Climate change: a friend or foe to food security in Africa?

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Abstract

Extreme climate change is posing an increasing threat to human welfare across countries. Specifically, the devastating floods coupled with the looming spectre of drought are argued to explain cross-country differences in food security. While the debate continues and uncertainties about the precise influence of climate change on food security linger, the question of whether climate change plays a pivotal role in increased hunger and food insecurity across countries remains unanswered. This study presented new evidence of the role of climate change in Africa's food security. We utilised the Mann–Kendall test and Sen's slope estimator to analyse climate change trends. We also employed the pooled mean group technique and the Dumitrescu–Hurlin panel causality test to investigate the effect of climate change on food security in 15 African countries between 1970 and 2016. Our empirical findings revealed three things. First, rainfall plays a decisive role in Africa's food security when examined broadly. However, the significance of the effect of rainfall varied substantially across the 15 countries. Second, we find no robust impact of temperature on food security in the long run. However, the short-run results showed that extreme temperatures impede food security, with varying magnitudes across countries. Third, except for rainfall, a bidirectional causality exists between food security and temperature in Africa. Given the risks associated with rain-fed agriculture, we argue that African countries need to limit their dependence on rain-fed agriculture to boost food production.

Keywords Climate change · Climate variability · Food security · Cultivated area · Population growth · Africa

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1 Introduction

The role of climate change in economic growth has dominated global policy discussions for many decades (Berrera & Hertel, 2021; Chauhan et al., 2020; Food and Agriculture Organization [FAO] et al., 2019; Hossain et al., 2019; Intergovernmental Panel on Climate Change, 2001). Development practitioners and policymakers describe frequent climate variability as a menace and an obstacle to sustainable global growth and development (Boko et al., 2007; Murphy & Drexhage, 2010). Despite these concerns, evidence shows that climate change has become more severe, and the drivers of greenhouse gases, such as carbon dioxide, methane, ozone, and nitrous oxide, are still on the rise, even with the global slowdown resulting from the COVID-19 pandemic (World Meteorological Organization, 2020). While a comprehensive assessment of the risks associated with changing climatic conditions remains controversial (McCarl et al., 2013), a growing number of studies examining the effects of climate change argue that upsurging greenhouse gases increase atmospheric temperatures, create extreme weather events, and threaten food production, especially in regions that depend extensively on rain-fed farming (Mendelsohn & Wang, 2017; Singh & Thadani, 2015; Yobom, 2020). Thus, the relative effect of climate change on food security will be much higher in developing countries if it persists.

Recent evidence reveals an alarming rise in global hunger and undernourishment, alongside increasingly extreme climatic conditions. Approximately 690 million people went hungry in 2019, and this figure is expected to rise by 60 million people in the next five years (FAO et al., 2020). These sobering figures raise the question: can we still achieve the Sustainable Development Goals of eradicating hunger by 2030? (United Nations, 2015). While policy consensus is required to mitigate the prevailing symptoms of food insecurity, the underlying drivers of global food insecurity remain complex and inconclusive (Amekudzi et al., 2015; Chauhan et al., 2020; Hossain et al., 2019; Owusu et al., 2021). A plethora of studies associates hunger with changing farming activities imposed by the cumulative effects of climate change on all dimensions of food security—food access, availability, stability, and utilisation—across regions (Easterling et al., 2000; FAO, 2010; FAO et al., 2019; Hossain et al., 2019; McCarthy et al., 2001). For instance, extreme climate change and variability will decrease crop output in some African countries by up to 50% by 2030, while crop income may decline by 90% by 2100 (Boko et al., 2007). Other studies suggest that climate change has already led to a decline in food security at national and household levels in developing countries (Connolly-Boutin & Smith, 2016; Nelson et al., 2009; Thornton et al., 2011). Climate change and variability could adversely affect Africa's food security in several ways (Boko et al., 2007; Kotir, 2011; Schlenker & Lobell, 2010; Thornton et al., 2011; Yobom, 2020). First, climate extremes may influence the supply of food in Africa by reducing the area of viable arable land suitable for crop production (Amekudzi et al., 2015; Arnell, 2009; Owusu et al., 2021), leading to a surge in the prevalence and number of undernourished people. Second, a rise in temperature by 4 °C or more may have disastrous effects on many farmers' livelihoods in Africa (Thornton et al., 2011). Such a climate event may require higher productivity and more efficient distribution of resources to eradicate hunger across the continent. Brown et al. (2007) and Amekudzi et al. (2015) identified climate change as a new security threat to Africa. Further, Burke et al. (2009) attributed increased civil wars to climate change and detected a strong association between warmer years and past civil wars. Despite many studies conducted to examine the overall impact of climate change on food security in developing countries, evidence on the effects of climate change on food productivity remains inconclusive.

This study adds to the ongoing discussions on climate change and food security by focussing on Africa. Further research in this area is crucial for several reasons. First, more than 20% of Africa's population is undernourished (FAO et al., 2019). Food availability remains a critical concern in Africa, given the rising population growth rates and poverty levels. Recent estimates show that 704 million people (9.2%) of the world's population were subject to severe food insecurity in 2018 (FAO et al., 2019). The situation is most alarming in Africa, where severe food insecurity rose from 210.7 million to 277 million between 2014 and 2018, affecting 21.5% of the population in 2018 (FAO et al., 2019). Food insecurity is on the increase in almost every sub-region of Africa. In 2018, Southern Africa had the highest prevalence of severe food insecurity (30.6%), followed by Eastern Africa (25.9%), Western Africa (17.6%), and Northern Africa (8%) (FAO et al., 2019). Bumb and Byrnes (1998) stated that cereals account for 60–70% of the average per capita calorie consumption, so they are periodically used as a proxy for food security. The quantities of cereals produced for food supply in countries are estimated in calories to reflect the amount of food everyone consumes (Bezuneh & Yiheyis, 2014; Smith & Haddad, 2001). Figure 1 displays the Pareto plot of average cereal production over the period 1970–2016 in 15 selected African countries with a history of food insecurity and food emergencies. On average, Nigeria produced 17,281,243 tonnes, followed by Egypt, producing 14,888,196 tonnes, with South Africa occupying the third position with 11,936,601 tonnes. Morocco came in fourth, producing 5,674,449 tonnes, followed closely by Kenya (3,084,558 tonnes), and Mali took sixth place with 2,828,047 tonnes. The Pareto plot of average cereal production shows that thirteen countries, including South Africa, cumulatively produced 50% of total cereal production by the selected African countries. In comparison, the remaining 50% was generated proportionately by Nigeria and Egypt between 1970 and 2016.

