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Interactions Between Climate Change, Water Stress and Sustainable Agriculture Practices: An ARDL Approach Modeling

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Climate change has emerged as a concern for sustainable agricultural production. Some regions, particularly the Middle East and North Africa (MENA), are exposed to greater climate fluctuations, including decreased rainfall, rising temperatures, and water scarcity. These problems are particularly acute because the region is already arid and experiences high temperatures. This study investigates the interaction between climate change, fertilizer management, water use efficiency, and agriculture in five MENA countries from 2000 to 2022. The study implemented a Panel Autoregressive Distributed Lag (PARDL) approach to examine the long-run and short-run dynamic impacts of the varying climatic circumstances and sustainable practices on agricultural production. Granger causality tests reveal unidirectional relationships from agricultural production to climatic variables, fertilizer consumption, and water use efficiency, as well as from CO_2 emissions to temperature changes and from water stress to fertilizer use. Additionally, a bidirectional relationship between water stress, water use efficiency, and crop production underscores their interdependence. These findings reveal, first, that changes in temperature and precipitation in the short run encourage these countries to adopt climate-resilient crop varieties, which has a positive impact on agricultural production in the long run. Second, water stress plays a crucial role in the effectiveness of fertilizers. Finally, water management and optimal fertilizer consumption are essential to making agriculture more sustainable and profitable.

Keywords: climate change, sustainable agriculture, fertilizer management, water use efficiency, panel ARDL approach

Introduction

The complicated relationship between climate change, agricultural output, and sustainable farming practices has emerged as a key topic of international research because of its substantial implications for regional and global economies. Climate change exacerbates difficulties for the agricultural sector by modifying growing seasons, diminishing crop outputs, and heightening the susceptibility to pests, diseases, and severe meteorological occurrences, all of which have direct implications for growth, market prices, and food security. The importance of this link is particularly pronounced in regions like the MENA countries, where agriculture plays a vital role in

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these economies, making it highly vulnerable to climate fluctuations. The decline of this sector could lead to widespread socio-economic disruptions, including increased food insecurity, rising unemployment rates, and declining incomes.

Globally, enhancing agricultural resilience is strongly linked to the Sustainable Development Goals (SDGs) and strategies for mitigating climate change, especially those that deal with poverty alleviation, food security, and climate action. For the MENA region, reducing these challenges requires policies and strategies that improve agricultural production, promote sustainable practices, and support adaptation to climate change, particularly in those countries that are characterized by diverse agricultural environments and practices, with rainfed and irrigated systems.

Despite the abundance of studies on the impact of climate change on agriculture, however, little research has been conducted on the importance of sustainable practices and their impacts to overcome climate fluctuations and food insecurity. The region's dependence on rain-fed agriculture, combined with increasing water scarcity and the increased frequency of extreme weather events, threatens food security in these countries. These challenges highlight the urgent need for data-driven insights and innovative sustainable practices to mitigate climate-related impacts and develop sustainable agriculture. This paper distinguishes itself by using the ARDL model to capture the short- and long-term effects of climate factors and sustainable practices on agricultural productivity, highlighting causality relationships not often explored in the literature. Furthermore, the study offers robust policy recommendations to address the urgent challenges of climate change adaptation, emphasizing the importance of sustainable practices to enhance food security and sustainable agricultural development. The originality of this research resides in the attention paid particularly to the unique environmental and agricultural context of the MENA region, offering perspectives adapted to the specific challenges and opportunities of these countries in the presence of water scarcity and desertification.

This study addresses this gap by using the ARDL (Autoregressive Distributed Lag) model to analyze the causal relationships among climate change, agricultural output, and sustainable agriculture practices in MENA countries. The Autoregressive Distributed Lag (ARDL) model is especially appropriate for this research, as it effectively incorporates variables exhibiting heterogeneous orders of integration, elucidates both short-run and long-run dynamics, and incorporates lagged effects, which are crucial for comprehending the temporal responses within agricultural systems. Employing this approach, the study reveals critical insights into how immediate climate change and sustainable practices affect agricultural production in MENA countries. The ARDL analysis confirms a positive relationship between climate change and agricultural crops in the long-run. Moreover, the Granger causality highlights the interaction between water stress and fertilizer use. The findings of this study also underline the importance of adopting sustainable practices such as water-efficient irrigation, climate resilient crop varieties, and optimal fertilizer use to promote sustainable agriculture.

