Journal of Agricultural Sciences
(Tarim Bilimleri Dergisi)

J Agr Sci-Tarim Bili
e-ISSN: 2148-9297
jas.ankara.edu.tr

Balancing Climate Sensitivity and Resilience: Environmental Impacts on Selected Crop Yields in Turkiye

Muhammed Benli[a*], Rabia Özdemir[b]

[a]*Department of Economics, Faculty of Economics and Administrative Sciences, Bilecik Seyh Edebali University, Bilecik, TÜRKİYE*

[b]*Institute of Graduate Studies, Bilecik Seyh Edebali University, Bilecik, TÜRKİYE*

ARTICLE INFO
Research Article
Corresponding Author: Muhammed Benli, E-mail: muhammed.benli@bilecik.edu.tr
Received: 11 November 2024 / Revised: 09 January 2025 / Accepted: 14 January 2025 / Online: 29 July 2025

Cite this article
Benli M, Özdemir R (2025). Balancing Climate Sensitivity and Resilience: Environmental Impacts on Selected Crop Yields in Turkiye. *Journal of Agricultural Sciences (Tarim Bilimleri Dergisi),* 31(3):670-689. DOI: 10.15832/ankutbd.1583278

ABSTRACT

This study investigates the impact of climate factors—temperature, precipitation, and CO_2—on the yields of key crops (wheat, potatoes, and rice) in Turkiye, aiming to inform climate-resilient agricultural practices. Using an Autoregressive Distributed Lag (ARDL) approach, the research examines short-run and long-run relationships between crop yields and climate variables from 1981 to 2020. The results indicate that wheat and potatoes cointegrate with climate variables, suggesting a stable long-term relationship. Wheat yields benefit from moderate increases in temperature and CO_2 but are sensitive to excess precipitation. Similarly, potatoes are adversely affected by prolonged high temperatures and excessive rainfall, though CO_2 shows a delayed positive impact. In contrast, rice yields show no long-run relationship with climate factors, responding instead to short-term variations and having a significant sensitivity to excessive precipitation and high temperatures. These findings underscore the need for crop-specific management strategies to adapt to climate variability, enhancing crop resilience and optimizing yields in Turkiye's diverse agricultural landscape.

Keywords: Agronomic Yield, Climate Variability, ARDL

1. Introduction

Turkiye's agricultural sector is foundational to its economy, supporting rural livelihoods, generating export revenue, and ensuring food security for a growing population. As one of the world's most agriculturally diverse countries, Turkiye produces many crops, including wheat, rice, and potatoes. However, the sector faces mounting challenges from climate change, as rising temperatures, fluctuating precipitation patterns, and increasing levels of atmospheric CO_2 affect crop growth, yield stability, and agricultural sustainability (Bozoglu et al. 2019). Understanding how these climatic factors influence crop yields is vital for Turkiye's future agricultural resilience, particularly as the country adapts to intensifying climate variability.

The effects of temperature, precipitation, and CO_2 on crop yields are complex and often vary significantly by crop type (Hatfield et al. 2011; Meng et al. 2017; Makowski et al. 2020). Temperature, for example, can promote or inhibit growth depending on the crop's specific heat tolerance and growth stage (Kaushal et al. 2016). While moderate warmth can increase growth rates and accelerate development, excessive heat can stress plants, impair photosynthesis, and reduce yields (Sharkey, 2005; Zhu et al. 2021; Bernacchi et al. 2023). Precipitation, similarly, is crucial for crop water availability; however, too much rain can lead to waterlogging, nutrient leaching, and reduced oxygen availability in the soil, particularly in water-sensitive crops (Kaur et al. 2020; Loreti & Striker 2020). Atmospheric CO_2, while a key component of photosynthesis, has a variable impact: it can enhance photosynthetic rates in many C3 crops, potentially increasing yields, but these benefits may be constrained by other limiting factors such as heat and water availability (Lawlor & Mitchell 1991; Bishop et al. 2014; Boretti & Florentine 2019). Consequently, Turkiye's crops face differing responses to these environmental variables, requiring crop-specific analyses to understand their immediate and sustained impacts.

Given the diverse responses of crops to climatic variables, investigating both short-run and long-run relationships between yield and climate factors is essential. Cointegration analysis offers a way to determine whether a long-term equilibrium relationship exists between crop yields and environmental variables such as temperature, precipitation, and CO_2. If cointegration is present, it suggests that climatic factors have a sustained impact on crop yields, with any short-term deviations likely adjusting back to equilibrium over time. For these crops, long-term and immediate responses must be understood to assess climate impacts fully. In contrast, for crops without cointegration relationships, short-run dynamics dominate, indicating that yields are more susceptible to immediate climatic fluctuations rather than sustained trends. This distinction between long- and short-term dynamics is particularly relevant for policymakers and farmers seeking to implement climate adaptation measures tailored to each crop's needs.

This study employs an Autoregressive Distributed Lag (ARDL) approach (Pesaran & Shin 1998; Pesaran et al. 2001) to analyze the yields of three key crops in Turkiye: wheat, potatoes, and rice. By applying ARDL models, we can evaluate whether each crop yield is cointegrated with temperature, precipitation, and CO_2 levels and, where cointegration exists, estimate both short-run and long-run coefficients. Specifically, we address three key research questions:

i. Which crops exhibit a long-run cointegration relationship with climate variables? Identifying cointegration provides insight into whether crop yields maintain a stable, long-term dependency on environmental conditions, signalling resilience or sensitivity to sustained climate trends.

ii. How do short-run dynamics influence crop yields, particularly for crops without a long-term cointegration relationship? For crops without cointegration, yield changes are driven by short-term climatic fluctuations, requiring an understanding of immediate responses to temperature, precipitation, and CO_2.

iii. How do temperature, precipitation, and CO_2 interact across crops, and what crop-specific management strategies can mitigate climate risks? By understanding the unique effects of each variable and their interactions on different crops, we can propose adaptive practices to optimize yields in the face of climate change.

This study's findings will guide agricultural planning and climate adaptation methods in Turkiye, offering comprehensive insights into the distinct requirements of each crop under diverse climatic situations. For wheat and potatoes, where long-term resilience may depend on sustained relationships with climate variables, our results will highlight how these crops adjust to climatic changes over time. Our focus on short-run dynamics will shed light on the adaptive measures needed to buffer against rapid environmental fluctuations for crops such as rice, which may be more vulnerable to immediate climatic variability. By distinguishing between crops with and without long-run dependency on climate variables, we aim to provide actionable insights for targeted interventions that promote sustainable agricultural productivity in Turkiye. In doing so, this study offers a novel contribution to the growing body of research on climate change and agriculture by focusing on Turkiye. While many previous studies have explored the impacts of climate variables on crop yields in regions such as southern Europe, Southeast Asia, and North America, this study fills a significant gap by:

- Examining the short- and long-term effects of temperature, precipitation, and CO_2 on key crops (wheat, rice, and potatoes) in Turkiye using the ARDL bounds testing approach.

- Providing a comprehensive analysis incorporating interaction effects between climate variables, offering more profound insights into their combined impacts on crop productivity.

By focusing on Turkiye's unique agricultural context, this study enhances understanding of the climate-yield relationship in a semi-arid setting and offers broader implications for regions facing similar challenges.

2. Material and Methods

This study investigates the impact of key climatic variables—temperature, precipitation, and atmospheric CO_2—on the yields of three major crops in Turkiye: wheat, potatoes, and rice. We employ the ARDL bounds testing approach using time series data for the period 1981-2020. All series are in their natural logarithmic forms, allowing us to interpret the estimated coefficients in elasticity form. Summary information about the data used in the analyses is presented in Table 1, and the descriptive statistics of the series are provided in Table 2.

Table 1- Summary of the variables

Target Variable	***Proxy Variable***	***Symbol***	***Definition***	***Source***
Crop Yield	Crop yields	$YIELD$	Yields are measured in tonnes per hectare	Our World in Data
Temperature	Surface temperature	$TEMP$	Average annual surface temperature (in degrees Celcius). The air temperature measured 2 meters above the ground, encompassing land, sea, and in-land water surfaces.	Our World in Data
Precipitation	Precipitation	$PREC$	Annual precipitation per unit area (mm)	Republic of Turkiye Ministry of Environment, Urbanization and Climate Change
Carbon Emissions	CO_2 emissions	CO_2	CO_2 emissions from fossil fuels and industry. Land-use change is not included.	Our World in Data

Table 2- Descriptive statistics

Variables	*No. of obs.*	*Mean*	*Std. Dev.*	*Min*	*Max*	*Skewness*	*Kurtosis*
$WHEAT$	40	2.257	0.347	1.758	2.965	0.507	2.096
$POTATO$	40	26.122	5.233	16.487	35.377	-0.075	2.261
$RICE$	40	6.225	1.426	4.379	9.056	0.345	1.622
$TEMP$	40	11.404	0.889	9.256	13.329	0.118	2.945
$PREC$	40	577.85	65.157	445.000	717.000	0.066	2.574
CO_2	40	240 m	108 m	79.2 m	431 m	0.250	1.841
ln_WHEAT	40	0.803	0.150	0.564	1.087	0.314	1.996
ln_POTATO	40	3.242	0.210	2.803	3.566	-0.487	2.622
ln_RICE	40	1.803	0.227	1.477	2.203	0.186	1.499
ln_TEMP	40	2.431	0.078	2.225	2.590	-0.112	3.058
ln_PREC	40	6.353	0.114	6.098	6.575	-0.191	2.537
ln_CO_2	40	19.186	0.495	18.187	19.881	-0.370	2.078

Using an ARDL modelling framework, we analyse short- and long-run relationships between crop yields and environmental factors. The ARDL approach enables us to assess whether each crop yield has a cointegration relationship with climatic variables, indicating a stable long-term dependency, or if it is predominantly influenced by short-term fluctuations short-term fluctuations predominantly influence it.

The ARDL model was selected due to its flexibility in handling variables integrated of different orders, I(0) or I(1), making it suitable for our dataset. Unlike traditional cointegration techniques, the ARDL approach does not require all variables to be integrated at the same order (Pesaran & Shin 1998; Pesaran et al. 2001; Hassler & Wolters 2006; Kripfganz & Schneider 2023). In other words, ARDL is uniquely equipped to handle variables that are a mix of I(0) (stationary) and I(1) (non-stationary), provided none are I(2). This eliminates the need for uniform integration orders, reducing the risk of misspecification. Bounds testing allows for cointegration analysis regardless of whether variables are I(0) or I(1). Moreover, ARDL models capture both short-term dynamics and long-term equilibrium relationships within a single framework. This dual capability ensures that transient impacts are not overlooked while providing insights into steady-state behavior. ARDL spreads explanatory power across time periods by including lagged variables, naturally reducing correlations between regressors. This addresses potential multicollinearity without requiring additional transformations. The model captures temporal adjustments, allowing us to account for the delayed effects of variables on outcomes. This is particularly important in agricultural contexts, where climatic and economic changes influence yields over time. It accommodates gradual adjustments to shocks, which provides a realistic depiction of how systems stabilize after external factors change. ARDL incorporates lag structures for all explanatory variables, enabling the examination of distributed effects over time. This is particularly useful in identifying lagged or cumulative impacts of climatic variables such as precipitation and temperature. By including lagged dependent variables, ARDL reduces the risk of biased estimates caused by endogeneity, making the results more reliable. ARDL remains robust in small-sample settings, where other methods may fail due to limited statistical power. This is particularly valuable in such studies, where data availability may be constrained. The ARDL framework includes bounds testing for cointegration, which provides a rigorous statistical basis for validating long-run relationships. This ensures that the identified relationships are not spurious.

