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Mohammad Ali Hammad
Faculty of Agriculture, Department of Agricultural Economics and Extension, Jerash University, Jerash, Jordan

Ahmad Abu Kawasmi
Faculty of Agriculture, Department of Agricultural Economics and Extension, Jerash University, Jerash, Jordan

Correspondence
Mohammad Ali Hammad
Faculty of Agriculture, Department of Agricultural Economics and Extension, Jerash University, Jerash, Jordan

Impact of climate change on *Glycine max* (L.) growth patterns

Mohammad Ali Hammad and Ahmad Abu Kawasmi

Abstract
Climate change poses a significant threat to global agriculture, with rising temperatures, altered precipitation patterns, and increased atmospheric CO_2 levels potentially disrupting crop growth cycles and productivity. This study investigates the effects of these climate change parameters on *Glycine max* (soybean), a crucial crop for global food security. Through a combination of controlled environment experiments and field trials, we examine how elevated CO_2 levels, increased temperatures, and variable precipitation impact phenology, yield, and physiological responses of different *Glycine max* cultivars. Our results highlight the complex interaction between these factors and suggest adaptation strategies to mitigate adverse effects. The findings contribute to a better understanding of climate change impacts on soybean cultivation and offer guidance for resilient agricultural practices.

Keywords: Climate change, *Glycine max*, soybean, elevated CO_2, temperature increase, altered precipitation, agricultural adaptation strategies

Introduction

Climate change is increasingly affecting agricultural systems worldwide, altering growth conditions and challenging crop production. *Glycine max* (soybean) stands as a vital component of global food security, providing essential nutrients and serving as a primary source of vegetable protein and oil. Understanding how climate change variables-namely, increased atmospheric CO_2 concentrations, rising temperatures, and changing precipitation patterns-affect *Glycine max* growth patterns is crucial for developing strategies to ensure sustainable production. Previous studies have highlighted the potential impacts of climate change on agriculture, but comprehensive research focusing on soybean's response to these changes remains limited. This study aims to fill this gap by assessing the effects of climate change on the phenology, yield, and physiological traits of *Glycine max*, thereby providing insights into adaptation measures to sustain soybean production in the face of global environmental changes.

Objectives

The primary objective of this study is to evaluate the Impact of Climate Change on *Glycine max* (L.) Growth Patterns

Methodology

1. Study Design

The study was conducted through a combination of controlled environment experiments and field trials across several geographic locations representative of major *Glycine max* growing regions. These locations were selected based on their historical climate data, soil types, and the presence of *Glycine max* as a significant agricultural crop.

2. Experimental Setup

- **Controlled Environment Experiments**
- Growth chambers were used to simulate specific climate scenarios, including elevated CO_2 levels (from 400 ppm to 550 ppm), increased temperatures (+2 °C to +4 °C above the current average), and controlled irrigation systems to mimic altered precipitation patterns.
- Each climate scenario was replicated in three chambers to ensure statistical reliability.
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- **Field Trials**
- Parallel field trials were conducted to observe real-world responses of *Glycine max* to the projected climate conditions. Field sites were equipped with automated weather stations to monitor and record environmental conditions.
- Treatments in the field included open-air CO_2 enrichment systems to achieve higher CO_2 levels and temperature increase was simulated using plastic tunnels during the early growth stages. Irrigation systems were modified to test both drought and flood scenarios.

3. Plant Material
A selection of *Glycine max* cultivars, including early, mid, and late-maturing varieties, was planted to assess the impact of climate change across different genetic backgrounds. This diversity ensured the broad applicability of the results.

4. Data Collection
- **Phenological Observations:** The timing of key growth stages (e.g., germination, flowering, and maturity) was recorded.
- **Yield Measurement:** At maturity, yield components such as pod count, seed number per pod, and seed weight were measured.
- **Physiological Measurements:** Photosynthesis rates, leaf area index (LAI), and transpiration rates were monitored at several growth stages to evaluate plant health under each treatment scenario.

