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ARTICLE

The Impacts of Climate Change, Agricultural Productivity, and Food Security on Economic Growth in Tunisia: Evidence from an Econometrics Analysis

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ABSTRACT

This study investigates the effects of climate change, agricultural productivity, and food security on economic growth in Tunisia from 1990 to 2022. Employing an Autoregressive Distributed Lag (ARDL) model, the findings reveal that lagged agricultural productivity significantly contributes to economic growth, underscoring agriculture's pivotal role in the national economy. Analysis with a Vector Autoregressive (VAR) model highlights the detrimental effect of rainfall variability on economic growth, emphasizing the vulnerability of Tunisia's rain-fed agriculture to climate change. With its semi-arid and arid climate, Tunisia already faces scarce and irregular rainfall, a challenge intensified by climate change through reduced precipitation and altered seasonal patterns, resulting in prolonged droughts and sporadic, intense rainfall events. Granger causality tests reveal unidirectional relationships from economic growth to agricultural productivity, food security, and temperature variation, as well as from temperature changes to crop production. Additionally, a bidirectional relationship between crop production and food security underscores their interdependence. These findings highlight the pressing need for adaptive strategies to address the adverse effects of climate variability. Suggested measures include the implementation of climate-smart agricultural practices, such as efficient irrigation systems, resilient crop varieties, and sustainable soil management. Investments in sustainable agricultural practices and enhanced food systems are crucial to fostering economic re-

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silience and stability. This study offers valuable insights into the interplay between climate change, agriculture, and economic growth, contributing to the broader discourse on sustainable development and providing actionable policy recommendations to fortify Tunisia's agricultural and economic systems against escalating climate challenges.

Keywords: Agricultural Productivity; ARDL; Climate Change; Economic Growth; Food Security; Granger Causality; VAR

1. Introduction

The complex interplay between climate change, agricultural productivity, and economic growth has emerged as a focal point of global research due to its profound implications for both local and international economies [1]. Climate change intensifies challenges in agriculture by altering growing seasons, reducing crop yields, and exacerbating risks of pests, diseases, and extreme weather events, all of which directly affect food supply, pricing, and economic stability [2, 3]. The significance of this nexus is particularly pronounced in countries like Tunisia, where agriculture constitutes a substantial share of GDP and employment, making it highly vulnerable to climate variability. As agriculture forms the backbone of Tunisia's economy, its decline due to climate-related stressors could lead to widespread socioeconomic disruptions, including heightened food insecurity, increased rural poverty, and economic instability [4].

Globally, the importance of strengthening agricultural resilience aligns closely with the United Nations Sustainable Development Goals (SDGs), particularly those addressing food security, poverty reduction, and climate action. For Tunisia, addressing these issues requires policies and strategies that enhance agricultural productivity, ensure sustainable resource management, and support climate adaptation. Studies emphasize that advancing sustainable food systems and equitable resource distribution are critical for achieving food security and economic inclusivity, especially given escalating climate risks [5, 6].

Despite significant advancements in understanding climate change's impact on agriculture, a notable gap remains in addressing the localized impacts of climate variability on food security and economic growth in Tunisia. The country's reliance on rain-fed agriculture, coupled with increasing water scarcity and the increased frequency of extreme weather events, exposes its food systems to substantial risk. These challenges highlight the urgent need for data-driven insights and innovative solutions to mitigate climate-related impacts on Tunisia's agricultural sector.

While prior studies have extensively examined the interplay between climate change and agriculture, few have provided a localized analysis of its impact on both food security and economic growth in Tunisia a country uniquely vulnerable due to its dependence on rain-fed agriculture and increasing climatic variability. This study distinguishes itself by employing the ARDL model to capture the short- and long-term effects of climate factors on agricultural productivity and economic performance, highlighting bidirectional relationships not often explored in the literature. Furthermore, the study contributes robust policy recommendations that address the pressing challenges of climate adaptation, with a specific focus on enhancing food security and economic resilience in the Tunisian context. The originality of this study stems from its specific focus on Tunisia's unique environmental and agricultural context, providing insights tailored to the region's distinct challenges and opportunities.

This study addresses this gap by employing the ARDL (Autoregressive Distributed Lag) model to explore the intricate relationships among climate change, agricultural productivity, and food security in Tunisia. The ARDL model is particularly suitable for this research as it accommodates variables with mixed orders of integration, captures both short- and long-term dynamics, and accounts for lagged effects, which are essential for understanding delayed responses in agricultural systems. Through this approach, the study reveals critical insights into how immediate and sustained climatic changes, agricultural output and food security affect economic growth in Tunisia.

The findings of this study underline the importance of adopting climate-smart agricultural practices in Tunisia, such as water-efficient irrigation, climate-resilient crop varieties, and soil conservation strategies. Moreover, the ARDL analysis underscores the need for sustainable, closed-loop agricultural systems and adaptive management plans to enhance the resilience of food production. These strategies, combined with investments in sustainable agriculture and climate adaptation, are vital for securing food security and safeguarding rural livelihoods.

This study successfully achieved its aim of illuminating the interconnected impacts of climate change on Tunisia's agricultural sector and food security. The results provide a robust foundation for policy recommendations that promote sustainable agriculture, strengthen climate resilience, and support the country's economic and social stability when facing climate challenges.

2. Literature Review

The impact of climate change on agriculture is a well-documented issue, with extensive research highlighting shifts in temperature, precipitation patterns, and the frequency of extreme weather events.

Saleem et al.[7] highlight the significant threat climate change poses to agriculture, food security, and the achievement of sustainable development goals. Their analysis draws on data from research organizations, policy papers, newspapers, and other sources. While various industries grapple with the challenges of climate change, its impact on agriculture is particularly severe, as it directly undermines food production systems and heightens the risk of food insecurity. This creates alarming implications for global food systems, especially in countries where agriculture is a cornerstone of economic activity and productivity. Rising temperatures and shifting climatic patterns have jeopardized the survival of numerous species, intensifying biodiversity loss by altering ecological structures. These changes indirectly degrade food quality, increase costs, and disrupt distribution systems, further exacerbating food insecurity. The situation underscores the urgent need for robust regional and global policies aimed at mitigating climate change's effects on agriculture and food systems. To safeguard the planet's future, it is vital to implement strategies that reduce or adapt to the impacts of climate change. Addressing this global challenge requires a unified international commitment to mitigate its catastrophic consequences and ensure sustainable development for future generations.

Frimpong et al.[8] investigated the impact of climate change, agricultural advancements, and food availability on economic growth in West Africa over the period 1990 to 2020, employing a panel ARDL approach with data from 14 countries. Their analysis revealed that rising temperatures and extreme weather events significantly threaten food security in the region. Interestingly, the study found no substantial relationship between CO_2 emissions and economic growth. However, agriculture emerged as a critical driver of economic performance, while the effects of food availability on growth were mixed. These findings highlight the pivotal role of sustainable agricultural practices and improved food security in fostering economic resilience in West Africa. The study emphasizes the need for climate-adaptive strategies and investments in agriculture to safeguard economic stability in the face of ongoing climatic challenges.

Nor and Mohamad[9] explored the causal relationship between carbon emissions and agricultural productivity in Somalia from 1990 to 2019, utilizing the Autoregressive Distributed Lag (ARDL) model. Their findings revealed that agricultural productivity has a significant impact on environmental degradation. Interestingly, higher levels of agricultural productivity and GDP per capita were linked to reduced environmental degradation, underscoring the critical role of sustainable agricultural practices. The study highlights the need to prioritize environmentally friendly farming methods to balance economic growth with ecological preservation.

Marwan et al.[10] examined the relationship between climate change, technological inputs, energy consumption, and cereal production in India over the period 1965 to 2018. Employing the ARDL model and the Toda-Yamamoto Granger Causality techniques, their study revealed that temperature negatively impacts cereal production, whereas factors such as rainfall, arable land, energy consumption, fertilizer usage, and technological advancements positively influence it. They further identified a unidirectional causal relationship between these determinants and cereal production, highlighting the critical role of sustainable resource management and technological integration in enhancing agricultural productivity.

