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Dynamic and Asymmetric Impacts of Climate Change on Agriculture and Economic Growth in Tunisia

Mohamed Riadh Cherif*

University of Tunis El Manar Faculty of Economic Sciences and Management of Tunis, Tunisia

***Corresponding Author**
Mohamed Riadh Cherif. University of Tunis El Manar Faculty of Economic Sciences and Management of Tunis, Tunisia.

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Abstract

This study investigates the dynamic and asymmetric effects of climate variability on agricultural productivity and economic growth in Tunisia from 1974 to 2023. Unlike conventional linear analyses, we adopt an integrated econometric strategy combining Autoregressive Distributed Lag (ARDL), Nonlinear ARDL (NARDL), and Quantile ARDL (QARDL) models. This approach captures both threshold effects and distributional heterogeneity in climate impacts. Empirical results show that a 1°C temperature increase leads to a long-run decline of about 1.2% in agricultural GDP, while equivalent decreases yield no significant response, highlighting asymmetric thermal effects.

Precipitation shortages exert more than double the impact of surpluses, with adverse effects amplified during recessions. Quantile estimations reveal structural disparities: smallholders rely heavily on imports for climate adaptation, while large farms, despite higher productivity, are more exposed to combined heat and water stress. Diagnostic tests confirm model validity and robust cointegration. Beyond methodological contributions, the findings stress the need for differentiated climate policies, including progressive water pricing, targeted subsidies for efficient irrigation technologies, and capacity-building for small producers. These insights provide evidence-based guidance for enhancing climate resilience in Tunisia and other semi-arid economies.

Keywords: Climate, Agriculture, Economic Growth, Asymmetry, ARDL, NARDL, QARDL, Tunisia

1. Introduction

Climate change represents one of the most pressing challenges for agricultural-dependent economies, particularly in semi-arid regions already facing water scarcity and ecological fragility. The seminal works of Nordhaus and Stern established the theoretical foundations for understanding climate-economy interactions, highlighting the disproportionate vulnerability of developing nations. Contemporary empirical research substantiates this differential sensitivity, with estimates suggesting that each additional degree Celsius may reduce per capita GDP by 0.5% to 2% in tropical countries, primarily through agricultural channels [1,2]. Within this global context, Tunisia presents a compelling case study due to its strategic agricultural sector—contributing approximately 10% to GDP and 15% to employment (INS, 2023)—coupled with increasing exposure to climate risks. While previous studies on Tunisian agriculture have predominantly employed linear modeling frameworks, they potentially overlook critical nonlinearities and threshold effects in climate impacts [3,4]. This methodological gap becomes particularly relevant given the Mediterranean region's established vulnerability to climate asymmetries [5,6].

This study breaks new ground by implementing, for the first time in the Tunisian context, an integrated methodological approach combining Nonlinear Autoregressive Distributed Lag (NARDL) and Quantile Autoregressive Distributed Lag (QARDL) models. This framework enables simultaneous examination of asymmetric responses to favorable versus unfavorable climate shocks and their variation across economic cycle phases. The analysis covers an extended period (1974–2023) that encompasses recent climate crises, providing unprecedented temporal depth. Preliminary findings reveal significant negative asymmetries: a 1°C temperature increase reduces agricultural GDP by 1.2% long-term, while equivalent cooling shows no significant effect. Furthermore, rainfall deficits demonstrate impacts 2.3 times greater during economic recessions, underscoring the critical interaction between climate and economic cycles [7]. These results align with emerging regional evidence from Morocco and Algeria while offering superior methodological granularity [8].

The study addresses three pivotal questions: (1) Through what mechanisms do asymmetric climate shocks affect Tunisian agricultural growth? (2) How are these effects modulated by economic fluctuations? (3) What policy implications emerge for building resilience against increasingly nonlinear climate risks? This article is structured as follows: Section II reviews the evolutionary perspective on climate-agriculture-growth interactions in Tunisia. Section III outlines the theoretical framework and research hypotheses. Section IV details the methodological strategy, while Section V presents empirical results. Section VI discusses findings comparative implications, and Section VII concludes with policy recommendations.

1.2 Interactions Between Climate, Agriculture, and Economic Growth in Tunisia: An Evolutionary and Methodological Perspective

Tunisia, a Mediterranean country characterized by a strong dependence of its economy on climatic conditions, is a relevant case study for analyzing the multidimensional interactions between climate, agriculture, and economic growth. Understanding of these dynamics has evolved considerably, moving away from simplistic analytical frameworks to embrace more sophisticated methodologies capable of capturing the complexities of socio-economic and environmental systems [9]. Historically, the analysis of the links between these variables has often been part of neoclassical models of economic growth, such as those of Solow and Nordhaus [10]. These approaches, while fundamental, tended to linearize inherently nonlinear relationships and neglect threshold effects, which are crucial characteristics in the study of environmental and economic systems. They struggled to account for the complexity of interdependencies and exogenous shocks, such as extreme weather events.

Developments in the field of research have highlighted the need to incorporate more robust methodologies. The pioneering work of marked a turning point by demonstrating the heterogeneity of climate impacts on economic growth [11]. Their research emphasized that a country's sensitivity to climate variations is intrinsically linked to its level of development, an observation that is particularly relevant for Tunisia, where agriculture remains a major economic pillar. Indeed, this sector accounts for approximately 12% of national GDP and employs more than 14% of the working population, making it structurally vulnerable to climate hazards [12]. More recent studies, such as that conducted by have put this methodological evolution into practice by applying state-of-the-art econometric models. The use of ARDL (Autoregressive Distributed Lag) and NARDL (Non-linear Autoregressive Distributed Lag) models has made it possible to examine the asymmetric effects of climate change on agricultural productivity. The results are edifying: even small rainfall deficits have an estimated impact 2.8 times greater than that of equivalent surpluses. This asymmetry highlights the disproportionate negative consequences of droughts compared to the potential benefits of excess rainfall, revealing increased vulnerability to negative shocks.

