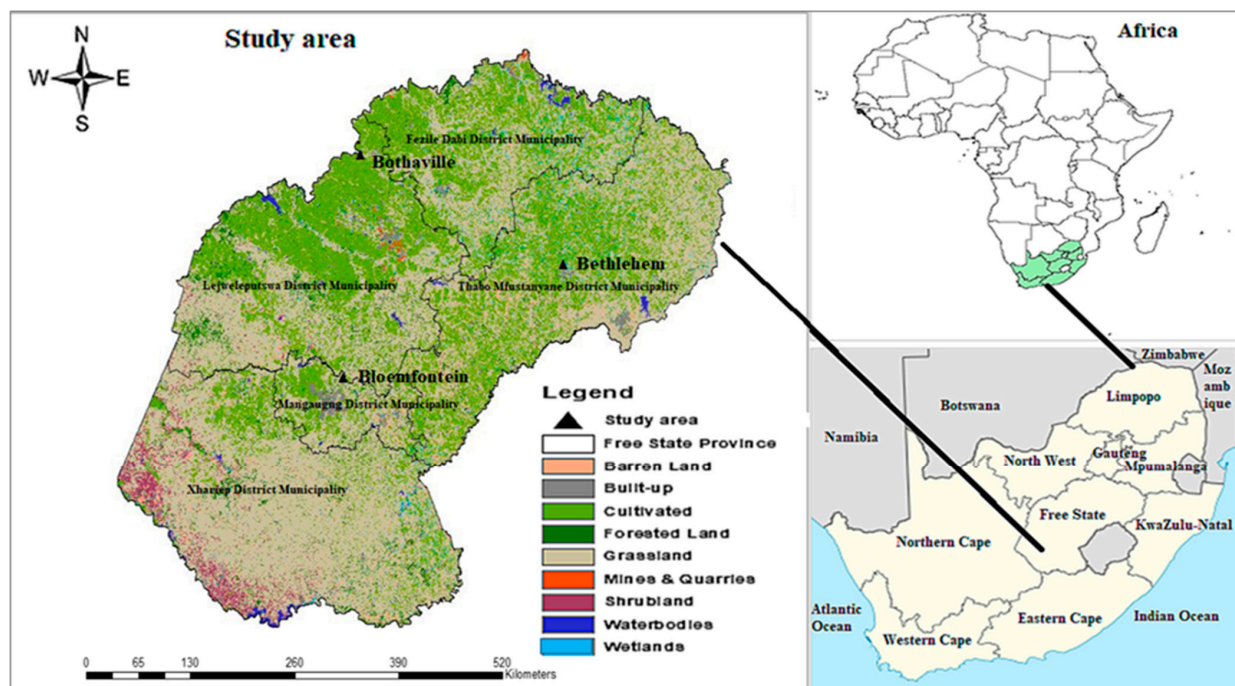


Figure 1. Geographical location, land cover, and the spatial dissemination of the selected study areas in the Free State Province.

Table 1. Details of the climate and soil in the study areas [45].

Attributes	Bethlehem (BTM)			Bloemfontein (BFN)			Bothaville (BTV)		
Conventional planting dates	Mid-November (15th)			Mid-December (15th)			Mid-November (15th)		
Climatic variables:									
Average annual rainfall (mm)	~788.53			~522.78			~575.22		
Average annual Tmax (°C)	23.5			28.1			27.6		
Average annual Tmin (°C)	7.1			10.5			11.4		
Annual ETO (mm)	1824			2099			1915		
General soil properties:									
Thickness of the topsoil horizon (m)	0.30			0.30			0.35		
Thickness of the subsoil (m)	1.5			1.9			0.9		
Dominant soil textural class	Sandy clay loam			Sandy loam			Sandy clay loam		
Clay content (%)	10–15			8–14			10–20		
Soil profile description:									
Horizon	A	B1-3	C	A	B1-5	C	A	B21	B22
Depth (cm)	0–30	30–95	95–180	0–30	30–140	140–220	0–30	35–90	90–120

2.2. Data Acquisition and Analysis

2.2.1. Climate Data

Historical monthly average rainfall (RF) and temperature (T) data between 1990 and 2020 were acquired from the Agricultural Research Council-Natural Resource and Engineering (ARC-NRE) archive database for all the study areas. The agrometeorological stations selected for this study had 30 years and more of climate data with over 90% data efficiency (i.e., less than 10% missing daily values) (Table 2). As described by Moeletsi et al. [46], the missing values in climate data are due to technical malfunctions (such as sensor failures) and environmental factors (such as floods). The data quality was rigorously monitored, and any missing values were substituted with the mean values obtained from the agrometeorological stations in close proximity [30]. Table 2 shows the selected agrometeorological climatic data used in the study.

Table 2. Selected agrometeorological climatic data used in the study.

Stations	Latitude	Longitude	Altitude (m)	Geographical Area	Date Range	Climatic Variables
Bethlehem (Lochlamond)	−28.1626	28.2953	1631	Eastern	1990–2020	RF, T
Bloemfontein (Glen)	−28.9500	26.3333	1304	Central	1990–2020	RF, T
Bothaville (Balkfontein)	−27.4000	26.5000	1280	Northern	1990–2020	RF, T

Note: RF-Rainfall, T-Temperature.

2.2.2. Maize Yield

The long-term historical maize yield data from 1990 to 2020 for Bloemfontein, Bethlehem, and Bothaville was attained from the Crop Estimates Committee (CEC) [47] of the Department of Agriculture, Land Reform and Rural Development (DALRRD), South Africa. The data were captured and visualized in Microsoft Excel 2016 with location, years, and yield values.

2.3. Occurrence and Severity of Agricultural Drought

Rainfed maize in South Africa is grown between October and March [18]. The long-term monthly rainfall and temperature data were organized based on the agricultural year, which runs from July to June of the following year, allowing for a continuous record of the growing season from October to March [18]. Drought occurrence was determined by counting the number of drought events over a study period (1990–2020). The severity of these droughts was then classified into three levels: moderate, severe, and extreme. This classification was based on two indices—the SPI and the SPEI. Both indices are widely used in drought studies and provide a standardized measure to identify and classify drought conditions [31].

2.3.1. SPI

The SPI is a normalized index that measures the likelihood of observed rainfall amounts occurring in a particular location compared to typical rainfall patterns over an extended reference period [48]. Additionally, the SPI is suggested by the World Meteorological Organization (WMO) as the primary meteorological measure for monitoring and examining drought conditions across various timescales [49]. The SPI requires only rainfall data as an input parameter. The SPI has an intensity scale in which both positive (wet events) and negative (dry events) values are calculated. The SPEI package built-in RStudio software version 4.0.2, a free software environment for statistical computing and graphics, was used to calculate the seasonal SPI values at 3 and 6-month intervals [50]. The 3-month interval was classified into four overlapping seasons: October–November–December (OND), November–December–January (NDJ), December–January–February (DJF) and January–February–March (JFM), while the 6-month interval covered the entire

maize growing season, October–November–December–January–February–March (OND–JFM). These specific seasons were analyzed because these intervals represent the critical phases of the maize crop’s life cycle. The chosen timescales (3 and 6 months) are most suitable for studying for an agricultural drought.

2.3.2. SPEI

The SPEI is computed similarly to the SPI; however, the SPEI requires monthly rainfall and temperature data as input parameters [51]. The SPEI integrates a temperature-related component. This characteristic allows the index to account for the impact of temperature fluctuations on the progression of drought episodes, forming an integral part of a core water balance calculation [31]. The potential evapotranspiration (PET) needed by the SPEI method was calculated using PET Thornthwaite’s calculation method [52] built in the SPEI package in RStudio software [50]. Thornthwaite’s method requires only monthly average temperature data and latitude coordinates of a particular area [34], which were readily available for the study areas. Similarly to SPI, the SPEI has an intensity scale in which both positive and negative values are calculated, identifying wet and dry events, respectively. The SPEI package in the R program also computed the seasonal SPEI values at a seasonal scale of 3 and 6 months. The categorization of drought levels of the SPI and SPEI [53] is shown in Table 3.

Table 3. The Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) categories of drought.