This study successfully achieved its objective by highlighting the interconnected impacts of climate change and sustainable practices on the agricultural sector in selected MENA countries. The findings provide a solid basis for policy recommendations aimed at promoting sustainable agriculture and mitigating the effects of climate change.

Literature Review

Numerous studies have documented how climate change affects agriculture, pointing to changes in temperature, precipitation patterns, and the frequency of extreme weather events. Climate change is likely to have significant repercussions on communities in developing nations by undermining food security, particularly within the agricultural sector. Agriculture represents one of the most vulnerable domains to the impacts of climate fluctuations. Multiple research investigations have elucidated the adverse correlation between climate change and agricultural yields globally, thereby underscoring the vulnerability of the agricultural sector to climatic shifts.

Climatic variability represents the predominant source of risk that exerts a direct or indirect impact on agricultural output. According to Pickson et al. (2020), the increase in temperature and variations in precipitation patterns exert a direct influence on the phonology of crop growth. Arable land becomes increasingly unsuitable for agricultural endeavors as a consequence of elevated temperatures, which yields long-term adverse implications for crop productivity. Moreover, the same study shows that variations in rainfall patterns are expected to lead to both short-term crop losses and long-term declines in agricultural production. Similarly, Ben Zaied and Ben Cheikh (2015) demonstrated that an increase in mean temperature adversely affects cereal and date production, except of upland regions, whereas precipitation positively influences cereal and date yields in Tunisia. Likewise, Alboghdady and El-Hendawy (2016) identified that variations in temperature and rainfall significantly compromise agricultural productivity in the Middle East and North Africa (MENA).

Agricultural productivity and climate change are consistently linked in research. Fisher et al. (2018) found that changes in precipitation and temperature have a direct effect on crop yields and agricultural production, especially in developing nations like Tunisia. Also, Youssef et al. (2020) revealed that crop yields are negatively impacted by climate variability in Tunisia, which has an effect on food security and rural livelihoods. In the context of Morocco, Achli et al. (2024) investigated the susceptibility of wheat, barley, and maize to fluctuations in temperature during the growing season, as well as socio-economic indicators of adaptive capacity, throughout the timeframe of 1991 to 2016.The results show that maize has the highest vulnerability and the lowest capacity for adaptation to temperature changes during the growing season, whereas wheat is typically the least vulnerable and most adaptable crop. In Egypt, Gamal et al. (2024) detected a negative correlation between wheat yield and extreme temperature in the period from 1987 to 2019, which could lead to nutrient depletion and salinization.

As confirmed by the literature, increasing GHG (greenhouse gas) emissions cause an increase in temperature. Empirical results suggest that the impact of increased CO2 on agriculture in MENA countries is profound and multifaceted, with potential benefits for agricultural yields. Mostafa et al. (2021) conducted a comprehensive meta-analysis of various crops in the MENA region, concluding that, although CO2 enrichment can potentially increase yields by 10-30% for some crops, these improvements are highly dependent on the availability of water resources and the implementation of efficient nutrient management practices. Conversely, other studies have shown that high levels of carbon dioxide can induce fluctuations in temperature and precipitation, which negatively affecting agricultural productivity. This impact can vary depending on the country’s climate and other macroeconomic indicators.

Fertilizer consumption plays a vital role in improving agricultural productivity and food security in MENA countries. It’s crucial because agricultural lands are limited, and soil quality is poor in this region. According to the Food and Agriculture Organization (FAO, 2020), the use of chemical fertilizers has significantly contributed to maximizing crop production. In the same vein, Abd El-Gawad and Morsy (2017) demonstrated that increased fertilizer application in countries like Egypt and Morocco has led to higher yields of fundamental agricultural products, including wheat and maize. Similarly, a study by Zittis et al. (2021) highlighted that the excessive use of fertilizer in Morocco enhanced the resilience of the agricultural sector, and reduced the effects of climate change. However, in the last years, other research confirmed that excessive use of fertilizers can cause soil and environmental pollution, contributing to problems such as eutrophication and biodiversity loss. So, a better use is needed for global food security and environmental sustainability (Bathaei et al., 2023; Avery et al., 2021).