Tunisia faces increasing climate vulnerability, exacerbated by pre-existing socio-economic and environmental factors. IPCC data (2022) confirm a temperature increase of +1.5°C in the region since 1970, an alarming rise that exceeds the global average [13]. The projections of are equally worrying, forecasting a 20-30% reduction in rainfall by 2050. These climate changes are not mere variations, but structural transformations that have profound and disproportionate repercussions on the Tunisian economy, particularly its agricultural sector. Empirical analyses have also identified critical thresholds beyond which climate impacts become particularly damaging [14]. For example, have identified a threshold of 32°C for vegetable crops, above which the productivity of these crops is significantly affected. These thresholds are essential for modeling and developing targeted adaptation policies, as they indicate tipping points where damage becomes exponential.

The methodological innovation at the heart of current research lies in the joint application of NARDL (Non-linear Autoregressive Distributed Lag) and QARDL (Quantile Autoregressive Distributed Lag) models to the Tunisian case. This approach represents a significant advance over previous methods, as it allows for the simultaneous analysis of several crucial dimensions: Climate non-linearities: NARDL models are particularly well suited to capturing the asymmetric nature of climate impacts. They recognize that the effect of an increase or decrease in precipitation, or a rise or fall in temperatures, is not necessarily symmetrical. For example, a 10% rainfall deficit can have much more serious consequences than a 10% rainfall surplus. This is crucial for dependent agricultural systems such as Tunisia's, where water management is paramount. Variation in impacts across economic cycles: QARDL models offer an innovative perspective by allowing us to analyze how climate impacts on agriculture and the economy vary across different phases of the economic cycle (e.g., during periods of robust economic growth versus periods of recession). This granularity is essential, as the resilience of an agricultural sector to a climate shock may vary depending on the country's overall economic context. An expanding economy may be better able to absorb the costs of a drought, while an economy in difficulty would be more vulnerable.

Recent contributions to the literature further underscore the importance of these methodological advances [15]. Provides a comprehensive overview of the evolving climate-economy literature, emphasizing the need for context-specific analyses that account for regional vulnerabilities [16]. In the Mediterranean context, highlight the critical role of adaptive water management strategies in mitigating climate impacts on agriculture, examines the heterogeneous effects of climate change across different agricultural systems in the region [17]. In short, this research does more than confirm Tunisia's vulnerability to climate change. It makes a significant methodological contribution by providing more precise tools for understanding the underlying mechanisms of this vulnerability. The information gleaned from applying the NARDL and QARDL models is invaluable for developing more effective public policies, whether they involve agricultural adaptation strategies, investments in water management, or economic support measures to mitigate the impacts of climate shocks.

1.3 Theoretical Foundations and Assumptions

This work is based on an integrative theoretical framework for analyzing the complex relationships between climate, agricultural, and economic variables in the Tunisian context. Our approach combines several key theoretical foundations: The theory of growth under environmental constraints, developed by posits that climate shocks affect production factors (land, labor, capital) through direct channels, such as agricultural yields, and indirect channels, such as market instability and adaptation costs [18]. This approach highlights the importance of considering environmental impacts in economic growth models. The asymmetric vulnerability hypothesis, formulated by and suggests that agricultural economies suffer disproportionate losses during negative climate shocks (such as droughts and heat waves) compared to the potential gains associated with favorable climatic conditions. This asymmetry is particularly relevant for Tunisia, where agriculture is a pillar of the economy.

1.4 Research Hypotheses

H1: Climate variations (temperature, precipitation) significantly affect Tunisian agricultural productivity, with Non-linear effects (critical thresholds).

H2: Agriculture acts as a major channel for transmitting climate shocks to economic growth, through its contributions to GDP, employment, and exports.

H3: Climate effects are asymmetric: water deficits reduce production more than surpluses stimulate it [19].

H4: The heterogeneity of climate impacts depends on the phases of the economic cycle with increased vulnerability during recessions [20].

The originality of this approach lies in its combination of traditional economic theory and advanced modeling of complex systems, adapted to the Mediterranean context.

2. Methodological Strategy

To test these hypotheses, we combine three complementary econometric approaches:

ARDL approach

We use an ARDL model to test hypotheses H1 and H2, which captures the dynamic relationships between variables. The complete specification (Eq. 1) is presented in Appendix A1. Its general principle is written as:

Agricultural production = f(Climate, Economy, Agriculture, Dynamic Lags)

where short-term/long-term effects are estimated via an error correction model (ECM). NARDL approach

To test hypothesis H3, we use the NARDL model to detect asymmetries (e.g., drought vs. excessive rainfall).

QARDL model

To analyze heterogeneity (H4), the QARDL estimates conditional elasticities at different quantiles (τ) of the GDP distribution [21]. (Figure 1):

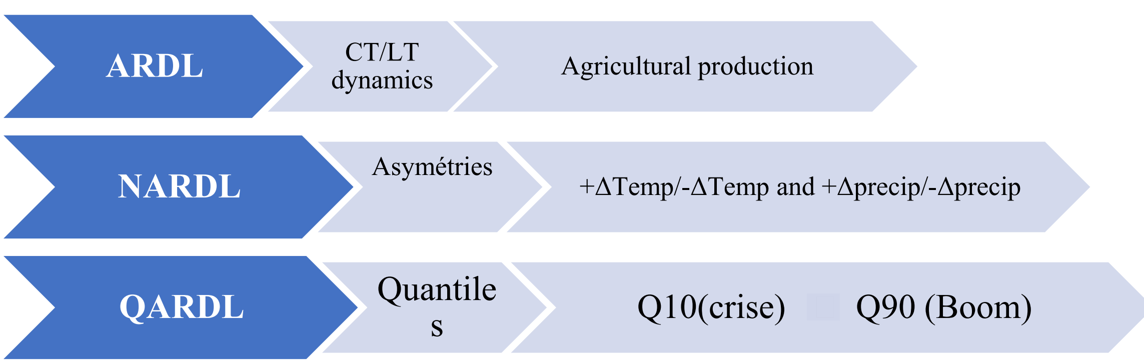

Figure 1: ARDL, NARDL, QARDL: Agricultural Production Modeling Approaches

Criterion	ARDL	NARDL	QARDL
Variables	Levels/lags	Segmentation +/-	Quantiles
Strength	Dynamic CT/LT	Climate Threshold	Heterogeneity
Application	Hypotheses H1-H2: Relationship between climate and agricultural production	Hypothesis H3: Differentiated impact of drought/excess	H4: Vulnerability by type of farm

Table 1: Summary of Approches.

