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RESEARCH ARTICLE

Simulating the Impacts of Climate Change on Sugarcane in Diverse Agro-climatic Zones of Northern India Using CANEGRO-Sugarcane Model

Geetika Sonkar[1] · Nidhi Singh[1] · R. K. Mall[1] · K. K. Singh[2] · Akhilesh Gupta[3]

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Abstract CANEGRO-Sugarcane model was used to assess the impact of climate change on sugarcane in different combinations of elevated temperature and CO_2 concentrations. Additionally, we used dynamically downscaled bias-corrected regional climate model (RCM) data using RegCM4 under RCP4.5 scenario (2040–2060) to project the future change in sugarcane stalk fresh mass (SFM) and sucrose mass (SM). The results showed an increase in temperature, rainfall and solar radiation in the future projections at the study site. The SFM and SM were found to be vulnerable (3–25% decrease) by increasing temperature (1–4 °C), however, a higher concentration (2–14% increase) was observed for both SFM and SM under elevated CO_2 levels (450–850 ppm). The combined effect of increased temperature and elevated CO_2 had a beneficial effect on SFM but negative on SM (more for rainfed condition). Overall, SFM was projected to increase by 3–39% (rainfed) and 7–47% (irrigated) in 2040–2060 relative to 1971–2000 in diverse agro-climatic zones of the region. Similarly, SM was projected to decrease by 9–69% (rainfed) and 6–37% (irrigated). In general, water stress conditions combined with the projected increase in temperature adversely affected the sugarcane. The findings suggest the development of a efficient water use, heat-tolerant cane variety and improved farm management strategies in the near future to assist the sugar industry and to adapt to the changing climate in northern India. This is required in the greater perspective of decrease in sucrose mass in spite of double-fold increase in CO_2.

Keywords Stalk fresh mass · Sucrose mass · RegCM4 · CANEGRO-Sugarcane

Introduction

It is likely that climate change can have a substantial impact on crop productivity and food security, which is considered as a major challenge and priority among the scientists (Aggarwal and Mall 2002; Mall et al. 2006; Lobell and Gourdji 2012; Srivastava and Rai 2012; Swaminathan and Bhavani 2013; Shrivastava et al. 2016, Ramachandran et al. 2017; Mall et al. 2018; Singh et al. 2018b; Rao 2018; Misra et al. 2019; Kalra and Kumar 2019; Gao et al. 2019). Scientific evidences support a warming trend and change in rainfall pattern over different parts of the world including India (Guhathakurta and Rajeevan 2008; IMD 2012; Kothawale et al. 2012; Bhatt et al. 2015; Oza and Kishtawal 2015; Asfaw et al. 2018; Dimri 2018; Zaz et al. 2019). It is also being observed that the frequency of cold days has decreased and hot days have increased (Dash and Mamgain 2011).

According to IPCC (2013), the global average temperature for the period 1800–2012 has shown an increment of 0.85 °C (95% CI 0.65 ± 1.06 °C), and by the end of twenty-first century, it is further projected to increase by

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✉ R. K. Mall
rkmall@bhu.ac.in

[1] DST-Mahamana Centre of Excellence in Climate Change Research, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi 221005, India

[2] Agromet Division, India Meteorological Department, New Delhi, India

[3] Department of Science and Technology, New Delhi, India

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0.3 ± 1.7 °C (RCP 2.6), 1.1 ± 2.6 °C (RCP 4.5), 1.4 ± 3.1 °C (RCP 6.0) and 2.6 ± 4.8 °C (RCP 8.5) relative to 1986 ± 2005. This increase in global mean temperature and the associated extreme events may have severe consequences for the agriculture sector (Rao et al. 2016; Pathak et al. 2019). The global CO_2 has recently crossed the level of 408 ppm in November 2018 (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html), which is projected to reach 730–1020 ppm toward the end of the twenty-first century (IPCC 2013). The recent climate projections for India have shown that it will experience the rise in surface temperature beyond 5 °C by the end of twenty-first century (Basha et al. 2017). However, large uncertainty exists in the confidence in magnitude of climate change at regional and local scales; still, there resides a scope for possible climate impact assessment on agricultural sector helping to formulate early and robust response strategies (Rao et al. 2016, 2017).