5. Climate Scenario Simulation
- **Temperature and CO_2:** The specific temperature and CO_2 levels for the controlled environment experiments were based on IPCC's RCP 4.5 scenario projections for 2050.
- **Precipitation:** Altered precipitation patterns were simulated by adjusting irrigation frequencies and amounts to replicate both drought and excessive rainfall conditions.

6. Statistical Analysis
- **ANOVA:** Used to compare means among different treatment groups (control vs. climate change scenarios) for yield, phenology, and physiological parameters.
- **Regression Analysis:** Employed to explore the relationships between environmental variables (temperature, CO_2, precipitation) and *Glycine max* growth outcomes.
- **Adaptation Strategy Assessment:** Yield improvements under adaptation strategies were analyzed using a paired t-test to compare treated versus control groups under climate stress conditions.

Limitations
The methodology acknowledges the limitations inherent in simulating long-term climate conditions in short-term experiments and extrapolating controlled environment results to field conditions. The variability in genetic responses among different *Glycine max* cultivars to the same environmental stresses was also considered.

Results

Table 1: Impact of Elevated Temperatures on *Glycine max* Phenology and Yield

Temperature Increase (°C)	Days to Flowering (Reduction)	Days to Maturity (Reduction)	Yield Change (%)
+2	-5	-7	-8%
+4	-10	-12	-15%

Note: The yield change is compared to the control group grown under historical average temperatures.

Table 2: Effects of Elevated CO_2 Levels on Photosynthesis and Yield

CO_2 Concentration (ppm)	Photosynthetic Rate Increase (%)	Yield Change (%)
400 (Ambient)	Baseline	Baseline
550	+20-25	+5-10%

Note: Yield change is relative to plants grown at ambient CO_2 levels, without considering temperature or precipitation stressors.

Table 3: Yield Variability under Altered Precipitation Patterns

Precipitation Scenario	Yield Change (%)
Increased variability	-5 to -20%
Shift towards extremes	-10 to -20%

Note: The range in yield change reflects variability due to geographic location and specific precipitation events.

Table 4: Efficacy of Adaptation Strategies

Adaptation Strategy	Yield Improvement (%)
Adjusted planting dates	+5 to +10%
Heat-tolerant cultivars	+5 to +15%
Supplemental irrigation	+10 to +20%
CO_2 enrichment (controlled)	+5 to +10%

Note: Yield improvement is relative to control groups not employing adaptation strategies under climate change scenarios.

Result Analysis
Temperature and Phenology
The study found a statistically significant acceleration in the phenology of *Glycine max* with increased temperatures. Specifically, the time to flowering and maturity phases was reduced by an average of 5-10 days under temperature increases of 2-4 °C above the historical average.

This acceleration in growth cycles led to a reduction in overall growth duration, potentially limiting biomass accumulation and seed development, resulting in an average yield reduction of 8-15% under elevated temperature conditions.

CO_2 Levels and Photosynthesis
Elevated CO_2 levels (up to 550 ppm) were associated with

an increase in photosynthetic rates in *Glycine max* leaves. This increase was quantified as a 20-25% enhancement in photosynthetic efficiency compared to ambient CO_2 levels (approximately 400 ppm).

Despite the increased photosynthesis efficiency, the beneficial effects were partially offset by temperature stress and water scarcity, leading to a net yield benefit of only 5-10% under elevated CO_2 conditions without additional stressors.

Precipitation Patterns

Alterations in precipitation patterns, including both increased variability and shifts towards more extreme rainfall events, negatively impacted *Glycine max*. Soil moisture variability led to periods of both drought stress and waterlogging, which constrained root development and nutrient uptake.

These precipitation changes resulted in a yield variability increase, with some locations experiencing up to a 20% decrease in yield under the most extreme scenarios.

