

Scarring Effects and Asymmetric Respons of Food Security to Climate Shocks: A PMG-ARDL Econometric Analysis for North African Countries(1990-2024)

Lilia Benmensour¹, Charefeddine Zedira², Nahed Hebbaz³

Abstract

This study investigates the equilibrium and dynamic relationship between climate change and food security in North Africa from 1990 to 2024, with a specific focus on analyzing "Scarring Effects" and the asymmetric response of food systems to environmental shocks. Utilizing the Pooled Mean Group (PMG-ARDL) heterogeneous dynamic panel model and the Wald test for linear constraints, the findings reveal a long-term co-integrating relationship, confirming that food stability is inherently tethered to climate stability. The results indicate that persistent temperature rises function as a "structural brake," diminishing agricultural efficiency. Furthermore, the study identifies a sharp asymmetry; the destructive impact of drought years significantly outweighs the recovery phase during periods of rainfall abundance. This phenomenon leaves deep "scars" on farmers' productive assets, leading to a profound inertia in returning to equilibrium, requiring approximately 2.7 years to dissipate the shock. The study concludes that ongoing demographic growth, coupled with climate fragility, necessitates a shift in the region's "developmental doctrine" toward proactive food sovereignty and the implementation of smart insurance systems that safeguard the production base, rather than relying solely on transient consumption subsidies.

Keywords: Food Security, Climate Change, PMG-ARDL Model, Scarring Effects, North Africa, Statistical Asymmetry, Wald Test.

Received: 15/07/2025 ; Accepted: 03/02/2026 ; Published: 10/04/2026

Introduction

The issue of food security in North Africa stands at a critical intersection between severe environmental fragility and an escalating dependence on volatile global macroeconomic shifts. This reality elevates the concept of "sustainability" from a mere theoretical framework to an existential imperative and a paramount security and social challenge. In a geographical region burdened by "structural water stress" and encroaching desertification, food security is no longer viewed as a static quantitative balance between production and consumption. Instead, it is understood as a system of Dynamic Resilience subject to the direct and non-linear impacts of anthropogenic climate change (FAO et al., 2023). Modern economic discourses suggest that countries in this region (Algeria, Tunisia, Morocco, Libya, and Egypt) are tangibly confronting the dilemma of "Planetary Boundaries." Accelerating climatic fluctuations and erratic precipitation patterns are leading to a rapid erosion of "Natural Capital," causing significant deviations in the aggregate agricultural production function and jeopardizing the capacity of ecosystems to meet the needs of future generations (Dasgupta, 2021).

The theoretical underpinning of this study posits that climate change in North Africa does not function as a simple exogenous variable, but rather as a "Risk Multiplier" that permeates the core of the economic fabric through multi-level transmission channels. From a production standpoint, hydrological shocks trigger declines in essential agricultural yields, exerting immense pressure on balance of payments due to the forced reliance on increased food imports (Janssens et al., 2020). In this context, global econometric studies

¹ Abbes Laghrour University, Khenchela, Algeria ; Laboratory Sustainable Development, Startups, and Finance. lilia.benmensour@univ-khenchela.dz (Corresponding Author)

² Abbes Laghrour University, Khenchela, Algeria ; Laboratory Sustainable Development, Startups, and Finance. zedira.charefeddine@univ-khenchela.dz

³ Abbes Laghrour University, Khenchela, Algeria ; Laboratory Sustainable Development, Startups, and Finance. hebbaz.nahed@univ-khenchela.dz

indicate that global warming has already slowed agricultural productivity growth in arid regions by more than 21% since 1961 (Ortiz-Bobea et al., 2021).

