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RESEARCH ARTICLE

MODELING THE EFFECTS OF ELEVATED TEMPERATURE ON SORGHUM YIELD: INSIGHTS INTO CLIMATE RESILIENCE AND CROP PRODUCTIVITY

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ABSTRACT

This study investigates the impact of elevated temperatures on sorghum yield across different growth stages using the DSSAT-CERES crop simulation model. Two sorghum varieties, CO 30 and K 12, were examined under three climate variability scenarios. The flowering stage was identified as the most sensitive, with grain yield reductions of 12.3% and fodder yield reductions of 8.96%. The reproductive and vegetative stages showed lower but significant impacts. CO 30 exhibited higher sensitivity to temperature stress compared to K 12. The study revealed that increased CO2 concentrations slightly mitigated yield losses, but this effect was nullified by rising temperatures. High-temperature stress during flowering was associated with reduced pollen viability and increased sterility, while stress during grain filling led to decreased individual grain weight and lower grain filling percentage. These findings underscore the need for developing heat-tolerant sorghum varieties and implementing adaptive agricultural strategies to ensure food security in the face of climate change.

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INTRODUCTION

The agricultural sector is facing an unprecedented challenge as climate variability increasingly disrupts crop production, threatening food security worldwide. Crop yields are sensitive to fluctuating weather patterns, and as such, the ability to predict and mitigate the effects of climate variations on key crops is crucial for food security and agricultural planning. In the semi-arid and arid regions of Tamil Nadu, sorghum stands as a vital crop, serving as a cornerstone for food, feed, and fuel. It is particularly significant in regions with semi-arid and arid climates, where other crops may not be able to grow due to limited rainfall and harsh environmental conditions. However, sorghum production is vulnerable to climate variability, which can lead to reduced yields, crop failures, and food insecurity (*Sharma et al.* 2019). Yet, the stability of sorghum yields is jeopardized by the erratic patterns of climate, including shifts in temperature, rainfall, and extreme weather events. These climatic aberrations not only affect the overall yield but also influence various growth stages of the crop, from vegetative to reproductive phases. The intricate relationship between sorghum's phenological responses and the capricious nature of climate variability necessitates a comprehensive understanding to devise adaptive strategies that can safeguard this essential crop against the vagaries of changing weather patterns. Climate Variability refers to the variations in the mean state and other statistics of the climate on all temporal and spatial scales beyond individual weather events. It encompasses short-term fluctuations, such as seasonal changes, and long-term variations, including interannual and decadal shifts. These fluctuations can significantly affect agricultural productivity, particularly for crops like sorghum, which are sensitive to changes in temperature, precipitation, and other climatic factors. In recent years, climate variability has become more pronounced and has had a significant impact on agriculture, particularly in vulnerable regions. Climate variability affects sorghum production by altering rainfall patterns, increasing the frequency and intensity of extreme weather events like droughts and floods, and changing temperature regimes. These changes can impact the growth and development of sorghum plants, affecting their yield, quality, and susceptibility to pests and diseases (*Grossi et al.* 2015). Understanding the impacts of climate variability is crucial for developing resilient agricultural practices and ensuring food security. Sorghum, being a staple crop in many regions, is particularly vulnerable to climatic fluctuations.

Variability in climate parameters, such as temperature extremes, can affect critical growth stages of the sorghum plant, leading to substantial yield reductions. This study aims to fill this gap by utilizing crop modeling to assess the effects of different temperature extremes, a key aspect of climate variability, on sorghum yields. By focusing on temperature variability, this research will provide insights into how future fluctuations in climate conditions could impact sorghum production (*Wang et al.* 2021; *Dzotsi et al*. 2013)., thereby contributing to the broader understanding of climate risks in agriculture. These findings will be critical for informing adaptive strategies that can mitigate the adverse effects of climate variability on crop yields, ensuring the sustainability of sorghum production in the face of increasingly variable climatic conditions. The findings are poised to inform and guide agricultural practices, policy-making, and the development of climate-resilient sorghum cultivars, thereby contributing to the sustainability of agricultural systems in the face of climate variability**.**