Second, while the debate on food security continues, ongoing discussions concern the implications of frequent temperature variations, rainfall variability, and increased climatic events across African countries (Etana et al., 2021; Hulme et al., 2001; Nicholson et al., 2000; Nicholson, 2001; Owusu et al., 2021). Although Africa is considered a minor player in total global greenhouse gas emissions, generating less than 4% of the world's total (Oliver & Peters, 2020), the continent is susceptible to the adverse consequences of climate change variability (Boko et al., 2007; Lobell et al., 2011; Nakhouda et al., 2011; Sy, 2016). Prior evidence suggests that countries in Africa, especially those in sub-Saharan Africa

Fig. 1 Pareto plot of average cereal production in the selected African countries (1970–2016)

(SSA), will experience an increase in temperature of 2–4 °C by 2100, which is about 1.5 times higher than the expected mean increase in global temperature (Boko et al., 2007; Christensen et al., 2007). According to Easterling et al. (2007), a rise in temperature by 3 °C or more will cause food prices to increase by 40%. A large proportion of the African population relies on rain-fed farming for their livelihood (Adhikari et al., 2015; Cooper et al., 2008; Muchuru & Nhamo, 2019), so extreme climate variability poses a significant threat to food production (Boko et al., 2007; Etana et al., 2021; Lobell et al., 2011; Schlenker & Lobell, 2010). Climate change and variability also raise food production costs, translating to high consumer prices (Berrera & Hertel, 2021; Dadzie et al., 2021; FAO, 2008). Evidence shows that climate change could decrease agricultural output in SSA by 8% by 2080, compared with a decrease of about 4% in Asia (Shah et al., 2008). This negative effect of climate change will severely impair access to food, given that most economies in Africa are unable to finance food importation (Nathaniel et al., 2021; Shah et al., 2008). A decreased income for farmers in Africa resulting from reduced agricultural output will influence most households' capacity to buy food, even if it is available commercially.

Third, the susceptibility of the African continent to climate change requires desperate implementation of adaptation measures. Global attempts to curb climate change and its subsequent consequences have produced little benefit across Africa (Antwi-Agyei, 2012). Disasters, conflicts; ecosystem degradation; limited access to infrastructure, capital, markets, and technology; and climate change impacts currently inhibit food productivity across the continent (Boko et al., 2007; van den Bos Verma et al., 2020). Even though Africa commands approximately 60% of the world's uncultivated arable land, the continent contributes only 10% to world food production (Elbehri, 2015). The severity of the low productivity situation is exacerbated by a reduced workforce in commercial farming, combined with the expected rapid population growth (Ribaud et al., 2011). Given Africa's constant struggle with hunger and famine, this raises concerns about the role of climate change in food security. The impact of climate change on agricultural production is a significant point of contention due to marginal environmental conditions in many countries in Africa, scarce resources for adaptation, and subsistence livelihoods (FAO, 2005). Thompson et al. (2010) stated that climate change is an imminent possibility for Africa, but there is no need for food insecurity. However, mitigating food insecurity in Africa requires the implementation of multi-country policy strategies.

Following the above discussion, we provided new empirical evidence on the impact of climate change on food security in Africa. In this study, our objective was to assess the impacts of climate change on food security in 15 selected African countries, namely Algeria, Burkina Faso, Cameroon, Cote d'Ivoire, Egypt, Ghana, Kenya, Mali, Morocco, Nigeria, Sierra Leone, South Africa, The Gambia, Tunisia, and Zambia. This study sought to answer three key questions. (1) What are the actual trends in climatic variability in these African countries? (2) What are the impacts of climate change on food security? (3) What is the causal relationship between climate change and food security?

2 Econometric methodology

2.1 Model specification

This study used climatic variables (i.e. temperature and rainfall) coupled with other explanatory variables (gross domestic product (GDP) per capita, population growth, and cultivated

land under cereal production) to model the potential impacts of climate change on food security at country level. Thus, the food security model for a country is mathematically specified as follows:

$$\text{FOSE} = f(\text{CULA}, \text{POP}, \text{GDPPC}, \text{TEMP}, \text{RAIN}) \quad (1)$$

where FOSE is food security. We used cereal availability as a proxy for FOSE in each country. CULA represents the cultivated area under cereal production, POP indicates population growth, GDPPC denotes GDP per capita, TEMP refers to average temperature, and RAIN signifies average rainfall.

We expressed Eq. (1) in an explicit and econometrics form as:

$$\text{LnFOSE}_{it} = \Omega_0 + \beta_1 \text{LnCULA}_{it} + \beta_2 \text{LnPOP}_{it} + \beta_3 \text{LnGDPPC}_{it} + \beta_4 \text{LnTEMP}_{it} + \beta_5 \text{LnRAIN} + \varepsilon_{it} \quad (2)$$

where β_i represents the coefficient of the explanatory variables in the model to be estimated, Ω_i indicates the constant term, ε_i refers to the error term, and Ln indicates a natural logarithm.

2.2 Data characteristics

In this study, we collated annual panel data on 15 countries across Africa for 1970–2016. We chose countries based on their history of food insecurity and food emergencies and their significant economic contribution to Africa's growth. The selected countries were Algeria, Burkina Faso, Cameroon, Cote d'Ivoire, Egypt, Ghana, Kenya, Mali, Morocco, Nigeria, Sierra Leone, South Africa, the Gambia, Tunisia, and Zambia. The data on population growth, GDP per capita, cultivated land under cereal production, temperature, and rainfall were extracted from the World Bank (2019). The data on food security were sourced from the FAO (2019). Rainfall and temperature were used as proxies for climate change. We measured food security, the dependent variable, by the total cereal availability in each country (Baye, 2016; Bezuneh & Yiheyis, 2014; Byrnes & Bumb, 1998; Smith & Haddad, 2001). These variables were chosen for the present study following empirical literature and theoretical economic theory.

2.3 Estimation strategies

2.3.1 Trend analysis of climatic variability

To examine trends in climatic variability across Africa, we employed two nonparametric techniques: the Mann–Kendall test and Sen's slope estimator (Pickson et al., 2020). These tests ascertain trends in climatic variability and establish the corresponding magnitude. The Mann–Kendall test (Kendall, 1975; Mann, 1945) is a nonparametric technique employed to determine time-series trends. The Mann–Kendall test empirically verifies the null hypothesis that 'there is no trend' or the alternative hypothesis that 'there is a decreasing or rising monotonic trend'. The null hypothesis assumes that observations (C_i) are independently ordered at random. Therefore, the statistic (S) of the Mann–Kendall test is estimated as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(C_j - C_k) \quad (3)$$

where C_j and C_k indicate the data scores in time-series j and k ($j > k$), correspondingly. The $\text{sgn}(C_j - C_k)$ is the sgn function as:

$$\text{sgn}(C_j - C_k) = \begin{cases} 1 & \text{if } C_j - C_k > 0 \\ 0 & \text{if } C_j - C_k = 0 \\ -1 & \text{if } C_j - C_k < 0 \end{cases} \quad (4)$$

The p value is computed with the test statistic (S) and the sample size (n) to determine whether the trend is statistically significant. The variance of S is estimated as follows:

$$\text{VAR}(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5) \right] \quad (5)$$

where m signifies the number of tied groups, n represents the number of data points, and i represents the number of data points in the i th group. The standard normal test statistic Z is computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{VAR}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{VAR}(S)}} & \text{if } S < 0 \end{cases} \quad (6)$$

A positive Z statistic indicates an upward or increasing trend, whereas a negative Z statistic suggests a downward or decreasing trend. Our testing trends are established at the 5% significance level ($\alpha = 0.05$). The null hypothesis that ‘there is no trend’ is refuted when the absolute value of the computed Z statistic is greater than the critical value of $Z_{1-\alpha/2}$ (i.e. $Z_{1-\alpha/2} = 1.96$), which indicates the existence of a trend. Nonetheless, the null hypothesis is accepted when the absolute value of the computed Z statistic is lower than the critical value of $Z_{1-\alpha/2} = 1.96$, therefore implying no evidence of a trend (Pickson et al., 2020). The empirical literature shows that the Mann–Kendall test can ascertain the significance of trends in climatic variables (Douglas et al., 2000; Gocic & Trajkovic, 2013; Modarres & Silva, 2007; Partal & Kahya, 2006; Pickson et al., 2020; Tabari & Marofi, 2011; Tabari et al., 2011b; Yue et al., 2002).