The core problematique of this study lies in the state of "structural instability" afflicting the region's food systems. Severe climatic volatility has created a production gap that conventional means cannot bridge. These fluctuations do not merely inflict seasonal losses; they extend to degrading the system's capacity for "self-recovery." Consequently, food security becomes vulnerable to cumulative shocks that undermine long-term sustainability and inflate the import bill. Despite the wealth of literature documenting the direct quantitative effects of these fluctuations, a double research gap can be identified. On one hand, current econometric studies in the region lack a holistic sustainability perspective that integrates environmental and economic indicators into a single kinetic model. On the other hand, a methodological gap exists regarding the neglect of Asymmetric Responses to climatic shocks. Traditional models treat drought and rainfall abundance shocks as having equal effects, which contradicts the reality of complex systems (Wheeler & von Braun, 2013).

Building upon the aforementioned, this study seeks to address these deficiencies by providing a qualitative contribution that transitions from a static analysis to an advanced dynamic analysis using the Panel ARDL model. The added value of this research lies in its methodological ability to decouple long-term structural effects from transient fluctuations, in addition to statistically measuring the "Scarring Effect" and the speed of adjustment, which scientifically establishes the duration required for the system to return to equilibrium. Accordingly, the primary objective is to measure the resilience of food sustainability against climatic shocks and to provide evidence-based policy recommendations to enhance the dynamic resilience of food systems in North African countries.

Literature Review & Hypotheses Development

Modern economic and climate literature intersects at a fundamental point: environmental changes are no longer merely incidental exogenous variables but have become structural drivers of imbalances in food value chains. Based on a comprehensive survey of the literature, the study's hypotheses were formulated according to the following systematic linkage:

Structural Linkage Between Environmental Shocks and Food System Equilibrium

Pioneering studies such as (Wheeler & von Braun, 2013) argue that food sustainability depends on the systems' capacity to absorb shocks, a notion reinforced by (Rockström et al., 2009)'s theses on "planetary boundaries," which consider that exceeding environmental thresholds leads to irreversible losses in natural capital. In a related context, (Gaupp et al., 2020) warned of the risks of "concurrent failure" of environmentally interconnected food systems due to transboundary climate changes.

Accordingly, the primary hypothesis (**H0**) states that: **"Acute climate fluctuations lead to cumulative structural degradation of long-term food security sustainability, such that the negative effects of shocks outweigh the capacity of existing adaptation mechanisms to restore equilibrium."**

Impact of Heat Stress as a Structural Constraint on Agricultural Productivity

Empirical findings from (Ortiz-Bobea et al., 2021) and (Lesk et al., 2016) revealed that global warming subtracts a substantial portion of agricultural productivity growth, with rising temperatures acting as a "structural productivity tax." Studies by (Abbas et al., 2023) and (Beltran-Peña et al., 2020) support this view by demonstrating that exceeding "thermal thresholds" in arid regions reduces arable land area and weakens the biological efficiency of crops, as confirmed locally by (El-Gindy et al., 2022).

Consequently, we formulate the first sub-hypothesis (**H1**): **"There is a statistically significant negative long-term effect of rising temperatures on food security indicators in North African countries."**

Recovery Inertia and 'Scarring Effect' Dynamics in Developing Systems

A study by (Hasegawa et al., 2018) provided strong evidence that climate shocks cause "credit poverty" and a drain on productive assets that hinders the recovery process, an idea developed by (Anderson et al., 2020) to describe the state of "recovery inertia." (Kadigi et al., 2021) indicate that weak technological investment in the African continent prevents overcoming the "negative memory" of the food system after drought waves, which is clearly evident in dynamic models of the region (Zouabi et al., 2022; Ben-Hassen et al., 2021).

Based on this, the second sub-hypothesis (H2) states: **"The recovery process from climate shocks is characterized by statistical slowness (low error correction coefficient), indicating the presence of an extended scarring effect preventing a rapid return to equilibrium."**

Food Security Response to Resource Fluctuations: The Structural Asymmetry Hypothesis

"Threshold theory," alluded to in studies by (Cottrell et al., 2019) and (Janssens et al., 2020), suggests that negative shocks cause degradation in soil fertility and financial assets that cannot be fully compensated merely by the return of normal conditions. This aligns with observations by (Ahmed & Khaled, 2021) and (Boulahya et al., 2022) that the fragility of supply chains in North Africa makes absorbing crises much harder than benefiting from periods of abundance, a concept reinforced by "food surprises" from (Davis et al., 2023).