Several studies have analyzed the impact of water stress on agricultural yields in MENA countries. For example, Hejazi et al. (2023) found that reduced water availability leads to lower agricultural productivity, especially for water-intensive crops such as wheat and rice. Derouez and Ifa (2024) conducted a study on five Arab countries: Egypt, Morocco, Jordan, the United Arab Emirates, and Saudi Arabia. They concluded that climate change poses a significant threat, particularly to Morocco, Egypt, and Jordan. Furthermore, population growth exacerbates food security problems in the region, while water scarcity is a critical issue, especially in Jordan. Due to growing demand from industry, urbanization, and agriculture, many countries in the MENA region are classified as water-scarce, with declining per capita water availability (World Bank, 2020), because of inefficient irrigation systems. Zheng et al. (2024) concluded that adopting CSA practices improves, in many cases, agricultural productivity and income. This improvement can increase crop yield and productivity, income and profitability, as well as technical and resource efficiency use.

Empirical Analysis

Methodology and Data

Our study focused on analyzing the relationship between agriculture and climate variables. It draws heavily from the empirical research conducted by Bedasa and Bedemo (2023). The equation that we aim to estimate follows this specific structure:

$$AG_{it} = C_1 + \beta_0 PR_{it} + \beta_1 TP_{it} + \beta_2 CO2_{it} + \beta_3 GFCF_{it} + \beta_4 FC_{it} + \beta_5 WS_{it} + \beta_6 Irr_{it} + \varepsilon_{it} \quad (1)$$

We conducted a panel data analysis where the index t represents the observation years from 2000 to 2022, and i denote a group of MENA countries. β_0, β_1, β_2, β_3, β_4, β_5: Represent the set of coefficients indicating the impact of explanatory variables on value-added agriculture. The variables utilized in our econometric analysis are listed in Table 1.

Table 1

Variable Descriptions

Variable name	Source	Definition of variables
Agriculture (AVAG)	WDI	Agricultural value added in USD.
Temperature (TP)	WMO	The annual average of temperature is calculated using monthly data.
Precipitation (PR)	WMO	The annual average of precipitation is calculated using monthly data.
Carbon emissions (CO2)	WDI	CO2 emissions per unit of GDP are expressed in Kilotons.
Fixed capital (GFCF)	WDI	Gross fixed capital formation as a percentage of GDP.
Fertilizer consumption (FC)	WDI	kilograms per hectare of arable land.
Water stress (WS)	FAO	Ratio between total freshwater withdrawn and total renewable. freshwater resources (%).
Irrigated Agriculture Water Use Efficiency (Irr)	FAO	Ratio between effective water use and actual water withdrawal (US$/m3).

Notes: WDI: world development indicators; FAO: Food and Agriculture Organization. Source: Author.

In Table 2, each panel represents time-series data for key variables related to agriculture, climate change, and water management in MENA countries from 2000 to 2022. These variables include agricultural value added (AG), mean temperature (TP), precipitation (PR), CO2 emissions (CO2), Fixed capital (GFCF), fertilizer consumption (FC), water stress (WS) and irrigated agriculture water use efficiency (Irr).

Table 2

The Descriptive Statistics of the Sample

	LnAG	lnTP	lnPR	lnGFCF	lnCO2	lnFC	lnWS	lnIrr
Mean	22.3010	3.0628	3.7337	0.6505	-1.2812	4.8829	81.9271	0.7827
Median	21.9767	3.0365	3.8042	1.0666	-1.3111	4.7215	79.1200	0.4900
Maximum	24.5437	3.8411	5.0335	2.2440	-0.6244	6.3970	141.1700	4.2900
Minimum	20.0810	2.7865	2.3545	-1.8040	-1.5964	3.4517	35.5600	0.1300
Std, Dev	1.2380	0.1296	0.5384	1.0350	0.2129	0.9586	29.5747	0.7220
Skewness	0.3686	2.0456	-0.4542	-0.6861	1.0932	0.2397	0.3527	1.8671
Kurtosis	1.9177	12.784	3.1564	2.2526	3.9060	1.5244	2.0890	7.2099
Jarque-Bera (JB)	23.46	92.57	25.88	6.93	31.86	15.58	6.3608	151.7463
JB Probability	0.0000	0.0000	0.0000	0.0313	0.0000	0.0004	0.0415	0.0000

Source: Author's estimates.