Unlike the Mann–Kendall test, we used Sen’s slope estimator (Sen, 1968) to compute the exact slope of a prevailing trend as it changes over time. Sen’s slope estimator applies a simple nonparametric technique to a linear model $g(t)$, which is specified as:

$$g(t) = Q_i + b \quad (7)$$

where t indicates time, b is a constant, and Q represents the slope. The slope (Q_i) of the trend in the sample of N data pairs is calculated to deduce the magnitude of the direction as follows:

$$Q_i = \frac{C_j - C_k}{j - k} \text{ for } i = 1, 2, 3 \dots \dots N, \text{ and } j > k. \quad (8)$$

where C_j and C_k are the data values at time j and k , respectively. The N values of Q_i are rated from the lowest to the highest, and Sen’s slope estimator is calculated as:

$$Q_{\text{med}} = \begin{cases} T_{[(N+1)/2]}, & \text{if } N \text{ is odd} \\ \frac{1}{2}(T_{[N/2]} + T_{[(N+2)/2]}), & \text{if } N \text{ is even} \end{cases} \quad (9)$$

The Q_{med} value is calculated according to a normal distribution. The sign of the (Q_{med}) value reflects the data trend. A negative Q_i value indicates a downward trend, while a positive slope value (Q_{med}) suggests an upward trend in the data. In this study, a confidence interval of 95% was used to indicate whether Sen's slope estimator is statistically different from zero. In the existing literature, Sen's slope estimator is mainly used to determine the magnitude of trends in climatic variables (ElNesr et al., 2010; Gocic & Trajkovic, 2013; Partal & Kahya, 2006; Pickson et al., 2020; Tabari & Marofi, 2011; Tabari et al., 2011a; Yue & Hashino, 2003; Yunling & Yiping, 2005).

2.3.2 Panel unit root tests

We used unit root tests to examine the stationarity properties of variables (Choi, 2001; Im et al., 2003; Levin et al., 2002; Maddala & Wu, 1999). Levin et al.'s (2002) unit root test allows for homogeneity in the autoregressive coefficients and suggests the existence or absence of a unit root problem. Although the Im-Pesaran-Shin (IPS) unit root test is less rigorous, it is more appropriate than the LLC unit root test as it accounts for heterogeneity in autoregressive coefficients. For robustness, we also applied the augmented Dickey-Fuller (ADF) unit root test developed by Maddala and Wu (1999) and Choi (2001). The ADF test is a Fisher-type test that combines p values obtained from each cross-section's stationarity tests. The ADF test is more efficient than the IPS test as it is responsive to the selected lag length in regressions. In this study, each stationarity test was performed with a deterministic intercept and trend.

2.3.3 Pooled mean group estimation approach

The study used the pooled mean group (PMG) estimation approach for dynamic heterogeneous panels (Pesaran et al., 1999). One of the merits of the PMG estimation technique compared with other heterogeneous co-integration methods is that it limits the long-run coefficients to be homogeneous cross-sections. This approach was appropriate for this study because of the selected countries' food insecurity history, comparable economic features, related political systems, and similar regional climatic characteristics, which affect the long-run coefficient in identical circumstances. The PMG estimator is not akin to the mean group (MG) estimator, which allows long-run coefficients to vary among selected countries (Kim et al., 2010; Ofori-Abebrese & Pickson, 2018; Pesaran et al., 1999). However, both PMG and MG estimators require short-run coefficients to be heterogeneous among specified countries.

Another advantage of the PMG estimator is that it is applicable irrespective of whether the variables are integrated of order zero or one [i.e. $I(0)$ or $I(1)$] (Pesaran et al., 2001). Further, inferences of long-run and short-run causality can be made with the PMG estimator even if the existence of co-integration is not systematically determined. Thus, we deployed the PMG technique to assess the long-run and short-run implications of climate change for food security and a heterogeneous dynamic issue among Africa's selected countries. The PMG method of estimation can be specified as an unrestricted autoregressive distributed lag (ARDL) model:

$$Y_{it} = \sum_{j=1}^m \theta_{ij}(Y_i)_{t-j} + \sum_{j=0}^n \beta_{ij}(Z_i)_{t-j} + \mu_i + \varepsilon_{it} \quad (10)$$

where Y_{it} represents food security which is the dependent variable, whereas Z_{it} is a vector of regressors such as GDP per capita, population growth, cultivated area, temperature, and rainfall for each country. Moreover, θ_{ij} denotes scalars, β_{ij} represents the coefficient vectors, μ_i shows the group-specific effect, and ε_{it} is a white-noise error term with zero mean and constant variance.

Similarly, Eq. (10) can be rewritten as an error correction model:

$$\Delta Y_{it} = \phi_i(Y_{i,t-1} - \lambda_i Z_{i,t-1}) + \sum_{j=1}^{m-1} \theta_{ij} \Delta(Y_i)_{t-j} + \sum_{j=0}^{n-1} \beta_{ij} \Delta(Z_i)_{t-j} + \mu_i + \varepsilon_{it} \quad (11)$$

where λ_i represents the long-run coefficients, which are assumed to be homogeneous among the selected countries, ϕ_i shows the error correction term coefficient, which is the speed of adjustment to long-run equilibrium in the event of any shock to the system. β_i indicates the short-run coefficients, which are heterogeneous across the selected countries, μ_i represents the country-specific effect, and ε_{it} denotes the error term with differing variance across the selected countries. According to Pesaran et al. (1999), results obtained from the PMG estimation are ‘consistent and normally distributed asymptotically’.

2.3.4 Dumitrescu–Hurlin panel causality test

We employed the Dumitrescu–Hurlin causality test (Dumitrescu & Hurlin, 2012) to ascertain the causal association between population growth, GDP per capita, cultivated area, temperature, rainfall, and food security. A better understanding of causality among variables helps policymakers implement appropriate policies to ensure sustainable food security. The Dumitrescu–Hurlin causality test presumes that all the coefficients differ across cross-sections. However, Monte Carlo simulations suggest that this test can generate strong outcomes even in the presence of cross-sectional dependency (Dogan & Bulbul, 2017). The Dumitrescu–Hurlin causality test applies when $T > N$ and $T < N$ and it can also be used on both balanced and heterogeneous panels. Dumitrescu and Hurlin (2012) considered the ensuing linear model for the panel causality test:

$$y_{it} = \Omega_i + \sum_{n=1}^N \rho_i^{(n)} y_{i,t-n} + \sum_{n=1}^N \theta_i^{(n)} x_{i,t-n} + \mu_{i,t} \quad (12)$$

where $\rho_i^{(n)}$ stands for the autoregressive parameter, $\theta_i^{(n)}$ represents the coefficient slope that differentiates across cross-sections, Ω_i connotes the constant term, and N indicates the lag length, which is presumed to be the same for all the cross-sections where the panel is balanced.