Accordingly, we formulate the third sub-hypothesis (H3): **"The reaction of food security to climate fluctuations is characterized by structural asymmetry; where the severity of decline resulting from negative shocks (drought) outweighs the strength of recovery resulting from positive shocks (rainfall abundance)."**

Methodology & Data

This study adopts the "deductive econometric" approach to test the robustness of the proposed theoretical hypotheses. Given the dynamic nature of food security and its cumulative impact from shocks, Cross-Sectional Time-Series data (Balanced Panel Data) for North African countries (Algeria, Tunisia, Morocco, Libya, Egypt) for the period from 1990 to 2024 was used.

Specification of the Econometric Model:

The study relies on an Augmented Agricultural Production Function that integrates environmental and economic variables within a dynamic framework. The basic theoretical relationship for the Food Security Sustainability (FSS) indicator is formulated as a function of climate fluctuations and control variables as follows:

$$FSS_{it} = f(TEMP_{it}, RAIN_{it}, GDP_{it}, POP_{it})$$

For the purpose of estimating elasticities, reducing the impact of outliers, and transforming the relationship into a linear form, the natural logarithm (ln) transformation was applied to the variables, resulting in the final form of the standard model equation:

$$\ln FSS_{it} = \beta_0 + \beta_1 \ln TEMP_{it} + \beta_2 \ln RAIN_{it} + \beta_3 \ln GDP_{it} + \beta_4 \ln POP_{it} + \epsilon_{it}$$

Where:

- (FSS) = Food Security Sustainability index

- (TEMP) = Temperature deviation

- **(RAIN)** = Rainfall fluctuations
- **(GDP) and (POP)** are the economic and demographic control variables.
- **i** represents the cross-sectional units (the five North African countries).
- **t** represents the time dimension (period 1990 to 2024).
- **β1, β2** represent the elasticities of food security sustainability concerning climate fluctuations (test for H1).
- **β3, β4** represent coefficients of economic and demographic control variables.
- **ε_{it}** represents the random error term.

Econometric Strategy: The PMG-ARDL Model

To achieve the study's objectives and measure the "scarring effect," the Pooled Mean Group (PMG) estimator developed by (Pesaran et al., 1999) was selected. The competitive advantage of this model lies in its ability to disentangle the long-term structural effect from short-term transitory fluctuations according to the following dynamic equation:

$$\Delta \ln FSS_{it} = \varphi_i (\ln FSS_{it-1} \beta' X_{it}) + \sum_{j=1}^{p-1} \lambda_{ij} \Delta \ln FSS_{it-j} + \sum_{j=0}^{q-1} \gamma'_{ij} \Delta X_{it-j} + \mu_i + \varepsilon_{it}$$

The study focuses on two main parameters within this model:

- The Error Correction Coefficient (φ_i): The primary tool for measuring the "speed of recovery"; its value statistically reflects the "system inertia" and its ability to overcome shocks (testing H2).
- Long-run parameters (β): Used to measure the "structural thermal constraint" and the extent to which food stability depends on climate stability (testing H1).

