European Journal of Agronomy 144 (2023) 126760

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Indian sugarcane under warming climate: A simulation study

Rohit Jaiswal [a], R.K. Mall [a,*], Shubhi Patel [a,b], Nidhi Singh [a], Nisha Mendiratta [c], Akhilesh Gupta [c]

[a] DST-Mahamana Centre of Excellence in Climate Change Research, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India
[b] Department of Agricultural Economics, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, India
[c] Department of Science and Technology, New Delhi 110016, India

ARTICLE INFO

Keywords:
Sugarcane
DSSAT
CANEGRO-Sugarcane
Climate change
Multi-model projection
Impact assessment

ABSTRACT

Multi-model climate projections are increasingly used to quantify the impacts of climate change on major staple crops under different climate change scenarios. Despite uncertainty associated with different climate projections, it helps in providing a direction and magnitude of change in crop production in future with different uncertainty levels. In this study, we used the CANEGRO-Sugarcane crop model driven by downscaled and bias-corrected simulations forced by different regional climate models (RCMs) for the mid-future (2040–2069) and far-future (2070–2099) under the two emission scenarios RCP4.5 and RCP8.5 to simulate the effect of climate change on sugarcane's stalk fresh mass (SFM) and Sucrose Mass (SM) over major sugarcane growing states of India. The result showed, out of three phenological phases analyzed, two were found to be Shortened (planting to emergence up to 14.5 days and emergence to stalk elongation up to 6.3 days) and one i.e., peak population to harvest get extended up to 9.5 days under RCP8.5, far-future. An increase in SFM is projected substantially in the mid-future under RCP 8.5 for the tropical state of Gujarat (11.2–18.1 %) and the least for Odisha (6.8 % to 10.7). On the contrary, SM was found to decrease overall except for the states of Uttar Pradesh, Maharashtra, Gujrat, and Andhra Pradesh. The changes in the SFM and SM were found to be regulated by the increase in maximum (Tmax) and minimum temperature (Tmin), decline in solar radiation (Srad), leading to an increase in SFM and a reduction in sugar content. Therefore, decline in SM in the future which may cause economic loss as sugarcane is one of the most important cash crops of India. With uncertainties in the magnitude of change, the findings are useful for plant breeders and policymakers to develop appropriate strategies to minimize the loss and enhance sugar production.

1. Introduction

The rising temperature up to 1.5 °C in the near term, would cause unavoidable increases in multiple climate and weather extremes and bring multiple risks to natural ecosystems and humans (very high confidence) (Ruane et al., 2014; IPCC et al., 2021). An increase in the intensity and severity of extreme weather events, like extended droughts, floods, tropical cyclones, and heatwaves will strongly affect one of the climate-sensitive sectors, agriculture (Chaubey et al., 2022). At the global level, this could raise serious challenges for food security additionally affecting a lot to the economy in countries whose large populations are directly or indirectly associated with agriculture, like India (Lobell and Gourdji, 2012; Mall et al., 2018; Sonkar et al., 2019; FAO, 2019; IPCC et al., 2021). Sugarcane (Saccharum spp.) a C4 plant is an economically important cash crop typically grown in tropical and subtropical climates throughout all seasons of the year. Because of the long growing season, the sugarcane's overall productivity is strongly governed by climatic factors (de Medeiros Silva et al., 2019).

In India sugarcane is cultivated all over the country from latitude 80°N to 330°N and is an important commercial crop. The optimum temperature for germination is 32–38 °C. And for ripening temperatures from 12 °C to 14 °C are desirable. The critical stages of sugarcane growth are germination, tillering, early growth, active growth and elongation. India is the second-largest producer of sugarcane (355.70 million tons, 19.7 %) after Brazil and is also the largest consumer influencing the livelihood of about 50 million sugarcane farmers and around 0.5 million workers directly employed in sugar mills (DES, 2021). Among the states, Uttar Pradesh is the leading producer. The genetically modified seeds of sugarcane are also under development in India. It is expected that Sugarcane-based demand for sugar and energy might increase in future. Importantly, sugarcane yield is sensitive to changes in temperature, rainfall (RF), atmospheric CO_2 concentration and extreme weather

* Corresponding author.
E-mail address: rkmall@bhu.ac.in (R.K. Mall).

https://doi.org/10.1016/j.eja.2023.126760
Received 15 June 2022; Received in revised form 25 December 2022; Accepted 6 January 2023
Available online 28 January 2023

events driven by climate change (Mall et al., 2016; Ruan et al., 2018; Sonkar et al., 2020). High temperature and water stress are known to adversely impact the growth stages (germination, flowering and maturity) of the crop (Verma et al., 2019). The yield and quality of sugarcane are sensitive to changes in weather conditions specially during critical stages. The sugar recovery is maximum when the weather is dry with low humidity; bright sunshine hours, cooler nights with wide diurnal variations and very little rainfall during ripening period. Temperatures above 38 °C reduce the rate of photosynthesis and increase respiration.

Stalk Fresh Mass (SFM) and Sucrose Mass (SM) are important component of the sugarcane crop that determines its economic importance. A review of the literature shows that although there have been several studies on climate change and sugarcane response in India (Kumar and Sharma, 2014; Chandran and Anushree, 2016; Jyoti and Singh, 2020), there are only a few studies on crop simulation model-based approaches of assessment for sugarcane in India. These studies are based on an empirical approach using panel data, and regression analysis. To state a few, Kumar and Sharma, 2014, conducted an empirical analysis of the relationship between sugarcane yield and weather variables using the Ricardian approach and found a negative association between climate change on productivity. Based on the crop simulation approaches, a study by Sonkar et al. (2020) shows increased vulnerability to SFM and SM (3–25 % decrease) with an increase in temperature (1–4 °C) over Uttar Pradesh. However, a combined effect of increased temperature and elevated CO_2 levels showed an increase in SFM but a negative effect on SM (more for rainfed conditions). Ramachandran et al. (2017) over the Tamil Nadu region witnessed a decline in the sugarcane yield by 1.8 %, 2.6 %, and 2.8 % for the near, mid, and end-century periods respectively. A similar reduction in yield has been observed by Singh et al., 2021a in the Punjab region.

In line with the above, several other studies have found a decline in sugarcane production and yield due to climate variability and is projected to decline by 20 % with every 1-degree rise in temperature (Kumar et al., 2015). With the rising population and growing demand for sugar and energy, by 2050, sugar recovery and cane production need to be increased further without demanding the need for an additional production area. At present, the sugarcane is grown on 5.2 million ha with a sugar recovery of 11 % (DES, 2016).

India experienced a rise in average surface temperature from around 0.7 °C from 1901–to 2018 (Krishnan et al., 2020) with a substantial rise in T_{min} to T_{max} during recent decades showing warmer nights and rising winter temperatures (Singh et al., 2021b; Mall et al., 2021). This will certainly have significant repercussions for sugarcane productivity. Process-based crop simulation model (CSM) is a powerful tool for assessing the impact of climate change on crop production (Challinor et al., 2014). Out of several CSM available for agriculture impact assessment study, CANEGRO-Sugarcane (from Decision Support System for Agrotechnology Transfer (DSSAT)) are widely used. To study the response, the use of the projections made by Global Climate model (GCM) and Regional Climate Model (RCM) in association with the process-based crop simulation model serves as one of the reliable solutions. However, due to the uncertainty associated with climate model projections, scepticism remains on the magnitude of the decline in sugarcane yield too. In such a scenario, predictions based on a single climate model simulation are not reliable. Multimodel projections offer a great opportunity in a probabilistic way to quantify the uncertainty associated with the impact assessment of climate change. The uncertainty in different climate projections in the global climate models is mainly associated with structural differences and variations in model parameterizations.