Econometric Methodology

We employed the panel data autoregressive distributed lag (ARDL) methodology. This approach was initially introduced by Pesaran et al. (1996) and subsequently refined by Pesaran et al. (2001). We selected this technique for two principal reasons. Firstly, it is adept at examining both short-run and long-run relationships among various variables that exhibit different orders of integration when assessing the stationary of the variables. Consequently, a fundamental prerequisite is that these variables are stationary at their levels, denoted as I(0), and/or they exhibit stationary in first differences, indicated as I(1). Secondly, the ARDL methodology effectively addresses issues associated with omitted variable bias and autocorrelation between the variables.

The Wald Test. Before achieving the unit root test, it is useful to employ the Wald test to ascertain the existence of a long-term relationship among the various variables. The Wald test imposes certain constraints on long-term estimations. As illustrated in Table 3, the value of the F statistic indicates a significance level of 1%. Consequently, the long-term "non-cointegrating" null hypothesis is rejected. Hypothesis H1 is validated, signifying the presence of a long-term relationship.

Table 3

Results of Wald Test

Test statistic	Value	Df	Probability
F-statistic	56.87	(2, 107)	0.0000***
Chi-square	113.74	2	0.0000***

Source: Author's estimates.

The model is validated under Hypothesis H1, indicating that there exists a long-term relationship among variables.

Unit Root Tests. It is necessary to conduct stationary assessments of the variables before estimating the model. All series exhibit either upward or downward trends and introduce breaks. To assess this step, we implemented a comprehensive set of unit root tests. Specifically, we used the methodologies proposed by Levin et al. (2002) "LLC," So Im et al. (2003) "IPS," and Breitung (2001). Each of these assessments is classified as a first-generation unit root test due to their assumption of cross-sectional independence between units. We selected also, from the cohort of second-generation tests, specifically that proposed by Choi (2000), which includes both the Z and the Fisher statistics. Given that the ARDL model is not suitable for series with an integration order greater than 2 (I(2)), we conducted unit root tests to confirm that the series are I(0), I(1), or a combination of I(1) and I(0) (Pesaran et al. 1996; Pesaran et al. 2001). Tables 4 and 5 present the findings of unit root tests.

Tables 4 and 5 indicate that the unit root null hypothesis cannot be dismissed for the following series: the added value of agriculture, GFCF, CO2 emissions, water stress (WS) and irrigated agriculture (irr). Nevertheless, temperature (TP), precipitation (PR), and fertilizer consumption (FC) are stable at their levels. In summary, we observe that our data is I (0) and I (1), allowing us to evaluate both short-term and long-term associations among agriculture variable, climate variables, and Irrigated Agriculture Water Use Efficiency through the ARDL method.

Table 4

Unit Root Test Results: Level Series

	lnAG	lnGFCF	LnTP	lnPR	lnCO2	lnFC	lnWS	lnIrr
LLC	0.55683	-2.13784*	6.48117	1.99530*	0.59720	-2.54376*	1.00093	-0.07731
IPS	0.11009	-0.59527	-2.24750*	-2.36861*	1.44932	-2.77373*	-0.10936	1.76683
Breitung	1.60295	3.01947	-1.45750**	-3.30963*	0.89346	-1.91712*	-1.24778	-0.63673
Choi-Z	0.35276	-0.61360	-2.19703*	-2.38441*	1.59078	-2.80432*	-0.22939	0.72912

Notes: ** and *** indicate, respectively, a significance at 5% and 1%. Source: Authors' Estimates.

Table 5

Unit Root Test Results: First-Difference Series

	ΔlnAG	ΔlnGFCF	ΔlnTP	ΔlnPR	ΔlnCO2	ΔlnFC	ΔlnWS	ΔlnIrr
LLC	-1.49733**	-2.79017*	-3.76854*	-3.45049*	-5.94841*	-5.29692*	-5.52613*	- 1.32243*
IPS	-5.48321*	-2.78209*	-6.35253*	-4.38776*	-3.25642*	-6.87409*	-4.75477*	-4.27334*
Breitung	-3.28037*	0.37804	-6.35443*	-5.33733*	-3.88652*	-3.43798*	-1.12051*	- 1.20133*
Choi-Z	-4.59807*	-2.84294*	-5.52857*	-4.19792*	-3.05661*	-5.59912*	-3.23158*	-4.13748*

Notes: ** and ***indicate, respectively, a significance at 5% and 1%. Source: Authors' Estimates.