Asymmetry Modeling (Asymmetry Test)

To achieve the required analytical depth for testing hypothesis (H3), the (Shin et al., 2014) methodology was used to decompose the rainfall variable into positive (RAIN+) and negative (RAIN-) partial sums via the Wald test for linear restrictions. This procedure allows us to verify whether the "pain of drought" causes damage to sustainability far exceeding the gains from "rainfall abundance," according to the following equations:

$$RAIN^+_{it} = \sum_{j=1}^t \Delta RAIN^+_{ij} = \sum_{j=1}^t \max (\Delta RAIN_{ij}, 0)$$

$$RAIN^-_{it} = \sum_{j=1}^t \Delta RAIN^-_{ij} = \sum_{j=1}^t \min (\Delta RAIN_{ij}, 0)$$

Diagnostic Tests and Estimation Quality Criteria

To ensure the validity of the econometric estimation and avoid falling into the trap of "spurious relationships" given the regional interdependence of North African countries, the data were subjected to advanced second-generation tests according to the following sequence:

Cross-Sectional Dependence Test

Given the geographical proximity and shared economic and climate linkages among the five countries, we reject the null hypothesis of cross-sectional independence. Pesaran's (2004) CD test was used; ignoring this

dependence leads to biased and inconsistent parameter estimates. The presence of CD justifies the use of second-generation stationarity and cointegration tests.

Second-Generation Unit Root Tests (CIPS Unit Root Test)

Based on the confirmation of cross-sectional dependence, traditional tests like ADF or PP were abandoned in favor of Pesaran's (2007) CIPS test. This test is most efficient in dealing with cross-unit correlation and aims to ensure variables are stationary at level $I(0)$ or first difference $I(1)$, a crucial condition for applying the PMG-ARDL model.

Cointegration Test (Westerlund Cointegration Test)

To confirm the existence of a genuine (non-spurious) long-term equilibrium relationship linking food sustainability and climate fluctuations, the Westerlund (2007) test was performed. This test is characterized by its high power in detecting cointegration in panel data models while accounting for the heterogeneous structure of the data, thus lending reliability to the long-term elasticities to be estimated.

Operational Definition of Variables and Data Sources

To ensure the accuracy of the econometric analysis and avoid specification errors, variables were selected based on modern economic and climate literature. Tables (1) and (2) present the operational identity of these variables.

Table (1): Variable Significance and Role in Hypothesis Testing

Variable	Symbol	Type	Analytical Significance	Linked Hypothesis
Food Security Sustainability	FSS	Dependent	A composite index reflecting the dynamic stability of food supplies.	Main Hypothesis (H_0)
Thermal Deviation	TEMP	Independent	Measures the "Structural Brake" and biological exhaustion of resources.	Sub-Hypothesis (H_1)
Precipitation Volatility	RAIN	Independent	Measures the "Scarring Effect" and structural asymmetry (Drought vs. Abundance).	Sub-Hypotheses (H_2, H_3)
Gross Domestic Product	GDP	Control	Reflects the "Compensatory Capacity" via food imports and economic strength.	—
Population Growth	POP	Control	Measures demand pressure and the depletion rate of food surpluses.	—

Source: Prepared by the authors based on the literature review and relevant studies on food security and climate change.

Table (2): Data Specifications, Statistical Treatment, and Sources

Variable	Measurement Unit	Statistical Treatment	Primary Source
Food Security (FSS)	Composite Index	Natural Logarithmic Transformation (ln)	Food and Agriculture Organization (FAOSTAT)
Temperature (TEMP)	Degrees Celsius (C^0)	Annual Average (ln)	World Bank (Climate Change Knowledge Portal)

Precipitation (RAIN)	Millimeters (mm)	Decomposition into asymmetric shocks(-/+)	World Bank Data
Real GDP	Constant Dollars	Natural Logarithmic Transformation (ln)	World Development Indicators(WDI)
Population Growth	Percentage(%)	Annual Growth Rate	United Nations / World Bank

Source: Prepared by the authors based on World Bank (WDI) and FAOSTAT databases for the period (1990–2024), with logarithmic processing applied to ensure series stationarity.

Systematic Analysis of the Tables:

- Use of Logarithms (ln): Variables (FSS, TEMP, RAIN, GDP) were transformed into logarithmic form to reduce the impact of outliers and enable interpretation of coefficients as "elasticities," facilitating precise percentage-based measurement of food security sensitivity to climate changes.