Sugarcane is a major and economically important cash crop in the world in terms of production contributing approximately 75% of sugar production in the world (Kumar et al. 2019). India ranks second and is the largest producer of sugarcane occupying 4.73 mha cultivating area with 376.90 million tons of cane production (DES 2018) (http://www.agricoop.nic.in), wherein the state of Uttar Pradesh using 47% of the sugarcane area in the whole country (DES 2018). Sugarcane (*Saccharum* sp.) is mainly grown in the tropical and subtropical countries and has C_4 mechanism that fixes carbon, and sucrose is the main essence of this crop, which makes it economically important (Verma et al. 2019). This crop is widely affected by weather, viz. temperature, precipitation, atmospheric CO_2 concentration and extreme weather events (Kushwaha and Pal 2000; Srivastava and Rai 2012; Singels et al. 2014; Mall et al. 2016; Hussain et al. 2018; Ruan et al. 2018). High temperature and water stress in sugarcane may cause a drastic impact during the growth stages (germination, flowering and maturity) of the crop (Sanghera et al. 2019; Verma et al. 2019; Sanghera et al. 2018). In order to meet the growing demand of sugar and energy by 2050, around 630 million tonnes of sugarcane production with a sugar recovery of 11.5% (presently 10.5%) will be required. The increased production has to be achieved from the existing cane area (5.2 million ha) through improved productivity (presently 71–105 t/ha) and sugar recovery (11%) since further expansion in the cane area is not feasible (Solomon 2014; DES 2016). The average cane productivity in the state of Uttar Pradesh (UP) is 65 t/ha, and the average sugar recovery (10.23%) is lower than that of the national average. Therefore, there is still substantial scope to increase both productivity and sugar recovery of sugarcane crop in UP to meet the projected demand in 2050 (IISR 2015; Mall et al. 2016; DES 2016). Figure S1 shows the present and projected sugarcane production and sugar recovery in UP.

The impact of temperature, rainfall and elevated CO_2 considering climate change has been widely studied for sugarcane production (Silva et al. 2008; Chandiposha 2013; Misra et al. 2019; Verma et al. 2019). The negative response of extreme climate events (drought and tropical cyclones) on sugarcane and yields is evident from several studies (Zhao and Li 2015). The recent research by Ray et al. (2019) suggests that climate change has already affected several crops including sugarcane and is projected to decrease under future climate conditions. In India, Singh et al. (2019a) have estimated the variability of climatic factors on sugarcane production and yield and have found to have a negative impact. Kumar and Sharma (2014) and Kumar et al. (2015) found a negative association of climate change on the productivity, and it is projected to decline by 20% with every degree rise in temperature. Efficient management practices are required for the sustainable sugarcane production (Singh et al. 2018a, 2019b; Dhanapal et al. 2019). The projected impact of climate change showed that in South India, there will be a decline of 1.8%, 2.6% and 2.8% in the sugarcane yield for the near, mid- and end century periods (Ramachandran et al. 2017). In a study conducted for sugarcane response to elevated CO_2 concentration ($\sim$ 720 ppm), 30% increase in photosynthesis, 17% in height and 40% more biomass accumulation were observed (De Souza et al. 2008). As the increasing CO_2 on the one hand might have a beneficial impact, increasing temperature can adversely impact the sugarcane productivity. The expected change in rainfall pattern and water stress condition will further prove disastrous to water extensive crops such as sugarcane (Knox et al. 2010; Kumar et al. 2019; Pandey et al. 2019) raising future demand of more irrigational supply. In perspective of this, the agriculture sector would demand a more productive and water use efficient cane crop. The increased frequency and intensity of extreme weather events make the sugarcane production highly vulnerable (Gawander 2007; Gilbert et al. 2007; Knox et al. 2010; Chandiposha 2013; Bhaskaran and Nair 2014; Mall et al. 2016). Thus, it is important to understand the climate–CO_2–temperature nexus to understand how this crop will respond to these changes and plan robust adaptation strategies accordingly. This task though seems complex, can gain momentum with better understanding of the physiological response keeping in account the uncertainty in global climate.

Different crop-specific simulation models are in large use for the climate change impact assessment (Knox et al. 2010, Chunrong et al. 2017). FAO-AZM (dos Santos and Sentelhas 2014), CANEGRO-Sugarcane (Singh et al. 2010; Singels et al. 2014; Jones et al. 2015; Bhengra et al. 2016; Dias and Sentelhas 2017; Mishra et al. 2017; Singh et al.