We estimate each model separately for each crop to identify crop-specific relationships with temperature, precipitation, and CO_2.

The general ARDL (p, q1, q2, q3) model for crop yield can be specified as depicted in Equation 1:

$$\Delta YIELD_t = \alpha + \sum_{i=1}^{p} \phi_i \Delta YIELD_{t-i} + \sum_{j=0}^{q1} \beta_j \Delta TEMP_{t-j} + \sum_{k=0}^{q2} \gamma_k \Delta PREC_{t-k} + \sum_{l=0}^{q3} \delta_l \Delta CO_{2_{t-l}} + \theta ECT_{t-1} + \varepsilon_t \quad (1)$$

Where; $YIELD_t$ is the log-transformed yield for each crop in year t; $TEMP_t$, $PREC_t$, and CO_2 represent the log-transformed temperature, precipitation, and CO_2 levels, respectively. ECT_{t-1} is the error correction term derived from the cointegration relationship, representing the long-run equilibrium relationship for crops with cointegration, and ε_t is the error term.

We also include interaction terms ($TEMP \times PREC$, $TEMP \times CO_2$, and $PREC \times CO_2$) as additional independent variables in each crop's ARDL model to capture the combined effects of climate variables.

To assess the presence of a long-run relationship, we conduct the following steps:

Prior to estimation, we test each variable's stationarity using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. This step ensures that none of the variables is integrated of order two or higher (I(2)), as the ARDL approach is applicable only for variables that are I(0) or I(1) (Pesaran et al. 2001).

For each crop, we apply the ARDL bounds testing approach to test for a long-run relationship between yield and climatic variables. The F-statistic from the bounds test is compared to critical values to determine whether cointegration exists (Kripfganz & Schneider 2023):

If the F-statistic exceeds the upper bound, we conclude that a long-run relationship exists.
If the F-statistic is below the lower bound, we conclude that no long-run relationship exists.
If the F-statistic falls between the bounds, the result is inconclusive.

For crops with cointegration, we estimate an error correction model (ECM) to capture both short-run and long-run dynamics. The ECM includes an error correction term (ECT_{t-1}), which measures the speed at which the yield adjusts to deviations from the long-run equilibrium. A significant error correction term with a negative coefficient indicates that the yield returns to equilibrium following short-term fluctuations.

For crops without cointegration, we focus on the short-run coefficients derived from the differenced terms in the ARDL model. These coefficients capture the immediate impact of temperature, precipitation, and CO_2 changes on yield without assuming any sustained relationship.

3. Results and Discussion

This section presents the empirical findings of our analysis, highlighting the relationships between crop yields and environmental variables for wheat, potatoes, and rice. We detail the ARDL modelling approach's results, including the presence of cointegration for specific crops and the implications of the estimated short-run coefficients for all crops. The analysis is structured to emphasize the long-run relationships for each crop, following the discussion of the short-run dynamics.

It is essential to note a point that will be thoroughly examined later. Our analysis identifies a cointegration relationship for wheat and potatoes, suggesting a stable long-term equilibrium between these crop yields and the explanatory variables (temperature, precipitation, and CO_2 levels). This finding indicates that these factors have a sustained impact on the yields of wheat and potatoes over time. Consequently, we interpret both the short-run and long-run coefficients for these crops, examining their immediate responses to changes in environmental factors and their long-term adjustments. The long-run coefficients reflect the enduring influence of these variables on crop yields, while the short-run coefficients capture the more immediate responses to climate variability.

In contrast, we find no evidence of cointegration for rice, suggesting that rice yield does not maintain a stable long-term relationship with the explanatory variables within the scope of this study. As a result, we focus exclusively on the short-run dynamic for rice. By examining the short-run coefficients, we capture this crop's immediate and potentially more volatile responses to fluctuations in temperature, precipitation, and CO_2, reflecting its sensitivity to short-term environmental variability rather than any sustained, long-term adjustment path.

This distinction between crops with and without a cointegration relationship provides valuable insights into how different types of crops respond to climatic conditions, with implications for adaptive management practices tailored to each crop's specific yield behavior in response to environmental change.

As mentioned earlier, it is essential to ensure the variables are stationary before estimating the ARDL. Table 3 presents the results of the ADF and PP tests. The findings show that none of the variables is integrated at second order.

Table 3- Unit root tests

	ADF		***PP***	
Variable	***C***	***C/T***	***C***	***C/T***
CO_{2_t}	-2.508(0)	-2.033(0)	-3.977(11)***	-1.618(8)
ΔCO_{2_t}	-6.098(0)***	-6.713(0)***	-6.100(2)***	-7.937(9)***
$TEMP_t$	-0.712(1)	-7.078(0)***	-0.757(8)	-7.317(6)***
$\Delta TEMP_t$	-10.869(0)***	-5.910(3)***	-26.691(16)***	-28.363(15)***
$PRECIP_t$	-6.829(0)***	-6.768(0)***	-10.020(22)***	-11.642(26)***
$\Delta PRECIP_t$	-6.968(1)***	-6.855(1)***	-26.624(22)***	-28.496(21)***
$WHEAT_t$	-0.380(1)	-5.706(0)***	-1.278(2)	-5.842(3)***
$\Delta WHEAT_t$	-13.243(0)***	-13.142(0)***	-29.778(37)***	-49.329(37)***
$RICE_t$	-0.863(1)	-2.708(0)	-0.819(18)	-2.686(2)
$\Delta RICE_t$	-8.075(0)***	-7.972(0)***	-8.857(13)***	-8.832(14)***
$POTATO_t$	-2.124(2)	-3.394(1)*	-1.710(11)	-2.865(6)
$\Delta POTATO_t$	-5.890(1)***	-6.081(1)***	-7.525(6)***	-8.387(9)***
$TEMP \times PREC$	-6.710(0)***	-6.819(0)***	-7.263(11)***	-11.704(22)***
$\Delta(TEMP \times PREC)$	-6.981(1)***	-6.866(1)***	-26.891(23)***	-30.375(22)***
$TEMP \times CO_2$	-2.408(0)	-1.823(0)	-4.041(8)***	-1.364(7)
$\Delta(TEMP \times CO_2)$	-5.992(0)***	-6.682(0)***	-5.992(1)***	-7.181(6)***
$PREC \times CO_2$	-2.896(0)*	-6.136(0)***	-2.701(1)*	-6.279(7)***
$\Delta(PREC \times CO_2)$	-6.755(1)***	-6.682(1)***	-20.343(29)***	-28.999(23)***

Note: The lag lengths (given in parentheses) for the ADF test determined by the SIC, and the appropriate bandwidths for the PP test determined by the Newey-West Bandwidth. *** P<0.01, ** 0.01< P<0.05, * 0.05< P<0.10

3.1. Wheat

This section outlines the empirical findings from the ARDL analysis of wheat yield in Turkiye, focusing on both long-run and short-run relationships with the climatic variables (temperature, precipitation, and atmospheric CO_2). The analysis is based on the optimal lag length determined by the Akaike Information Criteria (AIC) for the model and the resulting coefficients from the ECM. The results are summarized in Table 3.

Table 3- ARDL results (wheat)

Model: $F(WHEAT_t/TEMP_t, PREC_t, CO_{2_t}, TEMP \times PREC_t, TEMP \times CO2_t, PREC \times CO_{2_t})$			
Optimal Lag Length: (2, 2, 2, 2, 2, 1, 2)		**F-stat:** 5.476**	
		Critical Values	
Significance Level		**Lower Bound**	**Upper Bound**
1%		3.800	5.643
5%		2.797	4.211
10%		2.353	3.599
Error Correction Model			
Variable	***Coefficient***	***Std. Error***	***t-stat***
C	-6791.130***	1083.531	-6.268
$\Delta WHEAT_{t-1}$	-0.556***	0.116	-4.809
$\Delta TEMP_t$	389.714**	147.387	2.644
$\Delta TEMP_{t-1}$	-613.946***	165.492	-3.710
$\Delta PREC_t$	236.853*	125.080	1.894
$\Delta PREC_{t-1}$	-449.036***	123.100	-3.648
ΔCO_{2_t}	13.623	32.091	0.425
$\Delta CO_{2_{t-1}}$	12.491***	2.870	4.351
$\Delta TEMP \times PREC_t$	-50.151*	26.402	-1.900
$\Delta TEMP \times PREC_{t-1}$	95.510***	25.814	3.700
$\Delta TEMP \times CO_{2_t}$	-3.966	5.978	-0.663
$\Delta PREC \times CO_{2_t}$	1.005*	0.522	1.927
$\Delta PREC \times CO_{2_{t-1}}$	-1.992***	0.464	-4.290
ECT_{t-1}	-0.658***	0.105	-6.268
Long-Run Coefficients			
$TEMP$	2223.352*	1264.872	1.758
$PREC$	1829.405*	940.200	1.946
CO_2	-120.904***	36.055	-3.353
$TEMP \times PREC$	-390.371*	200.010	-1.952
$TEMP \times CO_2$	13.236***	4.281	3.092
$PREC \times CO_2$	8.469*	4.234	2.000
Diagnostic Tests			
χ^2_{SER}	0.025 (0.975)	R^2	0.943
χ^2_{HET}	1.075 (0.426)	R^2_{Adj}	0.882
χ^2_{NORM}	1.588 (0.452)	F_{ist}	15.535 (0.000)
χ^2_{RAMSEY}	0.059 (0.812)	$Cusum$	Stable
DW	1.915	$Cusum(sqr)$	Stable

Note: Probability values in parentheses. χ^2_{SER}, χ^2_{HET}*χ^2_{NORM}, χ^2_{RAMSEY} denote the Breusch-Godfrey LM autocorrelation, Breusch-Pagan heteroscedasticity, Jarque-Bera normality, and model specification error test statistics, respectively. Cusum and Cusum of squares (sqr) represent the stability test statistics. Given the small sample size, the bounds test critical values are from Narayan (2005): Case III - unrestricted intercept and no trend *** P<0.01, ** 0.01< P<0.05, * 0.05< P<0.10.