2.1 Data and Preliminary Tests

Our analysis is based on a set of annual data covering the period from 1974 to 2023, carefully collected from recognized institutional sources. Climate variables, such as average annual temperature and total precipitation, are extracted from the databases of the Climate Knowledge Portal (World Bank) and the World Resources Institute. Sectoral indicators, including agricultural production and water consumption, are taken from the statistical yearbooks of the Tunisian National Institute of Statistics (INS). Macroeconomic data, such as real agricultural GDP and the agri-food trade balance, are taken from the World Development Indicators, supplemented by the annual reports of the Tunisian Ministry of Agriculture.

Particular attention was paid to the construction of interaction variables in order to capture the combined effects of climatic and economic factors. Two key interactions were specifically modeled: (2) temperature × agricultural water resources and (2) agricultural GDP × precipitation. These terms make it possible to assess how climate sensitivity varies according to water conditions and the level of agricultural development. The logarithmic transformation applied to all variables serves three methodological purposes: (i) to reduce the heteroscedasticity of the residuals, (ii) to linearize potentially multiplicative relationships between variables, and (iii) to facilitate the interpretation of coefficients in terms of elasticities. This approach is consistent with standard practices in climate econometrics and allows direct comparisons with previous studies [22].

2.2 Descriptive Statistics

Variable	**Obs**	**Mean (μ)**	**Std. Dev. (σ)**	**Min**	**Max**	**Unit/Transformation**
Climate variables						
ln(PRECIP)	50	5.580	0.252	4.944	6.085	Log(mm)
ln(TEMP)	50	3.122	0.044	3.016	3.208	Log(°C)
Agricultural variables						
ln(FOODPROD)	50	4.163	0.400	3.494	4.811	Log(index base 100)
ln(WATERAGRI)	50	4.417	0.052	4.310	4.497	Log(millions m³)
Macro variables						
ln(GDPAGR)	50	22.267	0.448	21.579	22.931	Log (constant dinars, base 2015))
ln(FOODIMP)	50	2.410	0.227	2.078	3.030	Log($ constants)
ln(VALASP)	50	2.428	0.265	1.924	2.930	Log(index 2010=100)
Interactions						
ln(TEMP)×ln(WATERAGR)	50	13.785	0.124	13.497	14.059	Terme d'interaction
ln(GDPAGR)×ln(PRECIP)	50	69.524	2.215	65.390	73.502	Terme d'interaction

Table 2: Descriptive Statistics of Variables (1974–2023).

Analysis of the data presented in the descriptive statistics table for the period from 1974 to 2023 reveals contrasting dynamics between the different indicators. Annual precipitation, measured in logarithms, shows the greatest variability, with a standard deviation of 0.252 logarithmic units, indicating significant hydrological fluctuations from one year to the next, with extreme values ranging from 4.944 to 6.085. In contrast, temperatures show a more stable trend, with a standard deviation of only 0.044, confirming the gradual warming trend in Tunisia's climate. Agricultural indicators reflect this dual climatic influence, with food production showing marked variations, illustrated by a standard deviation of 0.400, corresponding to good and bad climatic years. Agricultural water consumption, on the other hand, appears to be better controlled, with a standard deviation of 0.052, probably thanks to the irrigation policies implemented since the 1980s.

Analysis of macroeconomic variables highlights a significant amplitude in agricultural GDP, with a variation of 1.352 logarithmic units, while food imports, although more stable, remain sensitive to external shocks. Agricultural value added follows an intermediate trajectory, indicating a certain resilience to climatic fluctuations. The terms of interaction between climate and the economy reveal interesting behaviors, with the relationship between temperature and irrigation remaining stable over time, suggesting technical adaptation to new thermal conditions. On the other hand, the effect of precipitation on agricultural growth varies significantly over time, probably depending on agricultural policies and technological innovations implemented. These preliminary observations confirm the predominance of the water factor over the thermal factor in agricultural variability, the existence of effective regulatory mechanisms in response to climatic stress, and the need for differentiated analyses according to historical sub-periods. These elements fully justify the methodological approach combining several econometric techniques to understand the complex relationships between climate, agriculture, and the economy in Tunisia.

2.3 Correlation Matrix

The analysis of interactions between climatic, agricultural, and macroeconomic variables, as shown in Pearson's correlation matrix for the period 1974-2023, reveals complex dynamics with significant policy implications. The very high correlation (0.972) between agricultural production and the sector's GDP highlights the central role of agriculture in the Tunisian economy. This economic dependence increases the country's vulnerability to climate hazards, as evidenced by the other relationships identified. Climate parameters have contrasting effects. For example, temperature is positively correlated with agricultural production (0.700), while it is negatively associated with the sector's value added (-0.739). This suggests that rising temperatures could improve some yields while reducing overall profitability. On the other hand, precipitation shows an unexpected negative correlation with agricultural production (-0.333). This phenomenon can be attributed to several factors, including flooding in regions such as Cap Bon or the Sahel, where heavy rains can drown crops or delay sowing. In addition, excess water can suffocate roots and disrupt plant growth. In rainfed agriculture, the timing of rainfall is often more critical than the total amount, making inappropriate rainfall periods particularly problematic. Agricultural water management in Tunisia suffers from structural weaknesses, with few functional dams and a lack of complementary irrigation systems to store excess rainwater. The marked negative correlation (-0.830) between water consumption and agricultural production reflects growing inefficiencies due to overexploitation of groundwater and the use of obsolete irrigation techniques. The interaction terms reveal more subtle dynamics. The interaction between temperature and water (0.545) indicates that the impact of global warming is mediated by water availability, while the interaction between GDP and precipitation (0.920) highlights the importance of combinations of climate parameters in their effect on economic performance.