2018b, c; Parmar et al. 2019) and QCANE (Zu et al. 2018) have been widely used for various applications. These crop models require input of climate data from climate models and on ground observations for climate change impact analysis (Biggs et al. 2013; Jones et al. 2015; Mi et al. 2017). The increase in sugarcane yield and sugar recovery can only be achieved by understanding the crop response to the changing climatic conditions (Hussain et al. 2018). The use of mechanistic crop simulation model is a better tool to deal with the existing problem that can give a better insight into the existing and upcoming challenges (Singels et al. 2014; Zu et al. 2018). These models could play a crucial role in the impact studies and for planning and decision making. Very few research has been performed on the impacts of climate change on sugarcane growth, yield and sugar content in India. In an attempt to provide some insight into the possible impact of climate change on sugarcane crop, the present study aims to analyze: (1) the present trend and future climate over nine agro-climatic zones of Uttar Pradesh; (2) impact assessment of climate change on sugarcane stalk fresh mass (SFM) and sucrose mass (SM) at different CO_2 levels (450–850 ppm) and thermal stress (1–4 °C) and their combined effect using CANEGRO-Sugarcane model under irrigated and rainfed conditions; and (3) the magnitude of impacts of climate change in midcentury (2040–2060) on sugarcane stalk fresh mass and sucrose mass using RegCM4 (RCP 4.5).

Materials and Methods

Study Area and Data

The impact assessment was done at nine agro-climatic zones of Uttar Pradesh (Fig. S2) using historical baseline period (1971–2000) and future period (2040–2060) climate projections from regional climate model (RegCM4 under RCP4.5). Model outputs were then analyzed and summarized in order to address the objectives of the study. The daily-observed long-term weather data (maximum and minimum temperature, rainfall and solar radiation) from 1971 to 2000 were obtained from the India Meteorological Department (IMD), New Delhi. Mid-future RCM climate data (2040–2060) for RegCM4 (LMDZ; 0.5 × 0.5 km) were obtained from CCCR-IITM developed by National Center for Atmospheric Research (NCAR), ICTP Italy in 2010 (Giorgi et al. 2012).

CANEGRO-Sugarcane Model and Input Data Used

The CANEGRO-Sugarcane model developed by Inman-Bamber (1991) was used for simulating the sugarcane growth, development and yield (Jones et al. 2003). The model simulates carbon, crop development and included components of energy and water. Daily partitioning of assimilation between roots and aerial parts is simulated as a nonlinear function of total biomass. Within the model, daily mean temperature is responsible for controlling the canopy development rate as a linear function of thermal time without any upper limit and maintenance respiration as an exponential increase with the increase in temperature (Singels et al. 2005). Photosynthesis rate too shows an increase in temperature but at a declining rate (Singels et al. 2005, 2014). Being affected by temperature and water stress, the sucrose distribution within stalks is the basis of the framework for the sucrose accumulation component of the model. The maximum sucrose contents in the base of stalk (t/ha) are kept as 0.58 for sucrose partitioning parameter (Singh et al. 2010). The model input requires daily weather parameters (maximum and minimum temperatures, solar radiation and rainfall), soil physical properties (pH, EC, bulk density, organic carbon, etc.), and phenological information (date of planting, emergence, flowering and maturity, cane yield, biomass, sucrose percent, cane number, etc.) and genetic trait parameters specific for the cultivar. The validated CANEGRO-Sugarcane model for this region by Singh et al. (2010) has been used for impact assessments (Table S2).

Impact Assessment Experiments

The present study was made to assess the impact on sugarcane productivity in perspective of different climate change scenarios. This follows analyzing the change in sugarcane stalk fresh mass and sucrose mass on exposure to different levels of increase in temperature and elevated CO_2 concentrations. The impact assessment was made in three different assumptions. In the first step, the temperature gradually increased from 1 to 4 °C. In the second step, CO_2 concentrations were increased from 450 to 850 ppm. The third step was to see the combined effect of different levels of temperature and CO_2 concentrations (Table 1).

The yields were simulated under different assumptions, assuming that the area of the crop remained same in the future as in baseline. The change in stalk fresh mass and sucrose content (percent) in different climate change assumptions was calculated from the baseline. Sugarcane is an annual crop normally sown in February–March. The crop yield was simulated at two levels of management (http://krishikosh.egranth.ac.in/handle/1/77530):

(a) Irrigated yield assuming application of total 120–150 kg N/ha (half of N at the time of planting as basal and rest at 80–90 days after planting) and six irrigations as required during the cropping season.

Table 1 Hypothetical level of rising temperature and CO_2 over diverse agroclimatic zones of Uttar Pradesh, India

Scenarios	Parameters
Baseline (1971–2000)	Daily data inclusive of maximum and minimum temperatures, rainfall, solar radiation, fixed at CO_2 = 380 ppm during sugarcane growing season
Change in temperature (°C)	+ 1, + 2, + 3 and + 4
Change in CO_2 levels (ppm)	450, 500, 550, 600, 650, 700, 750, 800, 850 ppm
Combined changes of temperature (°C) and CO_2	Temperature + 1 with different levels of CO_2 (450–850)
	Temperature + 2 with different levels of CO_2 (450–850)
	Temperature + 3 with different levels of CO_2 (450–850)
	Temperature + 4 with different levels of CO_2 (450–850)
IPCC RCP scenarios (combined changes of temperature and CO_2)	
RCP 4.5	1.4 °C + 650 ppm
RCP 6.0	1.3 °C + 850 ppm
RCP 8.5	2.0 °C + 1370 ppm
RegCM4 model output for midcentury for RCP 4.5 (2041–2060)	Daily maximum and minimum temperatures, rainfall, solar radiation

(b) Rainfed productivity assuming application of 100–110 kg N/ha (half of the N as a basal dose at the time of planting and rest of the nitrogen at the grand phase) and assuming no irrigations.