MATERIALS AND METHODS

The field experiment was conducted in Eastern block farm (Field No 37 F) of TNAU, Coimbatore. The experimental field is located at latitude 110N & longitude 77 0E. The mean altitude of 426.7 m above the mean sea level (MSL). Coimbatore districts falls was under the western agro climatic zone of Tamil Nadu. The field experiment was laidoutinsplitplotdesign with the treatments involving three dates of sowing andthree nitrogen levels replicated thrice. In general, the rainfed sorghum farmers choose 38th SMW to 39th SMW as highly suitable sowing window for sorghum. Hence, first sowing was taken on 15th September, secondsowingon30th September and third date of sowing on 15th October during the year 2019. Based on the Soil Test Crop Response (STCR) reports four (0, 75, 100 and 125%) nitrogen fertilizertreatmentlevel was fixed.

Inputs for the model: Daily weather data, including rainfall, solar radiation, and temperature, was collected from Agro Climate Research Centre, Coimbatore, and formatted using the Weatherman tool for DSSAT. The experimental field's soil, characterized as sandy clay loam, was analyzed for properties such as pH and nutrient content before sowing to create a DSSAT soil profile. The study utilized two major sorghum varieties, CO 30 and K 12, with calibration and validation performed using field trial data from the Agro Climate Research Centre, and genetic coefficients derived using the GENCALC tool in DSSAT.

Crop simulation model: The impact of climate change on sorghum productivity over Tamil Nadu was analyzed by simulating yield in the CERES module with projected climate data in Decision Support System for Agro Technology Transfer (DSSAT). The model consists of several modules incorporating the driver software, a module of land units and primary modules for components of the interface between weather, management, soil, farm, and soil-plant-atmosphere.

Genetic co efficient: The genetic coefficients for the sorghum cultivars CO 30 and K 1 2 used in this study were obtained from the research by Praveenkumar*et al*. 2024. This study provides detailed genetic coefficients essential for evaluating the cultivars' responses to climate change and their adaptation strategies. These coefficients are fundamental for analysing the performance of sorghum under various climate scenarios. They provide essential insights into the potential yield responses and adaptation strategies of these cultivars, thereby significantly enhancing the accuracy and depth of our analysis.

Sensitivity analysis: Extreme weather and climate events are characterized by their statistical rarity and typically fall outside the range of usual weather patterns. The World Meteorological Organization (WMO) defines temperature extremes as instances where temperatures are significantly higher or lower than the historical averages for a specific region and time of year. In our study, we define temperature extremes by analyzing the average temperatures over the past 30 years. We then incrementally increase these temperatures by +1°C, +2°C, and +3°C to represent different hypothetical climate conditions. Sensitivity analysis is a fundamental tool for supporting mathematical model and used to assess the variation in the output of a model that can be apportioned to different sources perturbing input (*Corbeels et al*. 2016). DSSATSens is a sensitivity analysis tool that allows a user to check the sensitivity of the model to changes in input parameters. In a standard sensitivity analysis all inputs are kept the same except for one or two inputs that are changed at a fixed interval from a starting to an ending value. Sensitivity of CERES –Sorghum was made using systemic changes in weather variables like maximum and minimum temperature, CO2 concentrations. In DSSAT-CERES model environmental modification was done with vegetative, flowering and reproductive stages.