Ahmed et al.[11] utilized the Autoregressive Distributed Lag (ARDL) model and the bounds testing approach to cointegration, as proposed by Pesaran et al.[12], to assess the short- and long-term effects of climatic variables (temperature and average rainfall) on agricultural output in Egypt from 1980 to 2020. The ARDL results revealed that, in the long run, a 1% increase in the average annual temperature leads to a 2.962% rise in Egypt's agricultural value-added. Conversely, rainfall showed a negative but statistically insignificant effect on agricultural output. In the short run, the use of chemical fertilizers demonstrated a significant negative impact on agricultural value-added. This outcome is attributed to the excessive use of fertilizers, which can disrupt soil pH balance, increase pest infestations, acidify soil, reduce organic carbon content, and ultimately impair plant growth and yield. The findings underscore the importance of adopting sustainable agricultural practices to mitigate the adverse effects of climate and input mismanagement on agricultural productivity.

Doğanlar et al.[13] examined the impact of climate change on economic growth in the top 20 carbon-emitting countries worldwide, using both static and dynamic panel data analyses for the period 1990–2019. The results from the linear model tests revealed that temperature and precipitation do not have a statistically significant effect on economic growth in these countries. Furthermore, the study found bidirectional causality between temperature and economic growth, while no causal relationship was observed between precipitation and economic growth in the examined countries.

Pickson et al.[14] investigated the effects of climatic conditions on cereal production and their implications for food security in Africa, analyzing data from 1970Q1 to 2017Q4. Their findings indicate that rainfall positively influences cereal crop production, whereas average temperatures generally have an adverse effect. Additionally, the causality tests reveal a bidirectional relationship between climatic conditions specifically rainfall and temperature and cereal production, highlighting the interconnected dynamics between climate and agriculture in the region.

Lobell et al.[15] demonstrate that rising temperatures and altered precipitation significantly affect crop yields and agricultural productivity. The Intergovernmental Panel on Climate Change[16] warns that climate change is likely to disrupt growing seasons, decrease yields, and increase the incidence of pests and diseases, thereby threatening food security.

Research consistently links climate change to agricultural productivity. For example, Fisher et al.[17] show that variations in temperature and precipitation directly impact crop yields and agricultural output. In developing countries like Tunisia, Battisti and Naylor[18] find that climate change exacerbates existing agricultural vulnerabilities, particularly in rain-fed crop regions.

Advancements in agricultural productivity can stimulate broader economic growth by boosting rural incomes, enhancing food security, and supporting related industries such as agro-processing[19]. Conversely, declines in productivity due to climate change can hinder economic development, worsen poverty, and strain national resources[20].

In Tunisia, Youssef et al.[21] reveal that climate variability adversely affects crop yields, impacting food security and rural livelihoods. Their study links increased temperatures and shifting precipitation patterns to reduced agricultural productivity, which in turn affects the national economy. Similarly, Ben Naceur et al.[22] discuss the economic challenges Tunisia faces due to climate-induced agricultural disruptions.

The World Bank[23] outlines various adaptation measures, such as improved irrigation, crop diversification, and investment in climate-resilient technologies. Tunisia has implemented policies to enhance agricultural resilience and promote sustainable practices. Belghiti et al.[24] evaluate these efforts and assess their effectiveness in ensuring long-term economic stability.

Yang et al.[25] highlight that rising global temperatures and altered precipitation patterns are increasingly impacting crop yields and agricultural productivity. The study notes that extreme weather events, including prolonged droughts and intense rainfall, are becoming more frequent, disrupting agricultural activities and threatening food security.

Singh and Kumar[26] explore the resilience of agricultural systems to climate change, indicating that while some regions might benefit from longer growing seasons, the overall negative effects such as increased pest pressure and reduced water availability are likely to outweigh these benefits, particularly in arid and semi-arid regions.

The Food and Agriculture Organization of the United Nations[27] provides a comprehensive analysis of how reduced agricultural productivity impacts national economies, revealing that declines in crop yields lead to higher food prices, exacerbating poverty and economic instability, especially in developing countries.

Khalil et al.[28] assess the significant economic impacts of climate change on agricultural productivity, finding that reduced yields from key crops like wheat and barley could lead to higher food imports, increased national debt, and economic strain on households reliant on agriculture.

Bouaziz et al.[29] analyze how climate variability affects Tunisia's agriculture and economy, noting that increased temperatures and erratic rainfall are diminishing crop yields and agricultural productivity. Their research underscores the need for localized adaptation strategies to mitigate these impacts and enhance resilience.

Fares and Jaziri[30] evaluate Tunisia's adaptation efforts, finding that while advancements have been made in irrigation and crop management, there are still significant gaps in implementing comprehensive adaptation measures and supporting smallholder farmers.

Ahmed et al.[11] discuss the complex interdependencies between climate change, agricultural productivity, and economic growth, emphasizing the bidirectional nature of these relationships. Climate change impacts agricultural productivity, which in turn influences economic growth, while economic activities also contribute to climate change, creating a feedback loop.

Lee et al.[31] use a Vector Autoregressive (VAR) model to analyze data from multiple countries, including Tunisia, finding significant evidence of causality running from climate change to agricultural productivity and from agricultural productivity to economic growth.

Tadesse and Gebre[32] employ Granger causality tests to explore these relationships in Sub-Saharan Africa, suggesting that climate change reduces agricultural productivity, which in turn leads to slower economic growth. The study also highlights that improvements in agricultural productivity can mitigate some negative effects of climate change on economic growth, underscoring the importance of adaptation strategies.

Ben Ali et al.[33] use an Autoregressive Distributed Lag (ARDL) model to examine the long-term and short-term causal relationships between climate change, agricultural productivity, and economic growth in Tunisia. Their study finds that climate change has a long-term negative impact on agricultural productivity, which in turn hampers economic growth, though short-term effects vary based on crop types and regional factors.

Hamed and Trabels[34] apply a Structural Equation Model (SEM) to explore the interdependencies within Tunisia's agricultural sector. Their findings indicate a significant causal pathway from climate change to economic growth through its impact on agricultural productivity, and they highlight the role of government policies in either exacerbating or mitigating these effects based on their focus and implementation.

Prakash[35] explored the causes of climate change in India and examined its effects on agricultural production across various regions. She highlighted that climate change is worsening the challenges faced by India's agricultural sector, which is already under pressure from rising food demand. Agriculture is crucial to India's economy, providing livelihoods for a large part of the population and contributing 17.4% to the nation's GDP (Economic Survey, 2015–2016). Prakash noted that factors such as droughts, heat waves, storms, floods, delayed monsoons, and temperature shifts impact agricultural activities like planting, tending, and harvesting seasonal crops (Zaid, Rabi, and Kharif). Her research indicated that climate change has led to shifts in cropping patterns and reduced yields for crops such as sugarcane, groundnuts, and paddy in states including Gujarat, Maharashtra, Odisha, West Bengal, Uttar Pradesh, and Bihar. Some regions, such as Bihar, Maharashtra, and Kerala, have shown climate variability with areas experiencing drought while others face frequent flooding. This environmental instability often leads to crop failures, resulting in severe debt for farmers, with tragic outcomes in some cases. Prakash also emphasized the broader impacts, including threats to food security, changes in nutrition quality, shifts in pest and disease patterns, and an increasingly challenging life for economically vulnerable populations.

Hassana and Mohamed[36] applied the Autoregressive Distributed Lag (ARDL) approach and cointegration analysis to examine the dynamic effects of economic factors (domestic investment, rural population growth) and environmental factors (carbon emissions and rainfall) on agricultural productivity in Somalia from 1990 to 2023. They found that increased domestic investment and rural population growth have a positive long-term impact on agricultural output, underscoring the importance of human capital development and agricultural infrastructure investment. Conversely, higher carbon dioxide emissions were shown to harm agricultural productivity, highlighting the urgent need to address climate change. Rainfall also proved to be a key factor in boosting agricultural output, stressing the value of effective water management and conservation efforts. To achieve sustainable agricultural growth, support economic development, and enhance food security in Somalia, the authors recommended investments in agricultural infrastructure, carbon emissions reduction, rural development, and initiatives promoting water management and conservation.

Derouez and Ifa[37] utilized the Auto-Regressive Distributed Lag (ARDL) approach and Vector Error Correction Model (VECM) to analyze data from 1990 to 2022, investigating the short- and long-term relationships between food security, climate change, population growth, water resources, and renewable energy desalination in five Arab countries: Morocco, Egypt, Jordan, Saudi Arabia, and the United Arab Emirates. Their findings indicate that climate change presents a substantial threat, particularly for Morocco, Egypt, and Jordan. Additionally, population growth intensifies food security challenges across the region, while water scarcity stands out as a critical issue, especially in Jordan.