The Climate Change Scenario

The baseline (1971–2000) and projected (2040–2060) climate data from regional climate model (RegCM4) developed by the National Center for Atmospheric Research (NCAR) were used for the study (Giorgi et al. 2012). These data with a 50-km resolution have been downloaded for the Representative Concentration Pathway (RCP) 4.5 scenario from Centre for Climate Change Research, Indian Institute of Tropical Meteorology (IITM), Pune, India, for the South Asia Domain. The calibrated and validated CANEGRO-Sugarcane model was used for simulating the baseline yield and future yield for different agro-climatic zones of the state. Scientific research infers that regional climate model (RCM) outputs do not convincingly account for several physical processes (Maraun 2016). Inappropriate conceptualization, parameterization and spatial averaging within grid cells make them inherit systematic model errors (Qian et al. 2016). On account of this, the RCM (RegCM4) climate data used in the study were first bias-corrected following the methods suggested by Qian et al. (2016). The quantile mapping method was applied in the study to remove the biasness.

The first step includes fitting a cumulative probability distribution (CDF) F_{obs} (X_{obs}) to the observed station data, and another distribution $F_{grid\text{-}p}$ ($X_{grid\text{-}p}$) was fit to the RCM grid data. The "bias-corrected" grid data $X_{grid\text{-}p\text{-}corrected}$ were then obtained by mapping the values in a grid to the probability distribution of the observed under the current climate as follows:

$$X_{grid-p-corrected} = F_{obs}^{-1}\left(F_{grid-p}\left(X_{grid-p}\right)\right)$$

In the second step, we then followed the equidistant CDF matching method (Li et al. 2010; Qian et al. 2016) to bias correct the future RCM data (2040–2060) using the assumption that the difference that exists between the observed and model (RCM) values under current climate will be followed up in the future. Thus, the bias-corrected future RCM data $X_{grid\text{-}f\text{-}corrected}$ can be derived as:

$$X_{grid-f-corrected} = X_{grid-f} + F_{obs}^{-1}\left(F_{grid-f}\left(X_{grid-f}\right)\right) - F_{grid-c}^{-1}\left(F_{grid-f}\left(X_{grid-f}\right)\right)$$

where $F_{grid\text{-}f}(X_{grid\text{-}f})$ represents the CDF of the model (RCM) data $X_{grid\text{-}f}$ at the model (RCM).

Results and Discussion

Climate Variability and Projected Future Change Over Diverse Agro-Climatic Zones

The annual maximum and minimum daily temperature for 1971–2000 at different agro-climatic zones ranged between 27.0 and 32.6 °C and 14.3 and 19.5 °C, respectively (Table S1). Moving from southeast (VZ) to northwest (BTZ) of the state, there was a gradual decrease in the observed annual maximum and minimum temperature. Figure S3 shows an overall increasing trend in annual minimum temperature over all nine agro-climatic zones; however, a decreasing (increasing) trend in the maximum temperature over several zones (BTZ, WPZ, MWZ, SWZ) was observed. Figure S4 shows the changes in temperature projected by RegCM4 under RCP4.5, relative to the baseline period at different agro-climatic zones. Overall, our results indicated the increase in annual maximum and minimum temperature between 1.4–2.6 °C and 1.6–2.4 °C, respectively, for 2040–2060. The observed annual total rainfall for 1971–2000 at different agro-climatic zones ranged between 713 and 1415 mm (Table S1). Overall, RegCM4 projections show an increase in annual rainfall and rainy days in 2040–2060; however, a decrease in rainy days in MWZ was observed (Fig. S4). There is an increase in coefficient of variation (CVs) pointing to higher inter-annual rainfall variability in the future. The annual daily solar radiation for 1971–2000 at different agro-climatic zones was ranging between 16.4 and 21.1 $MJ/m^2/day$ (Table S1). Overall, RegCM4 projection does not show a significant change in 2040–2060 under RCP4.5 scenario (Fig. S4).

