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Research Paper

Assessment of climate change impact on sorghum (*Sorghum bicolor*) production and adaptation strategies in the western zone of Tamil Nadu

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ABSTRACT

This study examines the possible effects of climate change on sorghum in the western zone (WZ) comprising Coimbatore, Tirupur, and Erode districts of Tamil Nadu. The DSSAT crop simulation model was used to simulate sorghum yields with considering various planting dates and amounts of fertilizer application. The downscaled CCSM4 climate model data was utilized for the historical baseline period spanning from 1991 to 2020, as well as for future pridicted data from 2021 to 2099, under the RCP 4.5 scenarios. The key findings indicate that there is a projected yield decline range of -1.3% to -12.5% for the near century (2021-2040), -6.2% to -23.7% for the mid-century (2041-2070), and -12.6% to -30.5% for the end century (2071-2099). The sorghum yield experiences a high decrease at the end of the century (276.83 kg ha^{-1}), mid-century (178.16 kg ha^{-1}), and lastly in the near century (89.4 kg ha^{-1}). The study revealed that a enhanced fertilizer application can have a minor positive effect on sorghum productivity. The study underscores the significant threat that climate change poses to food security in Tamil Nadu and emphasizes the need for adaptation strategies to protect agricultural productivity.

***Key words*: ** Sorghum, CERES-sorghum, Calibration and validation, Climate change impact, RCP 4.5, Adaptation strategies

Sorghum bicolor serves as a valuable dual-purpose crop, offering both nutritious animal feed and food for numerous countries. Renowned for its nutritional richness and adaptability to diverse climates, it stands as a dependable choice for farmers worldwide. Apart from its role in animal husbandry, sorghum can be processed into flour for baking or prepared in various dishes such as porridge and bread. Its versatility and sustainability render it an indispensable asset for communities striving to bolster food security and cater to the needs of both humans and livestock. Sorghum are a climate-resilient crop, meaning that they can grow in a variety of conditions, including drought and high temperatures. This makes them a viable option for farmers in climate change-affected areas (Bhattacharya *et al.,* 2022).

Climate variability and patterns have great environmental and socio-economic consequences. Global food and nutritional security are under threat because of climate change and crop production. Climate variability has a negative impact on crop production and has a major impact on farm planning, especially under worldwide rainfed conditions (Boomiraj *et al.,* 2012). In India, the pressure of climate change is deeply felt in rainfed agriculture. Crop productivity is strongly dependent on rainfall and temperature, it varies widely due to inter-annual climate variability (Sandeep *et al.,* 2017). Even at minimum warming levels, crop yields are likely to drop globally, with considerable losses expected, especially across tropical regions (Challinor *et al.,* 2014). Among many weather variables, temperature and rainfall fluctuations are known to be the key parameters that directly influence crop growth and development. These stresses play a significant role in lowering yields to a greater degree by modifying the physiological and biochemical properties of crops.

The study investigates the impact of climate change on sorghum productivity in the WZ of Tamil Nadu, aiming to inform policymakers and farmers about potential adaptation strategies and promote sustainable agricultural practices to ensure food security.

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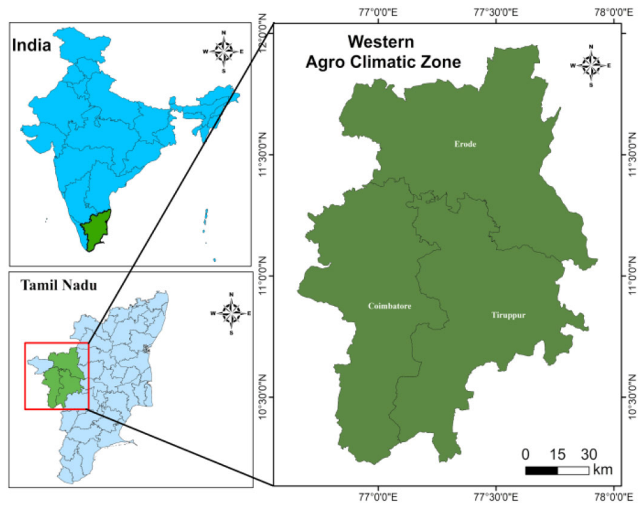

Fig. 1: Study area of western zone of Tamil Nadu

MATERIALS AND METHODS

Study area

The Western Zone comprises the Coimbatore, Tirupur, and Erode districts in the Western Ghats and Foothills region. The map of the study area is given below in Fig. 1. The climate ranges from temperate in the hills to tropical in the lowlands. The area boasts various soil types, including red, black, and laterite. Annual rainfall in this zone totals 715 mm. WZ accounts for 5.52% of the total net sown area of Tamil Nadu. WZ has a moderately cultivable area, with 0.56 million hectares dedicated to sorghum cultivation.