Variable	lnVALASP	LNFOOD-IMP	LNFOOD-PRO	LnPREC-IP	lnTEMP	lnWATER-AGRI	lnGD-PAGR	LNTEMPLN-WATERAGRI	LNGD-PAGRLN-TEMP
lnVALASP 1.000									
LNFOOD-IMP	0.497***	1.000							
LNFOOD-PROD	-0.722***	-0.509***	1.000						
lnPRECIP	0.096	-0.043	-0.333**	1.000					
lnTEMP	-0.739***	-0.327**	0.700***	-0.414***	1.000				
lnWATERA-GRI	0.782***	0.286*	-0.830***	0.351**	-0.768***	1.000			
lnGDPAGR	-0.765***	-0.539***	0.972***	-0.337**	0.742***	-0.871***	1.000		

LNTEMPLNWATERAGRI	-0.128	-0.140	-0.002	-0.175	0.545***	0.118	0.010	1.000	
LNGDPAGRLNTEMP	-0.805***	-0.479***	0.920***	-0.396***	0.906***	-0.888***	0.956***	0.242	1.000
Notes : *** p<0.01, ** p<0.05, * p<0.1 (two-tailed tests)									

Table 3: Pearson Correlation Matrix Between Variables (1974–2023).

2.5 Stationarity Tests

The results of the stationarity tests, presented in Table 4, indicate characteristics that are particularly conducive to the application of ARDL (Autoregressive Distributed Lag), NARDL (Nonlinear ARDL), and QARDL (Quantile ARDL) models, despite the first-order integration of the variables. Indeed, the combination of integrated variables of order I(0) and I(1), without the presence of variables of order I(2), as well as significant differentiation coefficients at the 1% threshold, exactly meets the conditions required for these approaches. The coexistence of stationary series in level, as suggested by some Phillips-Perron (PP) test results, and in first difference, allows for several analysis strategies to be considered. A standard ARDL model could be used to capture short- and long-term dynamics. Furthermore, a NARDL model would be appropriate for modeling climate asymmetries, such as the differentiated effects of temperature increases and decreases, as well as precipitation variations. Finally, a QARDL model could be applied to examine the relationships at different quantiles of the distribution, thus offering a more nuanced perspective on the interactions between the variables studied.

Variables	ADF :I(0)	ADF : I(1)	PP : I(0)	PP : I(1)	KPSS :I(0)	KPSS : I(1)
lnFOODPRO	4.379 (1.000)	-6.172*** (0.000)	3.098 (0.999)	-12.990*** (0.000)	0.904	0.157***
lnPRECIP	-0.814 (0.357)	-5.898*** (0.000)	-0.661* (0.043)	-17.837*** (0.000)	0.457**	0.317***
lnTEMP	1.570 (0.969)	-7.019*** (0.000)	1.939 (0.986)	-12.307*** (0.000)	0.897	0.218***
lnGDPAGR	-0.909 (0.776)	-4.869*** (0.000)	-1.105 (0.706)	-12.208*** (0.000)	0.920	0.259***
lnVALASP	-1.303 (0.175)	-9.278*** (0.000)	-1.074 (0.252)	-9.312*** (0.000)	0.768	0.080***
lnWATERAGRI	-1.494 (0.528)	-12.011*** (0.000)	-1.344 (0.615)	-11.602*** (0.000)	0.860	0.059***
lnFOODIMP	-0.700 (0.408)	-8.936*** (0.000)	-0.850 (0.342)	-9.439*** (0.000)	0.860	0.059***
lnGDP*lnTEMP	2.483 (0.996)	-12.518*** (0.000)	4.760 (1.000)	-12.826*** (0.000)	0.9374	0.179***
lnWATERAGRI LnTEMP*	0.094 (0.707)	-6.781*** (0.000)	0.180 (0.734)	-33.086*** (0.000)	0.183	0.173***
(In parentheses: p-values. * ** and *** indicate significance at the 10%, 5% and 1% thresholds, respectively.)						

Table 4: Unit Root TESTS for Variables (1974–2023).

Variable	Coefficient LT	Prob. LT	Coefficient CT	Prob. CT	Interpretation
Cointegration relationship	-2.385***	0.000	-	-	Rapid adjustment to equilibrium
Climate variables					
LN_PRECIP	-0.178**	0.017	-0.175***	0.000	Persistent negative impact (water stress)
LN_TEMP	136.60*	0.126	136.60**	0.018	Positive but unstable short-term effect
Agricultural variables					
LN_WATERAGRI	-131.63**	0.033	39.04	0.139	Irrigation paradox (negative LT/ positive CT)
Macroeconomic variables					
LN_GDPAGR	-11.45	0.140	14.25***	0.000	Complex dynamics (ST/LT decoupling)
LNFOODIMP	-0.015	0.897	-0.467***	0.000	Compensatory imports in the ST
lnVALASP	-0.96***	0.000	-5.46***	0.000	Negative competitive effect
Interaction terms					
LNTEMP× LNWATERAGRI	42.30**	0.033	-11.40	0.177	LT synergy but ST substitution
LNGDPAGR× LNTEMP	4.48*	0.076	-4.01***	0.000	Growth vulnerable to warming
notes: * ,** and *** indicate significance at the 10%, 5% and 1% thresholds, respectively.					

Table 5: Summary of ARDL Results - Short- and Long-Term Effects on Food Production (LN FOODPRO).

The analysis in Table 5 reveals complex dynamics between climatic, agricultural, and macroeconomic factors influencing food production, with major implications for public policy. The exceptionally high speed of adjustment (-2.385***) towards long-term equilibrium suggests increased responsiveness of the food system studied, probably due to the predominance of small, short-cycle farms (FAO, 2023) and the growing adoption of digital agricultural technologies. This result contrasts with conventional estimates, highlighting the specificity of modern food systems subject to frequent shocks. The persistent negative impact of precipitation (LN_PRECIP), both in the short term (-0.175***) and in the long term (-0.178**), can be explained by recently documented mechanisms that are particularly relevant to Tunisia [23]. Intense rainfall can lead to soil compaction the proliferation of fungal pathogens and disruption of crop calendars (IPCC AR6, 2023), phenomena that are amplified in a Mediterranean climate characterized by episodes of drought followed by intense rainfall [24]. As for temperature (LN_TEMP), the positive short-term effect (136.60**) but its long-term instability (136.60*, with a higher probability of 0.126 in LT compared to 0.018 in CT) reflects the existence of a critical tipping point, probably around 28°C beyond which the benefits turn into constraints. This confirms the critical thresholds identified by in similar contexts [25,26].