- Data Homogeneity: Relying on standardized international sources (FAOSTAT, WDI) ensures "time-series homogeneity" for the five countries in the region, a prerequisite for the validity of panel data models.

- Rainfall Variable Decomposition: Note in Table (2) the reference to "decomposition into positive and negative shocks"; this procedure is the core of the "asymmetry" test (H_3) that distinguishes this research from traditional studies.

Results and Econometric Analysis

Descriptive Statistics and Correlation Matrix

Table (3) presents the statistical characteristics of the variables for the five North African countries for the period (1990-2024). The results show sharp fluctuations in the Food Security Sustainability Index (FSS), reflecting the structural fragility of the region's food systems.

Table (3): Descriptive Statistics and Correlation Matrix (N = 125)

Variables	Mean	Std. Dev.	LnTEMP	lnRAIN	lnGDP	lnPOP	VIF
ln FSS	4.125	0.452	-	-	-	-	-
ln TEMP	3.081	0.124	1.000				1.45
ln RAIN	5.458	0.887	-0.215	1.000			1.88
ln GDP	8.254	1.102	0.112	0.345	1.000		2.10
ln POP	1.856	0.354	0.085	-0.120	0.412	1.000	1.65

Source: Prepared by the authors based on Stata 17 output, using annual data retrieved from World Bank (WDI) and FAOSTAT databases for the period (1990–2024).

The descriptive results shown in Table (3) provide an initial, precise picture of the data used. Note that the rainfall variable (ln RAIN) recorded the highest standard deviation (0.887), statistically translating the acute rainfall variability characterizing the North African region. This significant data dispersion reflects the instability of water resources, directly exposing food security sustainability to unforeseen hydro-climatic shocks.

Regarding the correlation matrix, results show all cross-coefficients are within an acceptable range (below 0.80), initially indicating the independence of the explanatory variables from each other. The correlation between temperature and economic growth (ln GDP) is relatively weak, reinforcing the need for a dynamic model (like ARDL) to uncover deep long- and short-term relationships.

To ensure the model's econometric soundness, the Variance Inflation Factor (VIF) was examined; values ranged between 1.45 and 2.10. As these are well below the critical threshold (10), the study is free from multicollinearity. This means each explanatory variable makes a unique and independent contribution to explaining changes in food security, lending a high degree of reliability and statistical efficiency to the parameters estimated later.

Pre-Estimation Diagnostic Tests

Before estimating long- and short-term elasticities, the time series were subjected to second-generation tests to ensure estimation validity given regional interdependence.

Cross-Sectional Dependence Test (CD Test)

Results of the Pesaran (2004) test showed rejection of the null hypothesis (independence) at the 1% significance level; the statistical value reached 14.85. This confirms that North African countries form an interconnected geographic and climatic bloc, making second-generation tests the only correct methodological choice.

Table (4): Cross-Sectional Dependence (CD) Test Results

Test Name	Statistics	d.f.	P-value	Decision
Pesaran CD	14.852	-	0.000*	Presence of CD
Breusch-Pagan LM	45.206	10	0.000*	Presence of CD
Pesaran Scaled LM	12.314	-	0.000*	Presence of CD
Bias-corrected Scaled LM	11.950	-	0.000*	Presence of CD
*Note: Significant at 1% level.				

Source: Prepared by the authors based on Stata 17 output, employing Pesaran's (2004) Cross-Sectional Dependence (CD) test.

Second-Generation Unit Root Tests (CIPS Unit Root Test)

Based on confirmed CD, Pesaran's (2007) CIPS test was used, being more efficient than traditional ADF or PP tests for this case. CIPS results revealed that variables (FSS, TEMP, GDP) are stationary at first difference I(1), while the rainfall variable is stationary at level I(0). This mix in integration orders is the statistical justification for using the PMG-ARDL model, which flexibly handles different integration orders.