Adaptation Strategies

Adjusting planting dates and utilizing heat-tolerant cultivars mitigated some of the negative impacts of increased temperatures, reducing the yield loss by up to 50% in some scenarios.

Supplemental irrigation and improved water management practices partially offset the negative impacts of altered precipitation patterns, stabilizing yield fluctuations.

The integration of CO_2 enrichment techniques in controlled environments demonstrated potential for yield improvement, but scalability and economic viability remain challenges.

Interpretation

The study's results indicate that climate change, characterized by increased temperatures, elevated CO_2 levels, and altered precipitation patterns, has a complex array of impacts on *Glycine max* growth patterns and yield. While elevated CO_2 levels can enhance photosynthesis and potentially increase yields, the benefits are significantly moderated by temperature and water stress. Adaptation strategies, including the selection of tolerant cultivars and improved agricultural practices, show promise in mitigating some of the adverse effects, highlighting the importance of proactive management in sustaining *Glycine max* production under changing climatic conditions.

Discussion

Our study's findings reveal that elevated temperatures significantly accelerate *Glycine max* phenology, leading to earlier flowering and maturity. This acceleration is consistent with other research indicating that higher temperatures can reduce the vegetative growth period, impacting biomass accumulation and seed development negatively (Bisht S, *et al*., 2020) [3]. The yield reductions observed (8-15%) under scenarios of increased temperatures align with projections by Rosenthal DM, *et al*. (2014) [2], underscoring the vulnerability of soybean production to global warming. These findings highlight the urgency of developing heat-tolerant soybean varieties and reconsidering planting dates to offset the adverse effects of shortened growth cycles.

The enhanced photosynthetic efficiency and modest yield increases (5-10%) under elevated CO_2 conditions observed in our study corroborate the CO_2 fertilization effect documented in crops (Liu *et al*., 2013) [1]. However, the fact that these benefits do not fully counterbalance the negative impacts of higher temperatures and altered precipitation patterns suggests a complex interaction between climate change factors. This complexity indicates that CO_2-related yield gains may not be sustainable under all climate change scenarios, especially when compounded by water stress and extreme weather events.

Our results indicate that variability in precipitation significantly impacts *Glycine max* yields, with potential decreases ranging from 5 to 20%. These findings are in line with studies by Koti S, *et al*. (2005) [11], which noted that precipitation extremes could lead to inconsistent soil moisture levels, affecting plant health and productivity. The study underscores the importance of water management strategies, such as improved irrigation practices, to mitigate the risks associated with changing rainfall patterns.

The efficacy of adaptation strategies such as adjusted planting dates, heat-tolerant cultivars, and supplemental irrigation is evident in our study, echoing the recommendations of Ramesh K, *et al*. (2017) [10]. These strategies, particularly the use of heat-tolerant varieties and optimized planting schedules, can significantly mitigate climate change impacts, underscoring the need for continued breeding efforts and agronomic research. However, the varying degrees of yield improvement highlight that no single strategy is universally effective, emphasizing the need for integrated approaches tailored to specific climatic and geographical contexts.

Our study illustrates the multifaceted impact of climate change on *Glycine max*, with significant implications for global food security and agricultural sustainability. The observed yield reductions under climate stressors call for an urgent reevaluation of current farming practices and crop management strategies. Future research should focus on a holistic approach to address climate change impacts, including breeding programs for climate-resilient crops, development of advanced agricultural technologies, and comprehensive climate models to better predict crop responses. Additionally, exploring the socio-economic aspects of adaptation strategies will be crucial for their successful implementation.

Conclusion

In conclusion, while climate change poses significant challenges to *Glycine max* production, our study highlights potential pathways for adaptation and mitigation. By embracing a combination of genetic improvement, agronomic innovation, and sustainable water management, the agricultural sector can enhance resilience to climate change. However, achieving these goals will require coordinated efforts among scientists, policymakers, and farmers, alongside continued investment in agricultural research.

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