Sugarcane Stalk Fresh Mass (SFM) and Sucrose Mass (SM) in Different Scenarios (CO_2 Sensitivity and Thermal Stress)

Under this section of the study, for different levels of thermal stress and CO_2 concentrations, the sensitivity of SFM and SM was assessed. The SFM under rainfed (~ 3% at 1 °C to ~ 13% at 4 °C) condition and SM under irrigated (~ 5% at 1 °C to ~ 25%) and rainfed (~ 10% at 1 °C to ~ 40%) conditions showed a gradual decline with the subsequent increase in the temperature for all the respective zones. Under the irrigated condition, a mixed result was obtained where some zones showed an increase (~ 2% at 1 °C) in the SFM and others (BKZ, SWZ and VZ) showed a decrease (~ 7% at 4 °C) (Fig. 1). The findings of our study are consistent with de Carvalho et al. (2015) that showed reduced sugarcane yield in Brazil (A1B scenario for 2040–2060) primarily due to increased temperature causing increased evapotranspiration rate and reduction in water availability creating the need for more irrigational water. A supporting observation also comes from Jones et al. (2015) suggesting negative impact on sucrose content due to the increased temperature.

Interestingly, SFM and SM showed a gradual increase with the subsequent increase in CO_2 level both in irrigated (~ 2% at 450 ppm to ~ 14% at 850 ppm) and in rainfed conditions (~ 1% at 450 ppm to ~ 10% at 850 ppm) (Fig. 1). However, the increase in rainfed condition is less than the irrigated condition. General positive observations include an enhancement in CO_2 exchange rate (35%), water use efficiency (62% and 69–79%) and decline in stomatal conductance (37% and 41–43%) under elevated CO_2 conditions, though the impacts were nonlinear and growth stage specific (De Souza et al. 2008; de Carvalho et al. 2015).

Under the combined effect of temperature and CO_2, an overall increase (2–8%) of SFM in irrigated (more) and rainfed (less) conditions was observed to be less than independent effect of CO_2 (Fig. 2). At 1 °C and different CO_2 levels, the SFM increases. However, the temperature increase from 3 to 4 °C with different CO_2 levels, the gradual decline in SFM was observed. Moreover, the SM showed an overall decline (gradually) with gradual increase in temperature, but a large heterogeneity was observed in response to increase by 3 °C and 4 °C with different combinations of CO_2 (Fig. 3). As was observed in case of SFM, the decline in SM were comparatively higher in the rainfed condition. The study was supported by Vu et al. (2009), Zhao and Li (2015) and De Souza et al. (2008) who observed a greater increase in stem biomass (60%), stem fresh weight (55%), stalk fresh mass (24%), leaf area (50%), sucrose content (29%), higher sucrose production, less use of water, increased water use efficiency (34%), stem juice volume (124%) and sugarcane yield (15–59%) using combination of doubled CO_2 and high temperature particularly due to the increase in overall plant area. The increased plant area will increase the cumulative photosynthetic capability of the crop that will have an explicit role in increasing total biomass accumulation, production of stem juice and stem sugars (de Carvalho et al. 2015). The combined effect of elevated CO_2 and temperature increases the activity of phosphoenolpyruvate carboxylase enzyme (23–32%) and ribulose bisphosphate carboxylase oxygenase (15–28%) and thus the cane yield (Vu et al. 2009). The increase in sucrose content is suggested to be mainly governed by increased differential expression of genes responsible for photosynthesis and development (De Souza et al. 2008; Wang et al. 2017). Contrary, for combined temperature and CO_2 effect an increase up to 20% in stalk fresh mass and reduction in sucrose content (36%) and sucrose mass (33%) was observed by Singels et al. (2014).

The ripening phase of sugarcane is favored by low air temperatures and moderate water deficits (Alexander 1973). The low temperature and water stress decrease the growth rates such that less sugar is allocated to new parts and much is stored in the form of sucrose. It is during this phase when there is a gradual increase in sucrose levels in stalks and decrease in glucose and fructose percentage (Clements 1962; Cardozo and Sentelhas 2013). Thus, a warming during the ripening phase can decrease the sucrose mass as was observed in the present study.

About 80–90% sugarcane area is covered under irrigation, and therefore, only 10% sugarcane crop depends on the rainfall (Bhattacharya 2011). It is likely that the India (UP) will witness an increase in sugarcane production