Table (5): Results of Pesaran's (2007) CIPS Unit Root Test

Variables	Level [t-bar]	P-value	1st Diff [t-bar]	P-value	Status
ln FSS	-1.924	0.412	-4.351***	0.000	I(1)
ln TEMP	-2.055	0.320	-4.108***	0.000	I(1)
ln RAIN	-3.552***	0.002	---	---	I(0)
ln GDP	-1.604	0.655	-4.652***	0.000	I(1)
ln POP	-1.152	0.880	-3.904***	0.000	I(1)

Source: Prepared by the authors based on Stata 17 output using the study data.

(Note: ***, **, * indicate significance at 1%, 5%, 10% levels respectively).

Cointegration Test (Westerlund Cointegration Test)

To ensure the relationship between food security sustainability and climate fluctuations is not spurious, the Westerlund (2007) test, which accounts for cross-sectional dependence, was performed. The Westerlund test statistics confirmed a long-term equilibrium relationship (Cointegration) with high significance (P-value < 0.05). This result means the relationship is a genuine structural one, allowing us to proceed to parameter estimation.

Table (6): Results of Westerlund (2007) Panel Cointegration Test

Statistics	Value	Z-value	P-value	Robust P-value
G_t	-3.125	-2.451	0.007	0.010**
G_a	-12.402	-1.984	0.023	0.035**
P_t	-7.854	-3.105	0.001	0.002***
P_a	-14.208	-2.152	0.015	0.020**

Source: Prepared by the authors based on Stata 17 output using the study data

(Note: ***, **, * indicate significance at 1%, 5%, 10% levels respectively).

Model Estimation and Interpretation of Elasticities

The model was estimated using PMG-ARDL estimators, yielding the following results:

Table (7): Results of the Pooled Mean Group (PMG-ARDL) Estimation (Dependent Variable: ln FSS)

.Variables	Coefficient	Std. Error	t-Statistic	Prob.
Long-Run Coefficients				
ln TEMP	-0.684	0.141	-4.851	0.000
ln RAIN	0.312	0.090	3.466	0.001
ln GDP	0.458	0.071	6.450	0.000
ln POP	-0.182	0.080	-2.275	0.024
Short-Run Coefficients				
ECT_{t-1}	-0.365	0.081	-4.506	0.000
Delta ln TEMP	-0.152	0.101	-1.504	0.134
Delta ln RAIN	0.224	0.092	2.434	0.015
Constant	1.452	0.354	4.101	0.000

Source: Prepared by the authors based on Stata 17 output, using study data retrieved from World Bank and FAO databases (1990–2024).

The estimation results revealed a substantial divergence in the response of food security sustainability to climate pressures between the long and short run, interpretable through three dimensions:

First: Long-term Dynamics and the Structural Thermal Constraint (H_1):

Long-run estimates show that persistent temperature increases represent a "structural threat"; the temperature elasticity reached (-0.684) with strong statistical significance ($P < 0.01$). This means each 1%

increase in average temperature leads to a 0.68% erosion of sustainability. Economically analyzing this figure reveals the region suffers from "thermal exhaustion of resources," where climate becomes a "structural brake," diminishing agricultural sector efficiency and preventing its stabilization (confirming H₁).

Second: Error Correction Mechanism and the "Scarring" Psychology (H₂):

The Error Correction Term coefficient (ECT = -0.365) represents the most significant result; it confirms an equilibrium relationship but reveals a "structural inertia" in the recovery system. The system's ability to correct only 36.5% of its deviations annually means a single climate shock leaves an effect lasting approximately 2.7 years. This slowness statistically embodies the "Scarring Effect"; the region falls into an "accumulation trap," where a new shock hits the system before it recovers from the previous crisis's scars (confirming H₂).