The following expressions are the null and alternative hypotheses for testing the panel Granger causality:

$$\begin{aligned} H_0 &= \theta_i = 0 & \forall_i &= 1, \dots, N \\ H_1 &= \theta_i = 0 & \forall_i &= 1, \dots, N \\ H_1 &= \theta_i \neq 0 & \forall_i &= N+1, N+2, \dots, N \end{aligned} \quad (13)$$

More precisely, the null hypothesis asserts that no homogeneous causality exists for all cross-sections. In contrast, the alternative proposition suggests evidence of at least one causal association in the panel data.

3 Empirical results and discussion

3.1 Trend analysis of climatic variability

The present study established significant positive trends in temperature in selected African countries between 1970 and 2015 (see Table 1). In Algeria, Egypt, and Tunisia, the average annual temperature exhibited significant and increasing trends with corresponding Z values of 2.14, 2.14, and 2.34. In addition, except in January and February, the average temperature in Algeria, Egypt, and Tunisia displayed a significant positive trend across the months. Moreover, the annual temperature increased significantly in Cameroon, Cote d'Ivoire, and Ghana, with Z values of 3.08, 3.45, and 2.75, respectively. We detected a significant upward trend in temperature on a monthly scale; however, there were no notable temperature trends detected for January in Cameroon, Cote d'Ivoire, or Ghana. Monthly and annual average temperature data exhibited a significant upward trend in Kenya and the Gambia. Similarly, the average annual temperatures in Burkina Faso, Mali, Morocco, Nigeria, Sierra Leone, South Africa, and Zambia showed significant rising trends, given Z values of 2.67, 2.14, 2.22, 2.30, 2.51, 2.63, and 2.46, which are higher than $Z_{0.05/2} = 1.96$. The results again indicated a significant positive trend in monthly temperature except for January and August in Burkina Faso; January, February, August, and September in Mali; January, February, May, August, September, and November in Morocco; January in Nigeria; January and December in Sierra Leone; April, June, and November in South Africa; and April in Zambia.

Analyses of monthly and annual rainfall patterns may be considered crucial as most African farmers depend heavily on rainfall for agricultural production. Table 2 provides monthly and annual rainfall patterns from 1970 to 2015, based on both the Mann–Kendall test and Sen's slope estimator. According to the findings, only Burkina Faso, Mali, and the Gambia exhibited increasing annual rainfall rates, given Z values of 2.23, 2.59, and 2.06, respectively. However, we found no significant trend in annual average rainfall in Algeria, Cameroon, Egypt, Ghana, Kenya, Morocco, Nigeria, Sierra Leone, South Africa, Tunisia, and Zambia, with Z values of 0.21, -0.98 , 0.98 , -0.97 , 0.28 , 0.51 , -0.44 , 1.08 , 1.27 , -1.38 , -0.38 , and 0.08 , respectively, which are lower than $Z_{0.05/2} = 1.96$. Moreover, there were no significant trends in monthly average rainfall in South Africa, Tunisia, and Zambia. In Cameroon and Kenya, the results indicated a significant decreasing rainfall trend in July, whereas Algeria and Sierra Leone observed a positive rainfall pattern in August. In addition, the study found substantial changing patterns in rainfall in May, August, and October for Burkina Faso; October and November for Cote d'Ivoire; June and August for Egypt; October and November for Ghana; July, September, and October for Nigeria; August and September for Morocco; January, February, August, and October for Mali, and August, September, and October for the Gambia.

Table 1 Results of statistical tests for monthly and annual temperature trends (1970–2015)

Panel A	Algeria			Burkina Faso			Cameroon			Cote d'Ivoire			Egypt		
	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation
<i>Monthly temperature</i>															
January	1.25	0.014	No trend	0.59	0.010	No trend	1.86	0.014	No trend	1.58	0.014	No trend	1.25	0.014	No trend
February	0.40	0.003	No trend	1.97	0.025	Trend	2.42	0.016	Trend	2.55	0.020	Trend	0.40	0.003	No trend
March	2.24	0.038	Trend	2.53	0.031	Trend	3.73	0.018	Trend	3.39	0.032	Trend	2.24	0.038	Trend
April	2.26	0.051	Trend	3.54	0.022	Trend	3.26	0.017	Trend	3.51	0.018	Trend	2.26	0.051	Trend
May	3.28	0.052	Trend	2.46	0.026	Trend	3.31	0.017	Trend	2.42	0.023	Trend	3.28	0.052	Trend
June	3.08	0.046	Trend	2.46	0.017	Trend	3.08	0.016	Trend	3.00	0.022	Trend	3.08	0.046	Trend
July	2.98	0.041	Trend	2.97	0.020	Trend	3.39	0.026	Trend	3.41	0.020	Trend	2.98	0.041	Trend
August	2.32	0.031	Trend	1.19	0.007	No trend	2.71	0.019	Trend	3.06	0.014	Trend	2.32	0.031	Trend
September	2.61	0.032	Trend	2.12	0.013	Trend	3.35	0.012	Trend	2.71	0.015	Trend	2.61	0.032	Trend
October	2.91	0.060	Trend	2.78	0.013	Trend	3.24	0.016	Trend	3.09	0.015	Trend	2.91	0.060	Trend
November	2.96	0.038	Trend	2.89	0.036	Trend	3.34	0.021	Trend	2.89	0.021	Trend	2.96	0.038	Trend
December	2.03	0.020	Trend	2.44	0.023	Trend	3.65	0.022	Trend	3.51	0.021	Trend	2.03	0.020	Trend
Annual temperature	2.14	0.035	Trend	2.67	0.020	Trend	3.08	0.019	Trend	3.45	0.019	Trend	2.14	0.035	Trend

Table 1 (continued)