Abdi et al.[38] examined the negative impacts of extreme weather on food security in Somalia, assessing how climate change affects key crops (maize, sorghum, rice, wheat, sugarcane, bananas, and beans) using the autoregressive distributed lag (ARDL) method over the period from 1991 to 2019. Their findings show that increased rainfall boosts long-term yields of sorghum, sugarcane, and bananas, while reducing bean productivity. Temperature shifts, however, negatively influence long-term yields of sorghum, rice, and beans, though they temporarily increase rice and sorghum production in the short term. Interestingly, greenhouse gas emissions and expanded crop-harvested areas contribute to higher yields for several crops. Additionally, agricultural labor positively affects banana yields but has a limiting effect on other crops. Based on these insights, the study recommends adopting climate-resilient crop varieties, investing in irrigation systems, improving weather forecasting and early warning systems, and advancing sustainable land management practices.

Ajeigbe and Ganda[1] explored the links between food security, environmental sustainability, and sustainable growth across 63 countries, using the Generalized Method of Moments (GMM), Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS) methods over the period from 2010 to 2021. Their findings show that food exports, agricultural production, fertilizer use, foreign direct investment (FDI), population growth, and employment are positively correlated with economic growth while generally reducing poverty and unemployment, though population growth had an insignificant effect on unemployment. In contrast, food imports were positively associated with poverty and unemployment but had a negative impact on economic growth. To promote food security, inclusive growth, and reduce global inequality, the study suggests that nations, governments, and policymakers should emphasize eco-friendly economic and green policies to support sustainable agriculture. Encouraging innovation, sustainable land use, and responsible food processing can help reduce emissions and pollution, thereby supporting eco-friendly fishing, aquaculture, and agriculture to secure food supplies and advance the Sustainable Development Goals (SDGs).

3. Data and Methodology

3.1. Data Description

This study investigates the effect of climate change, agricultural sector and food security on economic growth in Tunisia using the Autoregressive Distributed Lag (ARDL) approach. The ARDL model offers several advantages over other econometric methods, such as SARIMA, ARMA, and ARIMA, making it well-suited for this analysis. Its flexibility allows it to handle variables with mixed integration orders stationary at level (I(0)) or first difference (I(1)) without pre-differencing or requiring large sample sizes. The ARDL model simultaneously estimates both short- and long-term relationships, providing a comprehensive understanding of variable dynamics. Its robustness addresses issues like autocorrelation and omitted variable bias, resulting in unbiased and efficient estimates. Unlike traditional cointegration techniques, which often require extensive datasets for reliable results, the ARDL model performs effectively even with smaller sample sizes. It uses optimal lag selection based on criteria like the Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC), enabling it to capture specific data dynamics effectively. Furthermore, it avoids the restrictive assumptions of traditional tests like Engle-Granger or Johansen, increasing its practicality and adaptability. These features make the ARDL model particularly suitable for examining complex relationships with limited data, offering clear and actionable insights into both short- and long-term effects [39].

This study employs annual time series data from 1990 to 2022, sourced from the World Bank's World Development Indicators (WDI) database [23] and the Climate Change Knowledge Portal of Tunisia. This period was selected due to the availability of comprehensive data for all model variables. Gross Domestic Product per Capita (GDPC) serves as the dependent variable, while the explanatory variables include the crop production index, value added by agriculture, forestry, and fishing, annual mean temperature, rainfall, and food security. To ensure normal distribution, these variables were logarithmically transformed. **Table 1** presents the variables and their logarithmic transformations.

3.2. Model Method

This study employed the Autoregressive Distributed Lag (ARDL) approach introduced by Pesaran et al. [12], a highly regarded econometric technique. The ARDL model excels in cases where variables are either stationary at level [I(0)] or integrated of order one [I(1)] or a combination of both integration orders, making it a preferred method compared to alternative approaches. It is particularly effective in capturing both short-term and long-term impacts of independent variables on economic growth. Furthermore, the ARDL approach is well-suited for small sample sizes and provides remarkable flexibility in handling variables with different orders of integration. By accommodating mutually cointegrated variables, whether I(0) or I(1), it enables a robust analysis of the relationship between dependent and independent variables (Nasrullah, et al. [40]. The ARDL model involves several systematic procedures. First, to determine the order of integration of the variables, the study employed the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Zivot-Andrews (ZA) unit root tests. Conducting these tests is crucial to ensure that the variables are stationary and not integrated beyond the second order, as variables with integration higher than the second order can compromise the accuracy of the results. Additionally, before examining causality, it is important to assess the cointegration properties of the variables. To determine whether a long-term relationship exists among the variables, the study applied the bounds cointegration test Noorunnahar, et al. [41]. This study investigates the impact of Climate change, Crop production, Agricultural Productivity, and Food Security on Economic Growth in Tunisia based on the model framework outlined by Atchadé and Norigbod [39]. The constructed model is as follows:

$$GDPC = f\,(Agri, FS, Temp, CP, Rain) \tag{1}$$

where:

- ***GDPC*** represents economic growth for each year in Tunisia.
- ***CP*** represents agricultural production for each year in Tunisia.

Table 1. Source and description of variables.

Variables	Description	Logarithmic Forms	Units	Sources
CP	Crop production (Agricultural production for each year	LCPI	Index	WDI
Agri	Agriculture, forestry, and fishing, value added	LAGRI	Constant 2015 US$	WDI
GDPC	GDP per capita	LCO2	Constant 2015 US$	WDI
Temp	Annual mean temperature	LMNT	°C	CHKP
Rain	Annual precipitation	LRain	Millimeter	CHKP
FS	Food security	LFS	Food production index (2014–2016 = 100)	WDI

WDI: world development indicators; CHKP: Climate change knowledge Portal.
Source: author.

- ***Agri*** represents the value added by agriculture, forestry, and fishing for each year in Tunisia.
- ***Temp*** represents the mean temperature for each year in Tunisia.
- ***Rain*** represents precipitation for each year in Tunisia.
- ***FS*** represents food security for each year in Tunisia.

Following logarithmic transformation, the empirical model is expressed as:

$$LGDPC_t = \alpha_0 + \alpha_1 LAgri_t + \alpha_2 LCP_t + \alpha_3 LTemp_t + \alpha_4 LRain_t + \alpha_5 LFS_t + \epsilon_t \tag{2}$$

Where: ε is the error term; $(\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5)$ are the coefficients.

To analyze the short-term and long-term effects of climate change, agricultural productivity, and food security on Tunisia's economic growth, Equation (1) can be reformulated to represent the long-run cointegration relationship within the ARDL framework as follows:

$$\begin{aligned}\Delta LGDPC_t &= \beta_0 + \beta_1 LGDPC_{t-1} + \beta_2 LAgri_{t-1} \\ &+ \beta_3 LCP_{t-1} + \beta_4 LTemp_{t-1} + \beta_5 LRain_{t-1} \\ &+ \beta_6 LFS_{t-1} + \textstyle\sum_{p=1}^{q} \gamma_1 \Delta LAgri_{t-p} + \\ &\textstyle\sum_{p=1}^{q} \gamma_2 \Delta LCP_{t-p} + \sum_{p=1}^{q} \gamma_3 \Delta LTemp_{t-p} + \\ &\textstyle\sum_{p=1}^{q} \gamma_4 \Delta LRain_{t-p} + \sum_{p=1}^{q} \gamma_5 \Delta LFS_{t-p} + \epsilon_t\end{aligned} \tag{3}$$

Note: Δ is the first difference; q is the optimum lag length; β_0 is the constant; $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$ are the short-run impact; $\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5$ *are the long-run impact;* $\epsilon_t \simeq$ *iid(0,Ɣ) is the error term.*

Specifically, we tested the null hypothesis, which posits the absence of any relationship, against the alternative hypothesis suggesting the presence of a significant long-term cointegration relationship. Based on this framework, the following assumptions were formulated:

$H_0 : \rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_5$, this null hypothesis indicates that in the long-term Climate change, Crop production, Agricultural Productivity, Food Security and Economic Growth are not cointegrated.

$H_1 : \rho_1 \neq \rho_2 \neq \rho_3 \neq \rho_4 \neq \rho_5$, this alternate hypothesis demonstrates that long term Climate change, Crop production, Agricultural Productivity, Food Security and Economic Growth are cointegrated.