The F-statistic for the bounds test is 5.476, which is significant at the 5% level. This indicates the presence of cointegration among wheat yield and climatic factors, which confirms that there is a stable long-term relationship between wheat yield and the selected climatic variables.

The short-run coefficients in an ARDL model capture the immediate or transient effects of environmental factors on wheat yields. The ECT, with a coefficient of -0.658 and a highly significant t-statistic of -6.268, reflects the speed of adjustment back to equilibrium following short-term deviations. This indicates that approximately 65.8% of the disequilibrium from the previous period is corrected in the current period, demonstrating a rapid adjustment towards the long-run equilibrium.

Temperature has varying effects on wheat yields at different lags, with both positive and negative significant coefficients. This variability suggests that while rising temperatures may boost yields in some periods, they may harm yields in others, possibly due to optimal versus extreme temperature thresholds for wheat growth. High temperatures may lead to heat stress, especially during sensitive growth stages, reducing yield (Yang et al. 2013; Ullah et al. 2022). On the other hand, moderately increased temperatures during colder months could extend the growing season, benefiting wheat yields (Lizana & Calderini 2013; Du et al. 2022). The positive and statistically significant coefficient (389.714) of current temperature suggests that a short-term increase in temperature positively influences wheat yield. This outcome may be attributed to temperature-favorable conditions that support wheat growth processes such as germination and vegetative growth (Khaeim et al. 2022). Conversely, the negative and statistically significant coefficient of -613.946 (t-statistic = -3.710) for the lagged temperature term indicates that prolonged exposure to higher temperatures from the previous period adversely impacts wheat yields in the current period (Asseng et al. 2011). This outcome could reflect the detrimental effects of accumulated heat stress on wheat, where sustained high temperatures may lead to reduced grain filling and lower crop resilience, resulting in yield declines over time (Tiwari et al. 2017; Ullah et al. 2022).

The coefficient for current precipitation is positive (236.853) and marginally significant, suggesting that increases in precipitation contribute positively to wheat yield in the short run (Howard et al. 2016; Chandio et al. 2021). This effect may be due to enhanced soil moisture availability, which supports wheat growth, particularly in regions where water is a limiting factor. However, the lagged precipitation coefficient is negative and statistically significant (-449.036). This suggests that excessive rainfall in the previous period could hinder growth by creating waterlogging, nutrient leaching, or pest proliferation, which can negatively impact wheat production in the subsequent period (Kim et al. 2024).

The coefficient for current CO_2 emissions (13.623) is not statistically significant, indicating that short-term changes in atmospheric CO_2 concentration may not immediately translate to observable effects on wheat yield (Conroy et al. 1994; Gifford 1995). The lagged CO_2 effect, however, is positive (12.491) and highly significant. This suggests that past increases in CO_2 concentrations positively affect current wheat yield, possibly due to the fertilization effect of CO_2, where higher CO_2 levels enhance photosynthesis and biomass accumulation in C3 plants such as wheat. This delayed effect aligns with existing literature, which often cites CO_2 as a beneficial factor for crop yields under certain conditions (Seneweera & Norton 2011; Taylor & Schlenker 2021).

Interaction terms between temperature, precipitation, and CO_2 reveal more subtle relationships, illustrating that the combined effects of these variables differ from their individual impacts. The coefficient for the current $TEMP \times PREC$ interaction term is negative and marginally significant (-50.151), suggesting that an increase in temperature combined with precipitation may have a detrimental short-term effect on wheat yield (Hatfield et al. 2011). This outcome could be due to excessive moisture or humidity combined with high temperatures, potentially leading to increased disease susceptibility or physiological stress in the wheat crop. In contrast, the lagged $TEMP \times PREC$ interaction term is positive and significant (95.510), indicating that the combined impact of higher temperature and precipitation in the previous period benefits current wheat yield. This might be due to enhanced soil moisture reserves benefiting growth after a period of combined heat and rainfall, promoting favorable conditions for wheat in subsequent periods (Kumar et al. 2023).

The coefficient for the current $TEMP \times CO_2$ interaction term is not statistically significant (-3.966), suggesting no immediate combined effect of temperature and CO_2 on wheat yield in the short term.

The current $PREC \times CO_2$ interaction term coefficient is positive and marginally significant (1.005), suggesting that precipitation combined with CO_2 contributes positively to yield in the short term, likely enhancing photosynthetic efficiency under adequate soil moisture conditions. The lagged $PREC \times CO_2$ term, however, is negative and significant (-1.992), indicating that sustained high levels of CO_2 and precipitation may ultimately harm yields, possibly due to soil oversaturation or other nutrient balance issues (Yu et al. 2022).

The long-run coefficients illuminate the persistent effects of surface temperature, precipitation, CO_2 emissions, and their interactions on wheat yield. Unlike the short-run dynamics, these long-run relationships reflect how sustained changes in these environmental factors influence wheat yield equilibrium over time. The long-run coefficients provide insights into the sustained impact of environmental factors on wheat yields, highlighting more permanent relationships once short-term fluctuations have settled. In the long run, the positive coefficient of CO_2 on wheat yields is statistically significant; suggesting that elevated CO_2 levels can benefit wheat productivity over time (Dubey et al. 2015). This long-term CO_2 fertilization effect implies that, as CO_2 concentrations continue to rise, wheat crops may experience yield improvements due to enhanced photosynthesis and possibly better water use efficiency.

The positive and marginally significant coefficient for temperature suggests that, in the long run, temperature increases contribute positively to wheat yield. This effect could stem from temperature's role in enhancing growth rates and potentially extending the growing season, which may benefit wheat production if temperatures remain within optimal limits (Ottman et al. 2012). However, the marginal significance indicates that this effect might be sensitive to context, such as regional climate variations and adaptive agricultural practices.

The positive and marginally significant coefficient for precipitation indicates that, over time, increased rainfall positively impacts wheat yield. Consistent moisture availability supports crop development and soil nutrient uptake, promoting higher yield levels (Kumar et al. 2023). This long-term benefit is particularly relevant in rain-fed agricultural systems where wheat productivity closely depends on precipitation patterns.

The negative and highly significant coefficient for CO_2 emissions suggests that sustained increases in CO_2 levels may reduce wheat yield in the long term. This adverse effect may seem counterintuitive, given the fertilization benefits of CO_2, yet long-term increases in CO_2 may alter other environmental factors or introduce stresses (e.g., temperature increases and soil pH changes) that negatively impact wheat (Alonso et al. 2009; Zhang et al. 2018). This result may also indicate that excessive CO_2 can intensify specific physiological stresses or disrupt optimal growth conditions, overshadowing any initial positive effects.

The interaction terms reveal complex dynamics between temperature, precipitation, and CO_2, underscoring that their combined effects differ from their isolated impacts on wheat yield. The negative and marginally significant interaction between temperature and precipitation implies that the combined effect may reduce wheat yield in the long run when these two factors increase simultaneously. This could reflect a climate stress threshold, where high temperature and high precipitation create unfavorable growing conditions, such as increased disease prevalence or soil degradation due to excessive moisture, ultimately impairing crop health (Conradie et al. 2021; Fan et al. 2022).

The positive and highly significant coefficient for the interaction between temperature and CO_2 suggests that the combined influence of elevated temperature and CO_2 enhances wheat yield in the long run. This effect likely stems from the fact that CO_2 fertilization can help plants utilize higher temperatures more effectively by enhancing photosynthesis and water-use efficiency (Gonsamo et al. 2021). This interaction may be particularly advantageous in semi-arid regions where increased CO_2 can mitigate some of the adverse effects of heat. The positive and marginally significant interaction between precipitation and CO_2 indicates that increased levels of both factors have a synergistic effect, benefiting wheat yield over the long term. This result may be attributed to the combined effect of adequate moisture and CO_2 enrichment, which support optimal photosynthetic activity and crop growth (Li et al. 2003). Increased precipitation may also enhance the uptake of CO_2-enhanced soil nutrients, creating favorable conditions for wheat yield improvement (Van Vuuren et al. 1997).

The long-run results highlight that while temperature and precipitation independently contribute positively to wheat yield, CO_2 exerts a significant negative impact when considered in isolation. However, the interaction terms suggest that CO_2, when combined with either temperature or precipitation, can mitigate some adverse effects and, under optimal conditions, improve wheat yield. These findings underscore the importance of examining environmental factors in isolation and combination, as their interactive effects may yield insights essential for understanding crop resilience and productivity under changing climate conditions. Adaptations in agricultural practices, particularly those that can balance temperature and moisture levels, may help leverage these long-run dynamics to sustain or improve wheat yield.

3.2. Potato

This section presents the empirical results from the ARDL analysis of potato yield in Turkiye, emphasizing both long-term and short-term relationships with the climatic variables. The analysis relies on the optimal lag length identified by the AIC for the model and the resultant coefficients from the ECM. The findings are presented in Table 4.

Table 4- ARDL results (potato)

Model: $F(POTATO_t/TEMP_t, PREC_t, CO_{2_t}, TEMP\times PREC_t, TEMP\times CO2_t,\ PREC\times CO_{2_t})$			
Optimal Lag Length: (2, 2, 2, 2, 2, 2, 2)		**F-stat:** 6.354***	
Significance Level		**Critical Values**	
		Lower Bound	**Upper Bound**
1%		3.800	5.643
5%		2.797	4.211
10%		2.353	3.599
Error Correction Model			
Variable	***Coefficient***	***Std. Error***	***t-stat***
C	-2279.411***	273.933	-8.321
$\Delta POTATO_{t-1}$	0.2760***	0.110	2.498
$\Delta TEMP_t$	-220.548**	79.688	-2.768
$\Delta TEMP_{t-1}$	-487.973***	97.457	-5.007
$\Delta PREC_t$	-75.488	67.618	-1.116
$\Delta PREC_{t-1}$	-485.471***	80.771	-6.010
ΔCO_{2_t}	-25.165	19.3114	-1.303
$\Delta CO_{2_{t-1}}$	51.535***	15.808	3.260
$\Delta TEMP\times PREC_t$	16.973	14.260	1.190
$\Delta TEMP\times PREC_{t-1}$	101.391***	16.849	6.018
$\Delta TEMP\times CO_{2_t}$	5.647	3.603	1.567
$\Delta TEMP\times CO_{2_{t-1}}$	-8.185**	2.969	-2.757
$\Delta PREC\times CO_{2_t}$	-0.573*	0.280	-2.046
$\Delta PREC\times CO_{2_{t-1}}$	-1.661***	0.282	-5.893
ECT_{t-1}	-0.838***	0.101	-8.321
Long-Run Coefficients			
$TEMP$	575.145	424.066	1.356
$PREC$	507.065	328.672	1.543
CO_2	-36.623*	18.361	-1.995
$TEMP\times PREC$	-106.205	69.655	-1.525
$TEMP\times CO_2$	4.992*	2.569	1.943
$PREC\times CO_2$	1.826	1.431	1.276
Diagnostic Tests			
χ^2_{SER}	0.691 (0.516)	R^2	0.987
χ^2_{HET}	0.950 (0.531)	R^2_{Adj}	0.972
χ^2_{NORM}	0.550 (0.760)	F_{ist}	66.274 (0.000)
χ^2_{RAMSEY}	2.453 (0.137)	$Cusum$	Stable
DW	2.197	$Cusum(sqr)$	Stable

Note: See footnote from Table 3

The F-statistic for the bounds test is 6.354, which is significant at the 1% level, indicating the presence of cointegration between potato yield and climatic factors. This confirms a stable long-term relationship between wheat yield and the selected climatic variables.