The impact of climate change on the production and productivity of crops such as wheat and rice has been extensively researched, however, for sugarcane crop most of the study attempted are from field to regional scale and has been done through environmental modification (by increasing temperature and CO2) on the model interface. For a country like India which stands at the 7th position in the climate risk Index, and whose substantial labour force is associated with sugarcane pre and post-production, a comprehensive evidence-based regional study on climate change impact assessment on sugarcane productivity under different climate projection scenarios is lacking. Considering the existing lack of evidence on sugarcane response to climate change at regional and national scales, the present study conducted, using CANEGRO-Sugarcane module from Decision Support System for Agrotechnology Transfer (DSSAT). The goals of the study are as follows:

- To investigate the impact of climate change on sugarcane crop phenology and yield (in terms of SFM as well as SM) over major sugarcane-growing states of India.
- To evaluate the uncertainty amongst RCMs outputs used as input weather variables in the CANRGRO-Sugarcane model.
- To assess the crop growth stages and yield under two different scenarios (RCP4.5 and RCP8.5) during two different time periods; mid-of-century (2040–2069) and far-of-century (2070–2099).

This will be the first comprehensive work to study the impact assessment of sugarcane crops in future in major sugarcane growing regions covering the entire India using multiple regional climate model outputs to understand the uncertainty and regional disparity in space and time.

2. Material and methods

2.1. Study area

According to the division by the Indian Council of Agricultural Research, the sugarcane producing regions have been classified into tropical and sub-tropical regions. The tropical regions are identified with long sunshine hours, cool nights with a clear sky and higher productivity (80 t/ha) and sugar recovery (Shukla et al., 2017) and comprise Maharashtra (MH), Karnataka (KA), Tamil Nadu (TN), Andhra Pradesh (AP), Gujarat (GJ), and Madhya Pradesh (MP), and Kerala (KE) states. While the sub-tropical region has lower productivity (60 t/ha) subject to the occurrence of climate extremes. This region covers Uttar Pradesh (UP), Bihar (BH), Uttarakhand (UT), Haryana (HR), Punjab (PU), Odisha (OD), West Bengal (WB), Assam (AS), Chhattisgarh (CH), and Jharkhand (JH). Finally, 11 major growing states (Fig. 1) making up a total of more than 95 % of the total production were selected for the study. Detailed characteristics of each state considered have been presented in Fig. 1.

2.2. Data and climate change scenarios

The daily gridded data on T_{min}, T_{max}, and RF was obtained from Indian Meteorological Department (0.5° X 0.5° resolution). Whereas, daily Srad (MJ/m^2/day) was computed using the Hargreaves and Samani method (Hargreaves and Samani, 1985). For the inter-model variability of climate change impacts, 5 RCM output from two Regional Climate models i.e., CCAM (Conformal-Cubic Atmospheric Model), and RegCM was used. CCAM ensembles were developed at CSIRO Australia and obtained from the Coordinated Regional Climate Downscaling Experiment- South Asia (CORDEX-SA) portal, managed by the Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM), India. From the CCAM ensemble, 4 dynamically downscaled projections were obtained which use initial-boundary conditions from four different Global Climate Models (GCM) viz. ACCESS1–0, CNRM-CM5, MPI-ESM-LR, and NorESM1-M at resolution 0.5° X 0.5°. Another RCM, RegCM data was downscaled using initial-boundary conditions of MPI-ESM-MR (GCM) at a spatial resolution of 0.25° X 0.25° at the DST-Mahamana Centre of Excellence in Climate Change Research (MCECCR), Banaras Hindu University, India. The data for RegCM were gridded to 0.5° x 0.5° resolution to obtain a coherent resolution. The modular predictions are inherent with biases

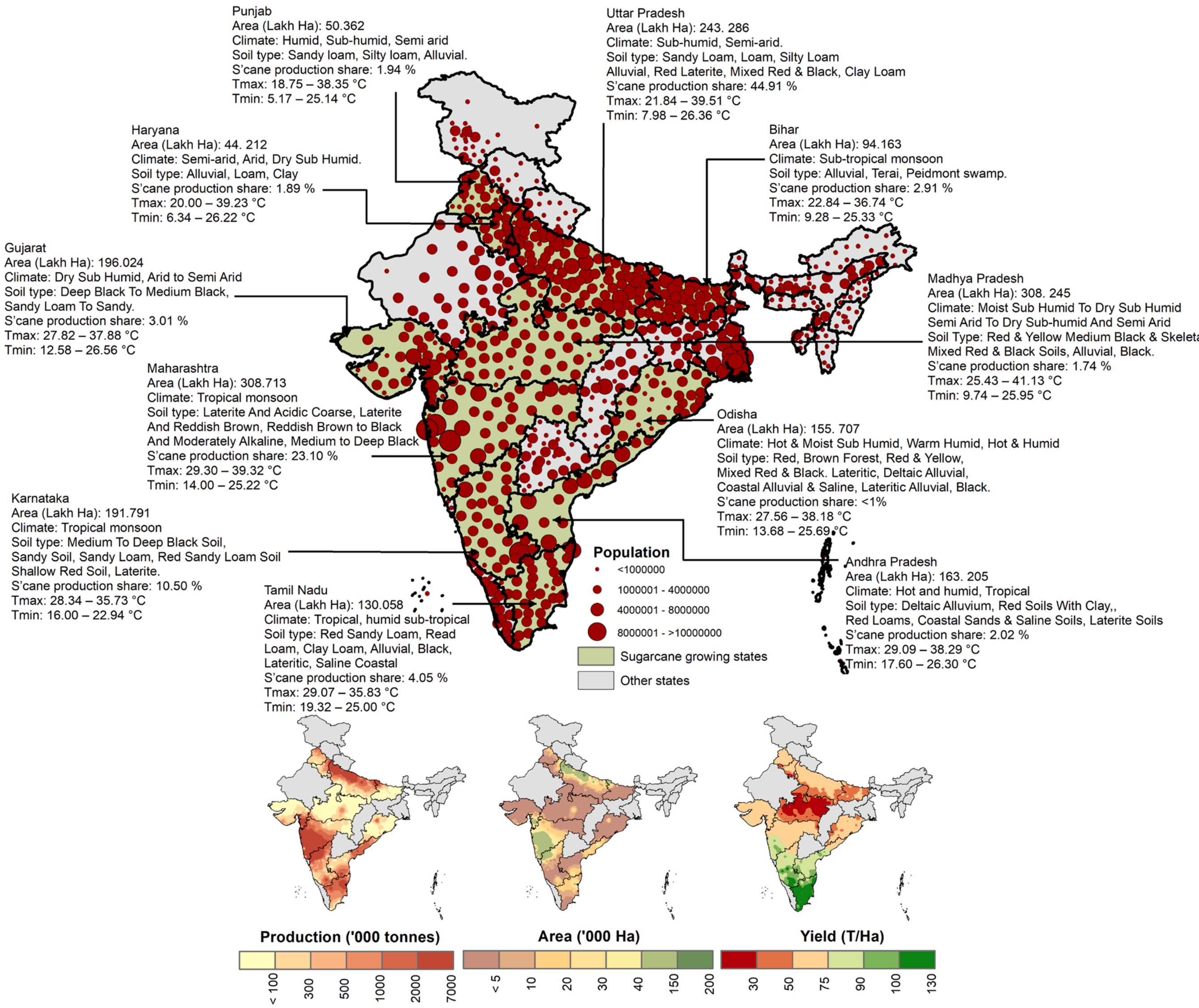

Fig. 1. Description of sugarcane growing states of India. a.) Population density b.) Production of sugarcane c.) Area under sugarcane cultivation and d.) Yield of sugarcane. Note – Data is an average for a period of 1997–98–2018–19. Population data collected from Population Census 2011.

subject to model parametrization and other complexities. Hence the data was bias-corrected using variance scaling for temperature (Singh et al., 2021c) and the linear scaling technique for RF (Jaiswal et al., 2022). From each RCM, data was generated under two representative concentration pathways (RCPs): RCP4.5 (climate-sensitive development scenario) and RCP8.5 (carbon-intensive development scenario) for two different periods i.e., 2040–2069 (mid-future) and 2070–2099 (far-future). The detailed descriptions of the RCMs used have been provided in Table S1. The change in monthly and seasonal temperature (T_{max}, T_{min}), and Srad in future was made in comparison to the baseline period;1980–2009 to quantify the changes under different scenarios during the sugarcane growing period.

