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Climate Change and Its Impact on Agricultural Productivity in the Carpathian Basin: An Econometric Assessment

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Abstract

This study examines the impact of climate change on agricultural productivity in the Carpathian Basin, a region spanning Hungary, Romania, Slovakia, Serbia, and Ukraine. Using panel data from 2000 to 2022 and econometric modeling, the research investigates how key climate variables temperature, precipitation, and CO_2 emissions influence crop yields across varying agro-ecological contexts. Secondary data were sourced from FAOSTAT, the World Bank, the European Environment Agency, and national meteorological agencies. Results from fixed effects regression models reveal that rising temperatures significantly reduce crop yields, particularly for heat-sensitive crops like maize and sunflower, with a 1°C increase linked to an average yield decline of 0.93 tons per hectare. Conversely, a 100 mm increase in annual precipitation corresponds to a 57% yield improvement, though extreme rainfall or drought events can negate these benefits. While CO_2 emissions exhibit a slight fertilization effect, their interaction with high temperatures results in further yield reductions. Control variables such as fertilizer use and irrigation show mitigating effects, though their influence remains limited in the face of persistent climate stress. The study highlights the urgent need for region-specific adaptation strategies, including enhanced irrigation infrastructure, climate-resilient crops, and cross-border policy collaboration. These findings contribute to the growing literature on climate-agriculture dynamics and offer actionable insights for strengthening food security and sustainability in the Carpathian Basin.

Keywords: *Climate Change, Agricultural Productivity, Econometric Assessment, Environmental Impact*

1. Introduction

Climate change has emerged as one of the most pressing challenges of the 21st century, with profound implications for food security, economic stability, and rural livelihoods across the globe (Abumhadi et al., 2012). Nowhere is this more evident than in regions like the Carpathian Basin, Eitzinger et al. (2013), a geographically and agriculturally significant area in Central and Eastern Europe that is highly sensitive to climatic variability. The Basin, encompassing much of Hungary and parts of Romania, Slovakia, Serbia, and Ukraine, is characterized by fertile plains, a favorable climate for diverse agricultural activities, and a long-standing agricultural tradition (Janišová et al., 2024). However Liverman (2013), its geographical vulnerability also makes it particularly susceptible to the adverse effects of global climate change.

Over the past few decades, Jánosi et al. (2023), the Carpathian Basin has experienced marked changes in climate patterns rising temperatures, shifting precipitation cycles, increasing frequency of droughts, and more frequent extreme weather events. These shifts threaten to destabilize agricultural systems that are the backbone of rural economies in the region (Khatri et al., 2024). While Gezie (2019), crop yields, soil fertility, and water availability are all influenced by climatic conditions, and smallholder farmers are among the most vulnerable to these shifts. Wolfe et al. (2018), the growing unpredictability of weather has made farming more difficult, with the timing and success of planting, harvesting, and crop growth now less certain than ever before.

Given the critical role agriculture plays in food production, economic development, and employment in the Carpathian Basin, it is essential to understand how climate change is affecting this sector (Werners et al., 2016). Policymakers, farmers, agribusinesses, and regional planners require reliable, data-driven insights to adapt strategies (Ajayi et al., 2024), inform climate-resilient practices (Goswami et al., 2023), and shape agricultural policy in ways that safeguard both productivity and environmental sustainability (Lankoski & Thiem, 2020).

This research aims to empirically assess the impact of climate change on agricultural productivity in the Carpathian Basin by using econometric modeling techniques. Affoh et al. (2022), It draws on panel data from 2000 to 2022, focusing on variables such as crop yield, temperature anomalies, precipitation levels, and carbon emissions. The goal is to quantify how fluctuations in these climate variables influence agricultural output across time and geography in the region.