The ARDL results for potato yields reveal the influence of environmental factors along with their interaction effects in both short-run and long-run dynamics. The ARDL model's short-run coefficients show these environmental factors' immediate impacts on potato yields. The ECT coefficient is -0.838, which is highly significant (at the 1% level) and indicates a strong adjustment back to equilibrium after short-term deviations. This suggests that 83.8% of any short-term disequilibrium in potato yields is corrected in the subsequent period, reflecting a rapid return to long-term stability after environmental shocks.

The lagged potato yield term, with a statistically significant coefficient of 0.2760, indicates a positive relationship with current yield. This suggests a degree of yield persistence: high yields in the previous period positively influence current yield, possibly due to favorable residual soil conditions, such as improved soil structure or nutrient levels, conducive to sustained growth. This persistence effect may also capture the momentum from prior agronomic success, where positive outcomes foster favorable conditions for subsequent yields.

The results show a mix of positive and negative significant coefficients for $TEMP$ at various lags, similar to the findings for wheat, indicating that temperature has complex and immediate effects on potato yields. The current temperature's coefficient is -220.548, which is statistically significant at the 5% level, indicating that immediate temperature increases negatively impact potato yield. This outcome reflects the physiological stress that potatoes experience under high temperatures, as potatoes are a cool-season crop optimized for moderate conditions (Momčilović 2019). Elevated temperatures can impede critical growth stages by accelerating the breakdown of proteins and affecting photosynthetic efficiency, which reduces overall yield. The even more pronounced negative lagged effect (coefficient of -487.973, significant at the 1% level) reveals that prolonged exposure to high temperatures intensifies stress and leads to substantial yield reductions. This likely results from cumulative damage, as sustained heat can disrupt cellular integrity, reduce tuber quality, and hasten the depletion of carbohydrates stored in tubers (Busse et al. 2019). The short-run response to temperature emphasizes that potatoes require stable, moderate temperatures for optimal growth, and prolonged heat represents a significant environmental threat to yield.

The impact of precipitation underscores the importance of water balance for potato growth. The coefficient for current precipitation (-75.488) is not statistically significant, indicating that immediate fluctuations in precipitation do not substantially affect potato yields. This could suggest that potatoes can tolerate short-term water variability, particularly if moisture needs are met through supplementary irrigation or if precipitation levels are within manageable ranges (Zhao et al. 2024). The significant negative effect of lagged precipitation (coefficient of -485.47) reveals that excessive rainfall in the previous period has a substantial adverse effect on current potato yield. This is likely due to waterlogging, where excessive moisture in the soil limits oxygen availability, interferes with root function, and promotes diseases such as fungal infections, all of which impair growth and reduce yield (Vanongeval & Gobin 2023; Kim et al. 2024). Potatoes are susceptible to these moisture extremes, and prolonged high precipitation can lead to deteriorated soil conditions that inhibit optimal root development (King et al. 2020; Murillo et al. 2021).

The impact of CO_2 highlights the crop's response to atmospheric changes. With a coefficient of -25.165, the effect of immediate CO_2 changes is not statistically significant. This indicates that short-term fluctuations in CO_2 concentration do not have a noticeable impact on potato yield, possibly because potatoes may not immediately respond to CO_2 variations within a single growth cycle (Lee et al. 2020). The positive and statistically significant lagged effect of CO_2 (coefficient of 51.535) suggests that previous increases in CO_2 contribute positively to current potato yields. This delayed response may be due to the fertilization effect of CO_2, which enhances photosynthesis and water-use efficiency in C3 crops such as potatoes. Over time, elevated CO_2 concentrations can increase biomass production and improve tuber formation, leading to higher yields (Donnelly et al. 2001). However, this beneficial effect is observed only after a period, possibly due to adjustments in crop physiology.

The interaction terms provide insights into how combined environmental factors influence yield, often in ways that differ from individual effects. The immediate interaction between temperature and precipitation is positive but not statistically significant (coefficient of 16.973), suggesting that short-term fluctuations in these combined factors do not strongly impact potato yield. The lagged $TEMP \times PREC$ interaction, however, is positive and highly significant (coefficient of 101.391), indicating that the combined effect of temperature and precipitation from the previous period positively impacts yield. This might imply that past conditions with balanced temperature and precipitation create favorable soil and moisture dynamics, fostering better conditions for potato growth in the subsequent period.

The immediate interaction between temperature and CO_2 (coefficient of 5.647) is not statistically significant, indicating that short-term combined changes in temperature and CO_2 do not have a measurable effect on yield. The lagged $TEMP \times CO_2$ term is negative and significant (coefficient of -8.185), suggesting that prolonged high temperatures combined with elevated CO_2 levels have a detrimental effect. This may be due to combined stress from temperature and altered respiration rates under elevated CO_2, which may disrupt crop physiological stability over time (Kiongo et al. 2024).

The immediate interaction between precipitation and CO_2 is marginally significant and negative (coefficient of -0.573), suggesting that current high levels of both factors slightly reduce yield, possibly due to the compounding of water stress with altered CO_2 dynamics. The lagged $PREC \times CO_2$ interaction is also negative and highly significant (coefficient of -1.661), indicating that sustained high precipitation and CO_2 levels harm yield over time. This may result from prolonged adverse soil conditions or disrupted nutrient balance due to high moisture and elevated CO_2.

In the long run, temperature, precipitation, CO_2 levels, and their interactions subtly affect on potato yield. The positive, though statistically insignificant, coefficient suggests that a gradual increase in temperature may have a beneficial effect on potato yield in the long run. While potatoes are sensitive to high temperatures in the short run, this result implies that potatoes could adapt to slight increases in temperature over time, potentially due to shifts in growing practices or regional adaptation measures. However, the lack of statistical significance indicates that this effect may not be reliable or substantial without favorable supporting conditions, such as sufficient moisture levels.

The positive, though not statistically significant, long-run coefficient for precipitation implies that increased precipitation could support potato yield over time. This effect may stem from stable water availability that supports crop resilience, especially during dry periods. However, the coefficient's insignificance suggests that while additional precipitation could be beneficial, its impact may vary significantly depending on other factors, such as temperature and soil drainage (Petrova et al. 2021).

The negative and marginally significant effect of CO_2 in the long run (at the 10% level) indicates that sustained increases in atmospheric CO_2 levels may have an adverse impact on potato yield. While CO_2 often enhances crop growth initially through the fertilization effect, this long-term negative impact may reflect indirect effects, such as heat stress and soil nutrient imbalances associated with high CO_2 environments. Over time, elevated CO_2 could disrupt potato growth due to cumulative physiological stresses, indicating that the benefits of CO_2 for potatoes may diminish or reverse with sustained exposure (Finnan et al. 2005).

The interaction terms reveal how combined environmental conditions affect potato yield over the long run, often in ways that individual effects alone do not explain. The negative but statistically insignificant coefficient for $TEMP \times PREC$ suggests that simultaneous temperature and precipitation increases over time may slightly reduce potato yield. This could occur due to increased disease prevalence, humidity-related stresses, or waterlogging when both temperature and moisture are high. Although not statistically significant, this result aligns with the idea that potatoes require a balanced environmental profile and may experience adverse effects if temperature and moisture levels are elevated for prolonged periods (Campbell et al. 2021).

This positive, marginally significant interaction $TEMP \times CO2$ suggests that elevated CO_2 may somewhat counteract the adverse effects of higher temperatures over time. In the presence of high CO_2, potatoes may experience enhanced photosynthesis and water-use efficiency, allowing the crop to withstand moderate temperature increases more effectively. This interaction effect indicates that CO_2 can moderately influence temperature stress in potatoes, though the marginal significance implies that this benefit may be limited or contingent on specific environmental thresholds (Yandell et al. 1988).

The positive, yet statistically insignificant, coefficient for the interaction between precipitation and CO_2 indicates that sustained increases in both factors may have a modestly positive effect on potato yield. This interaction may reflect improved growth conditions under elevated CO_2, where the additional moisture from precipitation supports nutrient uptake and reduces water stress, promoting yield stability. However, the insignificance of this effect implies that its impact might not be robust across different conditions or may only occur under optimal environmental circumstances.

In sum, the long-run results reveal that while temperature and precipitation individually suggest positive impacts on potato yield, they lack statistical significance, indicating that these benefits are not strong or consistent without other favorable conditions. CO_2, on the other hand, shows a marginally significant negative impact, suggesting that sustained high CO_2 levels might ultimately lead to physiological or environmental stresses that limit yield potential.

The interaction terms suggest that while CO_2 might mitigate some temperature-related stress over the long term, its benefits appear limited, and combined increases in temperature and precipitation could potentially harm yield. Overall, the long-run insights suggest that potatoes are most productive under stable and moderate environmental conditions, where neither temperature nor moisture levels are excessively high. While CO_2 can initially enhance growth, its long-term effects may be less beneficial or even detrimental, underscoring the need for climate-resilient strategies in potato cultivation.

Furthermore, the diagnostic test results suggest that the model is statistically sound. Breusch-Godfrey LM Test for Autocorrelation and Breusch-Pagan Test for Heteroscedasticity show no issues, indicating no autocorrelation or heteroscedasticity, which supports the robustness of the estimates. The normality test (Jarque-Bera) confirms normal distribution in residuals, enhancing the inferences' validity. Finally, model stability tests (CUSUM and CUSUM of squares): Both stability tests indicate that the model is stable, meaning the coefficients remain consistent over time, which adds reliability to the model’s interpretations.

3.3. Rice

This section presents the empirical results from the ARDL analysis of rice yield in Turkiye, emphasizing both long- term and short-term relationships with the climatic variables. The analysis relies on the optimal lag length identified by the AIC for the model and the resultant coefficients from the ECM. The findings are encapsulated in Table 5.