2.3. CANEGRO- sugarcane model

The CANEGRO-Sugarcane simulations model was used in the present study (Inman-Bamber, 1991; Hoogenboom et al., 2019). The CANEGRO-Sugarcane model is a well validated, widely used, robust model for impact assessment in Indian region (Sonkar et al., 2020). The reason for selecting CANEGRO over APSIM is as follows: In CANEGRO, thermal time calculation is based on different base temperatures, optimum temperatures, and maximum temperatures for different phenological stages while APSIM calculates it on fixed temperature (base temperature 9 °C, optimum temperature 32 °C, and maximum temperature 45 °C). Radiation use efficiency is cultivar specific parameter for DSSAT while it is constant for species in APSIM (Marin et al., 2015). Daily maintenance respiration in CANEGRO is calculated as a fraction of total dry biomass that depends on temperature while APSIM uses a zero-maintenance respiration approach (Jones, Singels, 2018).

The CANEGRO model requires weather data, soil physical properties (pH, EC, bulk density, organic carbon, etc.), management information (planting date, emergence date, etc.), and genetic trait parameters specific to the cultivar as input to simulate the daily growth and development of sugarcane crops. In CANEGRO- the submodel canesim canopy model described by Singels and Donaldson (2000) was used for simulating the progression of fractional interception of radiation. The model has been widely used in impact assessment on sugarcane for present and future periods in different regions (Jones et al., 2015; Sonkar et al., 2020). The calibrated and validated CANEGRO-Sugarcane model for India (Singh et al., 2010; Sonkar et al., 2020) has been used for the Impact assessment (Singels et al., 2014; Jones et al., 2015).

2.4. Crop simulation and analysis

CANEGRO sugarcane model was used to simulate the sugarcane phenology and yield in terms of SFM and SM with a baseline CO_2 concentration of 380 ppm for each climate scenario and period. Some pieces of evidence suggest that increases in CO_2 concentration do not affect sugar production, cane quality, leaf area, and dry biomass (Malan et al., 2017). Another result by Stokes et al. (2016) indicates that stomatal conductance gets reduced by 28 % at a CO_2 concentration of 720 ppm under well-watered conditions which do not have any effect on photosynthesis, biomass accumulation, or yield. Similarly, Jones, Singels (2018) also considered the zero-fertilization effect under no-water stress conditions. The aforementioned result suggests that there is no direct fertilization effect of increased CO_2 on sugarcane crops, keeping this fact in mind we also run the simulation with ambient CO_2 concentration under no-water stress conditions.

The module uses climate data as one of the input parameters. The sugarcane crop is sown from January to march and has a crop cycle of 12 months on an average varying from 10 to 18 months. However, in the present study, crop management inputs were considered the same for the whole region with sowing between January-march and harvesting in January-march of the next year. The initial field conditions were given as per the secondary data obtained for each state. The model simulates crop growth based on a validated genetic coefficient. For this study, already calibrated and validated genetic coefficients from (Singh et al., 2010; Singh et al., 2018) were used in the study (Table S2). This genetic coefficient has been parameterized for the study region and hence, further validation was not required. In order to quantify the response of SFM and SM to weather variables i.e. temperature the simulations were run at the potential level. This means that no water stress or nutrient stress was considered during the simulations. For the assessment of uncertainty associated with the magnitude of change in sugarcane performance, 20 climate scenarios were created (5 models x 2 scenarios x 2 time periods).

The analysis has been performed in three steps; in the first step grid-wise simulation of phenology as well as SFM and SM have been performed for baseline as well as 20 future climate scenarios. In the second step, for each grid, the difference between the simulated and baseline yield has been calculated as a percentage change. In the final step, each grid falling in the corresponding state has been aggregated for state-wise analysis.

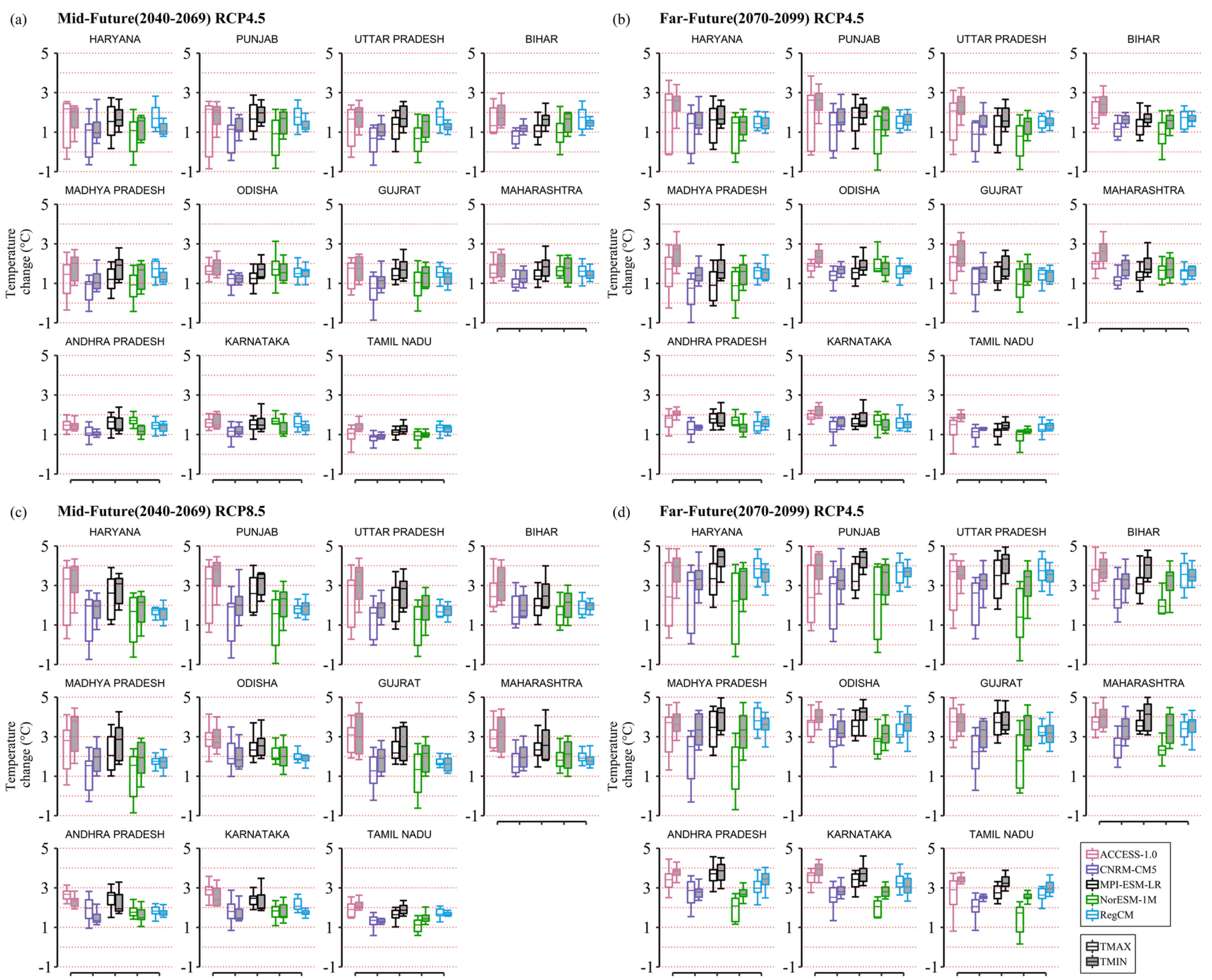

Fig. 2. Change in mean maximum temperature (T_{max}, ^{0}C) and minimum temperature (T_{min}, ^{0}C) as projected by climate models relative to baseline period (1980–2009) under different representative pathways during mid-future (2040–2069) and far-future (2070–2099) for 11 sugarcane growing states of India.