The originality of this study lies in its integrated use of econometric tools and its regional focus on the Carpathian Basin, which has been underrepresented in global climate-agriculture studies. While Coderoni & Pagliacci (2023), global assessments have highlighted general trends linking climate change to declining crop yields and productivity in vulnerable regions, few have delved into the Central and Eastern European context using micro-level panel data. Moreover Lah (2025), most existing literature treats agriculture and climate as sectoral silos rather than interconnected systems. This research bridges that gap by incorporating environmental, geographic, and economic data into a unified analysis.

Recent empirical studies provide strong evidence that climate variability has a significant impact on agricultural yields. For instance, Stephens (2024) found that in the United States, corn and soybean yields decline sharply once temperatures rise above certain thresholds. Lopez et al. (2021) demonstrated that temperature increases and precipitation shifts have reduced global maize and wheat yields, particularly in low-latitude regions. These findings support the hypothesis that rising temperatures, especially during critical crop growth stages, can reduce photosynthesis and increase evapotranspiration, leading to lower productivity.

In the European context, Didovets et al. (2019) emphasized that Central and Eastern Europe, including the Carpathian Basin, is highly vulnerable to climate-induced risks, particularly droughts and heatwaves, due to its continental climate. According to the European Environment Agency (EEA), Hungary has seen a 1.2°C increase in average temperature since the 1960s, with a marked increase in extreme temperature events. Rainfall patterns have also become more erratic, leading to both prolonged dry spells and sudden, intense rainfall episodes that disrupt planting and harvesting cycles.

These climatic stressors are particularly detrimental in regions where agricultural infrastructure and irrigation systems are limited. In Romania, for example, studies by Singh et al. (2023) have shown that yield losses due to drought are especially severe in maize and wheat, the two most widely cultivated crops in the Carpathian Basin. Similarly, Slovakia has recorded notable declines in barley and sunflower yields during years of elevated temperatures and below-average precipitation (Némethová, 2020 and Takáč & Ilavská, 2021). These findings justify the need for a focused regional analysis that integrates temperature, precipitation, and carbon emissions data to provide an econometric assessment of climate change impacts. While global models offer useful insights, they often obscure the micro-level variations that are critical for regional policy interventions. The Carpathian Basin, with its unique climatic conditions and socioeconomic reliance on agriculture, presents an ideal case for studying the intersection of environmental change and agricultural productivity.

Furthermore, the integration of carbon emissions as a variable in this study adds a novel dimension to traditional climate-agriculture models. CO_2 levels not only contribute to global warming but may also influence plant physiology, sometimes positively (via CO_2 fertilization) and sometimes negatively (via increased water stress and pest prevalence). Understanding this duality is essential for holistic policy planning. The research gap lies in the lack of region-specific, econometric, and integrative analyses of climate change impacts on agriculture in the Carpathian Basin. Previous studies are either global/continental, sector ally siloed, or descriptive. Your study contributes originality by applying panel econometrics to a geographically underrepresented region, integrating climatic, environmental, and economic factors, and generating policy-relevant insights.

In conducting this study, three central research questions are addressed: First, to what extent have temperature and precipitation changes affected agricultural productivity in the Carpathian

Basin? Second, what role do anthropogenic CO_2 emissions play in modifying productivity trends in the region? Third, how do these effects vary between countries and across different time periods within the Carpathian Basin?

2. Method

2.1 Participants

In this study, the term participants refer to the five countries that comprise the Carpathian Basin and serve as the units of analysis: Hungary, Romania, Slovakia, Serbia, and Ukraine. These countries were selected due to their geographical coverage of the Carpathian Basin and their strong dependence on agriculture. Each country represents a unique agro-ecological and economic context, offering valuable insights into how climate change affects agricultural productivity across differing environmental and policy landscapes. These countries were observed across a 23-year time frame (2000–2022), resulting in a balanced panel dataset composed of country-year observations. Agricultural productivity data and climate variables were collected annually, making each year a key unit for data analysis.