After establishing the long-term relationship between the variables of interest, the next step is to examine their short-term correlations. Utilizing the ARDL model allows for a detailed analysis of short-term dynamics and the error correction term, providing insights into the adjustment process toward equilibrium.

$$\begin{aligned}\Delta LGDPC_t &= \gamma_0 + \textstyle\sum_{p=1}^{q} \gamma_1 \Delta LAgri_{t-p} + \\ &\textstyle\sum_{p=1}^{q} \gamma_2 \Delta LCP_{t-p} + \sum_{p=1}^{q} \gamma_3 \Delta LTemp_{t-p} + \\ &\textstyle\sum_{p=1}^{q} \gamma_4 \Delta LRain_{t-p} + \sum_{p=1}^{q} \gamma_5 \Delta LFS_{t-p} + \\ &\mu ECM_{t-1} + \epsilon_t\end{aligned} \tag{4}$$

Where μ is the coefficients of ECM for short term dynamics. ECM shows the speed of adjustment in the long-term equilibrium after a shock in the short term.

After confirming the existence of a long-term relationship among the research variables, the next step involves validating the robustness of the findings through a series of diagnostic tests. To check for serial correlation, we applied the Breusch-Godfrey LM test Breusch and Pagan[42]. For assessing heteroscedasticity, the Breusch-Pagan-Godfrey test Breusch and Pagan[43] was utilized. Additionally, the stability of the model was evaluated using the CUSUM and CUSUM square tests.

In this study, we utilized the Granger causality test Granger[44] to explore the causal relationships among the selected variables. The test's null hypothesis assumes no Granger causality between the variables. Rejection of the null hypothesis indicates the existence of a causal relationship, which could manifest as unidirectional causality, bidirectional causality, or independence between the variables Noorunnahar, et al.[41]; Nasrullah, et al.[40].

3.3. Descriptive Statistics of Variables

The **Table 2** reveals that Tunisia's economic growth per capita (GDPC) has an average value of 3,240.52 units, with values ranging from 2,085.53 to 4,094.88, indicating moderate variability (standard deviation of 693.34) and reflecting fluctuations in the country's economic conditions over the years. The agricultural sector's contribution (AGRI) averages approximately 3.18 billion units, with a considerable spread from 1.81 billion to 4.64 billion, suggesting that agricultural productivity plays a dynamic role in Tunisia's economy. Agricultural production (CP) also shows notable variability, averaging at 83.57, with a high of 131.12 and a low of 43.97, indicating fluctuating yields that may reflect changing environmental conditions or agricultural practices. Food security (FS), with an average of 81.89, varies significantly, ranging from 46.69 to 122.95, showing the impact of economic and environmental factors on food access and availability. Climate factors, represented by mean temperature (TEMP) and precipitation (RAIN), show differing levels of variability. The mean temperature is relatively stable, averaging 20.58°C with little deviation, while precipitation is more variable, averaging 271.77 mm but fluctuating between 138.19 and 407.52 mm, likely affecting agricultural output and food security annually. Together, these variables paint a picture of Tunisia's economic and agricultural landscape, where climate and resource availability have significant implications for growth and food security.

Table 2. Descriptive statistics for variables.

Variables	GDPC	AGRI	CP	FS	TEMP	RAIN
Mean	3240.517	$3.18\text{x}10^9$	83.573	81.885	20.584	271.77
Maximum	4094.881	$4.64\text{x}10^9$	131.120	122.950	21.440	407.520
Minimum	2085.533	$1.81\text{x}10^9$	43.970	46.690	19.320	138.190
Std. Dev.	693.337	$8.63\text{x}10^8$	21.3842	19.767	0.477	58.853

Source: author's estimates.

In **Figure 1**, each panel represents time-series data for key variables related to agriculture, climate, and economic performance in Tunisia from 1990 to 2022. These variables include GDP per capita (GDPC), crop production (CP), mean temperature (TEM), precipitation (RAIN), agricultural value added (AGRI), and food security (FS). Here's an overview of the main trends observed:

GDP per Capita (GDPC): This trend likely shows an overall upward movement, reflecting economic growth in Tunisia over the years. However, any visible fluctuations may indicate periods of economic challenge, possibly due to climate impacts, global economic changes, or local conditions affecting agricultural productivity, which is an important sector in Tunisia.

Crop Production (CP): This series shows an increasing trend with some notable dips, indicating overall growth in agricultural output but with interruptions likely linked to adverse climate conditions or economic factors. These fluctuations highlight the sensitivity of crop production to environmental changes, such as temperature and rainfall variability.

Mean Temperature (TEM): A consistent upward trend in mean temperature suggests rising temperatures in Tunisia over the years, aligning with global climate change patterns. This increase may have significant implications for agriculture, as higher temperatures can affect crop yields and water resources, especially in a region already prone to arid conditions.

Precipitation (RAIN): The precipitation trend displays substantial variability, with a marked decrease around 2020. Such fluctuations highlight the irregular rainfall patterns that can disrupt agricultural cycles, potentially leading to lower crop production and increased food insecurity during drought years.

Agricultural Value Added (AGRI): This variable likely shows a gradual increase, indicating agriculture's growing or stable contribution to Tunisia's economy. However, any observed fluctuations may reflect the sector's vulnerability to external shocks, such as climate variability, which can directly impact productivity and economic stability.

Food Security (FS): This trend may reflect the challenges Tunisia faces in maintaining stable food security levels. Fluctuations here could indicate periods of vulnerability, potentially linked to crop production and economic conditions. Reduced precipitation or high temperatures can further strain food security, especially when local agricultural output is low.

Overall, **Figure 1** highlights the interconnectedness among climate factors (temperature and precipitation), agricultural outcomes (crop production and agricultural value added), economic performance (GDP per capita), and food security in Tunisia. Rising temperatures and variable precipitation patterns appear to pose significant challenges, emphasizing the importance of climate adaptation measures to ensure resilience in Tunisia's agriculture sector and broader economy.

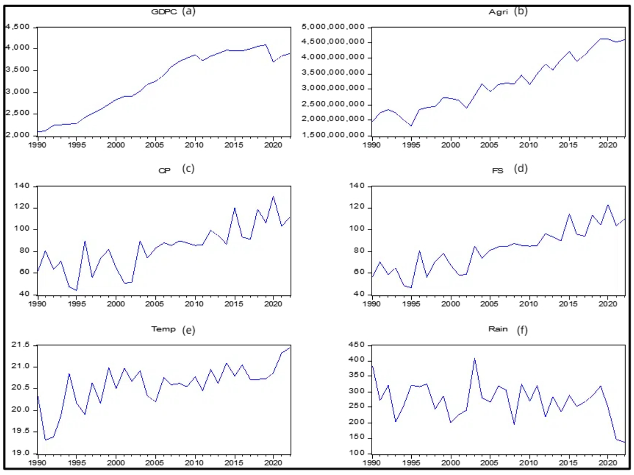


Figure 1. Historical trend of variables. (**a**): Historical trend of GDP per capita; (**b**): Historical trend of Agriculture, forestry, and fishing, value added; (**c**): Historical trend of Crop production; (**d**): Historical trend of Food security; (**e**): Historical trend of Annual mean temperature; (**f**): Historical trend of Annual precipitation.

Source: author's estimates.

4. Results and Discussion

4.1. Unit Root Tests

In this study, we employ two tests to detect autoregressive unit roots: the Augmented Dickey-Fuller (ADF) test[45] and the Phillips-Perron (PP) test[46]. The results of these stationarity tests are summarized in **Table 3**.

Our data initially exhibit a unit root at the level but become stationary after first differencing. This finding suggests that most variables are stationary at I(1) rather than I(0), meeting the requirements for causality analysis. Specifically, precipitation and crop production are stationary at the level, while economic growth, mean temperature, agricultural productivity, and food production were non-stationary at the level but achieved stationarity after the first differencing.

4.2. VAR Lag Order Selection Criteria

To determine the optimal ARDL model, we used the Akaike Information Criterion (AIC), which balances goodness of fit with model parsimony. The AIC suggested an optimal lag length of 1. Consequently, the ARDL (1, 1, 0, 1, 0, 0) model was selected, as it yielded the lowest AIC value. The lag selection is based on the AIC criterion, detailed as follows in **Table 4**.