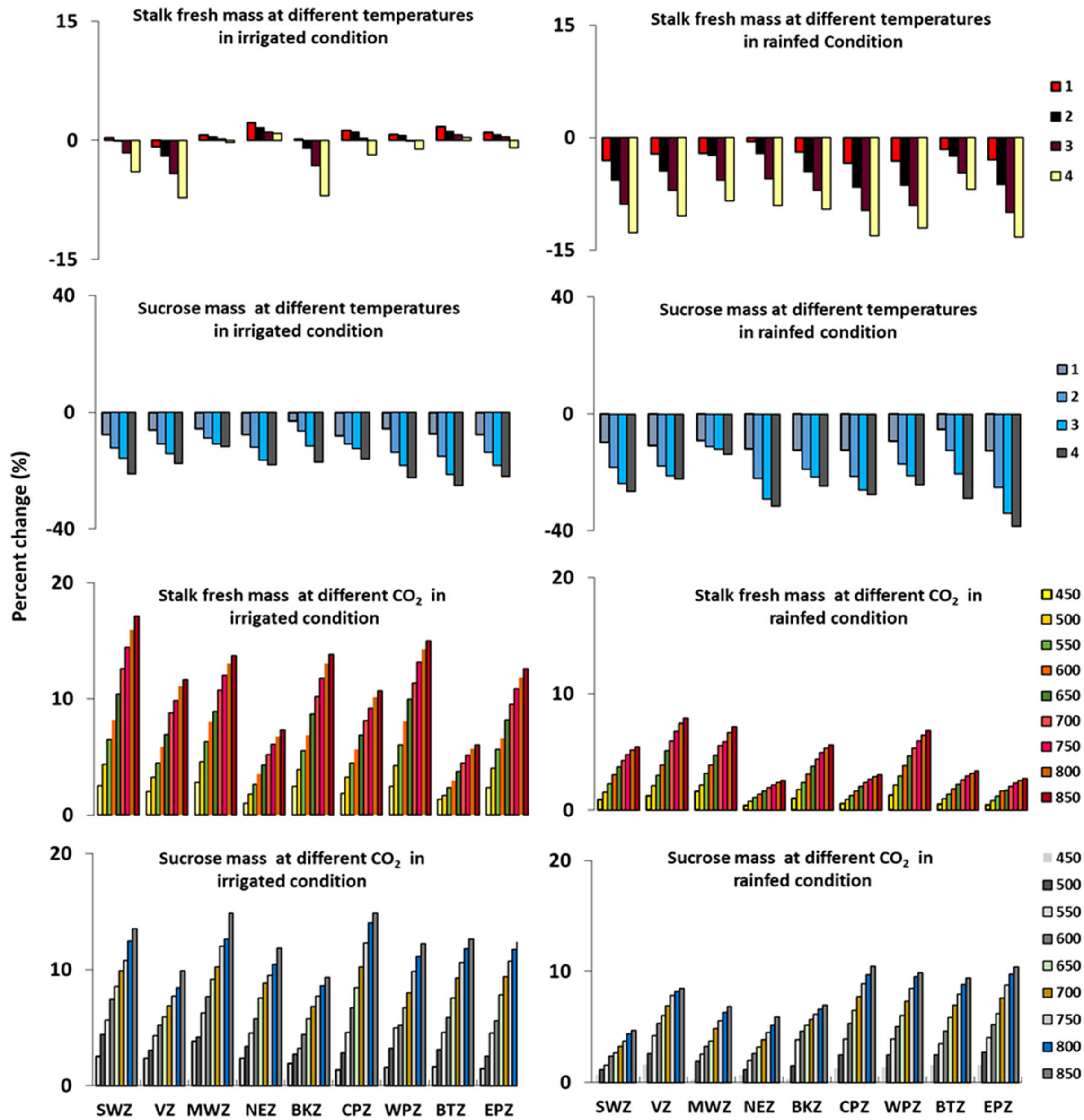


Fig. 1 Simulated change in SFM (%) and SM (%) at different CO_2 and temperature levels in the irrigated and rainfed conditions. The abbreviations of nine agro-climatic zones are *SWZ* South-Western Zone, *VZ* Vindhyan Zone, *MWZ* Mid Western Plain Zone, *NEZ* North Eastern Plain Zone, *BKZ* Bundelkhand Zone, *CPZ* Central Plain Zone, *WPZ* Western Plain Zone, *BTZ* Bhabhar and Tarai Zone and *EPZ* Eastern Plain Zone

without expanding the growing area. Temperature at different growth phases of the cane development influences the sucrose accumulation. A clear demarcation seen in our study is the reduced benefit of CO_2 fertilization effect and temperature in the rainfed SFM and SM. This supports the general finding that decreased water availability in the future can intervene the benefits to sugarcane yield. The fact being cane crop requires optimum rains during the vegetative growth phase that enhances growth, elongation and internodes formation (Srivastava and Rai 2012). A reduced water demand is for the ripening phase responsible for good-quality juice. Thus, as the drought condition in early and mid-growth stages may cause reduction in cane yield (low sucrose yield), in the late growth stages, a moderate drought can improve the sucrose content within stalks. In our study, we did not observe any specific spatial trend and the impact assessment showed heterogeneous results for different agro-climatic zones of Uttar Pradesh.