2.2 Data Collection

2.2.1 Instrument of Collecting Data

This study utilizes secondary data obtained from reputable international and national databases to ensure the reliability and accuracy of the analysis. The primary instruments for data collection include FAOSTAT, which provides agricultural productivity data in terms of crop yield measured in tons per hectare; the World Bank's World Development Indicators (WDI), which offer data on economic indicators and CO_2 emissions; and the European Environment Agency (EEA), which supplies climate-related data such as annual average temperature and total precipitation. In addition, data from the national meteorological and statistical agencies of Hungary, Romania, Slovakia, Serbia, and Ukraine were used for validation and further disaggregation to maintain regional specificity. The key variables collected for this study consist of crop yield as the dependent variable, along with annual average temperature (in degrees Celsius), total annual precipitation (in millimeters), and CO_2 emissions (in metric tons per capita). Several control variables were also included, such as fertilizer consumption, agricultural labor, and the percentage of irrigated land. To ensure consistency and comparability across different units and time periods, all data were standardized prior to analysis.

2.2.2 Techniques for Collecting Data

The data collection technique employed in this study was archival research, focusing on obtaining quantitative panel data from official databases. Data were downloaded in spreadsheet form for each country and year from official online portals, then merged and cleaned to ensure uniformity in measurement units and proper handling of missing values. Validation was carried out by cross-referencing multiple sources, such as the European Environment Agency (EEA) and national agencies, to enhance accuracy. Additionally, variables were transformed logarithmically where necessary to correct for skewness and stabilize variance for econometric modeling. To maintain reliability and accuracy, only officially published and peer-reviewed datasets were used, thereby ensuring high data integrity.

2.3 Data Analysis

The collected panel data were analyzed using quantitative econometric techniques through a series of systematic steps. First, descriptive statistics, including mean, standard deviation, minimum, and maximum values, were calculated for all variables. Next, panel unit root tests (Levin-Lin-Chu and Im-Pesaran-Shin) were performed to assess the stationarity of the time-series variables. The Hausman Test was then applied to determine the appropriate model specification, with results supporting the use of Fixed Effects (FE) estimation to control country-specific heterogeneity. Accordingly, a Fixed Effects regression model was employed to estimate the impact of climate variables on crop yield, accounting for time-invariant country characteristics while isolating the effects of changing climate indicators. Robustness was further ensured by applying robust standard errors clustered at the country level to address heteroskedasticity and autocorrelation, as well as testing alternative model specifications with lagged climate variables and different crop types. Finally, graphs and plots were generated to visualize trends in temperature, precipitation, and agricultural productivity over time. The entire analysis was conducted using Stata 17, with Microsoft Excel assisting in data handling and preliminary visualization.

3. Results

3.1 Descriptive Trends

Across the five countries in the Carpathian Basin Hungary, Romania, Slovakia, Serbia, and Ukraine there has been a clear pattern of rising temperatures and fluctuating rainfall. The annual average temperature increased from 9.5°C in 2000 to 11.1°C in 2022, with Hungary and Romania experiencing the steepest warming trends. At the same time, total annual precipitation declined by 8–12% in lowland areas, particularly reducing wheat and maize productivity. While national-level industrial CO_2 emissions decreased due to EU compliance and cleaner energy policies, agriculturerelated emissions from soil tillage and livestock either remained stable or slightly increased. As a result, crop yields displayed greater inter-annual volatility, especially for maize and sunflowers, which proved more sensitive to drought and heatwaves.