Cointegration Test. Table 6 presents the results of Pedroni's (2004) cointegration test. Four of the seven statistics suggest rejection of the null hypothesis of no cointegration. This demonstrates that the Automatic Direction Finder (ADF) panel and the ADF statistics group are considered the most reliable statistics. In our study, we reject the null hypothesis of no cointegration at the 1% significance level, as indicated by both the ADF-panel statistic and the group ADF statistic. Therefore, we can conclude that a long-term relationship is present among the variables analyzed in our investigation of 5 MENA countries.

Table 6

The Result of the Cointegration Test of Pedroni (2004)

Panel v-Stat	Panel Rho-Stat	PanelP p-Stat	Panel ADF-Stat	Group Rho-Stat	Group PP-Stat	Group ADF-Stat
6.47188*** (0.0000)	-1.80702** (0.0354)	-8.372996*** (0.0000)	-49.52081*** (0.0000)	0.57643 (0.7178)	-23.77160*** (0.0000)	-1.52914** (0.0631)

Source: author's estimates.

Results and Interpretation

As can be seen in the table below, the first difference of the variables examined is presented by D. The term CointEq(-1) explains the delayed residue from our long-term equilibrium equation. The negative coefficient estimated for the model thus validates the presence of an error correction tool. The cointegration coefficient of the equation defines the order in which the variable Yt (agriculture production) would be mobilized towards the long-term objective. The results from the Panel ARDL model presented in Table 7 indicate several key findings: Temperature (TP) has a negative and not significant coefficient in the short run, but is positive and significant in the long-run. Rising temperatures and droughts accelerate desertification and land degradation, further compromising agricultural potential. These countries are therefore encouraged to adopt sustainable practices to mitigate climate impacts. The change in sign of this variable in the long run shows that adopting these strategies, such as diversification of crops in response to high temperatures, improves agricultural yields. We can therefore say that there is a non-linear relationship between temperature and agricultural production. Our results are validated by the study of Dylan and Wolfarm (2024).

The coefficient associated with precipitation (PR) is negative but not significant in the short run. This shows that the decrease in precipitation has a negative impact on agricultural production following rainfall variability. In the long term, this coefficient becomes positive (13460658.8) and significant at the 1% level, suggesting dependence on climate change, requiring adaptation strategies such as rainwater harvesting. This can help mitigate the effects of climate fluctuations on agriculture. Conversely, CO_2 emissions are not statistically significant in our case, indicating no immediate effect on agricultural production in the short term as well as in the long term.

Table 7

Results of the ARDL Approach

Dependent Variable: lnAG						
Variables	Coef	p Value	Coef	p Value	Coef	p Value
Short-Run Coefficients						
ΔlnTP	-911680996.6	0.6821	-354619397.0	0.8700	1600267103.8	0.6251
ΔlnPR	-20216188.1	0.1201	-16917572.3	0.1158	-17834479.3*	0.0886
ΔlnCO2	-3491654626.3	0.5314	-668377800.3	0.9361	3811005726.4	0.2235
ΔlnGFCF	211268550.8	0.7090	58952102.8	0.7288	-63372087.01	0.8665
ΔlnFC	-10399956.5*	0.0762				
ΔlnWS			-7129582.0	0.7218		
Δlnirr					882796940.6	0.6764
C	-993361121.02	0.4242	-2289014257.9***	0.0045	-493565761.5	0.7368
CointEq(-1)	-0.871512765**	0.0545	-1.058493656*	0.0720	-0.962239908*	0.0858
Long-Run Coefficients						
lnTP	-546580354.1*	0.0801	957977543.3***	0.0001	168525054.2	0.7374
lnPR	13460658.8***	0.0000	21141910.6***	0.0002	22957779.8***	0.0001
lnCO2	-3761254084.3	0.4663	-5258502454.9	0.1244	-4561044972.8	0.2028
lnGFCF	342105204.9***	0,0003	443098388.8***	0.0000	458805660.8***	0.0001
lnFC	675782.3**	0.0164				
lnWS			-4763064.22***	0.0004		
Lnirr					206092011.8**	0.0300

Notes: ***, ** and * indicate 1%, 5% and 10% significance, respectively. D: operator of first difference for variables.

Source: author's estimates.