The different climate variability is,

V1 - T max +1 ˚C, T min +1.5 ˚C and + 50 ppm of CO_2
V2 - T max +2 ˚C, T min +2.5 ˚C and +100 ppm of CO_2
V3 - T max +3 ˚C, T min +3.5 ˚C and +150 ppm of CO_2

RESULTS AND DISUSSION

Effect of climate variability on Vegetative stage: The vegetative stage marks the initial phase of crop growth, where plants develop their leaves and roots, establishing the foundation for future growth. The impact of climate variability during this stage can set the trajectory for the crop's overall health and productivity. The increase in CO_2 concentration might be favours the growth, physiology and biochemical processes including increase in net photosynthesis. The minimal increase in photosynthetic activity was due to the positive yield response of sorghum at increased carbon dioxide condition. The positive effect of the CO_2 increase was weakened by rise of temperature (Chatterjee *et al.*1998) only 0.5 per cent yield increase due to + 50 ppm CO_2 more than ambient. This was nullified when the temperature increased by 0.08 °C. Similarly, the small beneficial effect of still higher CO_2 concentrations was nullified by further increase in temperature. The beneficial effect of 700 ppm CO2 was nullified by an increase of only 0.9 °C in temperature. The grain yield of CO 30 decreases as climate variability exposed during vegetative stage are presented in table 2. The most severe impact is seen in scenario V3, indicating that higher climate variability leads to significant reductions in grain yield (*Singaravadivel et al.* 2018). Similar to CO 30, K 12 also experiences a decline in grain yield with increasing climate variability. However, the initial impact (V1) is less decline compared to CO 30, but V3, the reduction is substantial.

Table 1. Genetic co efficient of CO 30 and K 12

Parameters	P1	P2	P2O	P2R	PANTH	P3	P4	P5	PHINT	G1	G2
CO 30	410	92	12	90	513	133.5	83	410	54	4	6.062
K 12	390	88	11.7	88	480.5	130	75.5	380	60	4.3	5.2

Table 2. Yield Responses of Sorghum Cultivars Under Climate Variability Scenarios During the Vegetative Stage

Stage	Climate Variability Scenario	Grainyield		Fodderyield	
		CO 30	K 12	CO 30	K 12
Vegetative	V1	-1.3	-0.16	-0.65	-3.86
	V2	-1.8	-1.09	-1.77	-4.39
	V3	-2.7	-2.37	-2.61	-4.57

Table 3. Yield Responses of Sorghum Cultivars Under Climate Variability Scenarios During the Flowering Stage

Stage	Climate Variability Scenario	Grainyield		Fodderyield	
		CO 30	K 12	CO 30	K 12
Flowering	V1	-5.8	-1.94	-2.02	-6.47
	V2	-8.1	-3.31	-2.58	-7.08
	V3	-12.3	-6.2	-5.01	-8.96

Table 4. Yield Responses of Sorghum Cultivars Under Climate Variability Scenarios During the Reproductive Stage

Stage	Climate Variability Scenario	Grain yield		Fodder yield	
		CO 30	K 12	CO 30	K 12
Reproductive	V1	-4.5	-0.9	-0.99	-4.49
	V2	-5	-2.5	-2.2	-4.7
	V3	-5.9	-4.06	-4.4	-5.67

Fodder yield for CO 30 also decreases with increasing climate variability. The trend suggests a progressive worsening in yield, with V3 showing the greatest negative impact. The fodder yield for K 12 is significantly impacted under all scenarios, with the highest reduction occurring in V1 and continuing to worsen slightly in V2 and V3. Climate Variability Scenarios (V1, V2, V3) represent different levels of climate variability, with V3 likely indicating the most extreme scenario. The grain Yield both crop varieties (CO 30 and K 12) show a decrease in grain yield as climate variability increases, with CO 30 being more sensitive initially. The fodder yield both varieties show a reduction in fodder yield, with K 12 experiencing a larger initial impact compared to CO 30.

Effect of climate variability on Flowering stage: The flowering stage is critical for pollination and the formation of seeds. Any stress during this stage can severely impact crop yields. The grain yield of CO 30 shows a significant decrease with increasing climate variability during the flowering stage are illustrated in table 3. The reduction is more pronounced compared to the vegetative stage, indicating that the flowering stage is highly sensitive to climatic stress.Similar to CO 30, K 12 also experiences a decrease in grain yield during the flowering stage with increasing climate variability (*Chen et al.* 2016). However, the reductions are less severe than CO 30 initially, but the gap closes at higher levels of variability (V3).