3.2 Econometric Model Results

Table 1. The fixed effects regression analysis generated the following statistically significant results

Variable	Coefficient	Std. Error	p-value	Interpretation
Temperature (°C)	-0.927	0.234	0.000	1°C increase → ~0.93 tons/has decrease in crop yield
Precipitation	0.0057	0.0014	0.001	Every additional 100 mm → ~5.7% yield increase
CO_2 Emissions	0.112	0.046	0.017	Slight positive effect (possible CO_2 fertilization)
CO_2 × Temp	-0.072	0.019	0.004	Interaction: high CO_2 + high heat → yield losses
Fertilizer Use	0.013	0.005	0.030	Fertilizer positively affects yield
Irrigated Land	0.008	0.003	0.048	Irrigation helps mitigate climate stress

p < 0.05, **p < 0.01, ***p < 0.001)

The model $R^2 = 0.68$, indicating that 68% of the variation in agricultural productivity is explained by the included variables. The Hausman Test confirmed the appropriateness of the fixed effects model ($\chi^2 = 28.7$, $p < 0.01$).

3.3 Spatial and Crop-Specific Impacts

Further disaggregation by country and crop type revealed notable variations in climate impacts. In Hungary, maize suffered yield losses of up to 15% in the extreme drought years of 2012 and 2022, while winter wheat proved more resilient. Romania showed a strong positive response of barley yields to increased precipitation, yet maize and sunflower remained vulnerable to heat spikes. Slovakia experienced more moderate effects due to relatively stable precipitation, with wheat yields only slightly decreasing in hotter years. By contrast, Serbia and Ukraine displayed the greatest yield variability, largely driven by extreme weather events, where the lack of irrigation infrastructure in rural areas further amplified losses.

3.4 Robustness Checks and Sensitivity Tests

To ensure accuracy and robustness of the results, additional analyses were conducted. Lagged climate variables (t–1, t–2) confirmed that previous years' temperatures had a cumulative negative effect on yield. Crop-specific regressions further revealed that maize and sunflower are highly sensitive to temperature anomalies, whereas wheat and barley respond more strongly to spring precipitation and are less affected by CO_2 changes. Moreover, the exclusion of outlier years such as 2003 and 2012 did not significantly alter the core findings, thereby reinforcing the stability of the model.

3.5 Interpretation and Implications

The econometric evidence clearly supports the hypothesis that climate change has a statistically and economically significant impact on crop productivity in the Carpathian Basin. The negative effect of rising temperatures is especially alarming for summer crops, while the non-linear role of precipitation suggests both droughts and flooding harm productivity.

Moreover, the CO_2 fertilization effect, often assumed beneficial in climate models, is offset when temperatures exceed optimal thresholds, confirming that warming outweighs any photosynthetic gains. These findings are consistent with previous research, including Schlenker and Roberts (2009), who reported declining U.S. crop yields at high temperatures; Lobell et al. (2011), who highlighted the negative impacts of heat stress on global cereal crops; and Olesen and Bindi (2002), who emphasized the vulnerability of Central and Eastern Europe to climate variability. Collectively, these results underscore the urgent need for region-specific climate adaptation policies, such as improved irrigation systems, climate-resilient seed varieties, and early warning systems for weather extremes.

Furthermore, descriptive statistics reveal notable trends across the five countries studied. Hungary, Romania, and Slovakia consistently demonstrated relatively high agricultural productivity, while Serbia and Ukraine showed greater variability in yield outcomes, particularly during drought years. Over the study period, average annual temperatures increased by 1.1–1.6°C across the region, with Hungary experiencing the sharpest warming trend. Precipitation levels fluctuated considerably, with a pattern of decreasing summer rainfall and increasing rainfall during early spring. CO_2 emissions exhibited a general downward trend due to industrial restructuring and increased energy efficiency.

The fixed effects regression model yielded statistically significant results that confirm the impact of climate variables on agricultural productivity. Temperature had a negative and significant coefficient ($p < 0.05$), indicating that increases in average annual temperature were associated with lower crop yields. This supports the hypothesis that heat stress reduces plant photosynthesis and increases evapotranspiration, especially during sensitive growth periods. For every 1°C rise in average temperature, crop yields declined by approximately 0.8 to 1.2 tons per hectare, depending on the crop type.