SPI/SPEI Values	Moisture Category
≥ 2.00	Extreme Wet
1.50 to 1.99	Severe Wet
1.49 to 1.00	Moderate Wet
0.99 to -0.99	Normal
-1.00 to -1.49	Moderate Drought
-1.50 to -1.99	Severe Drought
≤ -2.00	Extreme Drought

2.4. Agricultural Drought Trends

The modified Mann–Kendall test was used in the study to identify monotonic tendencies of monthly and seasonal agricultural drought (SPI and SPEI) trends (over 3-month and 6-month timescales) and their significance. The modified Mann–Kendall test, a non-parametric method requiring independent data, is widely used to detect trends in climatic or hydrologic time series [54]. It determines whether time series exhibit increasing or decreasing trends [55,56] and is particularly preferred when testing multiple stations within a single study [57,58]. While the Mann–Kendall test has been extensively applied to detect climate trends, especially in analyzing rainfall and temperature patterns [18], its use in studying drought trends using the SPI and SPEI has received comparatively limited attention. Therefore, our study sought to fill this gap. The analysis was performed using the ‘modifiedmk’ package in RStudio software, with a significance level set at 95% ($p < 0.05$). In the modified Mann–Kendall test, the test statistic ‘Z’ determines the trends: a positive Z value indicates an increasing trend, while a negative Z value signifies a decreasing trend [59]. In the context of the SPI/SPEI, an increasing trend (positive Z value) suggests that the SPI/SPEI values are rising over time, indicating a shift toward wetter conditions. Conversely, a decreasing trend (negative Z value) implies a decline in the SPI/SPEI values over time, signaling a trend toward drier conditions [60]. The computation process of the Z value [54] is presented using the following equations:

For the time series $x_1, x_2, \dots, x_n$, the Mann–Kendall statistic (S) is given as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (1)$$

The trend test is applied to a time series x_i that is ranked from $i = 1, 2, \dots, n - 1$ and x_j , which is ranked from $j = i + 1, 2, \dots, n$. Each of the data points x_i is taken as a reference point, which is compared with the rest of the data points x_j so that,

$$Sgn(x_j - x_i) = \begin{cases} 0, & (x_j - x_i) = 0 \\ -1, & (x_j - x_i) < 0 \\ +1, & (x_j - x_i) > 0 \end{cases} \quad (2)$$

Note that if $S < 0$, then later observations in the time series tend to be larger than those that appear earlier in the time series, while the reverse is true if $S > 0$.

The variance statistic is given as follows:

$$\text{Var}(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(i-1)(2i+5)}{18} \quad (3)$$

where t_i is considered the number of ties up to sample i . The standardized Mann–Kendall Test (Z) is computed as follows:

$$Z = \begin{cases} \frac{s-1}{\sqrt{\text{Var}(s)}}, & S > 0 \\ 0, & S = 0 \\ \frac{s-1}{\sqrt{\text{Var}(s)}}, & S < 0 \end{cases} \quad (4)$$

2.5. Impact of Agricultural Drought on Maize Yield

2.5.1. Standardized Yield Residual Series (SYRS)

In the Free State Province, there has been an increasing trend in crop production, including maize. This can be attributed to advancements in agricultural technology. These include more frequent and higher application of fertilizers, implementation of new crop cultivars, and enhanced techniques for weed management and soil preparation [61,62]. Therefore, to eliminate the bias ascribed to non-climatic factors, maize yield data for the studied areas (Bethlehem, Bloemfontein, and Bothaville) was detrended using a simple linear regression model [63,64] as indicated in Equation (5).

$$Y = \beta_0 + \beta_1 X + \epsilon \quad (5)$$

where Y is the maize yield, β_0 and β_1 denotes model parameters, X is the time or any variable that might have a trend, ϵ is the error term. Before computing residuals, predicted values for each observation in the data set have to be obtained using a fitted model as indicated by Equation (6). Detrended data are the residuals from the model, which is computed as the difference between actual yield value (Y) and predicted yield value ($\hat{Y}$) as indicated in Equation (7).

$$\hat{Y} = \beta_0 + \beta_1 X \quad (6)$$

Therefore, the detrended yield was computed as indicated in Equation (4) below and is presented in Figure 2a–c:

$$Y_{\text{detrended}} = Y - \hat{Y} \quad (7)$$

In order to facilitate the yield variability, the study employed z-score transformation. This standardizes the residuals derived from the regression model of the series that had been detrended. Consequently, we computed the SYRS characterized by a mean and standard deviation of 0 and 1, respectively [65]. The SYRS was used to assess the interaction between drought (seasonal SPI and SPEI 3, 6-month timescales) and SYRS. The SYRS analysis was performed using Equation (8) [66] below:

$$\text{SYRS} = \frac{X^i - \mu}{\sigma} \quad (8)$$

where SYRS is the Standardized Yield Residual Series, X^i is the detrended yield in a given year (i), μ is the mean of the detrended values over the study period, and σ is the standard deviation of the detrended yield values over the study period. Table 4 shows the SYRS classification according to different threshold values, adapted from Masud et al.'s [61] study.

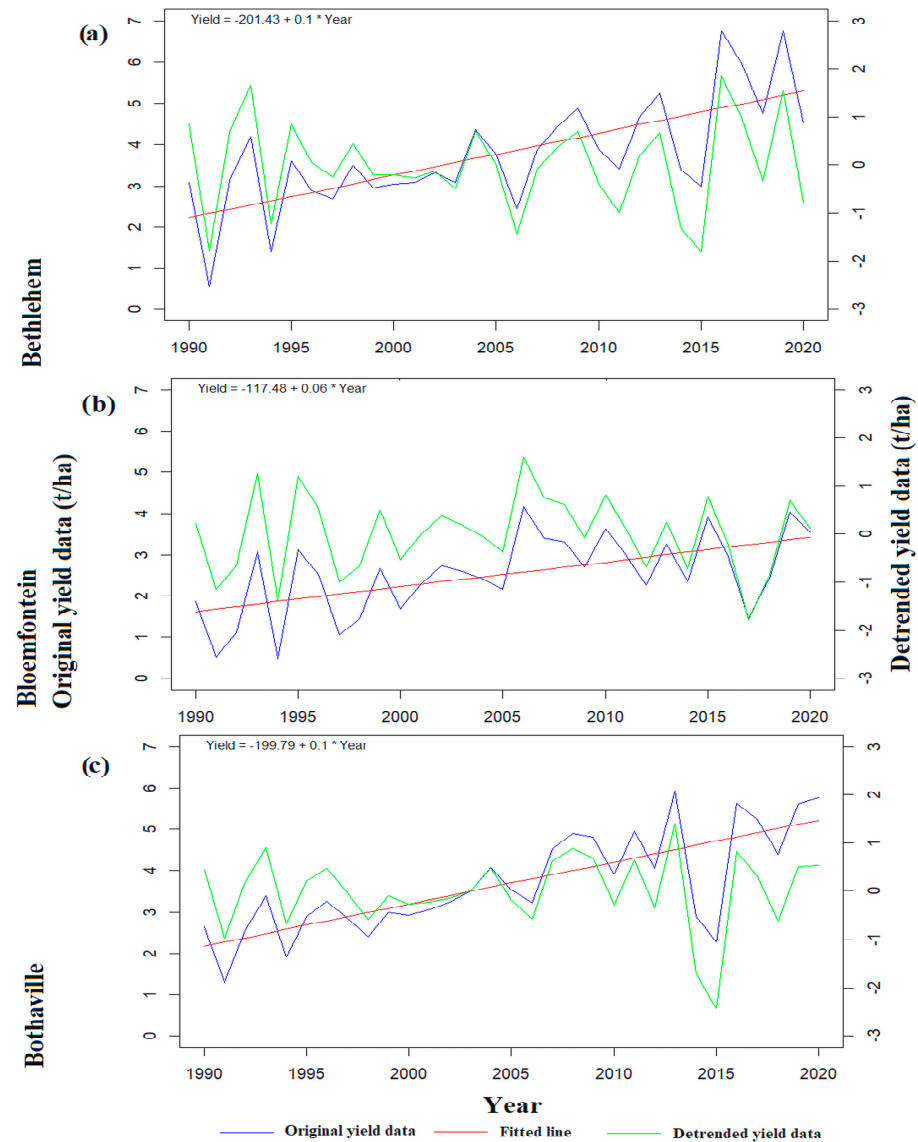


Figure 2. Detrended yield data for Bethlehem (a), Bloemfontein (b), and Bothaville (c) for the period 1990–2020.