Calibration and validation of CERES-Sorghum

The crop simulation model defines cultivars based on genetic coefficients, indicating their potential irrespective of environmental factors. Calibration and validation of the crop variety for specific cultivars are crucial for impact assessments. To address the lack of genetic coefficients of sorghum cultivar CO 30 in the DSSAT-CERES module, the field trial data were used in the GENCALC tool to derive the cultivar specific parameter. This ensured accurate phenological phases, growth, and yield parameters. Validation was achieved through field experiments with different sowing windows and fertilizer treatments, confirming the accuracy of the model's predictions.

The field experiment was conducted at the eastern bloc farm of TNAU, Coimbatore. The experiment involved three sowing dates and three nitrogen levels, with the 38th and 39th SMW being the most suitable sowing windows. The first sowing was on D_1 - September 15, D_2 - September 30, and D_3 - October 15, 2019. Based on soil test crop response reports, the nitrogen fertilizer (N_1-75, N_2-100 and N_3-125 %,) treatment level was fixed. Weekly biometric observations and crop management data were collected to calibrate and validate the crop under study. The data included soil, plant growth, and yield parameters such as dry matter production, plant height, leaf area index, panicle initiation day, anthesis day, physiological maturity day, grain yield, grain number/plant, fodder yield, and unit grain weight. The daily weather data comprising rainfall (mm), solar radiation (MJ m^{-2} day^{-1}), minimum temperature (°C), and maximum temperature (°C) during the crop period was acquired from the Agro Climate Research Centre, Coimbatore. Subsequently, this data was converted into the weather file format using the Weatherman tool in DSSAT.

Impact analysis

The yield of sorghum cultivars in WZ was simulated for future time scales ranging from 2021 to 2099 using calibrated CERES- sorghum model. The future data for the study was obtained from the CCSM4 Regional Climate Model (RegCM4.4) output under the RCP4.5 scenario for analyzing future productivity changes. The simulated results were visualized as spatial maps using the ArcGIS 10.3 tool. The percentage relative difference (RD%) from the base year (1991-2020) for sorghum productivity was worked out for the near century (2021-2040), mid-century (2041-2070), and end century (2071-2099) using the following formula

$$\text{RD \%} = \frac{\text{Average projected future yield} - \text{Average predicted base yield}}{\text{Average predicted base yield}} \times 100$$

Framing the adaptation strategies

The adaptation framework was developed using validated model to change sowing windows and fertilizer dosage. Six treatments were fixed:

A_1 - Early sowing (September 1^{st})

A_2 - Normal sowing (September 15^{th})

A_3 - Late sowing (September 30^{th})

A_4 - Early sowing with 25% increased nitrogen fertilizer application

A_5 - Normal sowing with 25% increased nitrogen fertilizer application

A_6 - Late sowing with 25% increased nitrogen fertilizer application.

Table 1: Genetic coefficients for the sorghum cultivar sorghum CO 30

Coefficients	CO 30
P1 (Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above TBASE during which the plant is not responsive to changes in photoperiod)	410
P2 (Thermal time from the end of the juvenile stage to tassel initiation under short days (degree days above TBASE)	92
P2O (Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P2O, the rate of development is reduced)	12
P2R - (Extent to which phasic development leading to panicle initiation is delayed for each hour increase in photoperiod above P2O - degree days)	90
PANTH (Thermal time from the end of tassel initiation to anthesis - degree days above TBASE)	513
P3 Thermal time from to end of flag leaf expansion to anthesis - degree days above TBASE)	133.5
P4 (Thermal time from anthesis to beginning grain filling - degree days above TBASE)	83
P5 (Thermal time from beginning of grain filling to physiological maturity - degree days above TBASE)	410
PHINT (Phyllochron interval: the interval in thermal time between successive leaf tip appearances -degree days)	54
G1 (Scaler for relative leaf size)	4
G2 (Scaler for partitioning of assimilates to the panicle -head)	6.062