Precipitation exhibited a positive and statistically significant effect on yield ($p < 0.01$). Specifically, a 100 mm increase in annual precipitation was associated with a 5–7% increase in crop productivity. However, this effect was nonlinear, with excessive rainfall beyond 900 mm per year in some countries leading to soil saturation and delayed planting.

Interestingly, CO_2 emissions were found to have a mixed effect. In the short term, moderate increases in CO_2 concentration had a slightly positive effect on yield due to enhanced photosynthesis (the CO_2 fertilization effect). However, when CO_2 levels were combined with high temperatures, the negative impact on yields intensified. This interaction term was statistically significant ($p < 0.05$), suggesting that the benefits of CO_2 fertilization are offset under conditions of extreme heat.

Control variables such as fertilizer use, irrigated land, and labor availability also showed expected relationships. Fertilizer application was positively correlated with yield increases, while labor availability did not show a statistically significant effect possibly due to mechanization trends in Hungary and Slovakia. Irrigated land share had a modest but positive impact on productivity in Romania and Serbia, where irrigation infrastructure is still expanding.

Sub-national analysis indicated that lowland regions such as the Great Hungarian Plain and southern Romania were more vulnerable to heat and drought stress. In contrast, upland and mountainous regions showed smaller variations in yield due to their cooler microclimates and more stable rainfall patterns. These spatial variations highlight the importance of tailoring adaptation strategies to local agro-ecological contexts.

Overall, the findings demonstrate a clear and statistically significant relationship between climate variables and agricultural productivity in the Carpathian Basin. Rising temperatures and erratic precipitation patterns present growing challenges for regional food security and rural livelihoods. While some adaptive capacity is evident such as increased use of fertilizers and adoption of drought-resistant crops these responses may not be sufficient to counteract long-term climatic trends.

These results reinforce the urgency for proactive climate adaptation strategies, including investments in irrigation infrastructure, climate-smart agriculture, and region-specific policy interventions. They also underscore the need for ongoing research to monitor emerging climate threats and evaluate the effectiveness of mitigation measures in preserving agricultural productivity in this vulnerable European region.

4. Discussion

The findings of this study confirm that climate change has had a statistically significant and regionally differentiated impact on agricultural productivity in the Carpathian Basin over the period 2000–2022. The negative effects of rising temperatures and erratic precipitation patterns are particularly evident, reinforcing concerns expressed in broader global and European agricultural climate studies.

The results align with Jan Alam (2025), who reported that agricultural yields, particularly for temperature-sensitive crops like maize, tend to decline sharply when temperatures exceed critical thresholds. In the Carpathian Basin, our econometric model found that a 1°C increase in average annual temperature reduced crop yields by approximately 0.93 tons per hectare. This supports earlier conclusions that even modest warming trends can have adverse consequences in temperate agro-climatic zones.

The positive relationship between precipitation and productivity observed in the form of a 57% increase in crop yields for every additional 100 mm of annual rainfall mirrors the conclusions of Javadinejad et al. (2021) and Najafi et al. (2019), who emphasized that rainfall variability is one of the most critical factors influencing crop output globally. However, consistent with Timár et al. (2024) findings, our study also reveals that precipitation extremes (both drought and excessive rainfall) can disrupt planting and harvesting cycles, particularly in lowland areas such as the Hungarian Great Plain and southern Romania.

The mixed effects of CO_2 emissions further contribute to an important policy debate. While Liu et al. (2025) and Timár et al. (2024) have documented the potential of elevated atmospheric CO_2 to enhance plant photosynthesis a phenomenon referred to as "CO_2 fertilization" our results suggest that this benefit is negated when elevated CO_2 is accompanied by excessive heat. The interaction term in our regression model, where CO_2 and temperature jointly exacerbate yield declines, aligns with Zhao et al. (2017), who emphasized that heat stress nullifies any positive physiological effects of CO_2 enrichment, especially in cereal crops.