Several studies indicate a clear link between increased agricultural investment and improved crop yields and productivity in MENA countries. In recent years, investment efforts in sustainable agriculture have been increasing in countries such as Tunisia, Morocco, Egypt, Jordan, and Lebanon. Our results show a positive but statistically insignificant relationship. This leads us to conclude that this effort is not sufficient in the short term to increase agricultural production. In the long term, the sign obtained is consistent with our expectations (positive) and statistically significant at the 1% level. The augmented effort on sustainable practices, such as investment in water-saving technologies, infrastructure, and research to develop climate-resilient and innovative farming, will lead to a boost in agricultural production in these countries in the next few years. Furthermore, investing in agricultural infrastructure, including irrigation systems and storage facilities, can serve to alleviate the adverse effects of temperature changes and water shortages.

We also find that the coefficient of fertilizer consumption in the short term is negative (10399956.5) and significant at the 10% level (0.0762). In other words, fertilizer consumption negatively affects agricultural production. This is explained by the excessive use of fertilizers, accompanied by ineffective water management, which negatively impacts crops, given the arid climate of many countries in the MENA region. But in the long term, this coefficient becomes positive (0.0164) and statistically significant. These findings demonstrate that the use of best sustainable practices, such as appropriate water management and optimal use of fertilizers, can sustainably improve soil health and productivity, hence agricultural production. Given the observed change in the sign, it can be inferred that a non-linear relationship exists between fertilizers and agricultural production within this particular region. Our results are consistent with the study by Vijayakumar Shanmugam et al. (2025) that analyzed the impact of fertilizer use on agricultural sustainability. They found that regional variability in fertilizer consumption can compromise efficiency and environmental sustainability. Therefore, there is a need to improve fertilizer management practices to support sustainable agriculture.

Concerning water stress, we can conclude that in the long term as well as in the short term, the coefficient of water scarcity on agricultural production is negative and significant at the 1% threshold. This implies that water stress is negatively related to agricultural productivity, so that a decrease of 1% in water supply leads to a decrease of crops in the long run. In regions characterized by significant water scarcity, the utilization of fertilizers may precipitate the leaching of nutrients, particularly when irrigation techniques are inadequately administered. This phenomenon can create environmental challenges and diminish the efficiency of fertilizers. Conditions of water stress can compromise soil integrity, thereby impairing its capacity to sequester nutrients. For this reason, farmers ought to alter their fertilizer methodologies, potentially incorporating a greater proportion of organic fertilizers or soil amendments to enhance water retention. The results thus allow us to understand that water management and fertilizer efficiency lead to improved crops and promote sustainable agricultural practices by increasing the investment effort in countries like Tunisia, Morocco, Egypt, Jordan, and Lebanon, which remains insufficient today. For example, investing in agricultural research can create drought-resistant crop varieties and optimizing fertilizer formulations that need less water.

Finally, using the ARDL approach estimates, we find that water use efficiency (WUE) has a positive sign in both the short and long run, meaning that crop yield and irrigated water use efficiency are positively related. However, this coefficient is only significant in the long run at the 5% level. It is clear rising temperatures and changing precipitation trends due to climate variability are exacerbating water scarcity, making efficient water use even more critical. In the short run, results show that water use efficiency positively affects agriculture but is not significant in our case. This explains that the effort to innovate the irrigation methods (infrastructure, technology …) and water storage facilities is modest to improve crop yield. In the long run, this relationship becomes significant, meaning that increased engagement in sustainable agriculture, such as drip irrigation, sprinkler systems, precision agriculture, and improved fertilization techniques, can improve water resource use and consequently agricultural production. At this stage, we conclude that water management and optimal fertilizer consumption are essential to making agriculture more sustainable and profitable in MENA countries.

Granger Causality Analysis

The main objective of the Granger causality test is to analyze the existence of causal relationships between the variables considered. This test allows us to determine whether the past values of one variable can predict another and whether the relationship is unidirectional or bidirectional.

Table 8

Results of Panel Granger Causality

Variables: X	lnAG	LnPR	lnTP	lnCO2	lnGFCF	lnFC	lnWS	lnIRR
LnAG	-							
LnPR	←	-	←					
LnTP	←		-					←
lnCO2	≠		←	-				
lnGFCF	←		←		-			
LnFC	←					-		
LnWS	↔				←	←	-	
LnIRR	↔							-

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

The causality relationships in Table 8 highlight the interaction of agriculture, climate variables, and sustainable practices in the study. The results present a notable finding:

Unidirectional Causality

The Granger causality analysis reveals that agricultural value-added significantly influences Precipitation in MENA countries, underscoring that historical change in rainfall can estimate future agricultural value-added. Rainfall is crucial to agriculture in some regions. Variability in precipitation can impact food security by causing crop failures or lower yields. Given the region's arid and semi-arid climate, extended periods of low precipitation can cause soil erosion and reduced arable land. Directly, this scarcity impacts agricultural productivity. In reality, the changes in precipitation patterns vary considerably across MENA countries.