3. Results

3.1. Projected changes in solar radiation, temperature, and rainfall

Under both RCP scenarios the, average Srad for subtropical states was found to be decreasing in the magnitude of 0.2–0.5 MJ/M^2/day for mid-future while during far-future it decreased at a higher magnitude i.e., from 0.4 to 0.9 MJ/M^2/day (Fig. S1). The long term monthly average of Srad for the growth period is given in Fig. S2. Over tropical states, heterogeneity in the change of Srad was observed, where the states like KA, AP, and OD depicted an increase in Srad during mid-future while the remaining states showed a decrease but the magnitude was less as compared to the subtropical states. Modular uncertainty found that RegCM showed an increment in all scenarios during the far future, unlike other climate models, NorESM projections showed an increase in Srad over tropical states under RCP4.5.

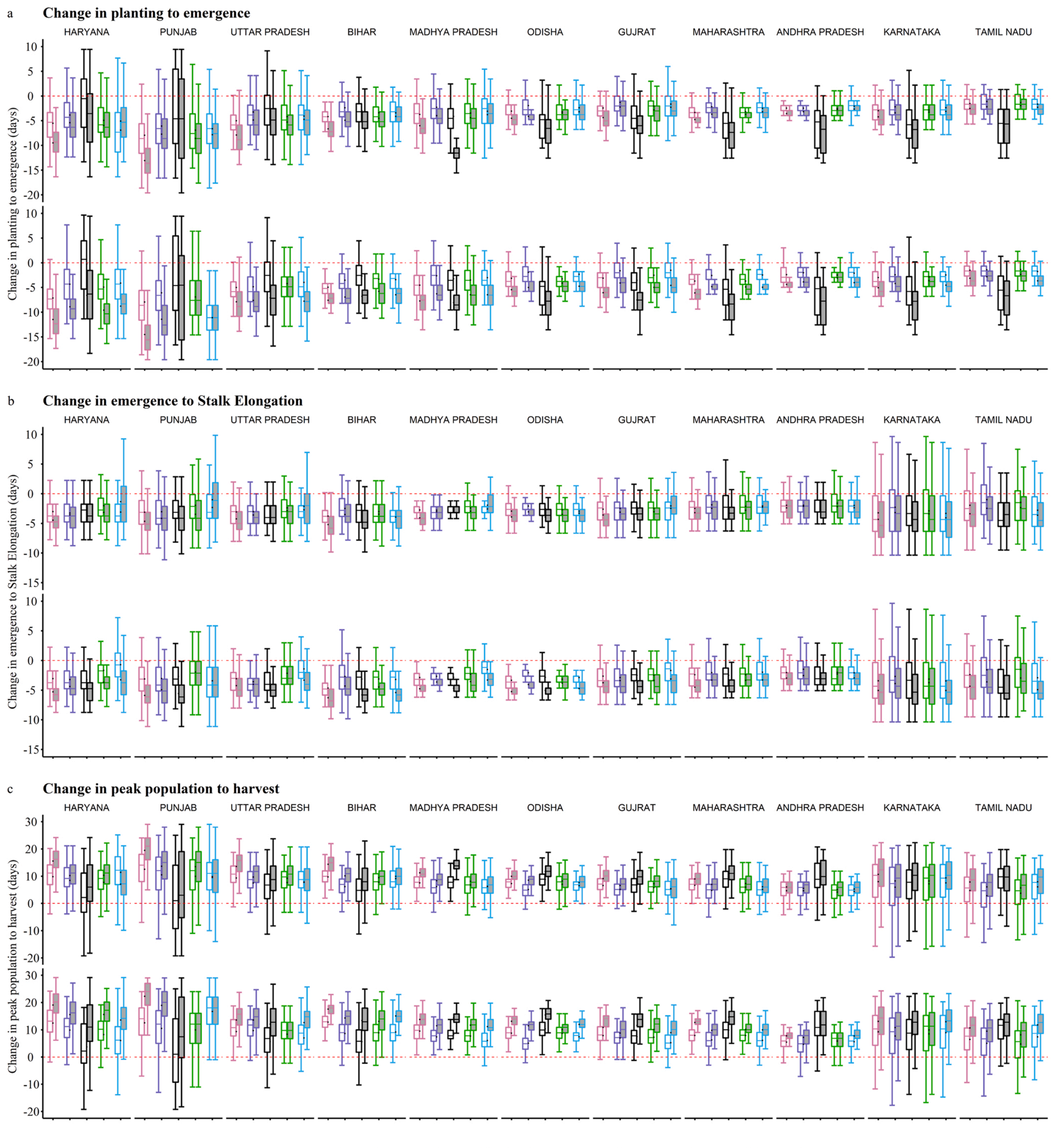

Fig. 3. Simulated change in phenological stages a) change in planting to emergence b) change in emergence to stalk elongation c) change in peak population to harvest (compared with baseline 1980–2009) in mid-future (2040–2069) and far-future (2070–2099) under RCP 4.5 and RCP 8.5 using different climate models for 11 states of India. The point within the box presents the mean value and median is given by line.

The baseline period average T_{max} for the tropical states ranged from 25 °C to 41 °C and for subtropical states from 18 °C to 40 °C. The average T_{min} ranged from 9 °C to 26 °C and 5–26 °C for tropical and subtropical states respectively. In all the climate change scenarios, there was an increment in the T_{max} and T_{min} as compared to the baseline (Figs. 2 & S3). The rate of increase was mostly similar in the mid and far future under RCP4.5 for T_{max} (0.4–1.9 °C) while T_{min} increased at a higher magnitude ranging from 0.9° to 1.9°C and 1.2–2.6 °C during mid-future and far-future respectively (Fig. 2). RCP8.5 on the other hand was associated with extreme temperature change with an increase in both T_{max} and T_{min} going above 4 °C in the far future. Amongst the climate models, ACCESS projected a higher increase while CNRM was associated with a mild increment.

RF didn't show any significant change in any of the scenarios. It showed a very slight increase in subtropical states (0.1–0.4 mm/day) and a decrease in tropical states (0.1–0.4 mm/day). RegCM and NorESM showed variation from the rest of the models (Fig. S4). The long term monthly mean of precipitation during the growth period is given in Fig. S5. The variability in annual average RF is found more in Tropical states compared to the subtropical states.

3.2. Projected changes in sugarcane phenology

Crops require a certain amount of growing degree days to complete the life cycle. Changes in the optimum temperature range alter the growth period of crops accordingly; for example, accelerated growth in case of increased temperature. The results from the present study show that sugarcane's planting to emergence period would get shorter in all climate change scenarios across the states (MPI-ESM-LR shows disagreement with other models). Under RCP4.5, the average length of planting to emergence was shortened by 1–9.3 days and a huge reduction was found under RCP8.5 (2–14.5 days), nearly similar in both periods (Fig. 3a). The regional variation was apparent for example states like OD and TN showed the highest shortening. While as per the ensemble mean change in planting to emergence shortened under both the scenarios and time periods (ranging from −1.94 days in GJ under RCP4.5 during mid-future to −12 days in PN under RCP8.5 during far-future) Table S3.