Table 5- ARDL results (rice)

Model: $F(RICE_t/TEMP_t, PREC_t, CO2_t, TEMP \times PREC_t, TEMP \times CO2_t,\ PREC \times CO2_t)$			
Optimal Lag Length: (1, 0, 1, 1, 2, 1, 1)		**F-stat:** 2.034	
		Critical Values	
Significance Level		**Lower Bound**	**Upper Bound**
1%		3.800	5.643
5%		2.797	4.211
10%		2.353	3.599
Error Correction Model			
Variable	***Coefficient***	***Std. Error***	***t-stat***
C	587.749***	139.314	4.219
$\Delta PREC_t$	-451.039***	86.488	-5.215
ΔCO_{2_t}	138.567***	28.690	4.830
$\Delta TEMP \times PREC_t$	96.149***	18.213	5.279
$\Delta TEMP \times PREC_{t-1}$	0.026**	0.011	2.312
$\Delta TEMP \times CO_{2_t}$	-24.573***	5.239	-4.690
$\Delta PREC \times CO_{2_t}$	-2.060***	0.355	-5.802
ECT_{t-1}	-0.179***	0.042	-4.219
Long-Run Coefficients			
$TEMP$	-775.623	1338.832	-0.579
$PREC$	-743.793	1078.579	-0.690
CO_2	99.837	129.650	0.770
$TEMP \times PREC$	166.459	231.318	0.720
$TEMP \times CO_2$	-12.665	20.846	-0.608
$PREC \times CO_2$	-5.554	5.831	-0.953
Diagnostic Tests			
χ^2_{SER}	0.455 (0.641)	R^2	0.961
χ^2_{HET}	0.213 (0.995)	R^2_{Adj}	0.940
χ^2_{NORM}	26.075 (0.000)	F_{ist}	45.778 (0.000)
χ^2_{RAMSEY}	0.077 (0.784)	$Cusum$	Stable
DW	1.929	$Cusum(sqr)$	Stable

Note: See footnote from Table 3.

Since the F-statistic is below the critical values at all significance levels, we conclude that there is no cointegration. This means that the variables ($TEMP$, $PREC$, CO_2, and interaction terms) do not share a stable long-run relationship with rice yields. Consequently, any observed associations are transient and do not imply a persistent, long-term equilibrium.

Without a long-term relationship, the interpretation focuses exclusively on short-run dynamics. This means that any changes in temperature, precipitation, or CO_2 levels may temporarily impact rice yields, but these effects are not sustained over time. For example, the negative and significant coefficient for precipitation indicates that increases in precipitation in the short run negatively impact rice yield. This result could be attributed to potential waterlogging, where excessive rainfall leads to poor soil aeration and oxygen availability, critical for rice root health (Colmer, 2002). Rice is often cultivated in flooded conditions, but extreme or unmanaged rainfall can disrupt its ideal growing environment, indicating that excess moisture must be carefully managed (Smith & Mohanty, 2018). The positive and significant coefficient for CO_2 suggests that increases in CO_2 levels have an immediate beneficial effect on rice yield. This effect likely reflects the CO_2 fertilization effect, where elevated CO_2 enhances photosynthesis and growth in C3 plants such as rice, increasing yield potential in the short run under favorable conditions (Lv et al. 2020).

The interaction terms between temperature, precipitation, and CO_2 provide insights into how these factors influence rice yield beyond their individual effects. The current $TEMP \times PREC$ interaction coefficient is positive and highly significant (96.149), suggesting that the combined effect of temperature and precipitation supports rice yield in the short run. This may indicate that favorable temperature conditions help rice tolerate increased moisture, benefiting growth by balancing the crop's water and thermal requirements. The lagged $TEMP \times PREC$ interaction term (0.026) is positive and significant, indicating a continued benefit from past favorable temperature and precipitation conditions. This delayed positive impact suggests that an earlier balance of temperature and rainfall conditions creates a conducive environment for current rice yield, possibly through soil moisture retention and favorable crop health (Agrawal et al. 1983).

The negative and significant coefficient for the $TEMP \times CO_2$ interaction term suggests that an immediate increase in temperature and CO_2 negatively impacts rice yield in the short run. This result implies that while CO_2 alone may benefit growth, its combination with higher temperatures can introduce stress, potentially due to increased respiration rates or other physiological changes that may counteract CO_2's positive effect under high-temperature conditions (Roy et al. 2024). The significant negative coefficient for the $PREC \times CO_2$ interaction indicates that combined high precipitation and CO_2 levels adversely affect rice yield in the short run. This result may reflect the compounding stress from excess water and elevated CO_2, which could disrupt the crop's balance of nutrients and gases in the flooded soil, thus hindering growth (Greenway et al. 2006).

Since these environmental factors do not sustain a long-term effect on rice yields, adaptive practices that respond to short-term changes (e.g., seasonal weather variations and CO_2 fluctuations) may be more effective for rice production. This could include adjusting irrigation during rainy seasons to prevent waterlogging or using climate-adaptive rice varieties better suited for fluctuating temperatures.

In sum, in the absence of cointegration, the analysis emphasizes short-run impacts only. The environmental factors $TEMP$, $PREC$, and CO_2 influence rice yields temporarily, but these effects do not form a stable, long-term relationship. This suggests that while managing these factors can help optimize yields in the short term, they are unlikely to provide sustained yield benefits without additional interventions or adaptations.

However, given the absence of cointegration, it is essential to re-specify the model in first differences rather than continuing with the previously specified ECM. An ECM assumes a stable, long-run relationship among the variables, meaning it relies on cointegration to model both short-run dynamics and adjustments toward a long-term equilibrium. When cointegration is absent, this assumption no longer holds, and the following issues arise:

- In an ECM, the error correction term is crucial for capturing the speed of adjustment back to equilibrium. Without cointegration, there is no meaningful long-run equilibrium, making this term statistically invalid and rendering its interpretation inappropriate.

- In the ECM, long-run coefficients describe stable equilibrium relationships between variables. Interpreting these coefficients would be misleading without cointegration, as they do not represent a stable long-run effect without a long-term relationship.

- Re-specifying the model in first differences allows for focusing solely on short-run effects, accurately reflecting the immediate impacts of changes in the independent variables on rice yield growth. This approach avoids assuming non-existent equilibrium relationships, ensuring the model captures only realistic short-term behaviors.

- Using a first-differenced model aligns with the statistical properties of the data, ensuring consistency and robustness in estimating the short-run relationships. This adjustment allows for a precise and valid analysis of immediate changes in environmental factors and their impact on rice yields, avoiding the pitfalls of misinterpreting long-run stability where none exists.

In the revised model, we apply an ARDL structure using only differenced terms, effectively focusing on short-run dynamics. This specification provided insight into how variations in CO_2 levels, precipitation, temperature, and their interactions immediately affect rice yield growth. By analyzing only the short-run coefficients, we avoid relying on a long-run relationship that the initial analysis indicated is absent. The results are summarized in Table 6.

Table 6- Short-run results (rice)

Model: $F(\text{RICE}_t/\ \text{TEMP}_t, \text{PREC}_t, \text{CO2}_t, \text{TEMP} \times \text{PREC}_t, \text{TEMP} \times CO_{2_t}, \text{PREC} \times CO_{2_t})$			
Optimal Lag Length: (1, 1, 0, 0, 0, 0, 0)			
Short-Run Coefficients (Conditional ECM)			
Variable	***Coefficient***	***Std. Error***	***t-stat***
C	0.020	0.015	1.399
$\Delta RICE_{t-1}$	-0.984***	0.169	-5.812
$\Delta TEMP_{t-1}$	-257.086*	143.771	-1.788
$\Delta PREC_t$	-396.832***	122.237	-3.246
ΔCO_{2_t}	82.619**	32.443	2.547
$\Delta TEMP \times PREC_t$	83.864***	25.601	3.276
$\Delta TEMP \times CO_{2_t}$	-14.217**	6.074	-2.341
$\Delta PREC \times CO_{2_t}$	-1.618***	0.455	-3.558
$\Delta(\Delta TEMP_t)$	-262.259*	144.164	-1.819

Note: *** P<0.01, ** 0.01< P<0.05, * 0.05< P<0.10.

The short-run results for rice yields reveal the immediate effects of environmental variables (temperature, precipitation, CO_2) and their interactions on rice production, focusing exclusively on transient, non-sustained impacts due to the lack of cointegration.

The significant (at the 1% level) and negative coefficient of -0.984 for the lagged rice yield suggests a negative autocorrelation in rice production. This means that higher yields in the previous period are associated with lower yields in the current period. This could indicate cyclical production effects, potentially due to nutrient depletion or other factors that reduce yield potential after a high-yield season.

The coefficient for $TEMP$ is negative and significant (-257.086, significant at the 10% level), indicating that higher temperatures reduce rice yields in the short term. This suggests that rice is sensitive to elevated temperatures, likely due to heat stress affecting growth stages such as flowering and grain filling (Nath et al. 2022).

$PREC$ significantly negatively affects rice yields, with a coefficient of -396.832 (significant at the 1% level). This suggests that excessive precipitation negatively impacts rice production, possibly due to waterlogging, which can damage roots and reduce nutrient absorption in rice paddies. Rice requires controlled water levels, and excess rainfall may disrupt optimal growth conditions (Talpur et al. 2013; Dos Santos et al. 2018).

CO_2 has a significant positive effect on rice yields, with coefficients of 82.619 (significant at the 5% level) and 83.864 (significant at the 1% level). This implies that higher atmospheric CO_2 levels enhance rice yield, likely due to the CO_2 fertilization effect, which boosts photosynthesis and water-use efficiency (Lv et al. 2020).

The interaction terms show mixed effects. The $TEMP \times PREC$ interaction has a significant negative coefficient of -14.217 (significant at the 5% level), indicating that combined high temperatures and excess precipitation may further reduce yields. This interaction likely reflects compounded stress on rice plants from heat and waterlogging. Other interactions show that the presence of CO_2 might help alleviate some adverse effects of temperature, but the overall impact remains dependent on the balance of these environmental conditions (Baker et al. 1995).

The significant negative coefficient for the $TEMP \times CO_2$ interaction indicates that simultaneous increases in temperature and CO_2 negatively impact rice yield. This suggests that while CO_2 alone can benefit growth, its positive effects are tempered or even reversed under high temperatures, possibly due to increased respiration rates or other physiological stresses that counteract CO_2's beneficial effects (Roy et al. 2024). The significant negative coefficient for the $PREC \times CO_2$ interaction implies that combined increases in precipitation and CO_2 reduce rice yield in the short term. This adverse effect may reflect stress from excess water combined with altered gas exchange or nutrient uptake issues under elevated CO_2, which can disrupt optimal growth conditions and reduce yield.

In sum, short-run dynamics for rice are primarily driven by sensitivity to temperature and precipitation, with higher temperatures and excessive rainfall leading to reduced yields. Rice is mainly affected by water management challenges and benefits from moderate temperature conditions. Positive CO_2 effects indicate that elevated CO_2 levels can boost yields, possibly by enhancing photosynthesis. However, this effect is not strong enough to counterbalance severe heat or excess precipitation impacts. The interaction terms indicate that while balanced temperature and moisture benefit rice yield, excessive or combined increases—particularly with CO_2—can lead to stress that undermines yield potential.