4.3. ARDL Model Estimation Results

The results from the ARDL model presented in **Table 5** indicate several key findings. The coefficient for LGDP (−1), representing lagged economic growth, is highly statistically significant with a value of 0.995, suggesting a strong positive relationship between past and current economic growth, implying that economic growth exhibits high persistence and that past performance is a reliable predictor of future growth. Conversely, LAGRI (current agricultural productivity) is not statistically significant, indicating no immediate effect on economic growth. However, LAGRI (−1) (lagged agricultural productivity) shows a significant positive impact on current economic growth, highlighting the importance of past agricultural productivity. The coefficient for LCP (crop production) is not significant, suggesting that crop production does not have a short-term impact on economic growth. Similarly, LFS (food secu-

Table 3. Unit root test results.

Variables	Level		1st Difference		Order of Integration
	ADF	PP	ADF	PP	
LGDP	−2.27	−2.28	−4.88***	−4.9***	I (1)
LAGRI	−1.08	−0.78	−5.5***	−11.71***	I (1)
LCP	−2.85*	−2.86*	−5.42***	−15.34***	I (0)
LFS	−0.323	−2.03	−5.93***	−14.6***	I (1)
LTEMP	−2.25*	−2.63*	−9.5***	−16.66***	I (0)
LRAIN	−3.88***	−3.69***	−8.8***	−10.83***	I (0)

***, **, and* denote significance respectively at the 1%,5%, and10%.
Source: author's estimates.

Table 4. VAR lag order selection criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	222.75	NA	3.40e-14	−13.9843	−13.7067	−13.894
1	350.34	**197.5***	**9.7e-17***	**−19.889***	**−17.950***	**−19.259***
2	378.63	32.850	2.12e-16	−19.8935	−15.7875	−18.2195

Source: author's estimates.
* Indicates lag order selected by the criterion
LR: sequential modified LR test statistic (each test at 5% level), FPE: Final prediction error, AIC: Akaike information criterion, SC: Schwarz information criterion, HQ: Hannan-Quinn information criterion.

rity) does not show a significant effect on growth, although LFS (−1) (lagged food security) is marginally significant at the 10% level, suggesting a small positive influence of past food security on current economic performance. The coefficients for LTEMP (temperature) and LRAIN (rainfall) are both statistically insignificant, indicating no short-term effects on economic growth. The constant term is also not significant. Model diagnostics reveal an R-squared of 0.98, indicating that the model explains 98% of the variation in economic growth, signifying a very good fit. The F-statistic of 242.45 with a p-value of 0.000 confirms the overall statistical significance of the model, while the Durbin-Watson statistic suggests no autocorrelation in the residuals. Overall, the model suggests that past economic growth and agricultural productivity are the primary short-term drivers of economic growth, while other factors like climate and food security do not show significant short-term effects in this context.

To ensure the model's stability and robustness, we performed several diagnostic tests. These included the Jarque-Bera test for normality, Q-statistics and Breusch-Godfrey tests for serial correlation, and the Breusch-Pagan-Godfrey test for heteroscedasticity. The results of these diagnostic tests are summarized in **Table 5**.

Table 5. ARDL model estimation results.

LGDP **ARDL (1, 1, 0, 1, 0, 0)** **Variable**	**Coefficient**	**Prob. ***
LGDP (−1)	0.995	0.000***
LAGRI	0.004	0.973
LAGRI (−1)	0.24	0.01***
LCP	0.195	0.431
LFS	0.29	0.425
LFS (−1)	0.129	0.09*
LTEMP	−0.026	0.946
LRAIN	−0.027	0.366
C	4.36	0.148
R-squared	0.98	Mean dependent var: 8.07
F-statistic	242.45	Durbin-Watson stat: 2.58
Prob (F-statistic)	0.000	

*Note: p-values and any subsequent tests do not account for model.
Source: author's estimates.

4.4. Diagnostic Test of the Model

After estimating the ARDL model, it is essential to assess its goodness-of-fit and confirm that it is free from econometric problems by conducting the following diagnostic tests in **Tables 6–8**.

Furthermore, analysis of the correlogram of the residuals and the square of the residuals in **Table 6** reveals that the residual is white noise.

The Breusch-Godfrey Serial Correlation LM Test is used to check for serial correlation in the residuals of a

Table 6. Robustness test of the estimated ARDL model.

Autocorrelation	Partial Correlation		AC	PAC	Q-Stat	Prob*
. *| . |	. *| . |	1	−0.171	−0.171	0.9057	0.341
. *| . |	. *| . |	2	−0.016	−0.046	0.9139	0.633
. |* . |	. | . |	3	0.085	0.077	1.1575	0.763
. *| . |	. | . |	4	−0.078	−0.053	1.3721	0.849
. | . |	. *| . |	5	−0.051	−0.072	1.4665	0.917
. *| . |	. *| . |	6	−0.032	−0.065	1.5057	0.959
. | . |	. *| . |	7	−0.043	−0.055	1.5806	0.979
. | . |	. *| . |	8	−0.033	−0.050	1.6262	0.990
. |**. |	. |**. |	9	0.321	0.320	6.1842	0.721
. *| . |	. *| . |	10	−0.186	−0.095	7.7905	0.649
. | . |	. | . |	11	0.040	−0.002	7.8689	0.725
. | . |	. *| . |	12	−0.075	−0.162	8.1639	0.772

Source: author's estimates.

regression model in **Table 7.** This indicates at the 5% threshold an absence of serial correlation in the residuals.

Table 7. Breusch-Godfrey serial correlation test LM.

Breusch-Godfrey Serial Correlation LM Test: Null Hypothesis: No Serial Correlation at Up to 2 Lags			
Test Statistics	**Value**	**Prob.**	**Value**
F-statistic	0.8	Prob. F (2,21)	0.46
Obs*R-squared	2.28	Prob. Chi-Square (2)	0.32

Source: author's estimates.

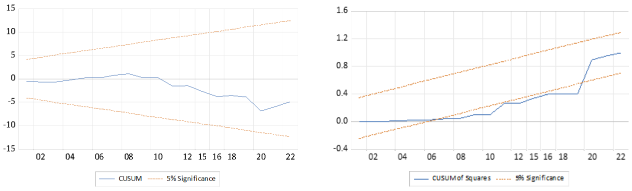
In addition, The Breusch-Pagan-Godfrey test checks for heteroskedasticity, which occurs when the variance of the errors is not constant across observations. **Table 8** implies that the residuals have constant variance, and there is no significant evidence of heteroskedasticity in the model.

Table 8. Test of heteroskedasticity: Breusch-Pagan-Godfrey.

Heteroskedasticity Test: Breusch-Pagan-Godfrey Null Hypothesis: Homoskedasticity			
Test Statistics	**Value**	**Prob.**	**Value**
F-statistic	0.662	Prob. F (8,23)	0.719
Obs*R-squared	5.99	Prob. Chi-Square (8)	0.65
Scaled explained SS	10.05	Prob. Chi-Square (8)	0.26

Source: author's estimates.

The cumulative sum of recursive residuals (CUSUM) test in **Figure 2**, as suggested by Pesaran, et al.[12], confirms the model's stability. However, the CUSUM of Squares test indicates the absence of cointegration, suggesting that the variables are unlikely to move together in the long run. Consequently, the analysis should shift its focus to exploring short-run dynamics, potentially using a Vector Autoregressive (VAR) model.



(**a**) CUSUM test (**b**) CUSUM of Squares test

Figure 2. CUSUM and CUSUM of squares tests.

Source: author's estimates.

4.5. Cointegration and Fundings

The ARDL bounds test results showed an F-statistic of 2.033 for our model, which is below the lower critical value of 2.08 at the 10% significance level. This suggests that there is no evidence of a long-run relationship among the variables. We employed the ARDL (1, 1, 0, 1, 0, 0) model, and a summary of the short-run estimation results is presented in the **Table 9.**

Table 9. Cointegration test.

Test Statistics		
F. Statistic	2.033	
Number of independent variables-k	5	
Critical Values (%)	**I (0)**	**I (1)**
1	3.06	4.15
5	2.39	3.38
10	2.08	3

Source: author's estimates.

Table 10 shows that the coefficient of determination (R-squared) reacted is 99% and the adjusted coefficient of determination is 98% which states that the model has a very good explanatory power.