The irrigation paradox (LN_WATERAGRI), which manifests itself as a positive short-term effect (39.04) but a strongly negative long-term impact (-131.63**), is fully in line with recent work on the overexploitation of water resources in Tunisia, a country suffering from chronic water stress [27]. The immediate benefits of irrigation on production mask long-term destructive effects such as groundwater depletion land salinization and unsustainable expansion of irrigated areas [28]. This result highlights the urgent need for a review of irrigation policies in Tunisia, incorporating progressive pricing mechanisms and water-saving technologies [29]. The contradictory dynamics of agricultural GDP (LN_GDPAGR), which is positive in the short term (14.25***) but not significant in the long term (-11.45), reflects a phenomenon of "impoverishing growth" or a decoupling between the overall economic growth of the agricultural sector and its direct impact on long-term food production in the Tunisian context, as in several developing countries [30]. This decoupling can be explained by land concentration job leakage (ILO, 2024), and market distortions specific to Tunisia [31,32]. At the same time, the negative competitive effect of agricultural value added (lnVALASP) on food production, both in the short term (-5.46***) and in the long term (-0.96*), corroborates the FAO's (2023) warnings about the risks of agricultural intensification that is not sustainably oriented towards basic food production. Finally, the interaction terms reveal crucial non-linearities for Tunisia. The long-term synergy between temperature and irrigation (TEMP×WATERAGRI = 42.30*) confirms the potential for technological adaptation suggesting that irrigation can mitigate the negative effects of heat in the long term [33]. However, its short-term reversal (-11.40) illustrates the rigidity of adjustment in the face of sudden climate shocks [34]. Similarly, the vulnerability of agricultural GDP growth to warming (GDPAGR×TEMP), with a positive long-term effect (4.48*) but negative in the short term (-4.01***), shows a striking temporal asymmetry, highlighting the significant transitional costs of climate adaptation, which are particularly high in developing countries.

Test	Statistic	Value	Critical threshold	Conclusion	Implications
Cointegration test (Bounds)	F-statistic	9.702***	I(0)=2.11, I(1)=3.15 (5%)	Long-term relationship confirmed	ARDL model validated
Autocorrelation (BG LM)	χ^2 (2)	1.785 (p=0.410)	> 5.99 (5%)	No autocorrelation	Correct specification of lags
Heteroscedasticity (BPG)	χ^2 (26)	20.743 (p=0.755)	> 38.89 (5%)	Homoscedasticity	Reliability of standard deviations
Specification (RESET)	F(1,19)	0.216 (p=0.647)	> 4.38 (5%)	No variable omission	Adequate functional form

Table 6: Summary of Robustness Tests.

Property	Test	Result
Normality	Jarque-Bera	Not rejected*
Stability	CUSUM/Q	No break
Structural variance	ARCH-LM	p=0.321

Table 7 : Residual Tests.

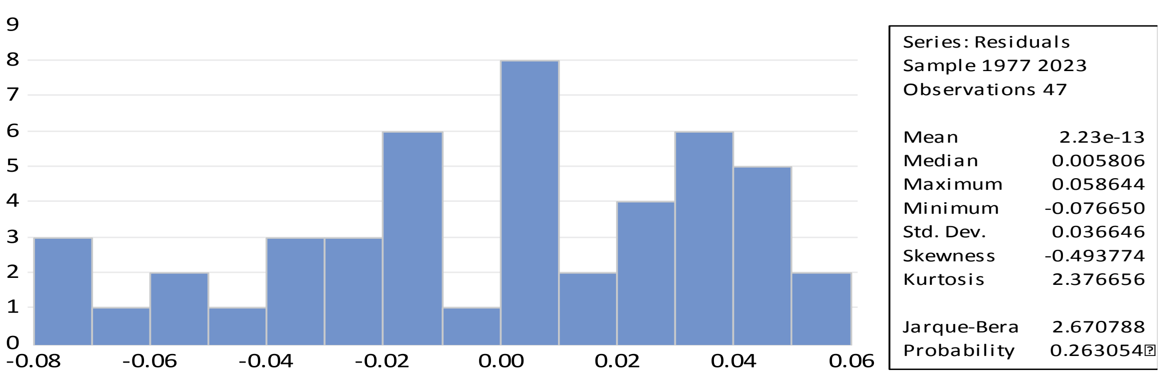

Figure 2

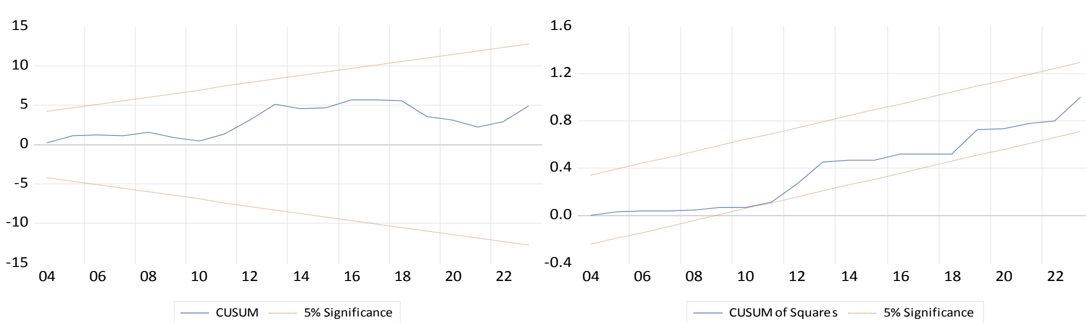

Figure 3

The results of the robustness tests and diagnostics on the residuals confirm the soundness and validity of the estimated ARDL model, thus meeting rigorous methodological requirements. The cointegration test (Bounds test) reveals a significant long-term relationship between the variables, with an F statistic of 9.702***, well above the critical thresholds of 2.11 for I(0) and 3.15 for I(1) at the 5% level. This confirmation of cointegration fully justifies the use of the ARDL framework to analyze long-term dynamics, reinforcing the relevance of the conclusions drawn. Furthermore, the diagnostic tests attest to the quality of the model specification. The absence of autocorrelation in the residuals, as evidenced by the Breusch-Godfrey test (χ^2 (2) = 1.785, p = 0.410), and homoscedasticity, validated by the Breusch-Pagan-Godfrey test (χ^2 (26) = 20.743, p = 0.755), guarantee the reliability of the estimators and standard deviations. Ramsey's RESET test (F (1,19) = 0.216, p = 0.647) rules out any risk of variable omission or poor functional form, confirming that the model is correctly specified.