The CO_2 fertilization effects observed in Turkiye are consistent with findings from semi-arid regions in southern Europe and North Africa, where elevated CO_2 levels similarly enhance yields, particularly for wheat and potatoes. Studies such as Long et al. (2006) and Ainsworth and Rogers (2007) have highlighted that CO_2 enrichment improves photosynthesis and water-use efficiency, especially in C3 crops such as wheat. However, these benefits are often conditional on sufficient water and nutrient availability, which aligns with Turkiye's results showing the interplay of precipitation with CO_2 impacts.

Nonlinear temperature effects observed in Turkiye, particularly for wheat and rice, mirror findings from Australia (Asseng et al. 2011) and the southern United States (Lobell et al. 2012). These regions report similar critical temperature thresholds beyond which yields decline significantly due to heat stress. This reinforces the importance of identifying crop-specific thresholds to guide adaptive agricultural practices.

The sensitivity of rice yields to precipitation variability in Turkiye is comparable to studies from Southeast Asia, where monsoon patterns and irrigation availability heavily influence water-intensive cropping systems. Research by Wassmann et al. (2009) and Peng et al. (2004) highlight similar dynamics, where rainfall variability critically determines yield stability, particularly for rice.

Insights from these regions highlight strategies like precision irrigation, crop diversification, and genetic improvements for heat and drought resilience, which could inform Turkiye's agricultural adaptation measures. For example, strategies discussed by Howell (2001) and Hatfield et al. (2011) emphasize the need for integrated water management and resilient crop varieties to combat climate impacts.

This comparative analysis situates the findings within a global framework, demonstrating the universality and context-specific nature of climate impacts on agriculture. By incorporating these studies, the discussion gains depth and emphasizes the broader applicability of the results to similar climatic regions worldwide."

Finally, while ARDL does not inherently require separate static analysis, we generate scatterplots to explore relationships between our key variables (e.g., precipitation, temperature, CO_2) and crop yields at their levels. These scatterplots provide a visual understanding of static relationships and validate the econometric findings.

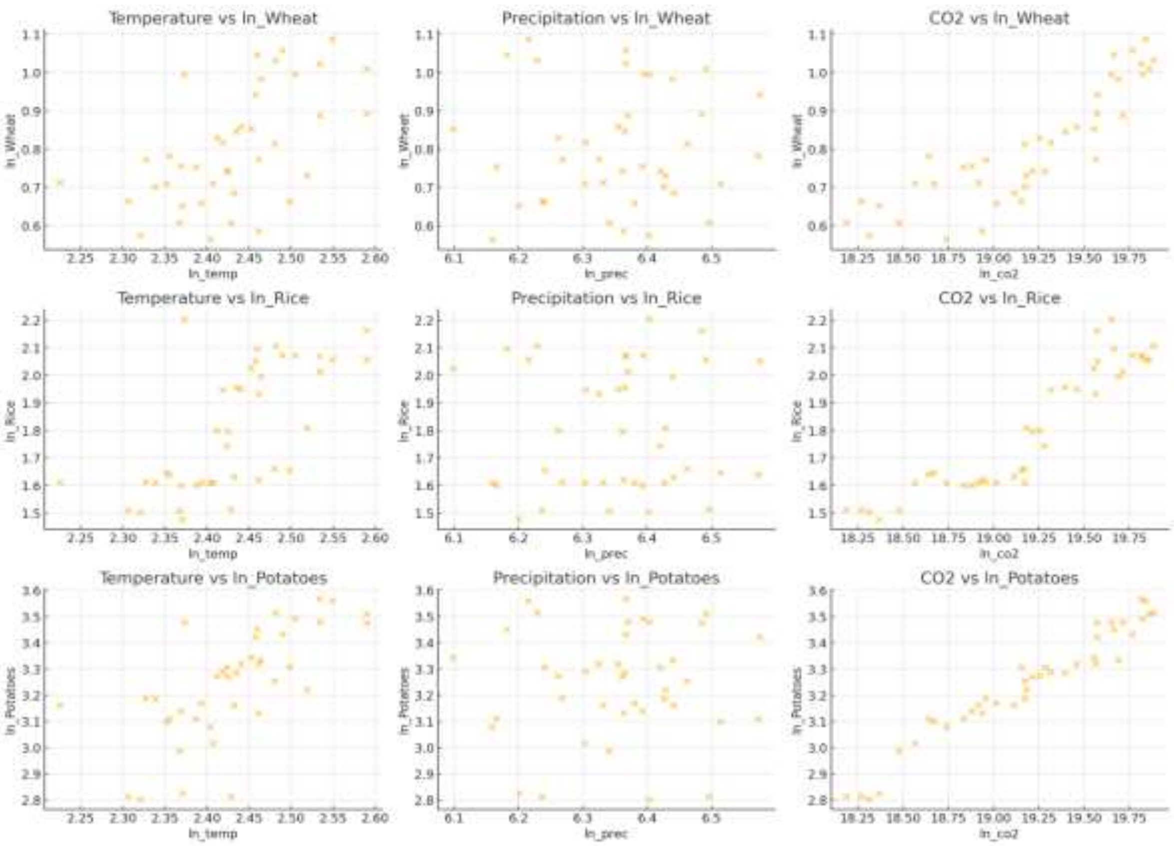

Figure 1- Static relationships

The scatterplots for wheat imply that moderate precipitation positively influences wheat yields as it provides the necessary water for growth. However, excessive precipitation can lead to waterlogging, reducing oxygen availability and negatively affecting yields. While rice thrives in waterlogged conditions, the scatterplot may reflect the adverse effects of excessive precipitation, such as flooding beyond optimal levels and disrupting oxygen availability and nutrient uptake. Potatoes are highly sensitive to waterlogging caused by excessive rainfall. This likely results in reduced yields, as reflected in the plot. However, moderate precipitation may provide sufficient moisture for tuber development.

Furthermore, wheat generally benefits from moderate temperature increases, especially in colder months, as it extends the growing season. However, extreme temperatures can induce heat stress, impairing photosynthesis and yield, evident in some negative relationships in the scatterplot. The scatterplot for rice may show a negative trend at higher temperatures, reflecting rice's sensitivity to heat stress, particularly during critical growth stages such as flowering and grain filling. The relationship in the plot likely highlights potatoes' preference for cooler growing conditions. Higher temperatures can accelerate metabolic stress, leading to reduced yields, as observed in the negative correlations.

Finally, the positive relationship in the wheat scatterplot aligns with the CO_2 fertilization effect, where elevated CO_2 levels enhance photosynthesis and water-use efficiency in wheat. However, other limiting factors (e.g., temperature) can moderate this effect. The scatterplot for rice may show a positive trend due to the short-term benefits of elevated CO_2, which stimulates photosynthesis in rice (a C3 crop). Yet, interactions with other environmental factors can alter this relationship. The scatterplot will likely capture the positive delayed effects of CO_2 on potato yields observed earlier. CO_2 enhances biomass and tuber formation, benefiting potato yields when other conditions are optimal.

4. Conclusions

This study comprehensively analyzes how climate variables—temperature, precipitation, and CO_2 levels—affect the yields of three essential crops in Turkiye: wheat, potatoes, and rice. Using an ARDL model, the research distinguishes between crops with a long-term dependency on climatic factors and those with only short-run responses, providing insights into how Turkiye's agriculture can adapt to climate change in a crop-specific manner.

The findings indicate that wheat and potatoes exhibit a long-term equilibrium relationship with the climate variables, suggesting that these crops respond to sustained climatic conditions. Wheat yields benefit from moderate increases in temperature and CO_2, which enhance growth and photosynthetic efficiency. However, extreme heat and excessive precipitation adversely affect yield by inducing heat stress and waterlogging. In the long run, temperature positively influences wheat yields, with a coefficient of 2223.352, indicating a substantial benefit from moderate heat. Precipitation also has a positive long-run effect, with a coefficient of 1829.405, suggesting that increased rainfall supports wheat growth. However, the CO_2 effect is negative, with a coefficient of -120.904, which may reflect diminishing returns or stress factors associated with elevated CO_2. Interaction effects reveal that $TEMP \times PREC$ has a negative coefficient of -390.371, highlighting potential challenges under combined heat and excessive precipitation, while $TEMP \times CO_2$ (13.236) and $PREC \times CO_2$ (8.469) suggest beneficial combined effects of temperature or precipitation with CO_2. The study's results emphasize that wheat yields could be optimized by implementing practices tailored to mitigate these climate impacts, such as developing drought-resistant and heat-tolerant varieties, altering planting schedules to avoid peak heat periods, and using improved irrigation techniques to manage water availability. Given the long-term dependency, wheat growers and policymakers must anticipate gradual climate changes and adjust practices accordingly, ensuring yield stability.

Similarly, potatoes demonstrate a long-run sensitivity to temperature, precipitation, and CO_2. Potato yields suffer significantly from prolonged exposure to high temperatures and excessive rainfall. In the long run, temperature positively impacts potato yields, with a coefficient of 575.145, reflecting the crop's ability to benefit from moderate heat conditions. Precipitation also has a positive effect, with a coefficient of 507.065, indicating that increased rainfall supports potato growth. However, the CO_2 effect is negative, with a coefficient of -36.623 which may reflect stress conditions under elevated CO_2 levels. Interaction effects show that $TEMP \times PREC$ has a negative coefficient of -106.205, indicating potential challenges under combined heat and precipitation, while $TEMP \times CO_2$ (4.992) and $PREC \times CO_2$ (1.826) suggest beneficial combined effects of temperature or precipitation with CO_2. This adverse response highlights the crop's sensitivity to temperature and moisture extremes, reflecting its need for stable, moderate growing conditions. While the delayed positive effect of CO_2 suggests a potential benefit under controlled conditions, this advantage may be offset by the stress introduced by heat and water imbalances. Therefore, adaptation strategies should focus on precise water management practices, possibly including controlled drainage systems to prevent waterlogging and soil degradation for potatoes. In addition, efforts to breed heat-resistant potato varieties or explore growing regions with optimal temperature ranges may help mitigate climate impacts on potato yield. Policies promoting efficient water use and sustainable irrigation systems can further enhance the resilience of potato production under increasingly variable climate conditions.