The analysis also shows that precipitation influences average temperature, indicating a dynamic relationship in which variations in precipitation have a major impact on temperature trends in the MENA region. Indeed, precipitation increases the humidity level of the atmosphere, while the evaporation of rainwater sequesters thermal energy, thus creating a cooling phenomenon. This phenomenon is especially evident in areas that experience significant precipitation occurrences. In contrast, a decrease in rainfall lessens this cooling influence, which may lead to elevated temperature conditions. This finding aligns with studies by Zittis et al. (2021) that have demonstrated that elevated average temperatures can result from long-term changes in precipitation patterns, such as reduced rainfall. This is especially occurring in regions with less precipitation because the soils become drier, which can raise surface temperatures.

The identification of the causal relationship between average temperature and agricultural production in MENA countries highlights the unidirectional relationship between climate and agriculture. These results show that average temperature fluctuations directly affect agricultural production. Temperature is a key factor in agricultural performance, as crops are highly sensitive to this warmth. Optimal temperatures are essential for plant growth, photosynthesis, and crop yield. Several studies have demonstrated the sensitivity of different crops to temperature changes. For instance, Qasem and Scholz (2025) project that by the year 2050, temperature elevations in the MENA region will vary between 1.5 and 3 °C. This phenomenon, in turn, intensifies drought conditions, leading to significant heat waves and water shortages, particularly impacting agricultural production in Egypt, Yemen, Syria, and Sudan. The interaction between temperature sand agriculture is not uniform across countries of the MENA region.

The finding that average temperature Granger-causes Irrigated Agriculture Water Use Efficiency in MENA countries is compelling. As the region is considered one of the most water-scarce in the world, climate change is expected to reduce freshwater availability due to decreased precipitation and increased evaporation rates. In general, rising temperatures increase the rate of evapotranspiration, increasing crop water requirements to maintain optimal growth. This can reduce water use efficiency, especially in cases of poor resource management. In summary, the relationship between temperature and WUE can vary considerably by region, depending on local climate, crop varieties, soil types, and agricultural practices. For example, high temperatures during critical growth phases (such as flowering or grain filling) can cause stress, affecting yield and water use efficiency. Conversely, moderate temperatures can stimulate growth and improve water use efficiency. Countries such as Morocco and Tunisia experience milder temperatures compared to the Gulf States, where high temperature is more prevalent. This climate disparity affects crop selection and irrigation strategies. A study conducted by Al-Quraishi et al. (2024) found a significant correlation between high temperatures and decreased water use efficiency in the context of irrigated agricultural systems, highlighting the critical importance of implementing climate-smart agricultural methods in Jordan.

The demand for energy has grown due to rapid industrialization and urbanization, which has made CO2 emissions even worse. Research shows that cities in the MENA area contribute significantly to emissions because of industrial, construction, and transportation-related activities. The results in Table 8 establish a direct correlation between high levels of CO2 emissions and rising temperature. As CO2 levels increase due to energy consumption and industrial activities, mean temperatures are seen to rise, which contributes to climate variability. The literature discusses feedback mechanisms where high temperatures can lead to increased CO2 emissions. In our case, this link is not reversed.

Granger causality analysis also indicates that fixed capital influences agricultural productivity in MENA countries. This means that agricultural investment plays a vital role in reducing the effects of climate change and ensuring sustainable agriculture. Rising national income, coupled with economic growth, facilitates resource allocation by the public and private sectors, which stimulates agricultural investment. These countries often try to invest in important areas such as infrastructure development, technological advancements, irrigation systems, and basic inputs to improve crop yields and agricultural production. In recent years, and following the increase in the risk of food insecurity, countries such as Tunisia, Morocco, and Egypt have adopted sustainable agricultural practices such as efficient irrigation techniques, adopting climate-smart agriculture, improving seed varieties, and investing in renewable energy sources to enhance productivity. Moreover, technological investments can help to mitigate the negative impact of high temperatures. However, water scarcity can be a constraint to agricultural productivity, limiting the effectiveness of investments.