In the case of the emergence to stalk elongation period, the average length was shortened by 1–3.9 days and 1.6–4.7 days during the mid to far-future respectively (RCP4.5; Fig. 3b). Under RCP8.5, the period was further shortened by 2.2–5.2 days and 2–6.3 days during mid to far-future respectively. Higher heterogeneity was found over KA and TN. While as per the ensemble mean, the shortening of emergence to stalk elongation was found in the range from 1.72 days in GJ under RCP4.5 during mid-future to 5.07 days in BR under RCP8.5 during far-future (Table S3).

Unlike, the above two phenological stages discussed, the peak population to harvest period would get lengthened by 4–9 days across the states in all the scenarios (Fig. 3c). Similarly, under the ensembled mean for the peak population to harvest gets lengthened by a range from 4.17 days in GJ under RCP4.5 during mid-future to 18.57 days in PN under RCP8.5 during far-future (Table S3). Overall, the planting to emergence to stalk elongation period will be shortened while the peak population to harvest period will get lengthened for all the scenarios irrespective of the RCM output used.

3.3. Sugarcane yield response with projected climate

The results revealed that SFM increased in all scenarios with variations in the magnitude of the increase. For example, the increase in SFM was limited in the far future. GJ showed the highest increment in SFM followed by MH. Over GJ, the change in SFM was between 11.2 % and 18.1 % during the mid-future and 8.6–16.3 % during the far-future under both scenarios. The minimum increase in SFM was observed over OD that varies from 3.8 % to 11 % during mid-future, and 4.5–7.6 % in far-future with some variations under two RCPs (Fig. 4a). Across the sub-tropical region, the change in SFM was highest over HR. Apart from spatial heterogeneity, differences in model performance were apparent as well. For example, in the case of PN NorESM showed a decrease in SFM. ACCESS and CNRM showed negligible change in SFM under RCP4.5, while under RCP8.5 scenarios ACCESS showed a substantial increment in mid and far-future. UP, the leading producer of sugarcane, showed diverse changes in SFM for different model simulations from + 0.8 % (CNRM) to + 8.7 % (RegCM) under RCP4.5 and − 0.2 % (NorESM) to + 6.8 % (MPI-ESM) in RCP8.5 (Fig. 4a). While considering the ensemble mean, the SFM found to be increasing by range from 0.47 % (KT) to 13.88 % (GJ) and 2.66 % (KT) to 14.93 % (GJ) for RCP4.5 and RCP8.5 respectively during mid-future while during far future it ranges 0.11 %(KT) to 12.61 % (GJ) and 2.54 %(KT) to 13.45 % (GJ) for RCP4.5 and RCP8.5 respectively (Table S3).

The SM is the economic component of the sugarcane crop which accounts for the sugar recovery. The regional disparity was found in the response of SM over the climate scenarios. Unlike SFM, the SM was found to decrease in all the climate change scenarios except for UP (except RegCM), GJ, MH, and AP (except ACCESS) where SM was found to be increasing under RCP4.5 (during both periods) and RCP8.5 (only during mid-future) (Fig. 4b). GJ showed a substantial increase in SM by 23 % (mid-century, CNRM) to 18.5 % (far-century) in RCP4.5 % and 18 % (mid-century, CNRM) to 7.5 % (far-century, CNRM and NorESM) in RCP8.5. HR showed a maximum decrease (9 %, RegCM) in the mid-century future under RCP8.5, but, the decreases in SM were prominent during the far future, under RCP8.5. OD showed a substantial decrease of 24.9 % (ACCESS) during far-future, under RCP8.5. KA is the state where the decrease in SM is found invariably. For Uttar Pradesh, under RCP4.5 all the models showed a positive change ranging from 3.1 % to 5.8 % except ACCESS and RegCM which showed a negative change of 1.1 % and 4.5 % respectively. Considering the ensemble mean, except few states a decline in SM was found for all states ranging from 0.09 % (HR) to 7.05 % (TN) and 3.53 % (HR) to 10.44% (TN) during mid-future under RCP4.5 and RCP8.5 respectively. In UP, GJ, MH, and AP the SM increases during mid-future; ranging from 4.85 % (UP) to 23.23% (GJ) and 2.74 % (UP) to 14.07 % (GJ) under both the scenarios respectively, while during far-future only under RCP4.5 changes in SM found to be positive (ranging from 2.03 % (UP) 19.30 % (GJ)) while under RCP 8.5 changes were found to be negative (Table S3).

4. Discussion

4.1. Projected change in climate

The results based on the Multi-Model Ensemble (MME) mean projections show a unanimous increase in temperature in all climate change scenarios under consideration and the future warming is higher in T_{min} than T_{max} over the Indian subcontinent. The increase in temperature over sub-tropical states was higher as compared to the tropical states. Inversely, Srad showed a declining trend for the subtropical states but mostly increased in tropical states. The incident Srad influence the T_{max} more than T_{min} by alteration and modifications in light extinction, cloud microphysical properties, thermal balance in the lower atmosphere, and solar insolation, this partly explains the comparative less increase in Tmax than Tmin (Padma Kumari, Goswami, 2010).

4.2. Phenology change under a warming climate

The optimum temperature range for sugarcane growth is between 10 °C and 40 °C with an average optimum value of 30 °C (Rupkumar and Subbaramayya, 1980). Supra-optimal temperature and water stress during various growth stages may cause a detrimental effect on the crop (Verma et al., 2019). Higher temperature generally shortens the crop growth phases by accelerating the plant development (Sparks et al., 2000; He et al., 2015; Carvalho et al., 2015). The CANEGRO simulates