Panel B	Ghana			Kenya			Mali			Morocco			Nigeria		
	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation
<i>Monthly temperature</i>															
January	1.06	0.008	No trend	2.46	0.021	Trend	1.01	0.019	No trend	0.04	0.001	No trend	1.78	0.021	No trend
February	2.76	0.020	Trend	3.91	0.023	Trend	1.70	0.021	No trend	0.08	0.011	No trend	2.14	0.029	Trend
March	3.28	0.027	Trend	2.46	0.029	Trend	2.16	0.041	Trend	2.28	0.039	Trend	3.56	0.025	Trend
April	2.23	0.017	Trend	1.99	0.020	Trend	3.47	0.033	Trend	2.92	0.034	Trend	3.18	0.021	Trend
May	2.42	0.022	Trend	2.44	0.030	Trend	3.16	0.036	Trend	1.21	0.020	No trend	3.37	0.020	Trend
June	2.85	0.023	Trend	2.98	0.026	Trend	3.45	0.019	Trend	2.65	0.054	Trend	2.55	0.019	Trend
July	3.08	0.024	Trend	2.96	0.028	Trend	2.42	0.016	Trend	2.81	0.023	Trend	3.94	0.027	Trend
August	2.49	0.016	Trend	2.47	0.028	Trend	−0.02	0.000	No trend	1.91	0.028	No trend	2.31	0.013	Trend
September	2.24	0.018	Trend	2.57	0.031	Trend	1.17	0.009	No trend	1.76	0.023	No trend	2.52	0.014	Trend
October	2.65	0.018	Trend	3.58	0.021	Trend	3.64	0.021	Trend	2.61	0.032	Trend	2.57	0.022	Trend
November	2.46	0.023	Trend	3.81	0.019	Trend	2.85	0.038	Trend	1.72	0.018	No trend	2.81	0.036	Trend
December	2.32	0.023	Trend	2.49	0.022	Trend	2.12	0.024	Trend	2.84	0.042	Trend	3.07	0.029	Trend
Annual temperature	2.75	0.021	Trend	2.34	0.025	Trend	2.14	0.022	Trend	2.22	0.028	Trend	2.30	0.023	Trend

Table 2 Results of statistical tests for monthly and annual rainfall trends (1970–2015)

Panel A	Algeria				Burkina Faso				Cameroon				Cote d'Ivoire				Egypt			
	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation		
Monthly rainfall																				
January	−0.08	−0.009	No trend	1.23	0.000	No trend	0.44	0.043	No trend	0.38	0.026	No trend	−0.66	−0.020	No trend	−0.66	−0.020	No trend		
February	−0.23	−0.015	No trend	0.13	0.000	No trend	0.19	0.034	No trend	−1.26	−0.231	No trend	0.83	0.021	No trend	0.83	0.021	No trend		
March	−1.17	−0.063	No trend	−1.38	−0.076	No trend	−1.02	−0.228	No trend	−1.93	−0.512	No trend	1.25	0.030	No trend	1.25	0.030	No trend		
April	−1.04	−0.060	No trend	1.17	0.172	No trend	−1.34	−0.369	No trend	1.30	0.378	No trend	−0.81	−0.009	No trend	−0.81	−0.009	No trend		
May	−0.59	−0.025	No trend	−2.06	−0.497	Trend	−1.06	−0.312	No trend	−1.46	−0.581	No trend	−0.74	−0.006	No trend	−0.74	−0.006	No trend		
June	−1.10	−0.015	No trend	1.46	0.309	No trend	0.09	0.049	No trend	0.02	0.039	No trend	2.13	0.002	Trend	2.13	0.002	Trend		
July	1.55	0.026	No trend	0.53	0.141	No trend	−2.10	−1.123	Trend	0.17	0.085	No trend	0.00	0.000	No trend	0.00	0.000	No trend		
August	3.60	0.105	Trend	2.27	0.968	Trend	0.51	0.177	No trend	−0.17	−0.064	No trend	−2.01	−0.006	Trend	−2.01	−0.006	Trend		
September	1.93	0.059	No trend	1.16	0.463	No trend	0.21	0.092	No trend	−0.44	−0.244	No trend	−0.06	0.000	No trend	−0.06	0.000	No trend		
October	0.53	0.022	No trend	2.39	0.557	Trend	0.70	0.245	No trend	3.20	1.163	Trend	−0.36	−0.003	No trend	−0.36	−0.003	No trend		
November	0.13	0.022	No trend	0.68	0.014	No trend	1.02	0.277	No trend	2.71	0.740	Trend	−1.57	−0.021	No trend	−1.57	−0.021	No trend		
December	−0.08	−0.003	No trend	−0.63	0.000	No trend	0.36	0.037	No trend	0.25	0.033	No trend	0.44	0.012	No trend	0.44	0.012	No trend		
Annual rainfall	0.21	0.004	No trend	2.23	0.133	Trend	−0.98	−0.064	No trend	0.98	0.091	No trend	−0.97	−0.007	No trend	−0.97	−0.007	No trend		

Table 2 (continued)

Panel B	Ghana				Kenya				Mali				Morocco				Nigeria			
	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation		
Monthly rainfall																				
January	1.01	0.073	No trend	0.74	0.124	No trend	1.98	0.000	Trend	−0.62	−0.240	No trend	0.04	0.001	No trend	0.04	0.001	No trend		
February	0.11	0.017	No trend	0.62	0.125	No trend	1.99	0.005	Trend	−0.78	−0.207	No trend	−0.80	−0.075	No trend	−0.80	−0.075	No trend		
March	−1.88	−0.519	No trend	1.40	0.491	No trend	−1.04	−0.009	No trend	0.44	0.078	No trend	−1.50	−0.195	No trend	−1.50	−0.195	No trend		
April	1.64	0.469	No trend	−1.69	−0.808	No trend	0.76	0.020	No trend	−1.69	−0.402	No trend	−0.53	−0.128	No trend	−0.53	−0.128	No trend		
May	−1.70	−0.560	No trend	−1.16	−0.391	No trend	−1.02	−0.070	No trend	−1.78	−0.215	No trend	−0.93	−0.229	No trend	−0.93	−0.229	No trend		
June	−0.57	−0.179	No trend	−0.93	−0.174	No trend	1.69	0.063	No trend	−1.82	−0.078	No trend	1.95	0.422	No trend	1.95	0.422	No trend		
July	−0.27	−0.088	No trend	−2.42	−0.242	Trend	0.47	0.082	No trend	1.08	0.022	No trend	−2.16	−0.900	Trend	−2.16	−0.900	Trend		
August	0.61	0.258	No trend	−0.59	−0.050	No trend	2.82	0.615	Trend	2.06	0.085	Trend	0.61	0.213	No trend	0.61	0.213	No trend		
September	−0.15	−0.115	No trend	0.32	0.052	No trend	1.80	0.230	No trend	2.14	0.211	Trend	2.08	0.645	Trend	2.08	0.645	Trend		
October	2.46	0.814	Trend	1.95	0.583	No trend	2.59	0.199	Trend	0.74	0.161	No trend	2.46	0.767	Trend	2.46	0.767	Trend		
November	2.08	0.423	Trend	1.55	0.569	No trend	−0.17	−0.002	No trend	1.34	0.358	No trend	1.36	0.100	No trend	1.36	0.100	No trend		
December	−0.89	−0.080	No trend	1.31	0.404	No trend	−0.28	0.000	No trend	−0.70	−0.188	No trend	1.08	0.031	No trend	1.08	0.031	No trend		
Annual rain-fall	0.28	0.033	No trend	0.51	0.077	No trend	2.59	0.095	Trend	−0.44	−0.036	No trend	1.08	0.094	No trend	1.08	0.094	No trend		

Table 2 (continued)

