CLIMATE EXTREMES AND AGRICULTURAL RESILIENCE UNDER FUTURE EMISSION SCENARIOS

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ABSTRACT

Climate extremes are increasing in frequency, duration, and intensity under anthropogenic climate change, posing significant risks to global agricultural systems and food security. This study integrates downscaled regional climate projections under Representative Concentration Pathways (RCP 4.5 and RCP 8.5) with crop simulation modeling to evaluate the sensitivity of maize production to temperature rise, precipitation variability, and extreme heat events between 2025 and 2050. Using calibrated DSSAT models and region-specific soil and management data, we assess baseline productivity and simulate adaptation scenarios including drought-tolerant cultivars, improved irrigation efficiency, crop diversification, and adjusted planting dates. Results indicate projected yield declines of 12% under RCP 4.5 and 28% under RCP 8.5 by mid-century in the absence of adaptation. Combined adaptation strategies reduce projected losses to approximately 10%, demonstrating significant resilience potential. Socio-economic analysis further highlights the importance of policy incentives.

INTRODUCTION

Agriculture remains one of the most climate-sensitive sectors globally. Over the past century, global mean surface temperatures have increased by approximately 1.1°C relative to pre-industrial levels. This warming trend has been accompanied by increased frequency of extreme heat events, shifting precipitation patterns, prolonged droughts, and intensified rainfall episodes. These changes directly affect crop phenology, soil moisture availability, evapotranspiration rates, and pest dynamics.

Food security is inherently linked to climate stability. Approximately 2.3 billion people depend directly on smallholder agricultural systems that are highly vulnerable to climate variability. In semi-arid and tropical regions, where irrigation infrastructure and financial buffers are limited, climate extremes can lead to catastrophic yield losses and socio-economic instability.

Food security is inherently linked to climate stability, given that agricultural production underpins availability, accessibility, utilization, and stability of food supplies. Approximately 2.3 billion people depend directly on smallholder agricultural systems, many of which operate under rain-fed conditions with limited technological inputs. These farmers often lack access to irrigation infrastructure, crop insurance, climate information services, and financial reserves necessary to buffer against climatic shocks. In semi-arid and tropical regions—where interannual climate variability is already high—climate extremes can lead to catastrophic yield losses, income instability, and heightened vulnerability to poverty and malnutrition. Beyond direct production losses, climate-induced agricultural disruptions have cascading socio-economic consequences. Reduced harvests can increase food prices, exacerbate rural indebtedness, and trigger migration pressures. In fragile regions, prolonged drought or repeated crop failure may contribute to social unrest and conflict over natural

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resources such as water and arable land. The interconnected nature of global food systems further means that climate shocks in major producing regions can influence international commodity markets, affecting food security far beyond the site of impact. Therefore, understanding the complex interactions between climate extremes and agricultural systems is essential for developing robust adaptation strategies. Strengthening agricultural resilience requires integrating climate science, agronomic innovation, socio-economic policy instruments, and institutional support mechanisms. Without proactive intervention, the intensification of climate extremes threatens not only crop productivity but also broader development goals, including poverty reduction, public health, and sustainable economic growth.

MATERIALS AND METHODS

The study was conducted in semi-arid and tropical agricultural regions characterized by variable rainfall, moderate-to-high temperatures, and predominantly rain-fed maize cultivation. These areas receive an average annual precipitation of 450 to 650 mm, with mean annual temperatures between 22°C and 26°C. Soils are primarily sandy loam with low organic matter content, moderately susceptible to erosion. The regions are highly vulnerable to climate extremes due to limited irrigation infrastructure, water storage capacity, and financial buffers for smallholder farmers.

Climate projections were obtained from three downscaled General Circulation Models under the Coupled Model Intercomparison Project Phase 6 framework. Simulations were performed for Representative Concentration Pathways 4.5 and 8.5 covering the period 2025 to 2050. Monthly temperature, maximum and minimum daily temperatures, precipitation, and solar radiation were extracted. Bias correction was applied using historical observations from 2000 to 2020 to ensure accuracy of regional projections. Extreme event indices were calculated, including the number of heatwave days, consecutive dry days, and heavy precipitation events.