Agricultural Value Added ($LAgriculture\,value\,added_{t-1}$): The coefficient of 0.175 (significant at the 10% level) suggests that agriculture's value added in the previous year has a positive and significant short-run impact on GDP per capita. This result underscores the importance of agriculture in Tunisia's economy, where improvements in agricultural productivity directly contribute to economic growth. This is consistent with findings of Chebbi[47], who examined the cointegration of various sectors within the Tunisian economy and found that all sectors are cointegrated, meaning they tend to move in tandem over time. He emphasized the importance of considering the agricultural sector in the analysis of intersectoral growth. In the short term, agriculture appears to play a partial role as a driving force for the growth of non-agricultural sectors, with its impact primarily benefiting the agro-food industry subsector.

Rainfall ($LRainfall_{t-1}$): The coefficient of -0.003 (significant at the 5% level) indicates that an increase in rainfall from the previous year has a notable negative effect on GDP per capita. This inverse relationship between lagged rainfall and economic growth can be attributed to several factors. While moderate rainfall supports agricultural productivity, excessive rainfall can lead to adverse outcomes, such as flooding, waterlogging, and soil erosion, all of which reduce crop yields and weaken agricultural performance. This decline in productivity can hinder economic growth, especially in agriculture-dependent economies. Furthermore, rainfall at inopportune times such as during harvest or outside the growing season can disrupt farming activities, diminishing its economic contribution. Poor water management infrastructure, including inadequate dams, reservoirs, and irrigation systems, exacerbates these challenges by failing to efficiently harness excess rainfall, often resulting in damage and inefficiencies. Excessive rainfall also has the potential to damage critical infrastructure, such as roads, bridges, and irrigation systems, thereby increasing public expenditure on repairs and reducing productivity in sectors like trade and transportation. In Tunisia, the uneven regional distribution of rainfall further complicates the situation. In fertile regions, excessive rainfall can lead to diminishing agricultural returns, while in arid areas, it may fail to sufficiently alleviate water scarcity, resulting in limited or negative economic impacts. Heavy rainfall in certain years has caused significant losses in staple crops, such as cereals and vegetables, in addition to damaging infrastructure. For olive cultivation, which is an important sector in Tunisia, moderate rainfall is beneficial, but excessive rainfall can lead to fruit drop and reduced yields. Research further underscores the broader challenges posed by extreme weather events. For instance, Wang et al.[48], using data from China's National Rural Fixed-Point Survey (2006–2015), demonstrate that both droughts and heavy rainfall negatively impact agricultural productivity and income. These disruptions often force farmers to shift to non-agricultural activities or migrate to urban areas, highlighting the significant risks extreme weather poses to food security and economic stability. Similarly, Deschênes and Greenstone[49] find that unseasonal rainfall adversely affects crop yields and agricultural income, ultimately impeding economic performance. These findings align with studies such as Bouaziz et al.[29], which indicate that erratic rainfall patterns negatively influence Tunisia's agricultural productivity and, consequently, its economy. By contrast, insufficient rainfall also hampers crop yields, disrupting the agricultural sector and further straining GDP growth.

Lagged GDP per capita ($LGDP\,per\,capita_{t-1}$): With a high coefficient of 0.958 (significant at the 10% level), this variable shows a strong positive persistence in economic growth from one period to the next. Past economic growth tends to influence current GDP positively, suggesting stable growth momentum over time.

Crop Production ($Crop\,production_{t-1}$) : Although it has a positive coefficient of 0.23, its p-value of 0.19 indicates that it is not statistically significant in the short run. This suggests that while crop production contributes to GDP, its short-term impact may be variable and less robust.

Food Security ($LFood\,security_{t-1}$): The positive coefficient of 0.42 suggests a potential positive effect on GDP per capita, although the relationship is not statistically significant (p-value of 0.265). Improvements in food security may impact the economy, but this effect may not be immediate or consistent.

Temperature ($LTemperature_{t-1}$): The coefficient of -0.063 is negative, indicating that rising temperatures may adversely affect GDP per capita, though the relationship is not statistically significant (p-value of 0.341). This finding, in conjunction with Bouaziz et al.[29], supports the notion that rising temperatures can harm agricultural output but may have less immediate effects in the short run.

The ARDL model highlights that agricultural productivity and rainfall are critical factors influencing Tunisia's GDP per capita in the short run. Agricultural value added shows a positive impact, emphasizing agriculture's role in Tunisia's economy. Conversely, the negative impact of rainfall aligns with concerns about climate change, as erratic rainfall patterns can disrupt agricultural productivity and reduce economic growth. These findings are consistent with those of Bouaziz et al.[29], who noted that climate variability, particularly temperature increases and unpredictable rainfall, adversely impacts agriculture and economic performance in Tunisia.

This analysis underscores the importance of climate adaptation strategies to mitigate the adverse effects of rainfall variability and rising temperatures on Tunisia's economy.

Table 10. VAR modeling for GDP.

Variables	**Coefficients**	**P-Value**
LGDP per capita$_{t-1}$	0.958	0.077*
LAgriculture value added$_{t-1}$	0.175	0.074*
LCrop production$_{t-1}$	0.23	0.19
LFood security$_{t-1}$	0.42	0.265
LTemperature$_{t-1}$	−0.063	0.341
LRainfall$_{t-1}$	−0.003	0.03**
R^2		0.987
R^2 **Adjusted**		0.984
P-value (Fisher statistic)		0.000***

Source: author's estimates.
Note: The coefficients marked with ***indicate significance at the 1% level, while **indicates significance at the 5% level, and *indicates significance at the 10% level.

The theoretical implications of the forecast error variance decomposition (FEVD) presented in **Table 11** provide insights into the interplay between climate change, agricultural development, food security, and GDP per capita growth. Economic growth shocks were initially 100% in year 1, declining to approximately 12.77% in period 2, further dropping to 10.24% in year 3, then rising to 21.18% in year 4. In subsequent years, the contributions fluctuated, reaching 20.3% and 19.17% in period 6 and stabilizing between 10–11% in years 7 through 10. This trend suggests that the nature of economic growth shocks is largely influenced by similar variations in climate change and other contributing factors in Tunisia.

The variance decomposition underscores the dominant role of agricultural production, which accounts for the largest share of economic growth variability, peaking at 80.14% in the second period and maintaining a strong influence over the long term (73–77%). The value added by agriculture also contributes significantly, with its impact ranging between 4.6% and 13.35%. Climate factors, such as mean temperature (LTEMP) and precipitation (LRAIN), initially have minimal influence but gradually increase their significance, indicating their delayed yet critical impact on growth. Food security (LFS), while having a smaller role, consistently contributes 2–3% throughout the periods. These results highlight the reliance of Tunisia's economic growth on agricultural productivity and value addition, the rising influence of climate factors, and the steady role of food security. To ensure sustainable growth, policymakers should focus on enhancing agricultural productivity, addressing climate change challenges, and strengthening food security measures.

4.6. Pairwise Granger Causality Tests

The specific objective of this study is to investigate the impact of climate change, agricultural productivity, and food security on economic growth in Tunisia. To achieve this, the study formulates and tests the following hypotheses:

H$_0$. *Climate change, agricultural productivity, and food security drive economic growth in Tunisia.*

H$_1$. *Economic growth influences climate change, agricultural productivity, and food security in Tunisia.*

The primary purpose of employing the VAR

Table 11. Variance Decomposition of economic growth.

Period	S.E.	LGDPC	LAGRI	LCP	LTEMP	LRAIN	LFS
1	0.031518	100.0000	0.000000	0.000000	0.000000	0.000000	0.000000
2	0.096342	12.77894	5.775232	80.13994	0.011349	0.000743	1.293787
3	0.133014	10.24465	13.35366	72.75724	2.264652	0.303386	1.076409
4	0.164124	21.18422	11.63682	62.44281	2.471890	0.564149	1.700112
5	0.218012	20.30944	6.595097	67.48634	2.098272	1.146218	2.364633
6	0.224629	19.17367	6.399059	67.20321	3.798561	1.079737	2.345758
7	0.319552	10.30982	6.000041	77.95964	2.020890	1.088745	2.620865
8	0.336484	10.28605	8.616758	73.54198	4.111203	1.043667	2.400338
9	0.446846	11.95273	4.889028	76.78773	2.376377	1.162134	2.832000
10	0.506662	10.53563	4.639805	77.08727	3.628710	1.322825	2.785756

Source: author's estimates.