In contrast, rice yields exhibit no long-run relationship with the analyzed climate variables, indicating a predominantly short-term response to temperature, precipitation, and CO_2 fluctuations. As a result, any observed associations are transient and do not imply persistent, long-term equilibrium. Short-run results reveal that higher lagged rice yields negatively influence current yields, with a coefficient of -0.984. This indicates cyclical production effects, possibly due to nutrient depletion or other residual factors after a high-yield season. Temperature has a significant negative impact, with a coefficient of -257.086, reflecting heat stress on sensitive growth stages like flowering and grain filling. Current precipitation negatively impacts yields (-396.832), likely due to waterlogging and nutrient disruption, while CO_2 positively affects rice yields (82.619), enhancing photosynthesis and water-use efficiency. Interaction effects include $TEMP \times PREC$ (83.864), which has a positive influence in the short run, while $TEMP \times CO_2$ (-14.217) and $PREC \times CO_2$ (-1.618) demonstrate negative combined impacts of these variables, reflecting compounded stressors on physiological or soil conditions. Adaptive management practices that respond quickly to seasonal weather variations, such as timely irrigation adjustments, crop rotation, and drainage control, are crucial for rice. Moreover, developing and using rice varieties that are tolerant to sudden temperature and precipitation changes can enhance resilience, allowing rice production to withstand the effects of an increasingly volatile climate.

The study's crop-specific findings underscore the importance of tailored climate adaptation strategies for Turkiye's agricultural sector. A one-size-fits-all approach to climate adaptation would not suffice, given the unique responses of wheat, potatoes, and rice to environmental changes. For wheat and potatoes, where yields are impacted by long-term climatic trends, sustainable adaptation strategies should be oriented toward managing gradual changes and ensuring resource availability to support steady growth. On the other hand, a focus on adaptive flexibility is essential for rice to mitigate the effects of short-term climatic variability.

To address these findings in a more specific manner, the following recommendations are proposed:

1. For Wheat:

- Develop advanced early warning systems to alert farmers about potential heatwaves or precipitation extremes, enabling proactive measures.
- Increase funding for research into wheat genetic improvements focusing on heat and drought resistance tailored to Turkiye's regional climate variability.
- Promote the adoption of no-till farming practices to improve soil water retention and reduce the vulnerability of wheat to sudden precipitation changes.

2. For Potatoes:

- Implement integrated water resource management systems, particularly in regions prone to waterlogging.
- Encourage crop insurance programs to support farmers in managing yield losses due to climate variability.
- Develop precision agriculture technologies, such as drip irrigation and moisture sensors, to optimize water use.

3. For Rice:

- Introduce floating rice varieties and enhance drainage infrastructure in flood-prone areas.
- Train farmers in seasonal risk assessment techniques to align planting schedules with favorable climatic windows.
- Pilot programs for rotational intercropping to stabilize soil structure and enhance resilience to water extremes.

4. Policy-Level Actions:

- Increase subsidies for precision agriculture tools, particularly for small-scale farmers who are most vulnerable to climate impacts.
- Expand farmer education initiatives, focusing on the application of adaptive practices such as optimized irrigation and climate-resilient crop choices.
- Foster collaboration between academic institutions and agricultural cooperatives to create region-specific adaptation blueprints based on this study's findings.

The implications of this study are especially relevant for policymakers, agronomists, and farmers in Turkiye. By employing a tailored strategy for climate adaptation, stakeholders can guarantee that each crop is prepared to address its unique climate risks. Policy initiatives should promote climate-smart agriculture, invest in research and development of climate-resilient crop varieties, and support efficient water management technologies. Additionally, fostering awareness and capacity-building among farmers can facilitate the adoption of practices that align with climate-responsive strategies, ensuring that agricultural productivity in Turkiye remains resilient amid climate challenges.

Specifically, this study's findings suggest several policy recommendations to address the adverse impacts of climate change on Turkiye's agricultural sector. First, improving water management strategies is essential to mitigate the effects of erratic precipitation patterns and ensure sustainable water use. Precision irrigation systems should be implemented to optimize water use efficiency, particularly for water-intensive crops such as rice. Additionally, rainwater harvesting and enhanced irrigation infrastructure can reduce vulnerability to water scarcity.

Crop diversification should also be prioritized. Subsidies and research incentives should encourage the cultivation of drought-tolerant and heat-resistant crop varieties, enhancing resilience. Supporting crop rotation practices can help maintain soil fertility and reduce the sector's exposure to climate extremes.

Technological innovations play a critical role in building resilience. Investments in agricultural technologies, such as remote sensing and early warning systems, can improve climate risk management. Developing and disseminating mobile applications to provide farmers with real-time weather forecasts and crop advisory services would further support adaptive practices.

Integrating climate resilience into national agricultural policies is equally important. Policies should align with Turkiye's broader climate action goals, ensuring that adaptation strategies are well-supported and effectively implemented. Conducting awareness campaigns and capacity-building programs can educate farmers on sustainable practices and the benefits of adopting climate-resilient measures.

Finally, fostering research and collaboration is vital. Establishing partnerships with international research institutions can facilitate knowledge sharing and the development of region-specific adaptation strategies. Expanding funding for research on the combined effects of climate variables on crop yields will refine predictive models and improve adaptation planning. These policy suggestions align with the study's findings and provide actionable steps to enhance the resilience of Turkiye's agricultural sector to climate variability and long-term change.

Ultimately, this study contributes to the broader body of research on climate adaptation in agriculture, illustrating that understanding crop-specific responses to climatic factors is essential for sustaining food security and economic stability. As climate conditions continue to change, Turkiye's agricultural sector can benefit significantly from these insights, guiding the development of adaptive measures that are not only scientifically sound but also practically feasible. By aligning agricultural practices with the unique needs of each crop, Turkiye can better safeguard its food supply and rural livelihoods, supporting a resilient agricultural future in the face of ongoing climate variability.

References

Ainsworth E A & Rogers A (2007). The response of photosynthesis and stomatal conductance to rising [CO2]: Mechanisms and environmental interactions. *Plant, Cell & Environment* 30(3): 258-270. https://doi.org/10.1111/j.1365-3040.2007.01641.x

Alonso A, Pérez P & Martínez-Carrasco R (2009). Growth in elevated CO2 enhances temperature response of photosynthesis in wheat. *Physiologia Plantarum* 135(2): 109-120. https://doi.org/10.1111/j.1399-3054.2008.01177.x

Asseng S, Foster, I A N & Turner N C (2011). The impact of temperature variability on wheat yields. *Global Change Biology* 17(2): 997-1012. https://doi.org/10.1111/j.1365-2486.2010.02262.x

Bernacchi C J, Ruiz-Vera U M, Siebers M H, DeLucia N J & Ort D R (2023). Short-and long-term warming events on photosynthetic physiology, growth, and yields of field grown crops. *Biochemical Journal* 480(13): 999-1014. https://doi.org/10.1042/BCJ20220433

Bishop K A, Leakey A D & Ainsworth E A (2014). How seasonal temperature or water inputs affect the relative response of C3 crops to elevated [CO2]: a global analysis of open top chamber and free air CO2 enrichment studies. *Food and Energy Security* 3(1): 33-45. https://doi.org/10.1002/fes3.44

Boretti A & Florentine S (2019). Atmospheric CO2 concentration and other limiting factors in the growth of C3 and C4 plants. *Plants* 8(4): 92. https://doi.org/10.3390/plants8040092

Bozoglu M, Başer U, Eroglu N A & Topuz B K (2019). Impacts of climate change on Turkish agriculture. *Journal of International Environmental Application and Science* 14(3): 97-103.

Busse J S, Wiberley-Bradford A E & Bethke P C (2019). Transient heat stress during tuber development alters post-harvest carbohydrate composition and decreases processing quality of chipping potatoes. *Journal of the Science of Food and Agriculture* 99(5): 2579-2588. https://doi.org/10.1002/jsfa.9473

Campbell R, Ducreux L J, Mellado-Ortega E, Hancock R D & Taylor M A (2021). Toward the design of potato tolerant to abiotic stress. *Solanum Tuberosum: Methods and Protocols* 387-399. https://doi.org/10.1007/978-1-0716-1609-3_19

Chandio A A, Gokmenoglu K K & Ahmad F (2021). Addressing the long-and short-run effects of climate change on major food crops production in Turkey. *Environmental Science and Pollution Research* 28(37): 51657-51673. https://doi.org/10.1007/s11356-021-14358-8

Conradie B, Piesse J & Strauss J (2021). Impact of heat and moisture stress on crop productivity: Evidence from the Langgewens Research Farm. *South African Journal of Science* 117(9-10): 1-7. https://doi.org/10.17159/sajs.2021/8898

Conroy J P, Seneweera S, Basra A S, Rogers G & Nissen-Wooller B (1994). Influence of rising atmospheric CO2 concentrations and temperature on growth, yield and grain quality of cereal crops. Functional *Plant Biology* 21(6): 741-758. https://doi.org/10.1071/PP9940741

Donnelly A, Craigon J, Black C R, Colls J J & Landon G (2001). Elevated CO2 increases biomass and tuber yield in potato even at high ozone concentrations. *New Phytologist* 149(2): 265-274. https://doi.org/10.1046/j.1469-8137.2001.00015.x

Du X, Gao Z, Sun X, Bian D, Ren J, Yan P & Cui Y (2022). Increasing temperature during early spring increases winter wheat grain yield by advancing phenology and mitigating leaf senescence. *Science of the Total Environment* 812: 152557. https://doi.org/10.1016/j.scitotenv.2021.152557

Dubey S K, Tripathi S K & Pranuthi G (2015). Effect of elevated CO2 on wheat crop: mechanism and impact. *Critical Reviews in Environmental Science and Technology* 45(21): 2283-2304. https://doi.org/10.1080/10643389.2014.1000749

Fan X, Zhu D, Sun X, Wang J, Wang M, Wang S & Watson A E (2022). Impacts of extreme temperature and precipitation on crops during the growing season in South Asia. *Remote Sensing* 14(23): 6093. https://doi.org/10.3390/rs14236093

Finnan J M, Donnelly A, Jones M B & Burke J I (2005). The effect of elevated levels of carbon dioxide on potato crops: A review. *Journal of Crop Improvement* 13(1-2): 91-111. https://doi.org/10.1300/J411v13n01_06

Gifford R M (1995). Whole plant respiration and photosynthesis of wheat under increased CO2 concentration and temperature: long-term vs. short-term distinctions for modelling. *Global Change Biology* 1(6): 385-396. https://doi.org/10.1111/j.1365-2486.1995.tb00037.x

Gonsamo A, Ciais P, Miralles D G, Sitch S, Dorigo W, Lombardozzi D ... & Cescatti A (2021). Greening drylands despite warming consistent with carbon dioxide fertilization effect. Global Change Biology 27(14): 3336-3349. https://doi.org/10.1111/gcb.15658

Hassler U & Wolters J (2006). Autoregressive distributed lag models and cointegration. *Allgemeines Statistisches Archiv* 90: 59–74. https://doi.org/10.1007/s10182-006-0221-5

Hatfield J L, Boote K J, Kimball B A, Ziska L H, Izaurralde R C, Ort D & Wolfe D (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal* 103(2): 351-370. https://doi.org/10.2134/agronj2010.0303

Howard J C, Cakan E & Upadhyaya K (2016). Climate change and its impact on wheat production in Kansas. Economics & Business Analytics Faculty Publications, University of New Haven.