Third: The "Asymmetry" Trap and Bias towards Structural Failure (H₃):

The Wald test rejected the equality of effects hypothesis (P = 0.003); the "pain of drought"

(-0.485) outweighed the "benefit of rainfall abundance" (0.154) by more than threefold. This disparity proves that adaptation mechanisms in the region are "fragile defensive buffers" that collapse under downward shocks and cannot exploit upturns to repair losses, making the return to equilibrium an elusive goal (confirming H₃).

Analytical Reading of the Study Hypotheses Validation

After reviewing the PMG-ARDL model outputs, we now assess the acceptability of the theoretical propositions and their correspondence with the extracted statistical evidence:

First: Evaluation of the Main Hypothesis (H₀) "Structural Deterioration and Adaptation Deficit"

- Statistical Decision: Full confirmation of hypothesis (H₀).

- Analysis: Results proved that food security in the region suffers not from "transitory disturbance" but from "equilibrium fragility." The ECT value of (-0.365) reveals a "structural inertia" making the effect of a single shock last approximately 2.7 years. This matches modern climate economics findings that the pace of successive shocks turns effects from transitory to permanent structural degradation, confirming current adaptation mechanisms' inability to restore equilibrium.

Second: Response of the First Sub-Hypothesis (H₁) "Thermal Exhaustion as a Structural Brake"

- Decision: Statistical reliability of hypothesis (H₁) confirmed.

- Analysis: The temperature elasticity (-0.684) revealed an extended "erosive" relationship; a 1% temperature increase leads to 0.68% sustainability erosion. Economically, the region suffers from "thermal resource exhaustion," where chronic warming degrades soil fertility and depletes water stocks, consistent with (Ortiz-Bobea et al., 2021) on warming as a "structural brake."

Third: Verification of the Second Sub-Hypothesis (H₂) "Scarring Effect and Recovery Inertia"

- Decision: Evidence matches hypothesis (H₂).

- Analysis: Slow recovery speed proves a "negative memory" of the region's food system. Climate shocks do not end with the agricultural season but cause cumulative depletion of productive assets, explaining why crises leave deep "scars" on agricultural economy structure, supporting the (Lesk et al., 2016) thesis on the "Scarring Effect."

Fourth: Reliability of the Third Sub-Hypothesis (H₃) "Structural Asymmetry"

- Decision: Confirmation of asymmetry hypothesis (H₃).

- Analysis: Wald test results showed a clear bias in impact; the "pain of drought" (-0.485) outweighed the "benefit of abundance" (0.154) more than threefold. This disparity proves local adaptation mechanisms have very limited "upward flexibility" while collapsing entirely under "downward shocks," aligning with (Shin et al., 2014) on fragile economic systems' "failure bias" facing climate extremes.

Table (8): Summary of Hypothesis Testing Results

Hypothesis	Associated Variable / Model	Expected Impact (Theory)	Statistical Result (Empirical)	Final Decision
Main (H ₀)	PMG-ARDL Model	Structural Deterioration	ECT = -0.365	Sustained
Sub (H ₁)	ln TEMP	Negative Impact (Inhibitor)	0.684-	Accepted
Sub (H ₂)	ECT (Recovery Speed)	Sluggishness (Scarring Effect)	2.7Years to Recovery	Accepted
Sub (H ₃)	Wald Test (Rain)	Asymmetry	F = 8.54	Accepted

Source: Prepared by authors based on results derived from the (PMG-ARDL) model and Wald linear restriction test for the period (1990-2024).

The cumulative results in Table (8) confirm that food security sustainability in North African countries is under a 'double pressure': a long-term structural thermal pressure and an acute short-term rainfall variability pressure. The joint confirmation of the main hypothesis (H₀) and all three sub-hypotheses (H₁, H₂, H₃) provides strong statistical evidence that current adaptation mechanisms (e.g., horizontal agricultural expansion or random imports) are 'palliative solutions' that do not address the core problem of 'recovery inertia.' Based on the confirmation of the 'scarring effect' and response asymmetry to shocks, continuing traditional policies will inevitably deepen climate dependence, necessitating a shift from 'reactive' to 'structural proactive' policies detailed in the recommendations section."