Table 4. Standardized Yield Residual Series (SYRS) threshold values and their corresponding categories.

SYRS Values	Categories of SYRS
$SYRS > 1.5$	High yield increment
$1.0 < SYRS \leq 1.5$	Moderate yield increment
$0.5 < SYRS \leq 1.0$	Mild yield increment
$-0.5 < SYRS \leq 0.5$	Normal
$-0.5 < SYRS \leq -1.0$	Mild yield losses
$-1.0 < SYRS \leq -1.5$	Moderate yield losses
$-1.5 < SYRS < -2.0$	High yield losses
$SYRS \leq -2.0$	Extreme yield losses

2.5.2. Correlation between Drought (SPI/SPEI) and SYRS

Given the non-linear relationship between drought indices and SYRS [66], Spearman's Rank Correlation Coefficient (r_s) was used. This method is a measure of monotonic relationships between two variables, whether non-linear or linear [67]. The r_s was employed to assess the direct impact of drought, as measured by the SPI and SPEI (3, 6-month), on SYRS across various growing seasons for each area. The seasons are based on 3-month and 6-month timescales, which correspond to different growth stages of maize. For instance, the OND season covers the stages of maize germination, emergence, and establishment. NDJ and DJF cover the tasselling and silking stages. The JFM season covers the grain-filling stage, and the ONDJFM season covers the emergence-grain filling stages. This coefficient ranges from +1 to −1. A positive r_s value indicates a positive correlation, a negative r_s value indicates a negative correlation, and zero r_s indicates no correlation between variables [67]. These r -values were used to determine the correlations and identify the seasons most affected by drought. The analysis was performed using the 'Hmisc' package at a 95% confidence level, allowing for a 5% margin of error in RStudio program V 4.0.2 to calculate the correlation coefficients and p -values (determines the correlations' significance).

2.5.3. Resilience of Maize to Agricultural Drought

In order to emphasize the impact of drought on maize during maize growing season at area specific, we computed the Crop Drought Resilient Factor (CDRF) for each studied area in the Free State Province. Mohammed et al. [31] defined CDRF as the crop's capacity to endure external pressures, like drought, while preserving its structural integrity and operational processes. The CDRF was computed using Equation (9) below:

$$\text{CDRF} = \frac{d_{dr}}{d_{dt}} \quad (9)$$

where CDRF denotes crop resilience to drought in each area, d_{dr} denotes recorded yield in the driest year during the studied period, and d_{dt} denotes the detrended yield in the same year. In order to obtain the driest year, the SPI and SPEI were computed on 3-month and 6-month timescales. The 3-month timescale encompasses seasons such as OND, NDJ, DJF, and JFM, while the 6-month timescale covers the whole maize growing season (ONDJFM). Next, the study identified the lowest value ($\text{SPI/SPEI} \leq -2.00$ -extreme drought) of these indices for each area. Then, the study looked at which year this extreme drought (lowest value) occurred; the identified year was considered the "driest year" for a particular area and season. Table 5 below, adapted from the Mohammed et al. [31] study, shows the CDRF categories and the corresponding values.

Table 5. Crop Drought Resilient Factor (CDRF) classification by categories with their corresponding values.

CDRF Values	CDRF Categories
$\text{CDRF} > 1$	Resilient
$0.9 < \text{CDRF} < 1$	Slightly non-resilient
$0.8 < \text{CDRF} < 0.9$	Moderately non-resilient
$\text{CDRF} < 0.8$	Severely non-resilient

2.5.4. Maize Yield Loss Due to Agricultural Drought

To accentuate the yield losses indicated by SYRS, this study computed maize yield loss (%) using the maize yield loss rate, a method previously used and validated by Song et al. and Wang et al. [68,69]. Maize yield losses are predominantly influenced by extreme weather events such as droughts, heat waves, and flooding [69,70]. Technological developments, such as the application of fertilizers and changes in cultivars, can also influence maize yield [68]. Therefore, the detrended yield was used for analysis. Drought was considered the main factor influencing maize yield loss. Calculating the yield loss rate

is essential as it helps in determining strategic measures to avoid losses [68]. The yield loss rate in a given year was computed as a percentage of the maximum yield over the previous five years, as determined in Equation (10):

$$YL = \frac{Y_i - Y_m}{Y_m} \times 100\% \quad (10)$$

where

Y_L —yield loss is induced by agricultural drought, Y_i —detrended yield in a given (i) year, and Y_m —maximal detrended yield during the past 5 years [69].

For an overview, Figure 3 shows the flow diagram of materials and methods used.

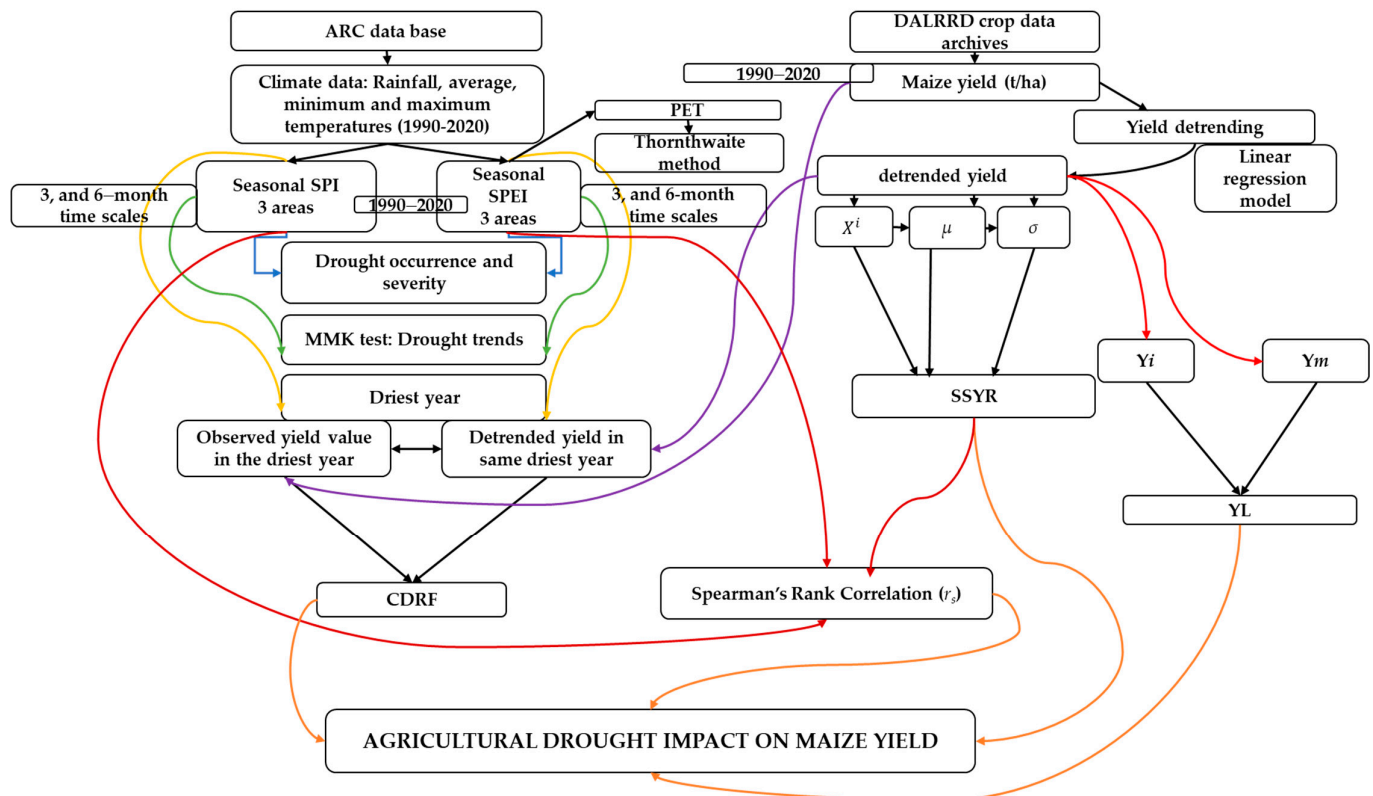


Figure 3. Flow diagram from acquiring data to analysis. The SPI and SPEI (drought indices), MMK test—modified Mann–Kendall test, CDRF—Crop Drought Resilience Factor, X^i —detrended yield in a given year (i), μ is the mean of the detrended values over the monitoring period, σ is the standard deviation of the detrended yield values over the study period, SSYR—Standardized Residual Series Y_i —detrended yield in a given year (i), Y_m —maximal detrended during the past 5 years, Y_L yield loss due to agricultural drought.