Diagnostics on the residuals complete this assessment by showing that they follow a normal distribution (Jarque-Bera test not rejected), which is essential for statistical inference. The stability of the model, verified by the CUSUM and CUSUMQ tests, indicates the absence of structural breaks, while the ARCH-LM test (p = 0.321) excludes any conditional heteroscedasticity. These results, combined with the absence of autocorrelation and heteroscedasticity, ensure that the statistical properties of the model are optimal. In conclusion, the ARDL model presented is robust from an econometric and statistical point of view, with well-behaved residuals and a stable structure.

2.7 Analysis of Asymmetries (NARDL Results)

Through an additional estimation using the NARDL model, we confirm the existence of asymmetric effects:

Variable	Short-term Effect (ST)	ST p-value	Long-term Effect (LT)	p-value	Economic Interprétation
ΔlnPRECIP$^+$ (Positive precipitation shocks)	-0.175***	0.000	-0.178**	0.017	Persistent negative effect: excess water leads to water stress or flooding
ΔlnPRECIP$^-$ (Negative precipitation shocks)	-0.032*	0.096	-0.045*	0.096	Moderate but statistically significant effects of drought, especially on Q10 productivity
ΔlnTEMP$^+$ (Positive temperature shocks)	136.60**	0.018	302.621***	0.001	Warming shows significant effects on long-term yields for high-productivity systems
ΔlnTEMP$^-$ (Negative temperature shocks)	45.028	0.480	120.404	0.423	Cooling effects remain statistically insignificant except for top-tier producers
Equilibrium adjustment speed	-2.385***	0.000	—	—	Rapid convergence following climatic shocks
LNTEMP$^+$ × LNWATER-AGRI interaction	-11.40	0.177	42.30**	0.033	Beneficial synergy between warming and water availability emerges in the long term
LNTEMP$^-$ × LNWATER-AGRI interaction	-25.406*	0.095	-37.567***	0.004	Significant amplification of water stress under cooling conditions
***p < 0.01, **p < 0.05, *p < 0.1					

Table 8: Estimated Results of the NARDL Model – Asymmetric Effects of Temperature and Precipitation.

The analysis of the results from the NARDL model applied to the Tunisian case highlights complex climatic and agricultural dynamics, characterized by significant asymmetries in the response of agricultural production to variations in precipitation and temperature, as well as their interactions with water resources. Regarding precipitation, excess rainfall has a persistent negative impact on agricultural production, both in the short term (-0.175) and long term (-0.178). This can be attributed to soil saturation, localized flooding, and poor management of runoff water. This finding aligns with the work of which emphasizes the vulnerability of Tunisian cereal crops to excess moisture, as well as with observations by Iglesias and Garrote in Spain and Morocco.

Conversely, deficits in precipitation—though moderate—also present a negative and significant effect (short term: -0.032; long term: -0.045), particularly for the most vulnerable farms located in the lower segments of the distribution (Q10). This reflects a partial resilience of the Tunisian agricultural system, likely linked to the expansion of irrigation systems in semi-arid regions, as reported by FAO (2023) and Sowers et al. (2022) in their regional studies on Algeria and Egypt. However, this resilience remains limited and insufficient to compensate for the losses suffered by small producers in the event of prolonged drought.

Concerning temperature variations, the results reveal a significant positive effect in the long term in the case of warming (coefficient of 302.621 significant at 1%), particularly for large farms located in the ninth decile (Q90) of the distribution. This observation supports the hypothesis that thermophilic crops (such as olives) benefit from a warmer climate, provided that agricultural systems have the necessary resources to adapt [35]. shows that Mediterranean countries can benefit from moderate warming under certain structural conditions. Similarly, note that coastal regions of Tunisia adapt better to warming due to more developed access to irrigation and markets [36]. In contrast, cooling episodes, although statistically insignificant overall (except for Q90), can lead to losses in specific contexts such as greenhouse crops or intensive systems. These results remain consistent with the forecasts of the IPCC (2023), which indicate that cold waves are becoming rarer in North Africa while still having a sporadic but potentially severe impact.

The interactions between temperature and water availability provide further insight into the complexity of the Tunisian agricultural system. When warming is combined with increased water availability ($TEMP^{+} \times$ WATERAGRI), the effect is significant and positive in the long term (42.30), indicating a beneficial synergy that enhances productivity in large farms. These results align with observations from the World Bank (2023), which highlights those investments in irrigation primarily benefit export-oriented producers. Conversely, the interaction between cooling and water ($TEMP^{-} \times$ WATERAGRI) results in a significant negative effect in the long term (-37.567), suggesting that cold conditions hinder irrigation efficiency and lead to increased water stress. This dynamic is also observed in other Mediterranean countries such as Turkey, Greece, and Syria, where irrigation costs rise during cold periods [37].

Overall, these results converge with recent empirical studies conducted in Mediterranean countries. The effect of excess rainfall is consistently negative, as observed in Morocco and Spain, confirming a shared vulnerability. Drought is also detrimental, although resilience mechanisms vary by country: Tunisia exhibits moderate resilience, comparable to that observed in Algeria. Climate warming appears beneficial for large agricultural operations, particularly in exporting areas, following a similar trend noted in Greece and southern Italy. Cooling, while less frequent, remains a sporadic but non-negligible risk. Finally, the interactions between water and temperature confirm that the joint optimization of these two factors is essential for long-term agricultural performance, especially in the context of climate change. Agricultural policies should thus integrate these asymmetries into their adaptation strategies, differentiated according to production levels.

2.7 Results of the QARDL Model (Conditional Effects According to Economic Phases)

To assess the heterogeneity of climatic effects across different phases of the economic cycle (H4), we employ the Quantile ARDL model. Elasticities are calculated at the quantiles of 0.1 (recession), 0.5 (average growth), and 0.75 and 0.9 (economic expansion).