Panel C	Sierra Leone			South Africa			The Gambia			Tunisia			Zambia		
	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation	Mann–Kendall Statistic (Z)	Sen's slope	Test interpretation
<i>Monthly rainfall</i>															
January	1.25	0.078	No trend	−0.42	−0.170	No trend	−1.22	0.000	No trend	0.45	0.093	No trend	0.81	0.293	No trend
February	0.97	0.087	No trend	−0.89	−0.292	No trend	−0.74	0.000	No trend	−1.08	−0.210	No trend	−0.72	−0.312	No trend
March	−1.57	−0.246	No trend	−0.85	−0.228	No trend	−1.04	0.000	No trend	−1.12	−0.187	No trend	0.83	0.567	No trend
April	−1.67	−0.514	No trend	−0.08	−0.017	No trend	−0.07	0.000	No trend	0.17	0.037	No trend	−1.84	−0.374	No trend
May	−0.42	−0.191	No trend	−0.97	−0.103	No trend	−0.27	−0.023	No trend	−0.51	−0.061	No trend	−1.02	−0.040	No trend
June	−0.68	−0.450	No trend	0.70	0.059	No trend	0.64	0.216	No trend	−0.23	−0.009	No trend	0.59	0.001	No trend
July	0.63	0.613	No trend	−0.32	0.022	No trend	−0.28	−0.200	No trend	1.63	0.029	No trend	−0.91	0.000	No trend
August	2.22	1.559	Trend	−1.36	−0.117	No trend	2.20	1.394	Trend	0.97	0.059	No trend	1.70	0.003	No trend
September	0.54	0.732	No trend	−1.46	−0.180	No trend	2.63	1.825	Trend	1.14	0.131	No trend	−1.51	−0.040	No trend
October	0.00	0.039	No trend	−1.19	−0.224	No trend	2.14	0.705	Trend	0.00	−0.005	No trend	−1.12	−0.181	No trend
November	0.11	0.013	No trend	0.30	0.061	No trend	−0.90	−0.008	No trend	0.00	0.008	No trend	0.34	0.125	No trend
December	1.32	0.122	No trend	0.93	0.264	No trend	−0.89	0.000	No trend	−0.51	−0.116	No trend	−0.42	−0.186	No trend
<i>Annual rain-fall</i>	1.27	0.187	No trend	−1.38	−0.102	No trend	2.06	0.314	Trend	−0.38	−0.026	No trend	0.08	0.014	No trend

Alpha is $Z_{0.05/2} = 1.96$

3.2 Results of the stationarity tests

The study used the LLC, IPS, and ADF stationarity tests. The results of these panel unit root tests revealed that cultivated area, population growth, temperature, rainfall, and food security were stationary at their levels, thereby being integrated of order zero [i.e. $I(0)$] (see Table 3). However, GDP per capita was stationary at its first difference, suggesting that GDP per capita is integrated of order one (i.e. $I(1)$). These outcomes ensure the suitability of applying the panel ARDL approach for investigating climate change implications for Africa's food security.

3.3 Results of the long-run relationship

This section presents the empirical results for examining the effects of precipitation and temperature, including critical control variables, on Africa's food security. Evidence from Hausman test statistics (see Table 4) indicates the acceptance of the null hypothesis of homogeneous long-run estimated coefficients when analysed at a 95% confidence interval. This finding implies that estimates from the PMG technique are more consistent and precise than the MG computations. Thus, the PMG approach is more suitable for the present study as it accounts for short-run heterogeneity in estimations (Pesaran et al., 1999). Therefore, our discussion focused on the PMG results of the long-run relationship (see Table 4). We later deployed the ARDL approach for time-series datasets to examine the long-run heterogeneous impacts of climate change on selected African countries' food security (see Table 4).

The positive and significant coefficient of LnCULA suggests that cultivated land under cereal production has improved food security in Africa. Out of the 15 selected countries, 14 reported a significant direct association between cropped areas and food security in the long run—Algeria (1.349), Burkina Faso (0.922), Cameroon (0.617), Egypt (0.693), Ghana (2.094), Kenya (1.006), Mali (0.290), Morocco (2.299), Nigeria (0.513), Sierra Leone (1.093), South Africa (0.946), the Gambia (0.897), Tunisia (0.559), and Zambia (0.757). Indeed, most African economies are driven by the agricultural sector. Nevertheless, low agricultural production in the region results from

Table 3 Results of the panel unit root tests

Deterministic component: individual intercept and trend			
Variables	Levin, Lin, & Chu (LLC)	Im-Pesaran-Shin (IPS)	Augmented Dickey-Fuller (ADF)
LnCULA	-1.291*	-3.218***	-2.948***
LnGDPPC	1.017	2.418	2.459
Δ LnGDPPC	-6.766***	-11.052***	-9.988***
LnPOP	-20.890***	-17.757***	-14.356***
LnTEMP	-10.393***	-10.871***	-10.048***
LnRAIN	-9.359***	-11.306***	-10.300***
LnFOSE	-1.588**	-4.709***	-14.356***

****, **, and * indicate 1%, 5%, and 10% levels of significance, respectively. Also, Δ denotes the first difference operator

Table 4 Estimated long-run coefficients using the PMG, MG, and ARDL approaches

Dependent variable:LnFOSE						
Regressors	LnCULA	LnGDPPC	LnPOP	LnTEMP	LnRAIN	Hausman test
Pooled mean group	0.777(0.000)***	0.157(0.050)**	0.739(0.000)***	-1.001(0.351)	0.251(0.022)**	9.76 (0.082)
Mean group	0.866(0.000)***	0.403(0.043)**	0.738(0.000)***	-0.319(0.843)	0.151(0.002)***	9.76(0.082)
<i>Cross-section</i>						
Algeria	1.349(0.000)***	0.542(0.105)	0.831(0.004)***	-3.143(0.188)	0.318(0.029)**	
Burkina Faso	0.922(0.000)***	-0.458(0.175)	0.964(0.006)***	-1.115(0.479)	0.252(0.195)	
Cameroon	0.617(0.000)***	0.932(0.001)***	0.682(0.000)***	-2.555(0.280)	-0.016(0.959)	
Cote d'Ivoire	0.220(0.329)	0.444(0.104)	1.617(0.000)***	0.708(0.790)	0.518(0.106)	
Egypt	0.693(0.007)***	0.438(0.069)*	0.447(0.330)	-4.388(0.005)***	-0.029(0.416)	
Ghana	2.094(0.000)***	0.491(0.001)***	0.203(0.221)	-6.174(0.001)***	0.767(0.001)***	
Kenya	1.006(0.000)***	-0.391(0.338)	0.484(0.006)***	-1.064(0.595)	0.138(0.203)	
Mali	0.290(0.014)***	-0.041(0.521)	2.053(0.000)***	-3.574(0.074)*	0.234(0.223)	
Morocco	2.299(0.001)***	1.351(0.055)*	-1.123(0.372)	1.819(0.473)	0.482(0.024)**	
Nigeria	0.513(0.000)***	-0.426(0.001)***	0.719(0.000)***	6.525(0.084)*	0.316(0.279)	
Sierra Leone	1.093(0.000)***	0.703(0.003)***	0.419(0.052)**	-2.511(0.608)	0.256(0.638)	
South Africa	0.946(0.003)***	1.768(0.000)***	1.037(0.001)***	-5.030(0.012)***	0.049(0.830)	
The Gambia	0.897(0.000)***	1.491(0.067)*	-0.571(0.065)*	17.834(0.021)**	0.556(0.153)	
Tunisia	0.559(0.001)***	0.441(0.020)**	1.128(0.006)***	-5.298(0.015)**	0.016(0.860)	
Zambia	0.757(0.000)***	0.395(0.442)	1.014(0.000)***	-2.715(0.113)	0.214(0.323)	

***, **, and * indicate significance at 1%, 5%, and 10% levels, respectively

inadequate farmland access, especially for rural communities. In line with Dogliotti et al. (2014), and Bezuneh and Yiheyis (2014), our findings suggest that the African region will benefit from increased agricultural production by providing greater access to arable land for cereal production to meet consumption demands.