3. Results

3.1. Seasonal Drought Occurrence during Different Maize Growing Seasons

Figure 4a,b illustrates the seasonal variations in drought occurrences, as measured by the SPI and SPEI, during the maize growing season (October–March) for Bethlehem, Bloemfontein, and Bothaville from 1990 to 2020. In Bethlehem, drought events under the SPI were most common in the OND, DJF, and JFM seasons, occurring in 15 of the 30 years studied (Figure 4a). However, under the SPEI, the DJF and JFM seasons experienced drought in 14 of the study years (Figure 4a). In Bloemfontein, droughts under the SPI often occurred in the NDJ, DJF, and JFM seasons, with 13 of the study years experiencing drought. Conversely, under the SPEI, droughts were most frequent in the OND, NDJ, and JFM seasons, with drought occurring in 10 of the study years (Figure 4b). In Bothaville, drought events under the SPI frequently occurred in the NDJ season, with 12 of the study

years experiencing drought (Figure 4a). Under the SPEI, however, droughts were most common in the JFM season, with 14 of the study years experiencing recurrent droughts (Figure 4b). Considering the entire growing season (ONDJFM), Bethlehem experienced frequent droughts in 14 years under the SPI and 17 years under the SPEI. In Bloemfontein, 12 years faced drought under the SPI and 8 years under the SPEI. The SPI and SPEI in Bothaville recorded droughts in 11 years of the study period (Figure 4a,b). Overall, SPEI identified more droughts in Bethlehem and Bothaville than the SPI in Bloemfontein.

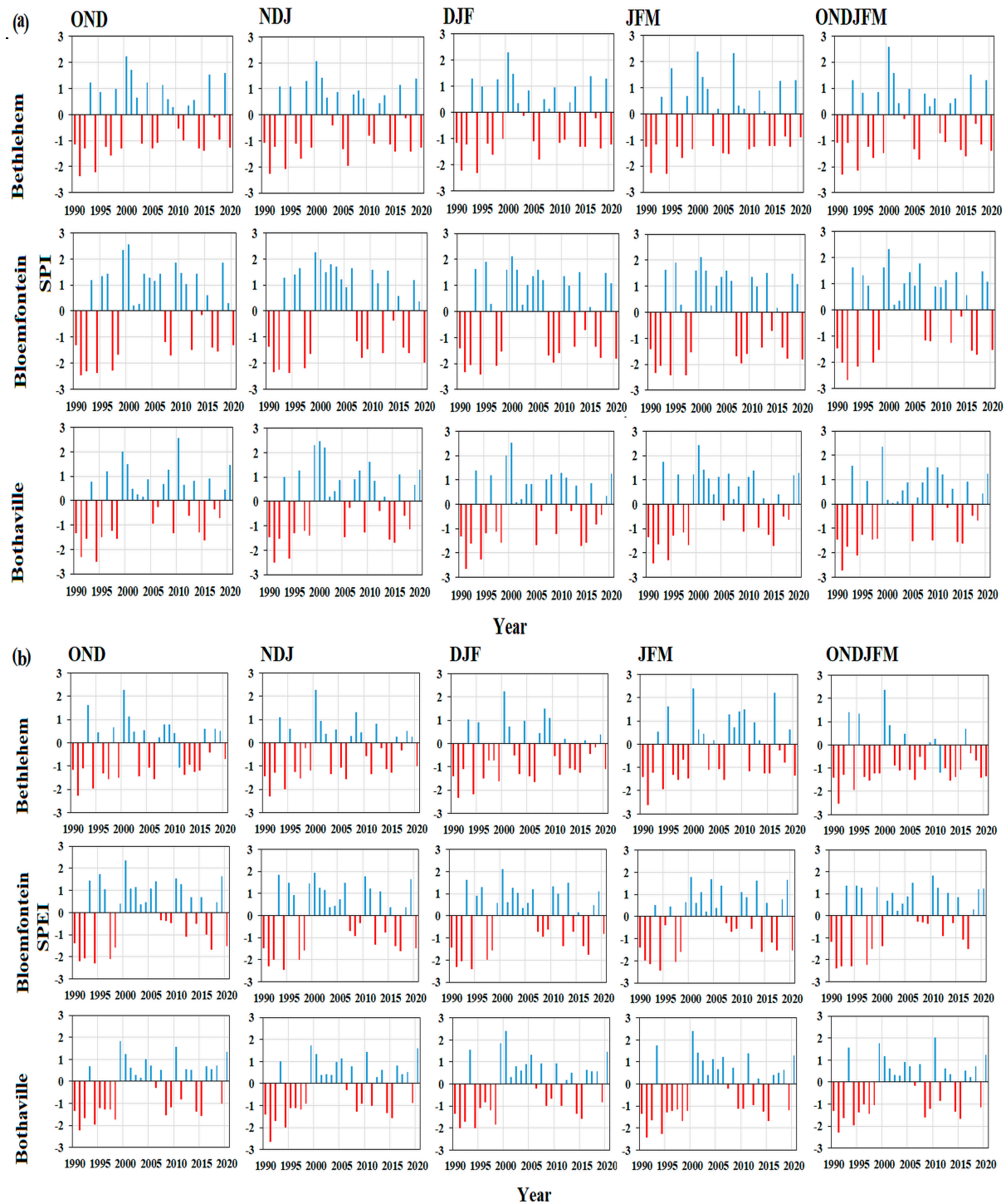


Figure 4. Temporal evolution of drought using the SPI (a) and SPEI (b) for Bloemfontein, Bethlehem, and Bothaville in various seasons between 1990 and 2020 over different seasons/stages of maize.

3.2. Characterization of Agricultural Drought during Different Maize Growing Seasons Based on the SPI and SPEI

Table 6 shows the drought severity in various seasons—OND, NDJ, DJF, JFM, and ONDJFM—for the period from 1990 to 2020. The findings indicate that Bethlehem, Bloemfontein, and Bothaville have experienced successions of moderate to severe droughts throughout all seasons since the 1990s. Following the SPI and SPEI, notable moderate droughts for Bethlehem were recorded in 1990/91, 1992/93, 1996/97, 1999/00, 2003/04, 2011/12, 2014/15 and 2015/16 across seasons. Severe droughts occurred in 1997/98 and 2006/07, and extreme droughts occurred in 1991/92 and 1994/95 (Table 6). For Bloemfontein, moderate drought was recorded in 1990/91 for both growing seasons. Severe droughts were observed in 1998/99 and 2017/18. Extreme droughts were observed in 1991/92, 1992/93, 1994/95, and 1997/98 (Table 6). For Bothaville, moderate droughts were recorded in 1990/91, 1995/96, 1997/98, 1999/00 and 2014/15. Severe droughts in 1992/93 and 2015/16 and extreme droughts in 1991/92 and 1994/95 (Table 6).

Table 6. Drought severity during various seasons for Bloemfontein, Bethlehem and Bothaville between 1990 and 2020.

Drought Severity and Notable Drought Years			
Study Areas	Moderate	Severe	Extreme
Bethlehem	1990/91	1997/98	1991/92
	1992/93	2006/07	1994/95
	1996/97		
	1999/00		
	2003/04		
	2011/12		
	2014/15		
	2015/16		
Bloemfontein	1990/91	1998/99	1991/92
		2017/18	1992/93
			1994/95
			1997/98
Bothaville	1990/91	1992/93	1991/92
	1995/96	2015/16	1994/45
	1997/98		
	1999/00		
	2014/15		

3.3. Trends during Different Maize Growing Seasons

Table 7a, b provides an overview of the monthly and seasonal drought trends for Bloemfontein, Bethlehem, and Bothaville. In Bethlehem, the SPI indicates significant decreasing trends on a monthly scale, suggesting drier/drought conditions. These trends are observed throughout all months. On a seasonal scale, decreasing trends are seen in all seasons, with significant trends in the DJF, JFM, and ONDJFM seasons (Table 7a). The SPEI shows decreasing trends from November to March, which are significant from December to March. However, October shows a significant increasing trend, indicating wetter conditions ($Z = 2.55$, $p = 0.011$) (Table 7b). In Bloemfontein, under the SPI, February and March show decreasing trends, with only March's trend being significant. On a monthly scale, February and March showed decreasing trends, with only March's trend being significant (Table 7a). However, from October to January, there are increasing trends, which are significant in October, November, and December. On a seasonal scale, the OND season shows non-significant decreasing trends ($Z = -0.05$, $p = 0.96$), while NDJ, DJF, JFM, and ONDJFM seasons indicate non-significant increasing trends (Table 7a). Under the SPEI, on a monthly scale, October shows significant increasing trends ($Z = 2.55$, $p = 0.01$). However, from November to March, there are decreasing trends, which are significant only in December,