Additionally, our findings regarding the role of adaptation measures such as fertilizer application and irrigation use show that while these strategies can mitigate productivity losses, they may not suffice under intensifying climate pressures. This insight echoes the work of Abebaw (2025) and Kassaye et al. (2022), who argue that without systemic, long-term adaptation strategies including crop diversification, technology transfer, and early warning systems climate resilience in agriculture will remain limited.

Spatially, we found that countries like Hungary and Slovakia, which have relatively stronger institutional capacities and better infrastructure, showed smaller fluctuations in productivity compared to Serbia and Ukraine. This observation supports Sam et al. (2019), who stressed that adaptive capacity is strongly linked to governance quality and economic resilience.

Furthermore, our findings contribute regionally specific knowledge to the body of literature that often generalizes Central and Eastern Europe under broader continental analyses. By disaggregating impacts across five nations and analyzing 23 years of data, this study offers granular insights into the agro-ecological vulnerabilities and adaptation needs of the Carpathian Basin.

Therefore, the discussion highlights five key implications: temperature rise is consistently detrimental, particularly for heat-sensitive crops such as maize and sunflower; rainfall variability necessitates adaptive water management through storage systems, drainage infrastructure, and climate-smart irrigation; CO_2 fertilization cannot be considered a guaranteed benefit when concurrent warming undermines its effects, especially for staple crops; adaptation must extend beyond agricultural inputs to include structural reforms, innovation, and climate risk governance; and finally, regional cooperation across Carpathian Basin countries is essential for knowledge-sharing, resource mobilization, and harmonization of climate-smart policies. Collectively, these conclusions underscore the urgent need for policymakers, researchers, and agricultural stakeholders to collaborate across borders in implementing adaptive strategies that are ecologically sustainable, economically viable, and socially inclusive.

5. Conclusion

This study provides robust empirical evidence that climate change has had a significant and regionally variable impact on agricultural productivity in the Carpathian Basin from 2000 to 2022. Using an econometric approach grounded in panel data analysis, the findings reveal that rising temperatures, shifting precipitation patterns, and interactions with atmospheric CO_2 levels have measurably influenced crop yields in the region. The results clearly demonstrate that temperature increases are detrimental to agricultural output, particularly for heat-sensitive crops such as maize and sunflower, where a 1°C rise in average annual temperature corresponds with substantial yield reductions. Conversely, precipitation generally exerts a positive influence on productivity, although its benefits are conditional and nonlinear; while moderate increases can enhance yields, extreme fluctuations such as droughts or excessive rainfall undermine planting schedules, soil health, and harvest efficiency. Similarly, the study contributes to the nuanced debate on CO_2 fertilization by showing that while elevated carbon dioxide can stimulate plant growth under ideal conditions, these gains are largely offset when combined with rising temperatures. Adaptation measures, including fertilizer use, irrigation, and improved technology, offer partial mitigation, but remain insufficient without broader structural reforms and policy innovations.

The implications of this research are significant for both theory and practice. By disaggregating data across Hungary, Romania, Slovakia, Serbia, and Ukraine, the study highlights country-specific vulnerabilities and adaptive capacities, with Hungary and Slovakia demonstrating greater resilience due to stronger governance and infrastructure. This underscores the need for region-specific adaptation strategies that recognize differing socio-economic and institutional contexts. For policymakers, the findings call for urgent investments in climate-resilient infrastructure, crop breeding innovation, and knowledge transfer systems, alongside early warning mechanisms for weather extremes. For researchers, the study emphasizes the importance of integrating econometric evidence with climate science to refine predictions of agricultural risk. Finally, for agricultural stakeholders, the evidence points toward the necessity of cross-border cooperation to harmonize policies and share resources. Collectively, these implications stress that only proactive, inclusive, and science-informed action will enable the Carpathian Basin to safeguard food security and maintain agricultural productivity in the face of accelerating climate change.

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