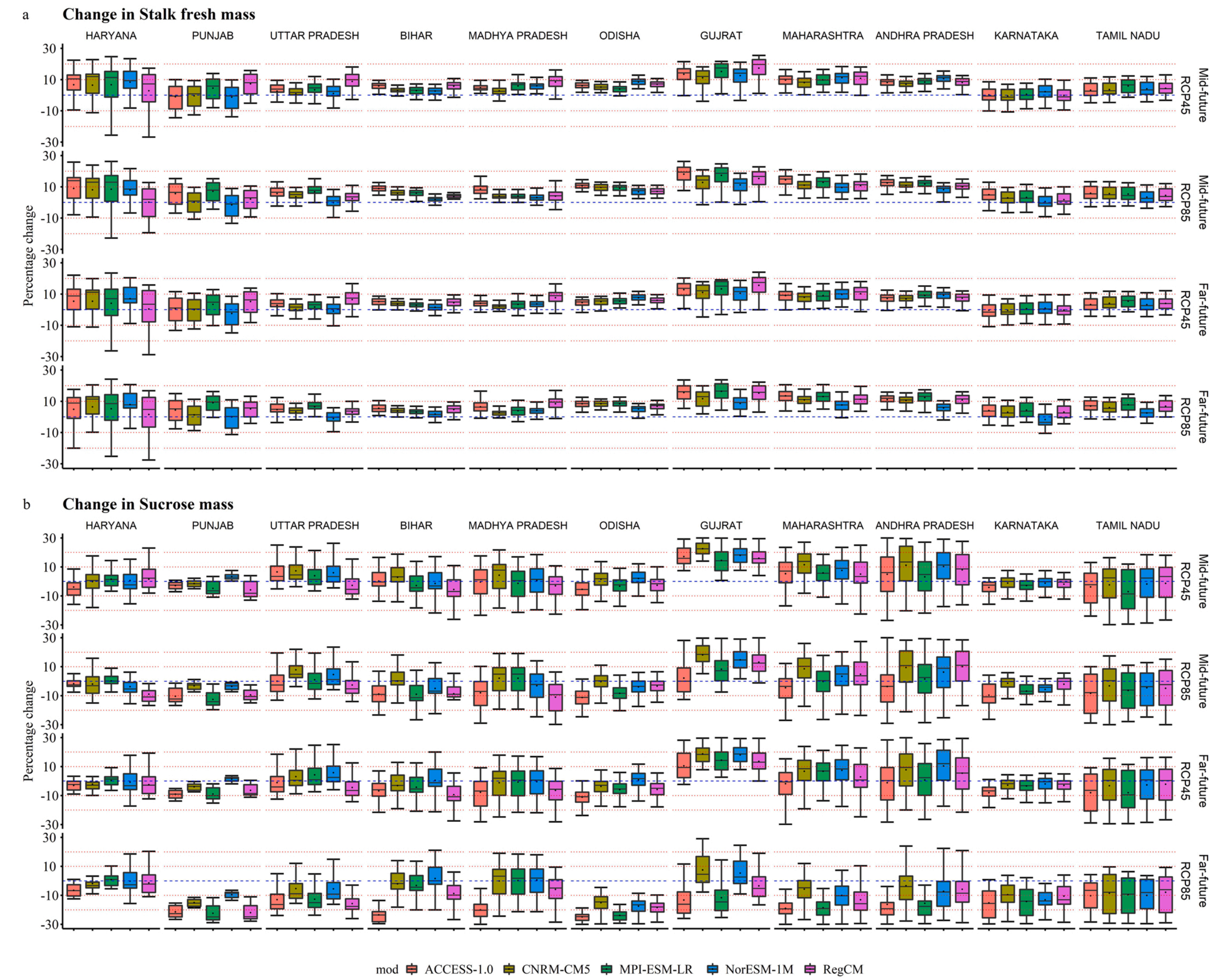

Fig. 4. Simulated change in a) SFM and b) SM (compared with baseline 1980–2009) in mid-future (2040–2069) and far-future (2070–2099) under RCP 4.5 and RCP 8.5 using different climate models for 11 states of India. The point within the box presents the mean value and the median is given by horizontal line.

phenology by the accumulation of a specified period of thermal time. Different stages like germination of the primary tiller, starting of stalk elongation, peak tiller population etc. start when the specific thermal time is accumulated. Elevated temperatures lead to accelerated accumulation of thermal time hence hastening the beginning of different phenological phases (Jones, Singels, 2018). The same was evident in the present study where we found shortening of the planting to emergence and emergence to stalk elongation period in future in response to the increment in temperature during future scenarios, with more substantial shortening expected in the far future under RCP8.5. The above results are in good agreement with those of (Ahmad et al., 2016). Following the trends in temperature rise, the shortening of the average day length of planting to emergence was higher over sub-tropical states compared to the tropical states. However, we report a lengthening of peak population and harvest dates.

4.3. Yield change under a warming climate

The gradual increase in temperature increases SFM (Sonkar et al., 2020). As found in the present study the increase in temperature has positively affected the SFM accumulation with an increase of up to 18 %. Our results are in good agreement with studies by Singels et al. (2014) and Zhao and Li (2015) who showed the combined effect of elevated CO_2 and temperature will lead to an increase in cane yield. CANEGRO model calculates biomass accumulation using Photosynthetically-active radiation (PAR) conversion efficiency. The higher the intercepted PAR, the higher the biomass accumulation. The increased biomass is caused by the increase in the fractional interception of PAR (FiPAR) driven by increased thermal time accumulation leading to increased canopy development. The present study also reports a high rise in SFM found over tropical states compared to subtropical states. This could be possible because tropical states witness less variability in weather parameters offering an idealistic climatic condition throughout the growing season whereas sub-tropical states often witness extreme weather events in different parts of the crop growth cycle. The findings are consistent with other studies as well (Zhao and Li, 2015; Sonkar et al., 2020).

Importantly, a mere increase in SFM doesn't benefit unless the sugar recovery also increases at the same pace. However, in the present study, we observed a decline in SM except for a few regions viz. UP, GJ, MH and, AP where it was found to be increasing. This could be due to a decrease in Radiation use efficiency (RUE) with crop age, also known as the reduced growth phenomenon (RGP) (Canegro simulate RGP partially by increased maintenance respiration and lodging) (Park et al., 2005; Jones, Singels, 2018), as well as it also gets lengthened to achieve an appropriate temperature regime for the accumulation of sucrose. The SM on the other hand in CANEGRO is affected by temperature and water stress (temperature response determined by FTCON species parameter (Table S4). Similar findings were obtained by Jones et al. (2015) as a result of a combination of the increased rate of maintenance respiration, assimilated demand for structural growth, and response of photosynthesis to increased temperature. Sugarcane requires a low-temperature period during the ripening phase (12–14 °C) which is important for the enrichment of sucrose (Fageria, Moreira, 2011). Because of the consistent warming projected in the future period, the subsequent decline in SM could be explained. Further, the temperature rise may break sucrose into glucose and fructose, additionally causing increased photorespiration that in turn cause a reduction in sugar accumulation. An increase in temperature leads to low sugar content in stalks (Jones et al., 2015; Sonkar et al., 2020). Nevertheless, the change in SFM and SM varied along with states, scenarios, and periods indicating regional disparity in crop response.

Sugarcane's vegetative phase has an optimal water requirement, failure to meet the desired water content will adversely affect the vegetative growth. The projected decline in RF thus will act as a limiting factor for overall SFM and SM. Thus, the impacts of climate change like rising temperature and shifts in precipitation regime were found to be adversely impacting the SFM and SM.

4.4. Uncertainty and limitations of the study

The use of climate model projections and crop simulation models is accompanied by inherent uncertainties subject to the intricate complexities of the models used (Lobell and Gourdji, 2012; Wang et al., 2017; Rahman et al., 2018; Zhang et al., 2019). Thus, it becomes mandatory to address the uncertainty generated by the results. To overcome the range of uncertainty arising due to the climate model, a multi-model approach was adopted in the study, yet substantial scope lies in the use of a greater number of climate models to improve the reliability of the results. Further, the simulation results obtained from CANEGRO can be advanced using a combination of other crop simulation models to cover the range of outputs and simulations. This helps in optimizing the yield parameters and their concordance with observed field data. It was assumed that the crop was grown under no stress conditions, adding another limitation to this conundrum. Because the impact of pest infections, weeds and diseases on a crop along with other weather events like a heatwave and cold wave, flood drought etc. conceives a potential to impact the yield and phenology response of the sugarcane along with weather parameters. A single crop variety also accounts for the limitation, for example, the use of different varieties and varied sowing dates can result in a significant yield response to the changing climate. Further, the crop simulation model uses a baseline CO_2 concentration of 380 ppm, which limits the understanding of crop response at elevated concentrations. Therefore, keeping in mind the encompassed uncertainties further research can be conducted for more comprehensive results.

5. Conclusion

The present study utilizes state of the art multimodal climate and crop simulation models to predict the change in Sugarcane's SFM and SM under different climate change scenarios for major sugarcane growing regions of India. In the very first national level comprehensive study of its type over India, the study reveals a significant rise in temperature (T_{max} and T_{min}) with a higher increment projected in T_{min} in all the scenarios. The increase intensifies under RCP 8.5 in far future scenario. However, the magnitude of the increase was limited in the tropical states of AP, TN, KA and MH. Srad shows a solar dimming in the subtropical states of India mainly the states covering the Indo-Gangetic plain. RF doesn't show any significant change in future. The study found a shortening of phenological phases from planting to emergence and emergence to stalk elongation possibly in response to the rising temperature. Whereas, the peak population to harvesting phase was extended in all scenarios. The important economical marker of sugarcane such as SFM shows an increase under all the climate change scenarios with higher magnitude in the mid-future, particularly for GJ and the minimum increase is projected over OD. Another important component of sugarcane's overall economic value, i.e SM is projected to show a reduction across major sugarcane growing regions of India except for states of UP, MH, GJ, and AP where it was found to be decreasing only under RCP8.5 during far-future. The tropical states of MH, GJ, and AP offer a complementary increase in Srad along with the rise in temperature that could offset the reduction in SM. The present study emphasizes that the sucrose recovery of major producing states needs to be compensated through reliable solutions. To maintain its position as a leading producer as well as consumer of sugarcane it becomes imperative for India to invest in the development of new heat and drought-tolerant varieties to compensate for the loss. Identification of new sources of sugar production, increasing efficiency of sugar mills, timely marketing of harvested canes and processing options are also the aspects that need to be emphasized.