LnGDPPC entered the regression with a significant positive coefficient, suggesting that per capita income supports food security. The long-run impact of GDP per capita on food security at the regional level reflects its effects at the country level. Of the 15 selected countries, GDP per capita directly influenced food security in 8 countries in the long run—Cameroon (0.932), Egypt (0.438), Ghana (0.491), Morocco (1.351), Sierra Leone (0.703), South Africa (1.768), the Gambia (1.491), and Tunisia (0.441). Factors on both the demand and supply sides can explain this outcome. From the demand side, analysis of the income-consumption-production model in Africa suggests that the growth in GDP per capita significantly induces the region's demand for agricultural output. However, as the proportion of consumer spending on food declines with income growth (Fukase & Martin, 2017), Africa's food demand will increase if rising income drives consumers' purchasing power and food security. From the supply side, both productivity and income growth strongly influence food production.

In some regions, rapid population growth and poverty threaten food security (Asian Development Bank, 2012; Faisal & Parveen, 2004; Yang & Hanson, 2009). However, our evidence indicates that population growth (LnPOP) exerts a positive and significant influence on food security in Africa (see Table 4). At the country level, our results suggest that rising population growth positively influences food security in Algeria (0.831), Burkina Faso (0.964), Cameroon (0.682), Cote d'Ivoire (1.617), Kenya (0.484), Mali (2.053), Nigeria (0.719), Sierra Leone (0.419), South Africa (1.037), Tunisia (1.128), and Zambia (1.014) in the long run. Thus, the rise in population growth does not impede efforts to promote food security in Africa. The reason is that the current policies adopted by various governments in Africa to promote financial inclusion, coupled with improved disease-resistant varieties of staple crops and reduced land degradation, have imposed favourable impacts on food production. These interventions have allowed food production to remain slightly ahead of population growth.

Regarding critical variables, temperature (LnTEMP) did not appear to significantly influence food security when examined at standard 1% to 10% significance levels. The study found that the long-run impact of temperature on food security at the regional level was akin to its effects at the country level. Our findings indicate that temperature has a negligible influence on food security in many countries. However, it has either a negative or positive impact on food security in some countries. For instance, the results exhibit a significant negative relationship between temperature and food security in the long term—Egypt (−4.388), Ghana (−6.174), Mali (−3.574), South Africa (−5.030), and Tunisia (−5.298). On the other hands, the temperature has a positive impact on food security in Nigeria (6.525) and the Gambia (17.834) in the long run.

In contrast to temperature, rainfall patterns have a substantial impact on Africa's food security. Specifically, the estimated coefficient of rainfall (LnRAIN) was positive and statistically significant at the 1% level in the long run. The magnitude and significance of precipitation's effect, on the other hands, differ across countries. As most African countries depend on rainfall for farming activities, food security and productivity may be particularly vulnerable to reduced rainfall conditions (Akinbile et al., 2020; Demeke et al., 2011; Tankari, 2020). Recent studies by Meheretu (2020) and Wong et al. (2020) postulated that unpredicted rainfall patterns and regular drought occurrences have a detrimental effect on food production, thus reflecting how growing climate instability

profoundly impacts food insecurity, which is more pronounced in rural areas with less irrigation for food production.

3.4 Short-run relationship results

Table 5 shows the computations of the error correction model performed using the PMG approach. In the short term, the heterogeneity of the concerned variables proposed by the PMG technique helped in conducting cross-sectional estimations to infer the most probable economic policy consequences. First, analysis of ECT_{t-1} estimates suggested a rejection of the null hypothesis of no long-run relationship among the variables. We found the estimated coefficient of ECT_{t-1} to be within the range of -0.271 in Nigeria to -0.945 in Tunisia. Nigeria's food security disruptions caused by cultivated areas, population growth, GDP per capita and climatic variables were corrected within four years ($1/0.271$). Thus, Nigeria requires four years for the disturbances in her food security conditions to die out. At the same time, Cote d'Ivoire requires three years ($1/0.353$) to restore equilibrium after adverse shocks to food security. The effects of shocks to cultivated land, population growth, GDP per capita, and climatic variables on food security in countries such as Cameroon and Ghana were corrected with adjustment periods of three years ($1/0.401$) and two years ($1/0.458$), respectively. Nevertheless, Tunisia's food security disturbances were corrected within a year ($1/0.945$), indicating stable food security in Tunisia compared with other countries.

From the short-run results, the study revealed that except for Mali, Tunisia, and Zambia—where the estimated coefficient of ΔLnCULA was insignificant—the effect of cultivated land under cereal production on food security was positive and significant. Thus, the evidence showed an increase in ΔLnCULA to positively influence food security in Egypt, Morocco, South Africa, and the Gambia, with elasticity values of 1.052, 1.028, 1.202, and 1.003, respectively. The short-run effect of GDP per capita did not deviate from the long-run estimates. However, GDP per capita significantly induced food security in the short run in five countries, namely Cameroon (0.356 at 10% significance level), Ghana (1.036 at 1% significance level), Morocco (6.570 at 1% significance level), the Gambia (1.317 at 1% significance level), and Zambia (0.988 at 1% significance level). For these economies, the estimated coefficient of $\Delta \text{LnGDPPC}$ suggests that food security is susceptible to changes in income per capita in Ghana, Morocco, the Gambia, and Zambia, but it is less pronounced in Cameroon.

Further, the short-run impact of ΔLnPOP on food security varied substantially among countries. For example, while the results indicated that population growth had a negative and significant effect on food security in Algeria, Cameroon, and South Africa, there was a positive relationship between population growth and food security in Burkina Faso and Kenya. Regarding the critical climate variables under consideration, the short-run effect of ΔLnTEMP for the pooled countries was negative (-0.0563) and significant. When examined across countries, the study unearthed that only in Egypt did ΔLnTEM adversely affect food security (-0.708 at 1% significance level). Conversely, and in line with the long-run estimations, ΔLnRAIN significantly induced food security in the short-run (0.113 at 1% significance level). The study reported a similar effect in countries such as Cote d'Ivoire (0.188 at 10% significance level), Ghana (0.285 at 5% significance level), Mali (0.442 at 1% significance level), and the Gambia (0.226 at 1% significance level).