Table 2: The test and deviation statistics for the calibrated cultivar CO 30

Variable Name	Observed	Simulated	RMSE	d-Stat	r-Square
Anthesis day	63	64	2.53	0.89	0.76
Byproduct (kg ha^{-1})	6457	6785	248.9	0.62	0.74
Tops weight at anthesis	7264	7561	197.2	0.66	0.79
Tops weight (kg ha^{-1})	9134	9758	453.5	0.89	0.88
Grain number / unit	1468	1512	91.9	0.92	0.87
Grain yield (kg ha^{-1})	3052	3127	104.7	0.91	0.69
Maturity day	99	100	3.5	0.87	0.63

RESULT AND DISUSSION

Calibration of the CERES-sorghum model

The genetic coefficients were determined by iterating over multiple runs of simulation data from field experiments. The derived genotype coefficients of sorghum cultivar CO 30 are presented in Table 1.

The CERES-sorghum model was calibrated and validated for preferred cultivars of sorghum CO 30. The test and deviation statistics for the calibrated cultivar CO 30 presented in Table 2. The test and deviation statistics for cultivar CO 30 show mostly positive results, with small percentage differences, low RMSE values, and high correlation coefficients. The calibrated cultivar demonstrates a good fit between observed and simulated values for various variables such as anthesis day, byproduct yield, tops weight, grain number, grain yield, and maturity day. The actual anthesis day was found to be in close agreement with the simulated values. The r-square value of 0.76 was observed. Akinseye *et al.,* (2017) calibrated the CERES-sorghum model for sorghum varieties of western Africa and reported r-square values of 0.6 and 0.85 for grain and fodder yield, respectively.

Validation of the CERES-sorghum model

The calibrated model for sorghum growth and yield was tested using field experimental data and validated for various sowing windows and nitrogen levels with other field data from 2019 to 2020. The results of the validation test indicate that cultivar CO 30 performs well in the tested conditions. The simulated results matched acceptable limits compared to field experiment data. A close relationship was found between observed and simulated values of anthesis and maturity days, with r square values of 0.64 and 0.61, respectively. The simulated grain and fodder yields were in good agreement with observed yields, with r square values of 0.85 and 0.86, respectively (Table 3).

Climate change impacts on sorghum

The future climate projections as per the CCSM4 Regional Climate Model (RegCM4.4) output under the RCP4.5 scenario for the western zone of Tamil Nadu reveals that the maximum temperature is expected to increase in near century (NC) from 0.6 to 1.1 °C, in mid-century (MC) from 0.9 to 1.5 °C, and in end century (EC) from 2.2 to 3.1 °C. The minimum temperature increases in NC are 0.8 to 1.4 ◦C, MC is 1.3 to 1.9 ◦C, and EC is 2.7 to 3.5 ◦C. In the case of rainfall, it increases from 4.5 to 9.2 % in NC, 14.21 to 22.31 % in MC, and 21.17 to 32% in EC.

Climate change is expected to lead to higher temperatures in many regions, which can negatively impact sorghum growth and development. Sorghum is sensitive to high temperatures, especially during critical growth stages such as flowering and grain filling. The sorghum yields the highest decrease in end century (352 kg ha^{-1}), followed by mid-century (180 kg ha^{-1}) and near- century (87 kg ha^{-1}). During the NC and MC, a similar trend of yield decline was simulated in Coimbatore and Tirupur districts. The highest yield decline was projected for Erode district in all time slices. Elevated temperatures can reduce photosynthesis, increase heat stress,

Table 3: The test and deviation statistics for the validation

Variable Name	Observed	Simulated	RMSE	d-Stat	r-Square
Anthesis day	62	64	1.6	0.85	0.64
Byproduct (kg ha^{-1})	6372	6672	252.4	0.86	0.85
Tops weight at anthesis	7332	7871	237.2	0.92	0.79
Tops weight (kg ha^{-1})	9536	9927	658.5	0.74	0.85
Grain number / unit	1441	1536	100	0.85	0.77
Grain yield (kg ha^{-1})	3020	3312	130.1	0.91	0.86
Maturity day	98	100	4.2	0.82	0.61

Table 4: Relative yield difference due to **c**limate change and various adaptation strategies for sorghum

Future time slices	Adaptation strategies					
	Current sowing	Early sowing	Late sowing	Early sowing + 25% fertilizer	Normal sowing + 25% fertilizer	Late sowing + 25% fertilizer
Near century (2021-2040)	-5.35	-7.26	-8.57	-6.33	-2.17	-4.9
Mid-century (2041-2070)	-11.2	-12.98	-14.57	-9.2	-7.67	-11.85
End century (2071-2099)	-17.9	-14.37	-22.67	-10.52	-13.22	-20.87