Funding

The authors thank the Climate Change Programme, Department of Science and Technology, New Delhi, for financial support (DST/CCP/CoE/80/2017(G)).

CRediT authorship contribution statement

Rohit K. Jaiswal: Methodology, Investigation, Formal analysis, Visualization, Data curation, Software, Validation, Writing - original draft. **R.K. Mall:** Conceptualization, Methodology, Supervision, Resources, Funding acquisition, Project administration, Writing - review & editing. **Shubhi Patel:** Formal analysis, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors wish to thank the Climate Change Programme, Department of Science and Technology, New Delhi for providing financial support (Award no.: DST/CCP/CoE/ 80/2017(G)). Authors are gratefully acknowledging the World Climate Research Programme's Working Groups, the former coordinating body of CORDEX and CMIP5. The climate modeling groups are sincerely thanked for producing and making available their model output. The authors thank the Earth System Grid Federation (ESGF) infrastructure and the Climate Data Portal hosted at the Centre for Climate Change Research (CCCR), Indian Institute of Tropical Meteorology (IITM) for providing CORDEX South Asia data (http://cccr.tropmet.res.in/home/esgf_node.jsp). The authors wish to thank the India Meteorology Department (IMD) for making available the observation dataset (http://www.imdpune.gov.in/Clim_Pred_LRF_New/ Grided_Data_Download.html).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126760.

References

Ahmad, S., Nadeem, M., Abbas, G., Fatima, Z., Zeb Khan, R., Ahmed, M., Ahmad, A., Rasul, G., Azam Khan, M., 2016. Quantification of the effects of climate warming and crop management on sugarcane phenology. Clim. Res. 71 (1), 47–61. https://doi.org/10.3354/cr01419.

Carvalho, A.L. de, Menezes, Rô, S.C., Nóbrega, R.S., Pinto, A., de, S., Ometto, J.P.H.B., von Randow, C., Giarolla, A., 2015. Impact of climate changes on potential sugarcane yield in Pernambuco, northeastern region of Brazil. Renew. Energy 78, 26–34. https://doi.org/10.1016/J.RENENE.2014.12.023.

Challinor, A., Watson, J., Lobell, D., Howden, S., Smith, D., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4, 287–291.

Chandran, A.B., Anushree, K.N., 2016. Climate change and sugarcane productivity in Karnataka. In: Climate Change Challenge (3C) and Social-Economic-Ecological Interface-Building. Springer, Cham, pp. 389–399.

Chaubey, P.K., Mall, R.K., Jaiswal, R., Payra, S., 2022. Spatio-temporal changes in extreme rainfall events over different Indian river basins. In: Earth and Space Science, 9. AGU. https://doi.org/10.1029/2021EA001930.

de Medeiros Silva, W.K., de Freitas, G.P., Coelho Junior, L.M., de Almeida Pinto, P.A.L., Abrahão, R., 2019. Effects of climate change on sugarcane production in the state of Paraíba (Brazil): a panel data approach (1990–2015). Clim. Change 154 (1–2), 195–209. https://doi.org/10.1007/s10584-019-02424-7.

DES, 2016. Pocket Book of Agricultural Statistics 2016. Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India, New Delhi. 〈https://https://eands.dacnet.nic.in/PDF/Agricultural_Statistics_2016.pdf〉.

DES, 2021. Pocket Book of Agricultural Statistics 2020. Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India,, New Delhi. 〈https://eands.dacnet.nic.in/PDF/Pocket%202020-%20Final%20web%20file.pdf〉.

Fageria, N.K., Moreira, A., 2011. The role of mineral nutrition on root growth of crop plants. Adv. Agron. 110 (Issue C), 251–331. https://doi.org/10.1016/B978-0-12-385531-2.00004-9.

FAO. (2019). 〈https://www.fao.org/faostat/en/#data/QCL〉.

Hargreaves, G.H., Samani, Z.A., 1985. Reference Crop Evapotranspiration from Ambient Air Temperature. American Society of Agricultural Engineers.

He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Zhuang, W., Jin, N., Yu, Q., 2015. Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. Agric. For. Meteorol. 200, 135–143. https://doi.org/10.1016/J.AGRFORMET.2014.09.011.

Hoogenboom, G., Porter, C. H., Boote, K. J., Shelia, V., Wilkens, P. W., Singh, U., White, J. W., Asseng, S., Lizaso, J. I., Moreno, L. P., Pavan, W., Ogoshi, R., Hunt, L. A., Tsuji, G. Y., & Jones, J. W. 2019. The DSSAT Crop Modeling Ecosystem, 173–216. doi: 10.19103/AS.2019.0061.10.

Inman-Bamber, N.G., 1991. A growth model for sugar-cane based on a simple carbon balance and the CERES• maize water balance. South Afr. J. Plant Soil 8 (2). https://doi.org/10.10520/AJA02571862_390.

IPCC, 2021. Climate Change 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jaiswal, R., Mall, R.K., Singh, N., Lakshmi Kumar, T.V., Niyogi, D., 2022. Evaluation of bias correction methods for regional climate models: downscaled Rainfall analysis over diverse agroclimatic zones of India. Earth Space Sci. https://doi.org/10.1029/2021EA001981.

Jones, M.R., Singels, A., Ruane, A.C., 2015. Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. Agric. Syst. 139, 260–270. https://doi.org/10.1016/j.agsy.2015.07.007.

Jones, Matthew R., Singels, A., 2018. Refining the Canegro model for improved simulation of climate change impacts on sugarcane. Eur. J. Agron. 100, 76–86. https://doi.org/10.1016/j.eja.2017.12.009.

Jyoti, B., Singh, A.K., 2020. Projected sugarcane yield in different climate change scenarios in Indian states: a state-wise panel data exploration. Int. J. Food Agric. Econ. 8 (4), 343–365.

Kumar, A., Sharma, P., 2014. Climate change and sugarcane productivity in India: an econometric analysis. J. Soc. Dev. Sci. 5 (2), 111–122.

Kumar, A., Sharma, P., Ambrammal, S.K., 2015. Climatic effects on sugarcane productivity in India: a stochastic production function application. Int. J. Econ. Bus. Res. 10 (2), 179. https://doi.org/10.1504/IJEBR.2015.070984.

Lobell, D.B., Gourdji, S.M., 2012. The influence of climate change on global crop productivity. Plant Physiol. 160 (4), 1686–1697. https://doi.org/10.1104/pp.112.208298.

Malan, C., Baartman, J., Berner, J.M., Patton, A., Hoffman, N., Singels, A., van Heerden, P.D.R., 2017. Effects of elevated CO2 on stomatal conductance, biomass partitioning and yield of sugarcane grown in absence of soil water deficit. In: Proceedings of the Second Agriculture and Climate Change Congress. March 2017, Sitges, Spain, Poster Paper, 26–28.

Mall, R.K., Chaturvedi, M., Singh, N., Bhatla, R., Singh, R.S., Gupta, A., Niyogi, D., 2021. Evidence of asymmetric change in diurnal temperature range in recent decades over different agro-climatic zones of India. Int. J. Climatol. 41 (4), 2597–2610. https://doi.org/10.1002/JOC.6978.