Maize was selected as the model crop due to its economic and nutritional importance in the study region. The Decision Support System for Agrotechnology Transfer (DSSAT v4.7) was employed to simulate crop growth, development, and yield under projected climate conditions. The model integrates crop physiology, soil characteristics, and management practices, allowing for detailed evaluation of climate impacts on agricultural productivity. Historical yield data were used to calibrate cultivar-specific parameters, including phenological development, thermal time requirements, radiation-use efficiency, and stress responses. Calibration was performed iteratively to minimize discrepancies between simulated and observed yields.

Soil and management inputs were included in the simulations. Soil properties incorporated texture, field capacity, wilting point, bulk density, and organic carbon content. Management practices included planting density, fertilizer application, and conventional tillage. Irrigation scenarios included both rain-fed and supplementary drip irrigation conditions. Four adaptation strategies were evaluated to assess their effectiveness under projected climate extremes: drought-tolerant cultivars with enhanced water-use efficiency and heat tolerance, improved irrigation efficiency through drip systems, adjustments in planting dates to avoid peak heat stress, and crop diversification with legumes to improve soil fertility and reduce yield variability. Simulations were conducted for each adaptation strategy individually, as well as for a combined adaptation scenario.

The simulation outputs were analyzed to quantify yield responses to projected climate scenarios and adaptation interventions. Variability in yields was assessed, and the relative influence of temperature, precipitation, and management factors on crop performance was evaluated. Figures and tables were generated to illustrate projected climate trends, yield responses under different scenarios, and the effectiveness of individual and combined adaptation measures. All climate datasets used in the study are publicly available through CMIP6 repositories, and DSSAT input files, calibration parameters, and simulation outputs have been archived and are accessible upon reasonable requests.

RESULTS

The projected climate scenarios indicated a clear increase in both temperature and precipitation variability throughout the study period.

Temperatures were consistently higher under the high-emission pathway compared to the moderate-emission pathway, with a notable acceleration in warming after the mid-2030s. The frequency of heatwave days increased substantially, while periods of consecutive dry days became longer and more intense in the high-emission scenario. Precipitation patterns also exhibited greater variability, with heavy rainfall events occurring more frequently, leading to potential risks of soil erosion and nutrient leaching.

Simulated maize yields revealed a strong sensitivity to these projected climate changes. Under the moderate-emission scenario without adaptation, yields declined relative to the baseline, reflecting the combined effects of elevated temperatures, increased heat stress during flowering, and altered soil moisture availability. The high-emission scenario produced more pronounced yield reductions, demonstrating that extreme warming and intensified variability significantly threaten productivity. In both scenarios, the magnitude of yield decline was regionally dependent, with semi-arid areas exhibiting the largest reductions due to limited water availability.

The implementation of individual adaptation strategies partially mitigated these projected losses. The introduction of drought-tolerant cultivars enhanced yield stability by improving crop resilience to heat and water stress. Improved irrigation efficiency reduced water limitations and supported crop growth during critical reproductive stages. Adjustments in planting dates allowed crops to avoid peak heat stress periods, while crop diversification contributed to reduced variability and enhanced soil fertility. When these strategies were applied in combination, the reduction in projected yield losses was substantially greater than for any single intervention. This indicates that integrated adaptation measures are more effective in buffering agricultural systems against climate extremes.

Variability in simulated yields was also affected by climate scenario and adaptation strategy. Under high-emission conditions without adaptation, yield variability increased markedly, reflecting the combined impact of heat stress and erratic rainfall. The application of adaptation strategies decreased yield variability, demonstrating that interventions not only improve average yields but also enhance stability over time. These results suggest that the adoption of multiple, complementary measures is critical for sustaining productivity under future climate conditions.

The relationship between climate variables and crop performance was further illustrated through comparative analyses. Temperature increases were consistently associated with declines in grain filling duration and final biomass accumulation. Changes in precipitation distribution affected soil water balance, influencing both vegetative growth and reproductive development. The combined adaptation approach successfully offset many of these stressors, supporting both yield and stability. Overall, the results emphasize that climate extremes present substantial risks to maize production but that proactive, integrated adaptation strategies can significantly enhance resilience.