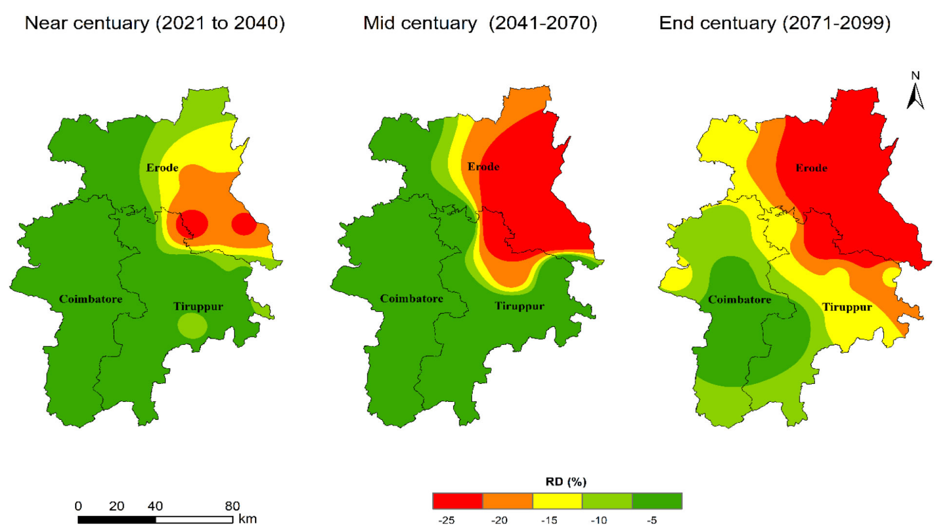

Fig. 2: Spatial distribution of the relative deviation percentage during the near, mid, and end century

and decrease grain yield in sorghum. The spatial distribution of relative deviation is presented in Fig.2. The results indicate that as temperatures increase, there is a corresponding decrease in sorghum yield across the different regions. On an average the sorghum yield decreases by 5.3% near century (2021-2050), -11.2% in mid-century (2021-2050) and -17.8% in end century (2021-2050), highlighting the significant impact of climate change on sorghum production in the region. In Tamil Nadu increasing temperatures and erratic rainfall patterns negatively affected sorghum yields, particularly in rainfed areas (Gupta and Sharma, 2016). The rising temperatures accelerated the phenological stages of sorghum, leading to shorter growth durations and reduced yields (Raju and Ramaiah, 2020). Additionally, extreme weather events such as droughts and floods further exacerbated the situation, resulting in significant yield losses. The sorghum production loss is due to various climate factors, like higher solar radiation and temperatures, which can increase evapotranspiration, leading to water stress even with more rainfall. Warmer temperatures might favour the spread of specific pests and diseases that are harmful.

Adaptation strategies

Climate change adaptation strategies in Tamil Nadu refer to the various measures and practices implemented by farmers in the southern Indian state of Tamil Nadu to cope with and mitigate the challenges posed by climate change, erratic weather patterns, and other environmental factors. It was observed that sorghum yield decreased across all adaptation strategies (Table 4).

The change in sowing window did not have any beneficial effects. Even the enhanced fertilizer application could not improve the yield much under early or late sown sorghum. The treatment with the least yield decline (-2.17%) was observed in the current planting strategy, coupled with increased fertilizer application. Similar trends were noted in the MC. In the EC, all combinations of treatments led to a decline in yield, with the least decline (-10.52%) observed in the early planting strategy with enhanced fertilizer application. Overall, the adaptation framework for sorghum in the WZ indicates that various combinations of treatments negatively impact sorghum yields. Despite attempts to mitigate these effects through strategies like increased fertilizer application and early planting, yield declines persist (Sandeep *et al.,* 2018). Pandey (2023) also opined that the present-day crop varieties may not be able to cope up with the adverse effect of climate change in late century in spite of various adaptation strategies. This underscores the necessity for further research and innovative solutions to address the challenges posed by climate change in sorghum production.

CONCLUSIONS

Climate change is significantly affecting sorghum yields, causing a decrease across all districts of WZ and time periods. The sensitivity of sorghum to high temperatures during growth stages underscores the need for adaptation strategies. Future research should focus on developing resilient sorghum varieties and sustainable agricultural practices to ensure food security. The analysis underscores the complex interplay between climate change, agricultural practices, and crop vulnerabilities, requiring immediate attention for livelihood protection and food security.

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