Conclusion and Policy Implications: From Econometric Estimation to the Horizons of Food Sovereignty**Synthetic Summary of Structural Outputs**

This study analytically transcends mere numerical description of the climate-food relationship in North Africa to reveal "transboundary fragility dynamics." The results from the PMG-ARDL model present a stark reality: the food security dilemma in the region is not a product of transitory resource scarcity, but a "structural resilience crisis" fueled by the interplay of three critical pathways:

- The Imperative of Long-Term Equilibrium (Main Hypothesis H₀): The study confirmed the hypothesis through high significance and the negative sign of the ECT. This statistical confirmation shifts the food security issue from an "emergency crisis" to a "deterministic structural equilibrium issue"; climate, economic, and demographic variables form an intertwined system pushing food security towards a "fragile" long-term equilibrium, making "climate resilience" an explanatory condition for regional development stability.

- Dependence on Chronic Thermal Exhaustion (H₁): The significance of the thermal coefficient (-0.684) proves that global warming in North Africa has become an "effective structural constraint," reducing

productive efficiency. This continuous "biological stress" acts as a brake preventing any traditional technological investment from yielding returns, consistent with (Ortiz-Bobea et al., 2021) that excessive heat is a permanent tax on food growth.

- The "Scarring" Psychology and Structural Recovery Inertia (H₂): Analysis of the adjustment speed (2.7 years) reveals a highly dangerous economic fact: climate shocks possess "long-term institutional memory." The long recovery period means each drought wave leaves a deep "scar" on the agricultural economy's body; producers liquidate assets to cover deficits, and when abundance years arrive, the system finds itself "financially exhausted" and unable to repair what was lost, embodying (Lesk et al., 2016)'s "Scarring Effect."

- The "Asymmetry" Trap Biased Toward Structural Failure (H₃): Confirming asymmetry via the Wald test represents the most critical result; it proves current policies are "deficient defensive buffers." While production collapses sharply under "downward shocks," it grows slowly and timidly under "upward breakthroughs." This negative bias, consistent with (Shin et al., 2014)'s methodology, confirms the region lacks "abundance capture" mechanisms, leaving it in perpetual pursuit of an unreachable equilibrium.

Proposed Policy Matrix: Towards a Proactive "Resilience Doctrine"

Based on the above, the study proposes a radical shift in the region's development doctrine, moving beyond the logic of relief to the logic of "sovereignty engineering":

- Building a "Sovereign Climate Shield": Decouple the historical link between "rainfall variability" and "bread provision" by transforming "treated irrigation" into a sovereign infrastructure not subject to weather fluctuations.

- Re-engineering Financial Safety (Asset Restoration, not Crop Insurance): Develop "smart climate insurance" systems based on satellites to protect the "productive base" (livestock, equipment), preventing producers from exiting the economic cycle and breaking the "scarring effect" loop.

- Governing the Triangle (Demography-Food-Water): Align population policies with limited environmental carrying capacity, redirect subsidies towards crops with a "low water footprint" and high added value.

Research Limitations and Horizons "Beyond Econometric Modeling"

Limitations: Despite methodological rigor, the study acknowledges "statistical shadow zones" related to informal agricultural sector data and subsistence family farming, which form a real safety net in crises but remain off official "radar screens." Additionally, sharp intra-country geographic and climatic variations (e.g., between humid northern and arid southern zones) require more detailed micro-data for higher spatial accuracy.

Future Prospects: This paper opens the door to major research questions:

- Water-Climate Geopolitics: The impact of observed asymmetry on transboundary conflicts over shared river basins.

- Agricultural Artificial Intelligence: Can algorithms break the "scarring effect" by optimizing resource allocation at critical shock moments?

- Humanizing Adaptation: Studying small farmer behavior facing "climate frustration" and its impact on rural-urban migration waves.

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