February, and March. On a seasonal scale, all the seasons reveal significant decreasing trends (Table 7b). In Bothaville, under the SPI, all the months indicate increasing trends, which are significant from October to February. On a seasonal scale, all the seasons indicate significant increasing trends (Table 7a). However, under the SPEI, on a monthly scale, only October ($Z = 0.71$, $p = 0.48$) and March ($Z = -0.33$, $p = 0.74$) show decreasing trends that are not significant, while other months show non-significant increasing trends. On a seasonal scale, all the seasons indicate decreasing trends that are significant in the OND ($Z = -2.81$, $p = 0.004$) and NDJ ($Z = -1.99$, $p = 0.04$) seasons (Table 7b). Significant decreasing trends are alarming because they indicate abridged rainfall, which contributes to groundwater in the rainy season, ultimately causing water shortages for agricultural activities, particularly maize production [71].

Table 7. Monthly and seasonal trends of the SPI (a) and (b) SPEI in Bethlehem, Bloemfontein, and Bothaville from 1990 to 2020.

(a) SPI						
Months/Seasons	Study Areas					
	Bethlehem		Bloemfontein		Bothaville	
	Z	p-Value	Z	p-Value	Z	p-Value
OCT	−5.62	0.00018 *	3.20	0.0014 *	7.03	0.019 *
NOV	−6.92	0.00045 *	4.62	0.017 *	5.69	0.04 *
DEC	−4.91	0.00089 *	3.62	0.00029 *	5.61	0.07 *
JAN	−5.99	0.00021 *	0.23	0.81	4.33	0.00014 *
FEB	−3.52	0.00043 *	−1.91	0.36	2.53	0.011 *
MAR	−2.93	0.0034 *	−3.33	0.00086 *	1.15	0.249
OND	−1.58	0.11	−0.05	0.96	2.56	0.01 *
NDJ	−1.90	0.06	0.31	0.76	3.62	0.029 *
DJF	−2.33	0.02 *	1.11	0.27	4.44	0.0091 *
JFM	−2.60	0.008 *	1.60	0.10	4.90	0.0024 *
ONDJFM	−3.20	0.0014 *	2.35	0.02	5.20	0.0046 *
(b) SPEI						
Months/Seasons	Study Areas					
	Bethlehem		Bloemfontein		Bothaville	
	Z	p-Value	Z	p-Value	Z	p-Value
OCT	2.55	0.011 *	2.55	0.01 *	−0.71	0.48
NOV	−0.33	0.73	−0.33	0.73	0.49	0.62
DEC	−3.69	0.00022 *	−3.69	0.0002 *	0.50	0.61
JAN	−7.53	0.00054 *	−7.52	0.0054	0.59	0.56
FEB	−10.53	0.00031 *	−10.52	0.0031 *	0.00	1.00
MAR	−12.56	0.00075 *	−12.56	0.0034 *	−0.33	0.74
OND	−1.95	0.05 *	−5.62	0.00018 *	−2.81	0.004 *
NDJ	−3.25	0.001 *	−6.92	0.00045 *	−1.99	0.04 *
DJF	−4.53	5.90	−4.91	0.00089 *	−1.82	0.06
JFM	−4.88	6.02	−5.99	0.00021 *	−0.46	0.09
ONDJFM	−4.90	6.24	−3.52	0.00043 *	−0.18	0.10

* Denote significant at $p < 0.05$.

3.4. Impact of Agricultural Drought on Maize Yield during Different Growing Seasons

3.4.1. Standardized Yield Residual Series (SYRS)

Figure 5 shows the time series trends of maize yield (t/ha), and Table 8 presents the results of the Mann–Kendall test (Z) and Sen's slope (β) for maize yield trends for Bethlehem a), Bloemfontein b) and Bothaville between 1990 and 2020. Figure 5 and Table 8 show that in the studied period, there was a significant ($p < 0.05$) increase in maize yield; this is indicated by increasing slopes from time series trends (Figure 5) and positive Z

and β values (Table 8). Overall, all three areas show a statistically significant increase in maize yield in the studied period. The β values represent the magnitude of the trend, with Bothaville showing the steepest increase. The Z values indicate the trend's strength, with Bethlehem and Bothaville showing stronger trends than Bloemfontein.

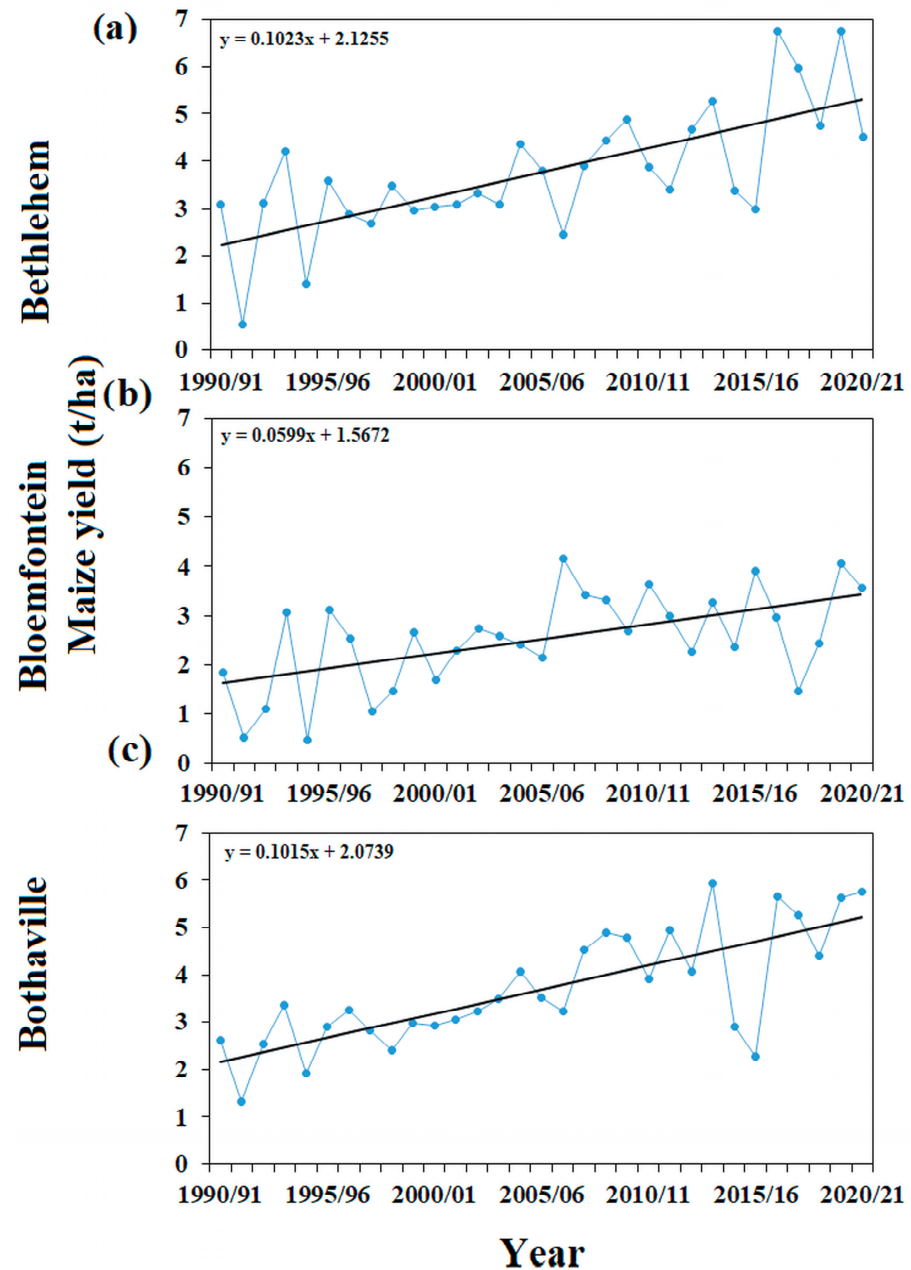


Figure 5. Time series maize yield (t/ha) trends for Bethlehem (a), Bloemfontein (b) and Bothaville (c) for the period 1990 to 2020.