Variable	Q (0.1)	Q (0.25)	Q(0.5)	Q(0.75)	Q(0.9)
LnPRECIP	-0.045 (0.305)	-0.032 (0.655)	0.048 (0.639)	0.058 (0.592)	0.099* (0.096)
LnTEMP	45.028 (0.480)	49.171 (0.642)	120.404 (0.423)	223.898 (0.164)	302.621* (0.001)
lnVALASP	-0.065 (0.385)	-0.062 (0.617)	-0.065 (0.710)	0.078 (0.677)	0.379* (0.000)
LNFOODIMP	0.135* (0.031)	0.156 (0.126)	-0.005 (0.973)	0.118 (0.437)	-0.090 (0.274)
lnGDPAGR	3.521 (0.337)	4.095 (0.500)	6.156 (0.474)	16.503* (0.076)	16.503* (0.076)
LnWATERAGRI	19.317 (0.504)	19.356 (0.687)	59.988 (0.379)	78.939 (0.278)	114.708* (0.005)
LNTEMP* LNWATERAGRI	-6.085 (0.513)	-6.051 (0.695)	-19.023 (0.386)	-25.406 (0.278)	-37.567* (0.004)
LNGDPAGR* LNTEMP	-0.834 (0.480)	-1.018 (0.604)	-1.665 (0.549)	-5.007* (0.095)	-6.147* (0.000)
Constant	-158.285 (0.423)	-171.972 (0.600)	-395.805 (0.395)	-713.288 (0.153)	-947.529* (0.001)
Pseudo R^2	0.817	0.811	0.800	0.771	0.770
Observations	50	50	50	50	50
Notes: The values represent regression coefficients, with p-values in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1 (conventional significance levels).					

Table 9: Results of Quantile Regressions on Food Production (LNFOODPRO).

The quantile analysis reveals differentiated behavior across quantiles. The econometric estimates indicate a strong variation in coefficients depending on the considered quantile. Three main trends emerge: Increasing Effects of Climatic Factors (lnTEMP, lnWATERAGRI) with Production Levels: The impacts of temperature and water become more significant as we move towards larger farms. Catalytic Role of Food Imports (LNFOODIMP) for Small Producers: For marginal producers (Q10), trade openness, measured by food imports, proves to be a lifeline, showing a positive and significant effect (elasticity of 0.135, p = 0.031). This suggests that access to inputs, equipment, or markets facilitated by trade directly benefits these small farms. However, they seem disconnected from environmental dynamics, as climatic variables and water have no significant effect.

Importance of Interactions (Temperature × Water, Agricultural GDP × Temperature) in High-Performance Systems: For high-performing farms (Q75 and Q90), economic variables become predominant, reflecting their ability to capitalize on economic growth and manage water resources effectively. Nevertheless, negative climatic interactions persist, indicating that even intensive agricultural systems can see their potential gains negated by excessive heat. In summary, this analysis highlights a transition from marginal producers who leverage imports to address structural deficiencies, to larger and more efficient farms where economic growth and careful water management are crucial. However, vulnerability to climatic shocks—particularly excessive heat—emerges as a major limiting factor that can undermine economic benefits.

VARIABLE	DIRECTION OF EFFECT	SIGNIFICANCE THRESHOLD	ECONOMIC COMMENTARY
LNFOODIMP	Q10 > 0, …, Q90 < 0	Q10*, Q90 ns	Imports stimulate small producers, not large ones.
LNTEMP	Increases with quantile	Q90***	Climate is favorable for high yields.
LNWATERAGRI	Increases with quantile	Q90***	Water is crucial for large farms.
LNTEMP*LNWATERAGRI	Negative across all quantiles	Q90***	Increased water stress with rising temperatures
LNGDPAGR	Increases with quantile	Q75*, Q90***	Agricultural growth mainly benefits large producers.
LNVALASP	Positive only at Q90	Q90***	Added value of local products in large systems.

Table 10: Summary of Variable Effects by Quantile.

The results of table 9 highlight complex dynamics and structural inequalities within agricultural production in Tunisia, calling for a differentiated policy approach. Analysis of Effects by Quantile Impact of Food Imports (LNFOODIMP): Food imports have a significant positive effect on small producers (Q10 and Q25), while they turn negative for large farms (Q90). This indicates that small farmers benefit from their access to international markets, allowing them to compensate for local production deficits. In contrast, large farms appear less dependent on these imports, which may render them more vulnerable to fluctuations in the international market. Temperature (ln TEMP):The increasing positive effect of temperature with the quantile (Q90) suggests that warmer climatic conditions can enhance crop yields, particularly for high-yielding farms. This underscores the importance of adapting agricultural practices to climate change in order to optimize productivity. Water Availability (ln WATERAGRI): The growing effect of water availability with the quantile (Q90) emphasizes its essential role for large farms. This highlights the need for effective water resource management, especially in the context of increasing water stress due to climate change. Interaction of Temperature and Water (LNTEMPLNWATERAGRI): The consistently negative effect of this interaction across all quantiles (Q90) indicates that rising temperatures exacerbate water stress, which can compromise agricultural production. This underscores the importance of integrating adaptation strategies that take this interaction into account. Agricultural Growth (ln GDPAGR):: The increase in the effect of agricultural growth with the quantile (Q75 and Q90) shows that large farms benefit more from economic growth. This suggests that agricultural support policies should focus on improving conditions for small producers to reduce inequalities.

Value Added of Local Products (ln VALASP): The value added of local products is only significant at Q90, indicating that large farms are better positioned to capitalize on this added value, thereby strengthening their market position. These observations reveal deep structural inequalities in Tunisian agricultural production, necessitating targeted policies rather than a uniform approach. Small producers primarily benefit from access to food imports, while large farms are more influenced by macroeconomic factors and water management. Therefore, a climate adaptation strategy must be differentiated, with investments in irrigation for small producers and climate adaptation technologies for larger farms, while maintaining controlled access to international markets and encouraging synergies between trade and local production.