Projected Changes in Sugarcane Stalk Fresh Mass and Sucrose Mass

Figure 4 shows projected change in irrigated and rainfed stalk fresh mass (SFM) and sucrose mass (SM) under the

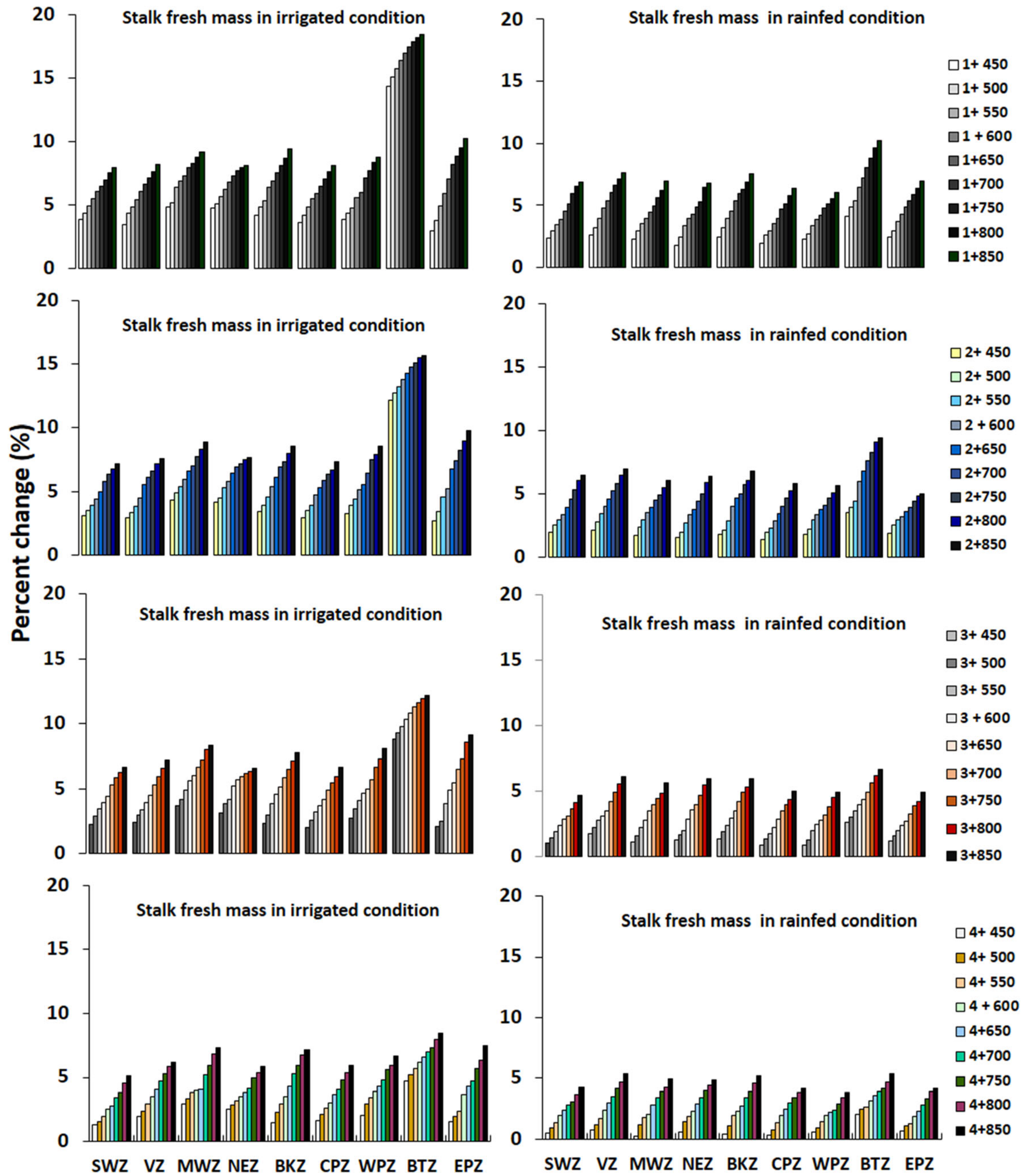


Fig. 2 Simulated change in SFM (%) due to the combined effect of temperature and CO_2 under the irrigated and rainfed conditions

RCP4.5 scenario during 2040–2060. As observed in the impact assessment ("Projected Changes in Sugarcane Stalk Fresh Mass and Sucrose Mass" section), the SFM shows an increase, while SM shows a decrease relative to baseline. The increase in SFM was higher in irrigated (7% in EPZ to 47% in BTZ) compared to rainfed (3% in EPZ to 39% in BTZ). Similarly, the decline in SM was higher in rainfed (− 9% in VZ to − 69% in BKZ) than in irrigated (− 6% in VZ to − 37% in BTZ). SFM shows an increase due to the increased interception of radiation from accelerated canopy development as well as increased radiation use efficiency and evapotranspiration. However, in BKZ, the SFM is expected to decrease due to the increased interception of radiation with acute water stress condition. Consistent with our study, an increase in SFM was reported for all the scenarios (Marin et al. 2013).