Table 8. Maize yield trend using Mann–Kendall test (Z) and Sen's slope (β) of maize in Bethlehem, Bloemfontein, and Bothaville between 1990 and 2020.

Areas	Z	Sen's Slope (β)	p
Bethlehem	4.98	0.10	0.00000064 *
Bloemfontein	3.18	0.06	0.0015 *
Bothaville	4.94	0.11	0.00000080 *

Note. * Denotes significant at $p < 0.05$.

Prior to computing the SYRS, the maize yield was detrended (see Figure 2a–c) to eliminate the effects of improved crop varieties, new agricultural technology, and fertilization. Figure 6 shows the temporal evolution of the SYRS across the studied areas (Bethlehem, Bloemfontein, and Bothaville) from 1990 to 2020. Between 1990 and 2020, the SYRS showed notable yield losses ($-1.0 < \text{SYRS} \leq -1.5$ (moderate yield losses), $-1.5 < \text{SYRS} < -2.0$ (high losses), and $\text{SYRS} \leq -2.0$ (extreme losses)) in 1991/92, 1994/95, 2006/07, 2014/15 and 2015/16 in Bethlehem, 1991/92, 1994/95, 1997/98, and 2017/18 in Bloemfontein and 1991/92, 2014/15 and 2015/16 in Bothaville (Figure 6a–c). The lowest value of the SYRS (-2.38 , extreme yield losses, 1991/92) was recorded in Bethlehem, followed by Bloemfontein (-2.11 , extreme yield losses, 2017/18) and Bothaville (-1.73 , high yield losses, 2015/16) (Figure 6a–c). Overall, yield losses were prevalent in Bethlehem, followed by Bloemfontein and Bothaville.

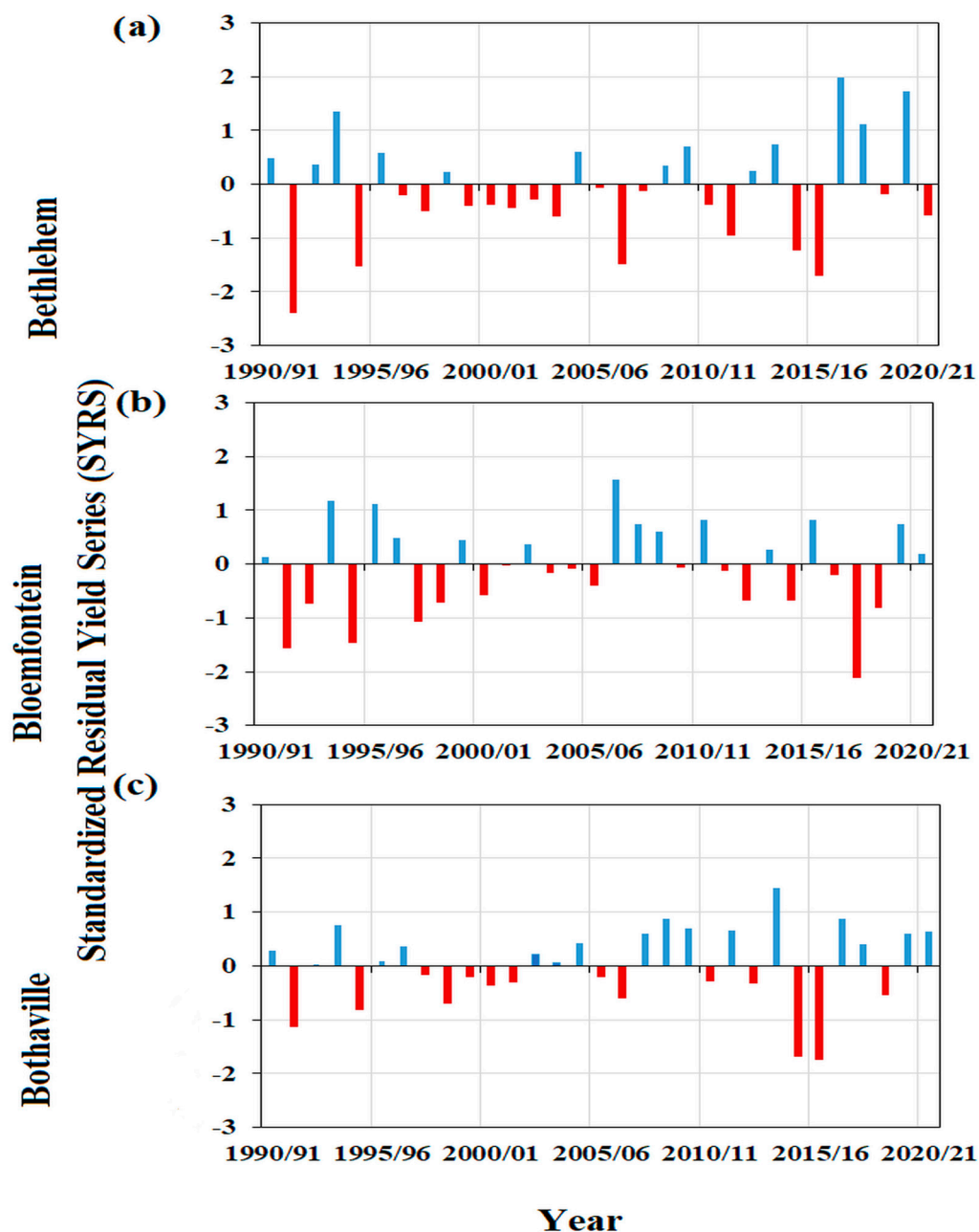


Figure 6. Temporal evolution of SYRS for Bethlehem (a), Bloemfontein (b) and Bothaville (c). The blue bar charts indicate yield increment, and the red bar charts indicate yield losses.

3.4.2. Correlation between Drought and SYRS on a Seasonal Scale

Table 9a,b shows the relationship between the calculated seasonal SPI and SPEI values and the SYRS for Bloemfontein, Bethlehem, and Bothaville from 1990 to 2020. These drought indices, which measure precipitation (SPI) and climatic water balance (SPEI), play a crucial role in maize yield [31]. The results indicate a significantly high positive correlation between the SPI, SPEI, and SYRS across all study areas and seasons. For the SPI 3-month time scale (SPI-3), the highest significant correlation was observed in the DJF season ($r_{sSPI-3 \text{ vs SYRS}} = 0.65$, $p = 7.26 \times 10^{-5}$) in Bethlehem, followed by Bloemfontein ($r_{sSPI-3 \text{ vs SYRS}} = 0.55$, $p = 0.0014$) over NDJ season and Bothaville ($r_{sSPI-3 \text{ vs SYRS}} = 0.51$, $p = 0.0034$) over DJF season (Table 9a). In contrast, for the SPEI 3-month time scale (SPEI-3), the highest significant correlation between the SPEI and SYRS was observed in Bloemfontein in the OND season ($r_{sSPEI-3 \text{ vs SYRS}} = 0.69$, $p = 2.12 \times 10^{-5}$), followed by Bethlehem in the JFM season ($r = 0.60$, $p = 0.00032$) and Bothaville in the JFM season ($r_{sSPEI-3 \text{ vs SYRS}} = 0.36$, $p = 0.04$) (Table 9b). For the SPI 6-month timescale (SPI-6), the overall maize growing season (ONDJFM), the highest correlation was observed in Bethlehem ($r_{sSPI-6 \text{ vs SYRS}} = 0.67$, $p = 3.40 \times 10^{-5}$), followed by Bothaville ($r_{sSPI-6 \text{ vs SYRS}} = 0.58$, $p = 0.00065$) and Bloemfontein ($r_{sSPI-6 \text{ vs SYRS}} = 0.54$, $p = 0.0018$) (Table 9a). Based on the SPEI 6-month timescale (SPEI-6), the highest significant correlation was observed in Bloemfontein ($r_{sSPEI-6 \text{ vs SYRS}} = 0.83$, $p = 1.07 \times 10^{-8}$), followed by Bethlehem ($r_{sSPEI-6 \text{ vs SYRS}} = 0.40$, $p = 0.03$) and Bothaville ($r_{sSPEI-6 \text{ vs SYRS}} = 0.21$, $p = 0.02$) (Table 9b). Overall, in the SPI 3-month timescale, high significant correlations were observed in Bethlehem. For the 3-month SPEI, high correlations were recorded in Bloemfontein. For the 6-month timescale, the highest correlation under the SPI and SPEI was recorded over Bethlehem and Bloemfontein, respectively.