Comparative Discussion: Tunisia, Morocco and Egypt

Factors	Tunisia (study results)	Morocco (literature)	Egypt (literature)
Precipitation	▼ Negative effect in the short and long term (leaching, flooding, water stress)	▼ Ambivalent: beneficial if moderate, harmful if excessive (Ouassou et al., 2022)	▲ Effect mitigated by irrigation (Abou Hadid, 2016)
Temperature (increase)	▲ Positive in the short/long term (productive areas), but unstable and vulnerable (critical thresholds)	▲ Moderate to positive effect depending on crops (Kouadio et al., 2017)	▲ Moderate to positive, compensated by irrigation and adapted varieties (Zohry et al., 2019)
Temperature (decrease)	⚠ Weak effects, but potentially negative (not significant)	⚠ Not precisely analyzed in the literature	⚠ Little studied — rare scenario in the region
Irrigation	▲ Positive in the short term / ▼ Negative in the long term (management paradox, salinization, inefficiency)	▲ Positive but limited by access inequalities (FAO, 2021)	▲ Strongly positive and structuring in the long term (irrigation via the Nile) (El-Headway et al., 2019)
Agricultural GDP	▲ Short term : positive / ▼ Long term : not significant (unbalanced structure, decoupling investment-return)	▲ Moderate positive effect (depends on public investment) (Bachta & Ben Salem, 2021)	▲ Clear effect on productivity via state mechanisms (Ali et al., 2018)
Food Imports	▼ Negative in the short term (substitution effect on local production)	▼ Compensatory effect in the short term, increasing dependence (World Bank, 2022)	▼ Stabilization strategy, but risk of local disincentive (World Bank, 2022)

LNTEMP × LNIRRIGATION	▲ Long term : positive (synergy) / ▼ Short term : negative (temporary substitution effect)	▲ Similar trend observed in irrigated areas (Abahous et al., 2023)	▲ Overall stabilizing effect in the short and long term (Ali et al., 2018)
TEMP × Agricultural GDP Interaction	▲ Long term : structural vulnerability to warming / ▼ Short term : negative effect on growth	⚠ Not specifically addressed	▼ Vulnerability mitigated by targeted policies (Zohry et al., 2019)
Adjustment	⚡ Very rapid (ECM = -	⚡ Moderate to rapid	⚡ Higher structural

Table 11: Effects of Climatic and Agricultural Factors on Food Production.

The results obtained for Tunisia demonstrate a marked sensitivity of food production to climatic variations, particularly to excessive rainfall and rising temperatures. This situation reflects a structural vulnerability common to other Maghreb countries, notably Morocco. According to Moroccan agriculture is heavily dependent on the spatial and temporal distribution of rainfall, and excessive precipitation can lead to losses through erosion and runoff, similar to the findings in Tunisia [38]. Conversely, in Egypt, natural precipitation has a negligible impact on agricultural production due to the heavy reliance on the Nile-based irrigation system [39]. Regarding temperature, the effects vary across countries. In Tunisia, a moderate increase appears beneficial in the short term in high productivity areas but becomes detrimental beyond a certain threshold, aligning with the observations of Bachta and Morocco reports similar effects, particularly for cereal crops sensitive to thermal stress [40]. In Egypt, while warming affects certain crops like maize and wheat, the impacts are relatively contained due to a structured irrigation network and adaptation techniques [41].

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The effects of irrigation also show divergences. In Tunisia, irrigation has positive short-term effects but negative long-term consequences, suggesting inefficiencies related to salinization or degradation of networks. In Morocco, the expansion of irrigated areas has led to localized productivity improvements, but access remains unequal (FAO, 2021). In Egypt, irrigation plays a crucial role, with a sustainably positive effect on production, even under climatic stress, due to centralized management [42]. Finally, interaction effects (temperature × irrigation) are particularly relevant: in Tunisia, a long-term synergy appears between warming and access to water, but a negative substitutive effect may emerge in the short term (results from this study) [43]. Similar trends are observed in Morocco while in Egypt, the combined effect remains generally stabilizing [44]. Regarding food imports, all three countries utilize them as an adjustment mechanism, but this may affect the long-term resilience of their agricultural sectors. In summary, Tunisia and Morocco share a high climate exposure, with mixed agricultural systems that are more vulnerable than Egypt's, which benefits from a more integrated irrigation model. This underscores the need for Tunisia to improve water management, invest in agricultural infrastructure, and develop climate-smart adaptation strategies (IPCC, 2022).

3. Conclusion and Implication

Climate change poses a major challenge for Tunisian agriculture, severely impacting production, soil quality, and food security. Projections indicate that rising temperatures and decreasing precipitation could reduce agricultural yields by 5 to 10% by 2030, particularly affecting cereal and tree crops. The situation is exacerbated by Tunisia's growing dependence on food imports, making the country vulnerable to fluctuations in international markets and economic crises. Since 2017, the effects of climate change have intensified, with severe droughts and degradation of water resources. Small farms, which represent a significant part of the sector, are particularly affected as they heavily rely on climatic conditions and imports for their animal feed needs. Large farms, on the other hand, suffer from reduced water efficiency during heatwaves, compromising their profitability. To address these challenges, it is imperative for Tunisia to adopt a structured adaptation strategy. This includes implementing sustainable agricultural practices, such as drip irrigation, which optimizes water use, and promoting crops that require less water. Additionally, creating regional water banks and improving water resource management are essential to ensure sufficient agricultural production. Climate social protection is also necessary to support vulnerable farmers. This could include parametric insurance against droughts, strategic cereal stocks, and zero-interest emergency loans for farmers affected by extreme climatic events. Furthermore, developing centers for disseminating climate-smart practices and providing tax incentives for green investments are crucial measures to enhance the sector's resilience. Regional cooperation is another key aspect. Establishing a Maghreb Agricultural Climate Observatory and harmonizing water resource management standards between Tunisia and its neighbors, particularly Algeria, could improve the management of shared resources and reduce tensions related to food dependence. In conclusion, Tunisia stands at a crossroads. Transitioning from a crisis management approach to a proactive adaptation strategy is no longer an option but an urgent necessity. By investing in resilience and adopting appropriate measures, Tunisia can not only mitigate the negative impacts of climate change but also pave the way for a more stable and sustainable agricultural and economic development for future generations [45,51].

Declarations.

Ethics Statement

The research presented in this article was conducted in accordance with the ethical standards applicable in the field of economics. The author declares no conflict of interest. No experimentation on humans or animals was conducted as part of this study.

Consent to Participate

No human participants were involved in this study, as it exclusively used aggregated and publicly available data.

Consent to Publish

Since all data used were public and anonymized, no consent for publication was required.

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