Granger causality test is to examine whether causal relationships exist among the variables under consideration. The test identifies whether past values of one variable can predict another and whether the relationship is unidirectional or bidirectional. The results in **Table 12** reveal a notable finding:

Unidirectional Causality: The Granger causality analysis reveals that LAGRI (agricultural value-added) significantly influences LGDPC (economic growth) in Tunisia, underscoring that historical changes in agricultural value-added can predict future economic growth. In the short term, increased agricultural value-added directly stimulates economic expansion through higher production and export activities. This relationship is particularly critical for Tunisia, where agriculture has traditionally played a central role in providing employment, supporting exports, and sustaining rural livelihoods. In 2023, Tunisia's economic growth slowed sharply to 0.4%, down from 2.6% in 2022. This decline was primarily driven by weak domestic demand and prolonged droughts that severely affected the agricultural sector. Unemployment rose from 15.2% in 2022 to 16.4% in 2023, reflecting contractions in labor-intensive sectors such as agriculture and construction. Agriculture and fisheries contribute 9.5% to Tunisia's GDP, while natural resource extraction, including oil and gas, accounts for 3.7%. Manufacturing industries notably mechanical and electrical equipment, textiles, leather, and agri-food represent 15.3% of GDP. Tourism, directly contributing 4% to GDP, exerts an indirect economic influence exceeding 10% (Economic Report, Tunisia[50]). Despite a 12.8% growth in services like hotels and restaurants in 2023, indicating a gradual recovery in tourism, the agricultural sector continued to face severe challenges. Adverse climatic conditions, persisting for a third consecutive year, led to an 11% decline in agricultural production. These dynamics highlight the urgent need for climate adaptation strategies to stabilize agricultural performance and bolster economic recovery. Agriculture's pivotal role in Tunisia extends beyond its economic contributions. It generates jobs for rural and low-skilled workers, boosting household incomes and aggregate demand. Agricultural growth also enhances food security by reducing reliance on imports and stabilizing domestic food supply. Furthermore, the sector stimulates other industries by creating demand for inputs like fertilizers and machinery and supplying raw materials for agro-industrial activities, amplifying its contribution to economic growth. These findings align with research by Ogundari[51], who identified unidirectional causality from agriculture to economic growth across 35 Sub-Saharan African countries, and Odero[52], who observed a similar causal relationship in Namibia. Abdelhafidh and Bakari[53] also highlighted bidirectional causality between agricultural investment and economic growth in Tunisia, emphasizing the importance of targeted policies to strengthen the sector. However, these perspectives contrast with studies by Bolarinwa and Ayodele[54] and Osei Asare and Baah-Boateng[55], which argue that economic growth drives improvements in agricultural productivity. Broader global research contributes to the ongoing debate about agriculture's role in economic development. For instance, Jatuporn et al.[56] analyzed data from Thailand (1961–2009) and found that economic growth significantly drives agricultural development. Agboola et al.[57] highlighted the diversity of opinions on this subject. While scholars such as Alola and Alola[58] and Mishra and Dash[59] advocate for agriculture as the foundation of economic development, others, including Gollin[60] and Dercon[61], argue that agriculture's impact is less significant and context-dependent. This underscores the complex, multidimensional relationship between agriculture and economic growth, which varies based on regional and structural dynamics.

The Granger causality analysis indicates that economic growth Granger-causes food security and crop production in Tunisia. This highlights the vital role of economic development in strengthening agricultural performance and ensuring consistent food availability. As the economy expands, national income increases, enabling both the government and private sector to channel more resources into agricultural development. These investments often target critical areas such as infrastructure, technology, irrigation systems, and essential inputs like fertilizers and seeds, collectively enhancing crop yields and overall agricultural productivity. Economic growth also accelerates the adoption of advanced agricultural technologies. Access to modern farming equipment, precision agriculture tools, and efficient irrigation systems significantly improves crop production, ensuring a stable and reliable food supply. Additionally, economic growth raises household incomes, particularly in rural areas, empowering farmers to adopt improved farming practices and diversify their crops. Higher incomes play a crucial role in reducing poverty, a significant obstacle to achieving food security. Enhanced economic performance facilitates more efficient food supply chains through investments in transportation, storage, and distribution networks. This minimizes post-harvest losses and ensures that food reaches consumers more effectively, thereby boosting food security. Furthermore, economic growth provides the financial resources necessary to counteract climatic challenges. This includes implementing adaptation measures such as cultivating drought-resistant crops and adopting climate-smart farming practices, safeguarding crop production and food availability. Economic growth also strengthens the government's ability to introduce policies aimed at improving food security, such as farmer subsidies, establishing agricultural zones, and stabilizing food prices. Additionally, advancements in education and healthcare associated with economic growth enhance human capital, improving farmers' knowledge and efficiency, thereby contributing to agricultural productivity and food security. Similar findings have been reported by Segbefia et al.[62], who identified a unidirectional relationship between economic growth and food security in five African countries, underscoring the role of economic development in addressing food security challenges.

The finding that food security Granger-causes mean temperature in Tunisia is compelling. It underscores the potential reverse impact of human activities aimed at improving food security on climate dynamics. Efforts to enhance food security often require intensifying agricultural production, expanding farmland, or altering land use, which can significantly affect local and regional climates. These changes may reduce vegetation and disrupt natural processes of heat absorption and reflection, contributing to shifts in mean temperature. Intensified agricultural practices, including the use of fertilizers, mechanized farming techniques, and energy-intensive irrigation systems, emit greenhouse gases such as methane and nitrous oxide, which accelerate climate warming. Additionally, converting natural landscapes into agricultural land to enhance food security can lead to deforestation and soil degradation, hindering carbon sequestration processes and exacerbating atmospheric warming. These findings align with Mahdavian et al.[63], who observed a unidirectional causality from food security to temperature in Iran. This underscores the need for sustainable agricultural practices that mitigate climate impacts while ensuring food availability.

The analysis also reveals that rainfall influences mean temperature, highlighting a dynamic relationship where variations in precipitation significantly affect temperature patterns in Tunisia. Rainfall increases atmospheric moisture, and the evaporation of rainwater absorbs heat, creating a cooling effect. This phenomenon is particularly pronounced in regions experiencing substantial rainfall events. Conversely, reduced rainfall diminishes this cooling effect, potentially contributing to warmer conditions. This finding aligns with research by Kane and Abubakar[64], who identified a bidirectional relationship between temperature and rainfall, demonstrating that temperature can influence rainfall patterns while rainfall affects temperature dynamics. However, Islam and Zakaria[65] reported no causal relationship between rainfall and average temperature, suggesting that the strength of this relationship may vary regionally or contextually.

Bidirectional Causality: The identification of bidirectional causality between mean temperature and agricultural production in Tunisia underscores the intricate and interdependent relationship between climate and agriculture. This finding suggests that changes in mean temperature directly influence crop production, while agricultural activities, in turn, affect local and regional temperature dynamics. Temperature is a critical determinant of agricultural performance, as crops are highly sensitive to temperature fluctuations. Optimal temperature ranges are essential for plant growth, photosynthesis, and yield. In Tunisia, extreme temperatures whether excessively high or low can disrupt these processes, leading to reduced crop productivity. Conversely, agricultural activities also contribute to temperature variations. Practices such as deforestation or the conversion of natural ecosystems into farmland reduce vegetation cover, alter surface albedo (reflectivity), and disrupt natural cooling processes, exacerbating local temperature changes. Furthermore, the use of fertilizers, irrigation, and mechanization releases greenhouse gases (GHGs) like methane and nitrous oxide, contributing to localized warming and broader climate change effects. The bidirectional relationship between climate change and agricultural production is well-documented. For example, Zafeiriou and Azam[66] highlight agriculture's reliance on favorable climatic conditions, such as optimal temperatures and adequate rainfall, to sustain food and fiber production. However, this interdependence presents significant challenges. Fofack and Derick[67] emphasize that rising global temperatures and sea levels pose barriers to agricultural productivity, while paradoxically, increased GHG emissions can boost crop yields in certain contexts. Their study also reveals that livestock production contributes significantly to GHG emissions, and activities such as crop cultivation and land use changes negatively impact global temperature levels. Agriculture's role in climate change stems from practices like enteric fermentation, deforestation, rice cultivation, agrochemical usage, and livestock and manure management. These activities are associated with GHG emissions and environmental pollution, including air, water, and soil contamination[68–70]. These findings align with predictions that climate change will reduce yields of cereal and horticultural crops, as highlighted by Rashid et al.[71] and Backlund et al.[72]. Moreover, Yasmeen et al.[73] emphasize the feedback loop between agricultural production and environmental factors, particularly temperature. This interplay underscores the need for sustainable agricultural policies to mitigate the adverse effects of climate change. Zhao et al.[74] also confirm the negative impact of rising temperatures on global crop yields, suggesting a predominantly unidirectional causality from temperature to crop production. Overall, these insights reinforce the urgency of adopting climate-resilient agricultural practices and policies to ensure sustainable food systems while minimizing agriculture's contribution to climate change.