Howell T A (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal* 93(2): 281-289. https://doi.org/10.2134/agronj2001.932281x

Kaur G, Singh G, Motavalli P P, Nelson K A, Orlowski J M & Golden B R (2020). Impacts and management strategies for crop production in waterlogged or flooded soils: A review. *Agronomy Journal* 112(3): 1475-1501. https://doi.org/10.1002/agj2.20093

Kaushal N, Bhandari K, Siddique K H & Nayyar H (2016). Food crops face rising temperatures: an overview of responses, adaptive mechanisms, and approaches to improve heat tolerance. *Cogent Food & Agriculture* 2(1): 1134380. https://doi.org/10.1080/23311932.2015.1134380

Khaeim H, Kende Z, Balla I, Gyuricza C, Eser A & Tarnawa Á (2022). The effect of temperature and water stresses on seed germination and seedling growth of wheat (Triticum aestivum L.). *Sustainability* 14(7): 3887. https://doi.org/10.3390/su14073887

Kim Y U, Webber H, Adiku S G, Júnior R D S N, Deswarte J C, Asseng S & Ewert F (2024). Mechanisms and modelling approaches for excessive rainfall stress on cereals: Waterlogging, submergence, lodging, pests and diseases. *Agricultural and Forest Meteorology* 344: 109819. https://doi.org/10.1016/j.agrformet.2023.109819

King B A, Stark J C & Neibling H (2020). Potato irrigation management (pp. 417-446). Springer International Publishing.

Kiongo S C, Taylor N J, Franke A C & Steyn J M (2024). Elevated Carbon Dioxide only Partly Alleviates the Negative Effects of Elevated Temperature on Potato Growth and Tuber Yield. *Potato Research* 1-21. https://doi.org/10.1007/s11540-024-09767-4

Kripfganz S & Schneider D C (2023). ardl: Estimating autoregressive distributed lag and equilibrium correction models. *The Stata Journal* 23(4): 983-1019. https://doi.org/10.1177/1536867X231212434

Kumar S, Sharma A, Pandey S, Paul S, Mishra H, Kesarwani A ... & Tiwari H (2023). Response of Different Moisture Regimes and Nitrogen Sources on Soil Health, Growth and Yield Attributes of Wheat: A Comprehensive Review. *International Journal of Plant & Soil Science* 35(20): 541-548. https://doi.org/10.9734/ijpss/2023/v35i203837

Lawlor D W & Mitchell R A C (1991). The effects of increasing CO2 on crop photosynthesis and productivity: A review of field studies. *Plant, Cell & Environment* 14(8): 807-818. https://doi.org/10.1111/j.1365-3040.1991.tb01444.x

Lee Y H, Sang W G, Baek J K, Kim J H, Shin P, Seo M C & Cho J I (2020). The effect of concurrent elevation in CO2 and temperature on the growth, photosynthesis, and yield of potato crops. *PloS One* 15(10): e0241081. https://doi.org/10.1371/journal.pone.0241081

Li F, Kang S & Zhang F (2003). Effects of CO2 enrichment, nitrogen and water on photosynthesis, evapotranspiration and water use efficiency of spring wheat. *Chinese Journal of Applied Ecology* 14(3): 387-393.

Lizana X C & Calderini D F (2013). Yield and grain quality of wheat in response to increased temperatures at key periods for grain number and grain weight determination: Considerations for the climatic change scenarios of Chile. *The Journal of Agricultural Science* 151(2): 209-221. https://doi.org/10.1017/S0021859612000639

Lobell D B, Schlenker W & Costa-Roberts J (2012). Climate trends and global crop production since 1980. *Science* 333(6042): 616-620. https://doi.org/10.1126/science.1204531

Long S P, Ainsworth E A, Leakey A D B, Nösberger J & Ort D R (2006). Food for thought: Lower-than-expected crop yield stimulation with rising CO2 concentrations. *Science* 312(5782): 1918-1921. https://doi.org/10.1126/science.1114722

Lopes M S (2022). Will temperature and rainfall changes prevent yield progress in Europe? *Food and Energy Security* 11(2): e372. https://doi.org/10.1002/fes3.372

Loreti E & Striker G G (2020). Plant responses to hypoxia: Signaling and adaptation. *Plants* 9(12): 1704. https://doi.org/10.3390/plants9121704

Makowski D, Marajo-Petitzon E, Durand J L & Ben-Ari T (2020). Quantitative synthesis of temperature, CO2, rainfall, and adaptation effects on global crop yields. *European Journal of Agronomy* 115: 126041. https://doi.org/10.1016/j.eja.2020.126041

Meng F C, Guo J, Zhou L, Xiong M M, & Zhang L (2017). Interactive effects of temperature, CO2 concentration and precipitation on growth and yield of crops. The Journal of Applied Ecology 28(12): 4117-4126. https://doi.org/10.13287/j.1001-9332.201712.023

Momčilović I (2019). Effects of heat stress on potato productivity and nutritive quality. *Hrana i ishrana* 60(2): 43-48. https://doi.org/10.5937/hraIsh1902043M

Murillo R P, Cáceres J V & Ruiz J L (2021). Dynamics of the Potato Root (Solanum Spp.) Under Different Levels of Soil Moisture, in the Geographical Region of Riobamba, Ecuador. ESPOCH Congresses: The Ecuadorian Journal of STEAM, 294-312. https://doi.org/10.18502/espoch.v1i1.9565

Narayan P K (2005). The saving and investment nexus for China: Evidence from cointegration tests. *Applied Economics* 37(17): 1979-1990. https://doi.org/10.1080/00036840500278103

Ottman M J, Kimball B A, White J W & Wall G W (2012). Wheat growth response to increased temperature from varied planting dates and supplemental infrared heating. *Agronomy Journal* 104(1): 7-16. https://doi.org/10.2134/agronj2011.0212

Peng S, Huang J, Sheehy J E, Laza R C, Visperas R M, Zhong X ... & Cassman K G (2004). Rice yields decline with higher night temperature from global warming. Proceedings of the National Academy of Sciences 101(27): 9971-9975. https://doi.org/10.1073/pnas.0403720101

Pesaran M H & Shin Y (1998). An autoregressive distributed-lag modelling approach to cointegration analysis. In Econometrics and Economic Theory in the Twentieth Century: The Ragner Frisch Centennial Symposium, ed. S. Steiner, 371–413. Cambridge: Cambridge University Press. https://doi.org/10.1017/CCOL521633230.011.

Pesaran M H, Shin Y & Smith, R J (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics* 16(3): 289-326. https://doi.org/10.1002/ja

Petrova L I, Mitrofanov Y I, Gulyaev M V & Pervushina N K (2021). Influence of various factors on crop formation and potato quality. *Ural Agrarian* Bulletin 4(207): 34-42. https://doi.org/10.32417/1997-4868-2021-207-04-34-42

Seneweera S & Norton R M (2011). Plant responses to increased carbon dioxide. Yadav, Shyam S., Redden, Robert J., Hatfield, Jerry L., Lotze-Campen, Hermann and Hall, Anthony E. (ed.) Crop adaptation to climate change. Chichester, West Sussex. United Kingdom. John Wiley & Sons. pp. 198-217

Sharkey T D (2005). Effects of moderate heat stress on photosynthesis: importance of thylakoid reactions, rubisco deactivation, reactive oxygen species, and thermotolerance provided by isoprene. *Plant, Cell & Environment* 28(3): 269-277. https://doi.org/10.1111/j.1365-3040.2005.01324.x

Taylor C A & Schlenker W (2021). Environmental drivers of agricultural productivity growth: CO2 fertilization of US field crops (No. w29320). National Bureau of Economic Research.

Tiwari A, Prasad S, Jaiswal B, Gyanendra K, Singh S & Singh K N (2017). Effect of heat stress on yield attributing traits in wheat (Triticum aestivum L.). *Int. J. Curr. Microbiol. App. Sci* 6(12): 2738-2744. https://doi.org/10.20546/ijcmas.2017.612.317

Ullah A, Nadeem F, Nawaz A, Siddique K H & Farooq M (2022). Heat stress effects on the reproductive physiology and yield of wheat. *Journal of Agronomy and Crop Science* 208(1): 1-17. https://doi.org/10.1111/jac.12572

Van Vuuren M M, Robinson D, Fitter A H, Chasalow S D, Williamson L & Raven J A (1997). Effects of elevated atmospheric CO2 and soil water availability on root biomass, root length, and N, P and K uptake by wheat. New *Phytologist* 135(3): 455-465. https://doi.org/10.1046/j.1469-8137.1997.00682.x

Vanongeval F & Gobin A (2023). Adverse weather impacts on winter wheat, maize and potato yield gaps in northern Belgium. *Agronomy* 13(4): 1104. https://doi.org/10.3390/agronomy13041104

Wassmann R, Jagadish S V K, Heuer S, Ismail A, Redona E, Serraj R ... & Rosegrant M (2009). Climate change affecting rice production: The physiological and agronomic basis for possible adaptation strategies. *Advances in Agronomy*, 101: 59-122. https://doi.org/10.1016/S0065-2113(08)00802-X

Yandell B. S, Najar A, Wheeler R & Tibbitts T W (1988). Modeling the effects of light, carbon dioxide, and temperature on the growth of potato. *Crop Science* 28(5): 811-818. https://doi.org/10.2135/cropsci1988.0011183X002800050019x

Yang X, Tang X, Chen B, Tian Z & Zhong H (2013). Impacts of heat stress on wheat yield due to climatic warming in China. *Prog Geogr* 32(12): 1771-1779. https://doi.org/10.1007/s10584-016-1866-z

Yu Y, Jiang Z, Wang G, Kattel G R, Chuai X, Shang Y & Miao L (2022). Disintegrating the impact of climate change on maize yield from human management practices in China. *Agricultural and Forest Meteorology* 327: 109235. https://doi.org/10.1016/j.agrformet.2022.109235

Zhang X, Högy P, Wu X, Schmid I, Wang X, Schulze W X & Fangmeier A (2018). Physiological and proteomic evidence for the interactive effects of post-anthesis heat stress and elevated CO2 on wheat. *Proteomics* 18(23): 1800262. https://doi.org/10.1002/pmic.201800262

Zhao F, Zhang Q, Lei J, Wang H, Zhang K & Qi Y (2024). Environmental factors influence the responsiveness of potato tuber yield to growing season precipitation. *Crop and Environment* 3(2): 112-122. https://doi.org/10.1016/j.crope.2024.02.002

Zhu T, Fonseca De Lima C F & De Smet I (2021). The heat is on: how crop growth, development, and yield respond to high temperature. *Journal of Experimental Botany* 72(21): 7359-7373. https://doi.org/10.1093/jxb/erab308