Table 9. Correlation between drought (3, 6-month SPI and SPEI) and SYRS.

						Interpretation
(a) SPI						No Correlation
		3-Month (SPI-3)		6-Month (SPI-6)		0
Areas	OND	NDJ	DJF	JFM	ONDJFM	0.1
Bethlehem	0.61	0.64	0.65	0.56	0.67	0.2
Bloemfontein	0.47	0.55	0.45	0.44	0.54	0.3
Bothaville	0.49	0.44	0.51	0.38	0.58	0.4
						0.5
(b) SPEI						0.6
		3-Month (SPEI-3)		6-Month (SPEI-6)		0.7
Areas	OND	NDJ	DJF	JFM	ONDJFM	0.8
Bethlehem	0.58	0.56	0.59	0.60	0.40	0.8
Bloemfontein	0.69	0.68	0.66	0.54	0.83	0.9
Bothaville	0.24	0.28	0.33	0.36	0.21	1

Note: The colours represent the strength of the correlation between variables, colours with low value indicates low correlation and colours with high values indicate high correlation.

3.4.3. Maize Yield Loss Due to Agricultural Drought

Table 10 shows the maize yield loss (%) associated with varying degrees of agricultural drought. The table below shows only the notable years where yield decreased according to SSYR. The YL ranged from -13.83% to -86.62% over Bethlehem. During moderate agricultural drought years, the highest YL recorded was -16.03% in 2014/15; in severe agricultural droughtyear/s, the YL was -27.69 in 2006/07 season, and in extreme years, the highest YL was -86.62% (Table 10). In Bloemfontein, the YL was in the range of -29.32 to -78.62% . The highest YL during severe and extreme years was -29.32% (2017/18) and -78.62% (1994/95), respectively. In these notable years, no moderate drought was recorded (Table 10). In Bothaville, YL was -14.04% (2014/15), -28.22% (2015/16), and -54.39% (1991/92) due to moderate, severe and extreme agricultural drought (Table 10). Overall, it is evident that drought has a huge impact on yield, with extreme drought impact greater than that of moderate to severe drought across all study areas.

Table 10. Maize yield loss relative to agricultural drought in Bethlehem (BTM), Bloemfontein (BFN), and Bothaville (BTV) from 1990 to 2020.

Areas	Season	Yield Loss (%)	SPI Values during Different Growing Seasons					SPEI Values during Different Growing Seasons					Drought Severity
			OND	NDJ	DJF	JFM	ONDJFM	OND	NDJ	DJF	JFM	ONDJFM	
BTM	1991/92	−86.62	−2.35	−2.25	−2.22	−2.28	−2.29	−2.29	−2.31	−2.32	−2.62	−2.51	Extreme
	1994/95	−44.18	−2.20	−2.08	−2.32	−2.30	−2.15	−2.00	−1.99	−2.18	−2.10	−2.30	Extreme
	2006/07	−27.69	−1.09	−1.96	−1.79	−1.54	−1.73	−1.57	−1.74	−1.64	−1.54	−1.50	Severe
	2014/15	−16.03	−1.31	−1.13	−1.32	−1.24	−1.36	−1.26	−1.13	−1.14	−1.27	−1.37	Moderate
	2015/16	−13.83	−1.39	−1.42	−1.32	−1.25	−1.61	−1.19	−1.27	−1.26	−1.24	−1.00	Moderate
BFN	1991/92	−69.86	−2.48	−2.35	−2.32	−2.34	−2.02	−2.20	−2.31	−2.32	−2.00	−2.29	Extreme
	1994/95	−78.62	−2.38	−2.38	−2.41	−2.41	−2.16	−2.31	−2.45	−2.41	−2.44	−2.39	Extreme
	1997/98	−49.44	−2.27	−2.21	−2.10	−2.43	−2.00	−2.10	−2.00	−2.10	−2.06	−2.24	Extreme
	2017/18	−29.32	−1.54	−1.63	−1.78	−1.75	−1.71	−1.67	−1.62	−1.78	−1.52	−1.51	Severe
BTV	1991/92	−54.39	−2.31	−2.52	−2.66	−2.43	−2.72	−2.23	−2.63	−2.00	−2.43	−2.69	Extreme
	2014/15	−14.04	−1.32	−1.57	−1.69	−1.26	−1.56	−1.37	−1.34	−1.37	−1.26	−1.35	Moderate
	2015/16	−28.22	−1.62	−1.71	−1.59	−1.7	−1.61	−1.57	−1.56	−1.58	−1.70	−1.68	Severe

3.4.4. Resilience of Maize to Agricultural Drought

Table 11 shows the Resilience of maize to agricultural drought based on CDRF for the three studied areas (Bethlehem, Bloemfontein, and Bothaville) for the period 1990–2020. The seasons considered were on a 3-month timescale (OND, NDJ, DJF, and JFM) and a 6-month time scale (ONDJFM). According to the SPI and SPEI under both the 3 and 6-month timescales, the driest year was the 1991/92 season in Bethlehem and Bothaville, and 1994/95 in Bloemfontein was the driest year based on the SPI and SPEI at 3-month and 6-month timescales (see Table 10). The CDRF value of 0.27 ($CDRF < 0.8$) in Bethlehem shows that maize was severely non-resistant to drought. Similarly, in Bloemfontein, the CDRF value of 0.42 indicates that maize was severely non-resistant to drought (Table 11). This indicates that maize in these two areas has a low ability to withstand drought while maintaining its structure and functions. Conversely, in Bothaville, the CDRF value of 1.13 ($CDRF > 1$) shows that maize was resilient to drought (Table 11), indicating that maize in this area can withstand drought.

Table 11. Maize resilience to drought at area-specific level.

Study Areas	Driest Year under Both SPI/SPEI at 3-Month and 6-Month Timescales	Maize Yield Recorded (t/ha)	Detrended Yield (t/ha)	CDRF Values
Bethlehem	1991/92	0.56	2.11	0.27
Bloemfontein	1994/95	0.48	1.46	0.33
Bothaville	1991/92	1.31	1.13	1.16

4. Discussion

Drought remains a significant threat to food security, particularly in arid and semi-arid regions. It directly impacts crop growth and anticipated yields. This study aimed to assess agricultural drought occurrence, severity, trends, and impact on maize yield over the maize growing season between 1990 and 2020 in the main areas producing maize, Free State Province, South Africa. The study results based on the SPI and SPEI showed that agricultural drought is widespread in the studied areas; it ranges from moderate to extreme. All the areas faced droughts across all maize growing seasons; however, Bethlehem (supposedly a wet area) frequently faced worse droughts across all seasons than Bloemfontein and Bothaville (dry areas). In support of the study findings, the study by Nembilwi et al. [72] revealed that the wetter area was highly impacted by drought compared to the dry area. While it is true that Bethlehem is generally considered a wetter area compared to Bloemfontein and Bothaville, the occurrence of droughts in Bethlehem could be attributed to various factors such as the following. (i) Climate variability: this climate phenomenon can disrupt normal precipitation patterns, leading to periods of reduced rainfall and increased drought risk. Richard et al. and Moeletsi and Walker [73,74]

asserted that frequent droughts are related to the high variability of interannual and intra-seasonal rainfall over most parts of southern Africa. (ii) Geographical location: Bethlehem is located in the eastern part of the Free State Province. Its geographical position puts it at a higher elevation and closer to the Drakensberg Mountains. Its proximity to these mountains affects the weather patterns in the area, and it is more exposed to dry, continental air masses coming from the inland areas of the province. These air masses can result in lower precipitation and contribute to drought occurrence. Dubey et al. [75] found that droughts prevailed more in high-altitude than low-lying areas. Overall, the SPEI showed that it detected more droughts in two areas (Bethlehem and Bothaville) than the SPI in one area (Bloemfontein). This is comparable to studies such as those by Tirivarombo et al. [27] that used the SPI and SPEI to quantify drought in Kafue Basin, Zambia; they found that the SPEI identified more droughts than the SPI. Additionally, the SPEI recorded droughts with increased duration and severity. Similarly, Tefera et al. [76] compared the performance of the SPI and SPEI in assessing drought in the Tigray Region, Northern Ethiopia. The study indicated that the SPEI performed better than the SPI, although there is a correlation between these indices in detecting drought at various timescales. In contrast to our findings, a study [77] conducted in the Agra Division of Uttar Pradesh, India, that used the SPI and SPEI found that these indices detected droughts similarly. Therefore, the SPEI can be reliable in quantifying drought. This is corroborated by Abara and Budiastuti [78], whose study indicated that the SPEI produces more reliable results than the SPI.