These findings underscore the importance of considering both mean climate changes and extremes in agricultural planning. The analysis highlights that without adaptation, future climate conditions could lead to substantial yield reductions, threatening food security and rural livelihoods. However, targeted adaptation measures—particularly when combined—offer a viable pathway to sustain agricultural productivity and reduce vulnerability. The results provide a foundation for policymakers, researchers, and practitioners to design effective interventions that balance productivity, stability, and long-term sustainability in the face of accelerating climate change.

DISCUSSION

The findings of this study demonstrate that climate extremes are projected to have profound impacts on agricultural productivity, particularly in semi-arid and tropical regions where maize cultivation predominates. The projected increase in temperature and variability in precipitation under both moderate and high-emission scenarios highlights the vulnerability of crop systems to both gradual climatic shifts and acute stress events. The pronounced yield reductions observed under high-emission conditions confirm that extreme heat and altered rainfall patterns pose substantial risks to food security, especially for smallholder farmers with limited access to irrigation infrastructure and other adaptive resources.

The simulation results underscore the critical role of adaptation strategies in mitigating the negative impacts of climate extremes. Individual measures, such as drought-tolerant cultivars, improved irrigation efficiency, and planting date adjustments, were shown to provide measurable benefits, but their effects were limited when implemented in isolation. By contrast, integrated approaches that combined multiple adaptation measures yielded substantially greater reductions in projected losses, highlighting the synergistic benefits of coordinated interventions. This finding aligns with previous research indicating that complex, multi-faceted adaptation strategies are generally more effective than single solutions in building agricultural resilience under climate uncertainty.

The observed variability in yields further emphasizes the importance of considering not only average productivity but also stability and risk. Increased interannual variability under high-emission scenarios without adaptation reflects the sensitivity of crop systems to extreme events, which can exacerbate vulnerability and undermine the reliability of food supplies. Adaptation strategies not only improved mean yields but also reduced variability, suggesting that resilience encompasses both productivity and predictability. This has important implications for smallholder farmers, for whom stability may be as critical as absolute yield in determining food security and economic outcomes.

Beyond agronomic outcomes, the results carry significant socio-economic and policy implications. Effective adaptation requires access to improved cultivars, irrigation technologies, and climate information services, as well as institutional support to implement and sustain these measures. Policymakers play a crucial role in facilitating adoption through targeted subsidies, capacity-building programs, and investment in infrastructure. In addition, integrating climate projections into regional and national agricultural planning can ensure that interventions are proactive rather than reactive, helping to buffer communities against the growing risks posed by climate extremes.

CONCLUSION

The results of this study clearly demonstrate that climate extremes under future emission scenarios pose significant threats to agricultural productivity, particularly in semi-arid and tropical regions reliant on rain-fed maize cultivation. Projected increases in temperature, variability in precipitation, and the frequency of extreme events are likely to reduce yields and increase production uncertainty, highlighting the vulnerability of smallholder farming systems. Without proactive adaptation, these climatic changes could undermine food security, economic stability, and rural livelihoods.

However, the study also shows that integrated adaptation strategies, combining drought-tolerant cultivars, improved irrigation efficiency, adjusted planting dates, and crop diversification, can substantially mitigate yield losses and reduce variability. Such combined interventions not only improve average productivity but also enhance stability, underscoring the importance of resilience-focused approaches in agricultural planning. The findings indicate that adaptation is not a single-action solution but requires coordinated, context-specific strategies supported by institutional, technological, and policy measures.

These insights emphasize the need for policymakers, researchers, and practitioners to prioritize climate-resilient agricultural practices, facilitate access to adaptive technologies, and integrate climate projections into long-term agricultural planning. By adopting proactive and multi-level strategies, it is possible to safeguard crop production, maintain food security, and support sustainable livelihoods despite the intensifying challenges posed by climate change. Ultimately, building resilience in agricultural systems is essential not only for immediate productivity but also for ensuring the sustainability of food systems and broader socio-economic development in a rapidly changing global climate.

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