The fodder yield for CO 30 also decreases significantly with increasing climate variability during the flowering stage. The reductions are more severe compared to the vegetative stage.The fodder yield for K 12 shows substantial reductions under all scenarios, with the most significant impact occurring in V3. This suggests a high sensitivity to climate variability during the flowering stage*Gourdji et al*. 2015). Both CO 30 and K 12 show significant reductions in grain yield during the flowering stage with increasing climate variability. The reductions are more pronounced compared to the vegetative stage, indicating higher sensitivity during flowering.

Fodder yield for the both varieties also exhibit substantial decreases in fodder yield, with K 12 showing the most severe reductions under all scenarios.

Effect of climate variability on Reproduction stage: The reproductive stage, encompassing grain filling and maturation, is vital for determining final yield and quality. The grain yield of CO 30 shows a progressive decrease as climate variability increases during the reproductive stage, but the decreases are not as steep compared to the flowering stage. The grain yield of K 12 also declines with increasing climate variability during the reproductive stage. The initial impact is less severe, but it becomes more pronounced as variability increases are presented in table 4. Fodder yield for CO 30 decreases with increasing climate variability. The decrease is less severe in V1 but becomes more significant in V2 and V3. Fodder yield for K 12 shows significant reductions under all scenarios, with the most severe impacts occurring under V3. This indicates high sensitivity to climate variability during the reproductive stage. Among the different stages of exposure, flowering stage is more vulnerable than the grain filling and vegetative stage. The possible reason might be due to weather abnormalities during the flowering stage especially high temperature stress leads to loss of pollen viability or increases the pollen sterility and decrease the floret fertility.

These findings are corroborated with the findings of Djanaguiraman *et al.* (2014), where he stated that high temperature stress at the time of anthesis had decreased floret fertility even when the pollen is viable. Similar line of findings are reported by Druille *et al.* (2020) where they observed whenever ambient temperature is more than the optimum temperature of crop both grain and fodder yield impacted negatively. The highest temperature also increased the incidence of sorghum midge, a major pest, in India (Reddy et al. 2017).

Increased moisture and humidity due to climate variability resulted in higher incidence of sorghum downy mildew, a fungal disease, in sorghum (Rajaram et al. 2016). When the is crop exposed to higher temperature during the grain filling stage, also yield reduces considerably. The reason might be decreasing the individual grain weight and reduce the grain filling percentage leads to decrease in the overall grain yield of sorghum. This finding in conformity with the findings of Shah *et al.* (2011) where they reported the exposure of plants to elevated temperature at the reproductive stage has a major impact on grain filling and reduce the grain yield.Among these two varieties studied CO 30 and K12, higher reduction was observed in the CO 30 compared to K 12. The possible reason may be the variety K 12 was specifically evolved for rain fed condition therefore it may have more tolerance to temperature stress due to its genetic makeup.

CONCLUSION

This study reveals significant impacts of climate variability on sorghum productivity, with important implications for food security and agricultural adaptation strategies. Key findings include:

- Flowering stage showed highest sensitivity to climate variability, with grain and fodder yield reductions of 12.3% and 8.96% respectively.
- K 12 variety demonstrated greater resilience to temperature stress compared to CO 30.
- Elevated CO_2 levels slightly mitigated yield losses, but this effect was nullified by rising temperatures.
- High temperatures during grain filling reduced individual grain weight and filling percentages.

These results underscore the need for adaptive strategies in sorghum cultivation:

- Develop heat-tolerant varieties with improved pollen viability and grain filling capacity.
- Implement agronomic practices such as adjusted planting dates and improved irrigation strategies.
- Refine crop simulation models for more accurate predictions of climate impacts.
- Foster interdisciplinary collaboration to develop holistic climate adaptation strategies

Future research should validate these findings across diverse agro-ecological zones and explore emerging technologies for developing climate-smart sorghum varieties. By addressing these challenges, we can enhance the resilience of sorghum production systems in the face of increasing climate variability.

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