Regarding agricultural drought severity based on the SPI and SPEI, the findings showed that drought severity differed with areas. Moderate agricultural droughts were prevalent in Bethlehem; severe agricultural drought was prevailing in all areas (Bethlehem, Bloemfontein, and Bothaville) and extreme agricultural drought in Bloemfontein. Agricultural droughts were noted explicitly in 1991/92, 1994/95, 1997/98, 2014/15, 2015/16 and 2017/18. Previous studies have highlighted the significant impact of these droughts. For instance, Monyela's [79] findings indicated that South Africa experienced its worst drought in the 1991/92 season, which had widespread impacts, particularly in agriculture [72,80]. Mbiriri et al. [29] found that one of the notable droughts occurred in 1991/92 with extreme drought and in 1994/95 with severe drought in the Free State province. Lyon and Mason (2007) and (2009) [81,82] ascertain that in 1997/98, South Africa encountered drought, which directly impacted the country's production, such that crops were severely stressed, particularly in northern and central parts of the country. Rouault et al. and Archer et al. [83,84] showed that many regions in southern Africa experienced severe drought in 2014/15. According to Archer et al. [83], in 2015/16, South Africa saw the worst drought on record. In addition, EM-DAT (<https://www.emdat.be/> accessed on 23 February 2022) declared that Free State Province and other provinces were affected by this drought. The South African Grain Information Service (SAGIS) indicated that maize production dropped by approximately 30% in this period. EM-DAT indicated that South Africa faced drought in 2017/18, which lasted for 13 months. The government implemented several measures to support farmers, including financial assistance [85] and programs to promote water conservation and efficiency [86]. The SPI and SPEI were able to identify extreme past droughts and more droughts (such as 1991/92 and 1994/95). Similar findings have been found by Masupha et al. and Phaduli [15,39].

Maize is a staple food for most people in South Africa; however, its production is defied by drought. The impact of drought on maize yield can be devastating, not only for farmers but also for consumers who depend on it for their daily sustenance. The results of this study indicated that the lowest value of the SYRS (high/extreme yield reductions) was recorded in Bethlehem (SYRS = -2.38), followed by Bloemfontein (SYRS = -2.11) and Bothaville (SYRS = -1.73). This suggests that these areas were significantly affected by agricultural drought. These findings align with other studies that assessed the impact of agricultural drought on crop yields. For instance, a study conducted in Hungary also used the SYRS to analyze the agricultural drought interaction with crop yield (maize and wheat) [31]. They found that the lowest SYRS for maize yield

was recorded in five regions, and they indicated that maize was significantly exposed and affected by drought episodes; thus, it was not resilient. It is also worth noting that these yield reductions in the studied areas occurred despite the advancements in crop varieties, agricultural technology, and fertilization, as these factors were eliminated when computing the SYRS. These findings highlight the importance of continued research and innovation in developing drought-resistant crop varieties and sustainable farming practices to mitigate the impacts of climate change on agriculture. The study also showed high significant positive correlations between the agricultural drought (measured by the SPI and SPEI at 3, 6-month timescales) and the SYRS in all studied areas and seasons. The highest was observed in Bloemfontein over the whole maize growing season (emergence-grain filling stages), ONDJFM, under the SPEI. The CDRF showed that maize was severely non-resilient ($CDRF < 0.8$) to drought in Bethlehem and Bloemfontein and resilient ($CDRF > 1$) in Bothaville. This indicates that maize is susceptible to drought events. Drought during the emergence of grain filling stages (ONDJFM) might have impacted growth and productivity, reducing yield. This is supported by findings from Abubakar et al. [40], which indicated that drought during maize germination, pollination, and grain filling could result in lower yields. Mohammed et al. [31] study found a significant positive correlation between drought indices yield residual series during the growing cycle for maize and wheat and suggested that these crops are susceptible to drought events, especially in the tasselling stage of maize, which led to lower yields. Aslam et al. [87] indicated that drought hampers germination, resulting in poor maize standing at the early seedling phase, hindering early maize establishment and reducing yield. Anami et al. [88] indicated that drought during the grain-filling period leads to low yield due to reduced kernel size.

To further accentuate the direct impact of agricultural drought on maize yield, all studied areas encountered losses due to moderate, severe, and extreme agricultural droughts with the highest maize losses observed over Bethlehem, followed by Bloemfontein and Bothaville. Moderate agricultural drought indicated a noticeable impact, and severe and extreme agricultural droughts showed a more substantial and detrimental effect on maize production. The findings are comparable with those reported by Li et al. [89], whose study found that 30%, 40%, and 50% of maize yield losses were induced by moderate, severe, and extreme droughts, respectively. Similar conclusions have been reached by Wang et al. [69], whose study found that maize yield losses of 3.2% and 14.0% were recorded during moderate drought and severe drought, respectively.

Although the SPI and SPEI have given a picture of drought conditions over the studied areas (Bethlehem, Bloemfontein, and Bothaville), there are still limitations to these indices. The SPI considers rainfall data only and neglects other climatic parameters. On the other hand, the SPEI involves multiple parameters (rainfall and PET) and is based on Thornthwaite's equation, which uses few climatic parameters to compute PET. Nevertheless, the outputs of this research are sufficient to draw the attention of decision-makers and policymakers to the impact of drought on maize production in the studied areas.

While this research has highlighted the impact of agricultural drought on maize production at a local level, the study recommends that further studies should explore the impacts of changing climate on crop production using other indices such as Crop Specific Drought Index (CSDI) and remote sensing indices like Normalized Difference Vegetation Index (NDVI), Standardized Soil Moisture index (SSMI) this will assist farmers, policymakers and decision-makers in developing strategies to mitigating the changing climate.

5. Conclusions

Maize is an essential crop in South Africa, playing a significant role in food production, livelihood maintenance, and the stability of the country's economy. Its susceptibility to water stress makes it highly vulnerable to drought. This study assessed agricultural drought occurrence and severity, trends, and impact on maize yield at a local level during the maize growing season (October–March) between 1990 and 2020. The results showed that agricultural drought (SPI and SPEI) incidences were more prevalent in Bethlehem and

Bloemfontein compared to Bothaville. Ag.D affected Maize production badly in 1991/92, 1994/95, 1997/98, 2006/07, 2014/15, 2015/16 and 2017/18. Bethlehem and Bloemfontein are more prone to extreme yield reduction. Across all areas, the correlation between the SPI and SPEI (3, 6-month) was relatively high, with Bloemfontein recording the highest significant correlation ($r_{\text{SPEI-6 vs SYRS}} = 0.83, p = 1.07 \times 10^{-8}$). Notably, yield losses (YL) were encountered across all studied areas, with Bethlehem and Bloemfontein more susceptible to extreme yield losses. The common years that experienced yield losses in all studied areas were 1991/92 and 1994/95. The highest YL recorded in Bethlehem, Bloemfontein, and Bothaville were due to extreme agricultural drought. The CDRF revealed that maize in Bethlehem and Bloemfontein was severely non-resilient to drought (CDRF < 0.8) and resilient in Bothaville. These findings showed that agricultural drought is a threat to maize production. In light of these findings, it is clear that proactive measures are needed to safeguard the future of maize production in these areas. The resilience of maize in Bothaville offers hope and a potential blueprint for adaptation strategies. However, the susceptibility of Bethlehem and Bothaville underscores the urgency of this issue. As climate patterns continue to evolve, understanding the drought impacts is crucial as this can assist in developing robust, sustainable solutions (e.g., drought-resistant maize cultivars/varieties) to ensure food security and economic stability. This study serves as a stepping stone toward that goal, but there is much work to be done. The future of our agriculture and, indeed, our nation depends on our collective action today.

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