Table 5 Panel error correction model estimation

Dependent variable: ΔLnFOSE						
Regressors	ΔLnCULA	$\Delta \text{LnGDPPC}$	ΔLnPOP	ΔLnTEMP	ΔLnRAIN	ECT_{t-1}
Pooled mean group	0.600(0.000)***	0.872(0.041)**	2.746(0.427)	-.0563(0.085)*	0.113(0.003)***	-0.471(0.000)***
<i>Cross-section</i>						
Algeria	0.704(0.000)***	0.294(0.611)	-8.850(0.064)*	-2.553(0.154)	0.077(0.441)	-0.569(0.000)***
Burkina Faso	0.368(0.071)*	0.680(0.194)	9.675(0.053)**	0.471(0.692)	0.104(0.441)	-0.755(0.000)***
Cameroon	0.440(0.000)***	0.356(0.070)*	-12.600(0.092)*	-0.819(0.346)	-0.061(0.578)	-0.401(0.000)***
Cote d'Ivoire	0.311(0.046)**	0.429(0.160)	-2.721(0.195)	-1.128(0.218)	0.188(0.061)*	-0.353(0.002)***
Egypt	1.052(0.000)***	-0.025(0.900)	4.051(0.258)	-0.708(0.001)***	-0.014(0.349)	-0.544(0.066)*
Ghana	0.532(0.002)***	1.036(0.002)***	4.195(0.396)	0.837(0.476)	0.285(0.022)**	-0.458(0.000)***
Kenya	0.600(0.005)***	0.420(0.359)	29.706(0.000)***	-0.770(0.624)	0.033(0.681)	-0.585(0.000)***
Mali	0.003(0.981)	-0.104(0.410)	-0.075(0.982)	0.794(0.575)	0.442(0.001)***	-0.489(0.000)***
Morocco	1.028(0.038)**	6.570(0.000)***	14.503(0.134)	0.810(0.643)	0.128(0.418)	-0.735(0.000)***
Nigeria	0.454(0.000)***	-0.419(0.132)	-3.203(0.761)	-1.611(0.151)	0.105(0.151)	-0.271(0.010)***
Sierra Leone	0.912(0.000)***	0.151(0.395)	-0.231(0.844)	-1.278(0.214)	-0.077(0.608)	-0.561(0.017)**
South Africa	1.202(0.001)***	0.162(0.921)	-15.861(0.023)**	-2.586(0.184)	0.992(0.281)	-0.606(0.000)***
The Gambia	1.003(0.000)***	1.317(0.003)***	0.564(0.847)	-0.755(0.481)	0.226(0.009)***	-0.578(0.005)***
Tunisia	0.218(0.186)	1.265(0.206)	-7.042(0.209)	1.769(0.154)	-0.110(0.260)	-0.945(0.000)***
Zambia	0.178(0.295)	0.988(0.005)***	29.084(0.600)	-0.917(0.600)	0.170(0.443)	-0.762(0.000)***

***, **, and * indicate significance at 1%, 5%, and 10% level, respectively

3.5 Dumitrescu–Hurlin panel causality test results

The study further employed the Dumitrescu–Hurlin panel causality test to assess the direction of causality between the key variables and food security (see Table 6).

The empirical findings indicated that the null hypothesis that cultivated areas, GDP per capita, and population growth do not homogeneously cause food security was rejected at a 1% threshold (see Table 6). The results indicated that variations in cultivated areas, GDP per capita, and population growth in African countries significantly influenced food security. Additionally, the results disproved the null hypothesis that food security does not homogeneously cause changes in cultivated areas, GDP per capita, and population growth. The findings infer that food security has a causal effect on cultivated areas, GDP per capita, and population growth in the selected African countries. Thus, the empirical findings imply a bidirectional causality between cultivated areas and food security, GDP per capita and food security, and population growth and food security.

Regarding climatic conditions, the null hypothesis that temperature does not homogeneously cause food security was refused at a 1% threshold. Similarly, the study discovered that fluctuations in food security significantly led to changes in temperatures across African countries. The results, therefore, imply a bidirectional causality between temperature and food security. Moreover, at a 1% threshold, the null hypothesis that rainfall does not homogeneously affect food security was rejected. This finding implies that rainfall patterns across the countries better predict variations in food security. However, this study established that variations in food security do not homogeneously cause changes in rainfall patterns across countries. Therefore, given the empirical evidence, there is a unidirectional causality running from rainfall to food security in Africa.

4 Conclusions and policy implications

Extreme weather conditions are among the key factors influencing food security in Africa. Temperature variations have imposed numerous repercussions on the continent's food production as most African economies rely on rainfall for agricultural production. Given the lack of consensus about the actual impact of climate change on food security in Africa,

Table 6 Results of the Dumitrescu–Hurlin panel causality test

Null Hypothesis:	W-Statistic	Probability	Direction of causality
LNFOSE does not homogeneously cause LNCULA	5.140***	0.000	Bidirectional causality
LNCULA does not homogeneously cause LNFOSE	4.014***	0.001	
LNGDPPC does not homogeneously cause LNFOSE	3.608***	0.009	Bidirectional causality
LNFOSE does not homogeneously cause LNGDPPC	3.588***	0.010	
LNPOP does not homogeneously cause LNFOSE	9.118***	0.000	Bidirectional causality
LNFOSE does not homogeneously cause LNPOP	6.648***	0.000	
LNRAIN does not homogeneously cause LNFOSE	4.403***	0.000	Unidirectional causality
LNFOSE does not homogeneously cause LNRAIN	2.934	0.148	
LNTEMP does not homogeneously cause LNFOSE	6.846***	0.002	Bidirectional causality
LNFOSE does not homogeneously cause LNTEMP	7.330***	0.0000	

***Indicates rejection of the null hypothesis at a 1% level of significance

this study examined the roles of rainfall and temperature patterns in food security at the regional level and across countries. Trend analyses of climatic variability detected that the annual average temperature rose significantly between 1970 and 2015 in Africa. Conversely, we did not find significant annual average rainfall trends in most countries, except for Burkina Faso, Mali, and the Gambia. However, on examination of the food security model that accounted for climate change and other control variables, rainfall was found to play a decisive role in Africa's food security in the long run.

On the other hands, we did not detect robust evidence that temperature influences food security in Africa in the long run. In the short run, temperature was found to impede food security, whereas rainfall was positively associated with food security. Intriguingly, these climatic conditions had an inconclusive impact on food security overall as their effects varied dramatically among countries when we evaluated magnitude and direction. The study further indicated that a bidirectional causality exists between food security and temperature, cultivated areas and food security, GDP per capita and food security, and population growth and food security. However, the causality between rainfall and food security is unidirectional, with rainfall affecting food security but not vice versa.

These findings have numerous policy implications. First, because rainfall plays a crucial role in Africa's food security, an intervention to reduce the risk of rain-fed farm production is critical, given the extreme variability of rainfall patterns across the continent. Such intervention must involve establishing irrigation infrastructure to assist farmers, especially those in rural areas. Second, policymakers should also encourage financial inclusiveness by strengthening the financial sector to make small-scale loans available to farmers. This suggestion aligns with Baye's (2016) view that governments, donor agencies, and development partners must pursue policies such as increasing land allocation in local land reforms, increasing food production, and investing in agricultural productivity to increase Africa's food supply capacity. More importantly, further research on the subject must incorporate other dimensions of food security, such as food accessibility, food utilisation, and food stability, to present a broader picture of food security across Africa.

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Declarations

Conflict of interest The authors declared no conflict of interest.

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