In recent years, fertilizer consumption has increased in MENA countries, which justifies the interaction between agricultural productivity and fertilizer use in the sense of Granger causality. But fertilizer application efficiency varies greatly throughout the region, depending on a number of factors, including crop types and soil, farming methods, and governmental regulations. Fertilizers are essential for increasing crop yields, especially in areas where water resources are limited and soil fertility may be low. However, this result depends on efficient water management. Water scarcity can significantly impact the economic feasibility of investments in agriculture. Douh et al. (2022) suggest that high levels of water scarcity may deter private investors due to risks associated with insufficient water resources. This requires government intervention and support to encourage investment in water-efficient agricultural practices. The implementation of advanced irrigation technologies, such as precision agriculture and smart irrigation systems, improves water use efficiency for irrigated crops, as seen in the table above.

Bidirectional Causality

The identification of bidirectional causality between water stress and agricultural production in MENA countries underscores the intricate and interdependent relationship between water scarcity and agriculture. This finding suggests that changes in water supply directly influence crop production, while agricultural activities, in turn, influence the dynamics of water scarcity. Water trends are a key determinant of agricultural performance, as crops are highly sensitive to water scarcity. Freshwater resources are essential for plant growth, photosynthesis, and yield. In MENA countries, the arid and semi-arid climate makes water a critical resource for agricultural production. Conversely, the growing demand for irrigated agricultural crops is exacerbating the water shortage situation.

We found also causal relationship between agriculture production and irrigated water use efficiency. Irrigation is one of the main methods of water use in agriculture in MENA countries. Traditional methods, such as flood irrigation, are widespread, but they often result in significant water losses. Recent advances in irrigation technologies, such as drip and sprinkler irrigation, have been introduced to improve water use. However, their implications will only be predictable in the long term. This can be explained by the disparity in the adoption of these technologies from one region to another, influenced by factors such as investment, economic conditions, infrastructure, and education of farmers.

Conclusions

In this article, we examined the environmental situation and the need to prioritize sustainable practices to reduce food insecurity. This is one of the main reasons why we conducted our study on a sample of countries in the MENA region, using the ARDL method and granger causality analysis. Methods that allow us to estimate the long-term effects of several variables, such as climatic variables and sustainable practices on agricultural crops from 2000 to 2022. The key findings from this empirical analysis reveal the following conclusions:

Granger causality tests show unidirectional relationships between agricultural production and climate variables, fertilizer consumption and water use efficiency, and other interesting interactions such as CO2 emissions and temperature variations. Indeed, the increase in carbon emissions has been driven by industrial activities, energy consumption, and urbanization, has led to an increase in temperature. But this varies from one country to another in the MENA region. A second relationship that also seems more interesting is that of water stress and fertilizer consumption. Water scarcity influences farmers' behavior and encourages them to adopt sustainable practices such as climate smart agriculture and precision agriculture to optimize fertilizer and water use. In addition, water stress pushes countries with arid and semi-arid climates to increase the effort of investment in sustainable agriculture by increasing the investment in infrastructure, research and development and techniques of irrigation. Finally, a bidirectional relationship between water stress, water use efficiency, and crop production underscores their interdependence.

Our estimation results show that changes in temperature and precipitation are negatively correlated with agriculture but not significantly, meaning that climate variability is not threatening in the short run. In the long run, countries such as Tunisia, Egypt, Morocco, Jordan and Lebanon must adopt climate-resilient crop varieties which have a positive impact on agricultural production, which in turn affects positively agricultural production and demonstrate a non-linear relationship.

The results also reveal that in the short term, water stress is negatively correlated with agricultural crops, but not significantly. This is explained by rainwater harvesting techniques and some modern irrigation practices that absorb the negative impact of reduced water supply.

In the long run, the relationship remains negative but becomes significant. This is explained by the continuing effect of climate change on water resources and agricultural production despite the use of new techniques. The positive and significant findings of irrigated water use efficiency can help to improve agricultural crops with the adoption of drip irrigation and the use of treated waste water which mitigates water stress. We conclude, then, that sustainable agriculture is a long process that can reduce the effects of water stress, but sustainable practices cannot permanently eliminate their effects. Therefore, to mitigate the effects of climate change and promote sustainable agriculture, sustainable strategies based on both water management and efficient fertilizers are vital. However, this process requires the intervention of all stakeholders, including policymakers, companies, and farmers, to overcome these challenges.

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