Mall, R.K., Singh, N., Singh, K.K., Sonkar, G., Gupta, A., 2018. Evaluating the performance of RegCM4.0 climate model for climate change impact assessment on wheat and rice crop in diverse agro-climatic zones of Uttar Pradesh, India. Clim. Change 149 (3), 503–515. https://doi.org/10.1007/s10584-018-2255-6.

Mall, R.K., Sonkar, G., Bhatt, D., Sharma, N.K., Baxla, A.K., Singh, K.K., 2016. Managing impact of extreme weather events in sugarcane in different agro-climatic zones of Uttar Pradesh. Mausam 67 (1), 233–250. https://doi.org/10.54302/mausam.v67i1.1187.

Marin, F.R., Thorburn, P.J., Nassif, D.S., Costa, L.G., 2015. Sugarcane model intercomparison: structural differences and uncertainties under current and potential future climates. Environ. Model. Softw. 72, 372–386.

Padma Kumari, B., Goswami, B.N., 2010. Seminal role of clouds on solar dimming over the Indian monsoon region. Geophys. Res. Lett. 37 (6) https://doi.org/10.1029/2009GL042133.

Park, S.E., Robertson, M., Inman-Bamber, N.G., 2005. Decline in the growth of a sugarcane crop with age under high input conditions. Field Crops Res. 92 (2–3), 305–320.

Rahman, M.H. ur, Ahmad, A., Wang, X., Wajid, A., Nasim, W., Hussain, M., Ahmad, B., Ahmad, I., Ali, Z., Ishaque, W., Awais, M., Shelia, V., Ahmad, S., Fahd, S., Alam, M., Ullah, H., Hoogenboom, G., 2018. Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. Agric. For. Meteorol. 253–254, 94–113. https://doi.org/10.1016/j.agrformet.2018.02.008.

Ramachandran, A., Praveen, D., Jaganathan, R., Rajalakshmi, D., Palanivelu, K., 2017. Spatiotemporal analysis of projected impacts of climate change on the major C3 and C4 crop yield under representative concentration pathway 4.5: insight from the coasts of Tamil Nadu, South India. PLoS One 12 (7). https://doi.org/10.1371/journal.pone.0180706.

Ruan, H., Feng, P., Wang, B., Xing, H., O'Leary, G.J., Huang, Z., Guo, H., Liu, D.L., 2018. Future climate change projects positive impacts on sugarcane productivity in southern China. Eur. J. Agron. 96, 108–119. https://doi.org/10.1016/j.eja.2018.03.007.

Ruane, A.C., McDermid, S., Rosenzweig, C., Baigorria, G.A., Jones, J.W., Romero, C.C., DeWayne Cecil, L., 2014. Carbon-temperature-water change analysis for peanut production under climate change: a prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3MP). Glob. Change Biol. 20 (2), 394–407. https://doi.org/10.1111/gcb.12412.

Rupkumar, K., Subbaramayya, L., 1980. Crop-weather relationship of sugarcane and yield prediction in northsouth Andhra Pradesh. J. Agric. Meteorol. 〈https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Crop-weather+relationship+of+sugarcane+and+yield+prediction+in+north-south+Andhra+Pradesh&btnG=〉.

Shukla, S.K., Sharma, L., Awasthi, S.K., Pathak, A.D., 2017. Sugarcane in India: package of practices for different agro-climatic zones(ICAR). AICRP (S) Tech. Bull. 1, 1–64.

Singels, A., Donaldson, R.A., 2000. A simple model of unstressed sugarcane canopy development. Proc. S Afr. Sugar Technol. Ass Vol. 74, 151–154.

Singels, A., Jones, M., Marin, F., Ruane, A., Thorburn, P., 2014. Predicting climate change impacts on sugarcane production at sites in Australia, Brazil and South Africa using the Canegro Model. Sugar Tech 16 (4), 347–355. https://doi.org/10.1007/s12355-013-0274-1.

Singh, J., Mishra, S.K., Kingra, P.K., Singh, K., Biswas, B., Singh, V., 2018. Evaluation of DSSAT-CANEGRO model for phenology and yield attributes of sugarcane grown in different agroclimatic zones of Punjab, India. J. Agrometeorol. 20 (4), 280–285.

Singh, S., Mall, R.K., Dadich, J., Verma, S., Singh, J.V., Gupta, A., 2021c. Evaluation of CORDEX- South Asia regional climate models for heat wave simulations over India. Atmospheric Research 248, 105228. https://doi.org/10.1016/J.ATMOSRES.2020.105228.

Singh, K.K., Mall, R.K., Singh, R.S., Srivastava, A.K., 2010. Evaluation of CANEGRO sugarcane model in east Uttar Pradesh India. J. Agrometeorol. 12 (2), 181–186.

Singh, H., Mishra, S.K., Singh, K., Singh, K., Pal, R.K., Gill, K.K., Kingra, P.K., 2021a. Simulating the impact of climate change on sugarcane production in Punjab. J. Agrometeorol. 23 (3), 292–298.

Singh, S., Mall, R. K., & Singh, N. (2021b). Changing spatio-temporal trends of heat wave and severe heat wave events over India: An emerging health hazard. *International Journal of Climatology*, 41(S1), E1831–E1845. https://doi.org/10.1002/joc.6814.

Sonkar, G., Mall, R.K., Banerjee, T., Singh, N., Kumar, T.L., Chand, R., 2019. Vulnerability of Indian wheat against rising temperature and aerosol. Environ. Pollut. 254, 112946 https://doi.org/10.1016/j.envpol.2019.07.114.

Sonkar, G., Singh, N., Mall, R.K., Singh, K.K., Gupta, A., 2020. Simulating the impacts of climate change on sugarcane in diverse agro-climatic zones of Northern India using CANEGRO-Sugarcane Model. Sugar Tech. 22 (3), 460–472. https://doi.org/10.1007/s12355-019-00787-w.

Sparks, T.H., Jeffree, E.P., Jeffree, C.E., 2000. An examination of the relationship between flowering times and temperature at the national scale using long-term phenological records from the UK. Int. J. Biometeorol. 44 (2), 82–87. https://doi.org/10.1007/S004840000049.

Stokes, C.J., Inman-Bamber, N.G., Everingham, Y.L., Sexton, J., 2016. Measuring and modelling CO_2 effects on sugarcane. Environ. Model. Softw. 78, 68–78.

Verma, R.R., Srivastava, T.K., Singh, P., 2019. Climate change impacts on rainfall and temperature in sugarcane growing Upper Gangetic Plains of India. Theor. Appl. Climatol. 135 (1–2), 279–292. https://doi.org/10.1007/s00704-018-2378-8.

Wang, E., Martre, P., Zhao, Z., Ewert, F., Maiorano, A., Rötter, R.P., Kimball, B.A., Ottman, M.J., Wall, G.W., White, J.W., Reynolds, M.P., Alderman, P.D., Aggarwal, P.K., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A.J., De Sanctis, G., Asseng, S., 2017. The uncertainty of crop yield projections is reduced by

improved temperature response functions. Nat. Plants 3 (8), 17102. https://doi.org/10.1038/nplants.2017.102.
Zhang, H., Zhou, G., Liu, D.L., Wang, B., Xiao, D., He, L., 2019. Climate-associated rice yield change in the Northeast China Plain: a simulation analysis based on CMIP5 multi-model ensemble projection. Sci. Total Environ. 666, 126–138. https://doi.org/10.1016/j.scitotenv.2019.01.415.
Zhao, D., Li, Y.-R., 2015. Climate change and sugarcane production: potential impact and mitigation strategies. Int. J. Agron. 2015, 1–10. https://doi.org/10.1155/2015/547386.