No Causality: No causal relationship was found between climate change (rainfall and temperature) and economic growth. Garcia and Hernandez[75] found no significant causal link between rainfall and economic growth in Sub-Saharan Africa, suggesting other factors may be more influential. Similarly, Smith and Jones[65] reported no causal relationship between rainfall and average temperature, indicating that changes in rainfall do not directly affect temperature variations.

The relationships in **Figure 3** highlight the interconnectedness of economic growth, agriculture, climate variables, and food security in the study.

Table 12. The VAR Granger causality test.

Variables:X	LGDPC	LAGRI	LCP	LFS	LTEMP	LRAIN
LGDPC	-					
LAGRI	→	-				
LCP	←	≠	-		-	
LFS	←	≠	≠	-		
LTEMP	≠	≠	↔	←	-	
LRAIN	≠	≠	≠	≠	→	-

Source: author's estimates.
Unidirectional relationship: Y causes X (→), X causes Y(←); No granger causality≠ ; and bidirectional relationship (↔)

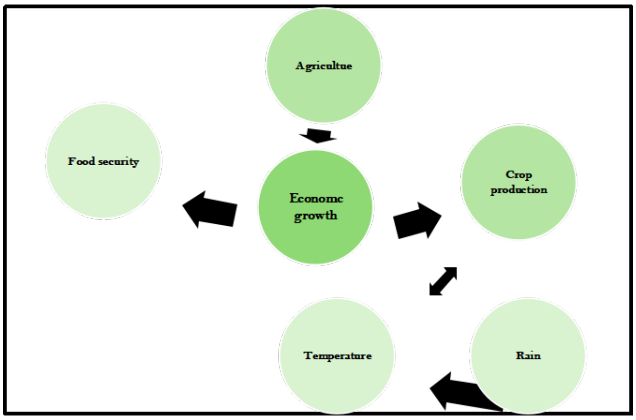


Figure 3. VAR Granger causality test.

Source: author's estimates.

5. Conclusions

This study explores the impact of climate change, agricultural productivity, and food security on economic growth in Tunisia from 1990 to 2022, employing advanced econometric methods such as the ARDL model and VAR Granger causality analysis. The findings underscore the role of agriculture in Tunisia's economy, revealing that lagged agricultural productivity significantly and positively influences economic growth, demonstrating the delayed but enduring effects of agricultural output. However, the short-term effects of lagged agricultural productivity on GDP are positive and statistically significant at the 10% level, while the impact of lagged crop production is positive but not statistically significant. These findings suggest that while past agricultural factors may have some influence on economic growth, their immediate effects are limited, highlighting the need for strategic and sustained interventions in the agricultural sector. The study also examines climatic factors, particularly rainfall and temperature. Rainfall is found to negatively affect GDP per capita, reflecting the disruptive effects of erratic precipitation on agricultural cycles. While temperature changes do not exhibit immediate significant effects, their indirect influence on crop yields is evident. The bidirectional causality identified between temperature and agricultural production highlights a complex feedback loop. Tunisia's reliance on rain-fed agriculture exacerbates its vulnerability to climate variability, posing challenges to food security and economic stability. In this context, Brown et al.[76] identify a significant relationship between precipitation shocks and GDP growth, observing that both droughts and heavy rainfall events contribute to a decrease in per capita GDP growth rates. Despite the agricultural sector being the most vulnerable to rainfall fluctuations, the study finds no direct impact on agricultural GDP growth. This aligns with the findings of the present study, where erratic rainfall disrupts agricultural cycles, ultimately affecting GDP growth, though it does not directly influence agricultural GDP in Tunisia. VAR Granger causality tests further reveal significant directional relationships between crop production and mean temperature, emphasizing the need for climate-smart agricultural practices. Approaches such as crop rotation, conservation agriculture, and heat-resistant crop varieties can mitigate the adverse effects of temperature on agriculture while reducing agriculture's impact on temperature. Rainfall also plays a pivotal role in regulating temperature in Tunisia, with higher precipitation potentially cooling the atmosphere and reduced rainfall contributing to temperature rises. The indirect relationship between rainfall and crop production underscores its importance in shaping local climate dynamics, particularly in regions sensitive to precipitation variations. Additionally, the findings reveal that food security influences mean temperature, highlighting the intricate interplay between human activities aimed at achieving food security and environmental factors. This necessitates the adoption of sustainable agricultural practices that balance food security with environmental stewardship to mitigate unintended climatic consequences. Economic growth is driven by agricultural productivity, which simultaneously drives food security and crop production in Tunisia, emphasizing the interdependence between these factors and their relationship with environmental dynamics. The bidirectional causality between crop production and mean temperature reinforces the critical role of rainfall in stabilizing and strengthening the agricultural sector to ensure food security. These results align with broader literature. For instance, Mukti et al.[77] examined the effects of climate change on economic growth in five Asian countries, finding that CO_2 and methane emissions significantly impact agriculture, fisheries, and forestry. However, changes in temperature and rainfall had limited direct effects, while agriculture played a substantial role in driving economic growth. Similarly, Maulidar et al.[78] analyzed the dynamic relationship between agriculture, economic growth, capital, labor, and CO_2 emissions in Indonesia, concluding that agriculture reduces CO_2 emissions over time while capital formation negatively impacts emissions in the long run. Granger causality analysis in their study highlighted a unidirectional relationship from agriculture to economic growth. These findings emphasize the need for adaptive strategies to address climate change's adverse effects on agriculture. Recommendations include adopting drought-resistant crop varieties, efficient irrigation systems, and sustainable farming practices to counter erratic rainfall and rising temperatures. Investments in rural infrastructure, market access, and technological innovation are crucial for enhancing productivity and food security. Policymakers should prioritize sustainable resource management and equip farmers with the tools and knowledge to adapt to changing climatic conditions.

Given that agriculture contributes significantly to Tunisia's GDP and employs a large segment of the rural population[47], addressing climate vulnerabilities is essential for securing food systems, stabilizing the economy, and promoting sustainable development. These findings contribute to the broader discourse on climate resilience and economic sustainability, providing a framework for similar studies in other developing countries facing comparable challenges. For instance, Ceesay and Ndiaye[79] recommended tree-planting initiatives, food security programs, and poverty reduction strategies to enhance agriculture's role in economic growth and environmental protection in The Gambia. To support these efforts, investments in research and development are needed to advance agricultural technologies and practices that enhance resilience to climate-induced stresses. Promoting crop diversification can mitigate the risks associated with dependence on a narrow range of crops, while climate-resilient agricultural technologies can boost productivity and reduce environmental impact. Improved rural infrastructure, such as roads and storage facilities, is essential for market access and economic growth. Capacity-building initiatives and education programs should empower farmers and rural communities to effectively adapt to climate change. For sustained economic growth, the government must prioritize investments in the agricultural sector, focusing on modern farming technologies, irrigation infrastructure, and research and development. Considering the sector's vulnerability to climate change, adopting sustainable and climate-resilient agricultural practices is crucial to ensuring its continued contribution to economic growth. Expanding rural financial services, improving market access, and supporting smallholder farmers can enhance agricultural value-added, driving inclusive growth. Tunisia's development strategies should recognize agriculture as a key sector for economic transformation, enabling the country to reduce inequality, promote regional development, and achieve sustainable economic growth. In the context of Tunisia's reliance on agriculture as a vital economic sector, fostering economic growth can reinforce the agricultural base and strengthen food security through targeted investments and policy support. This approach highlights the importance of promoting economic development as a strategy to address agricultural and food security challenges in the face of climate variability and resource constraints.

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Data Availability Statement

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Conflict of Interest

The author declares no conflicts of interest related to this study.

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