In a similar study over Brazil, de Carvalho et al. (2015) proposed that a loss in potential sugarcane productivity as high as 23% would be observed in 2041 to 2070. Ruan et al. (2018) in their study over Southern China found that

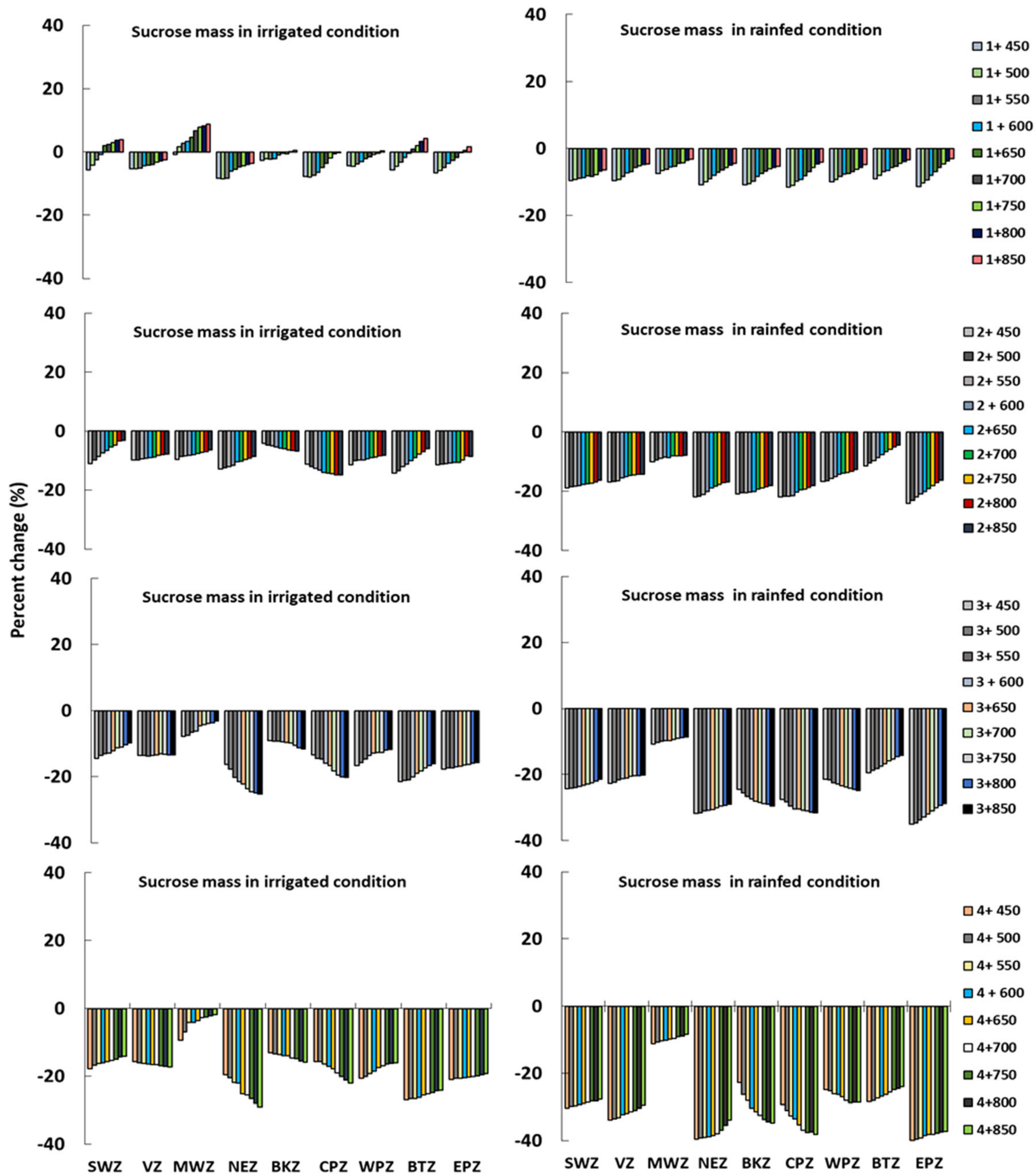
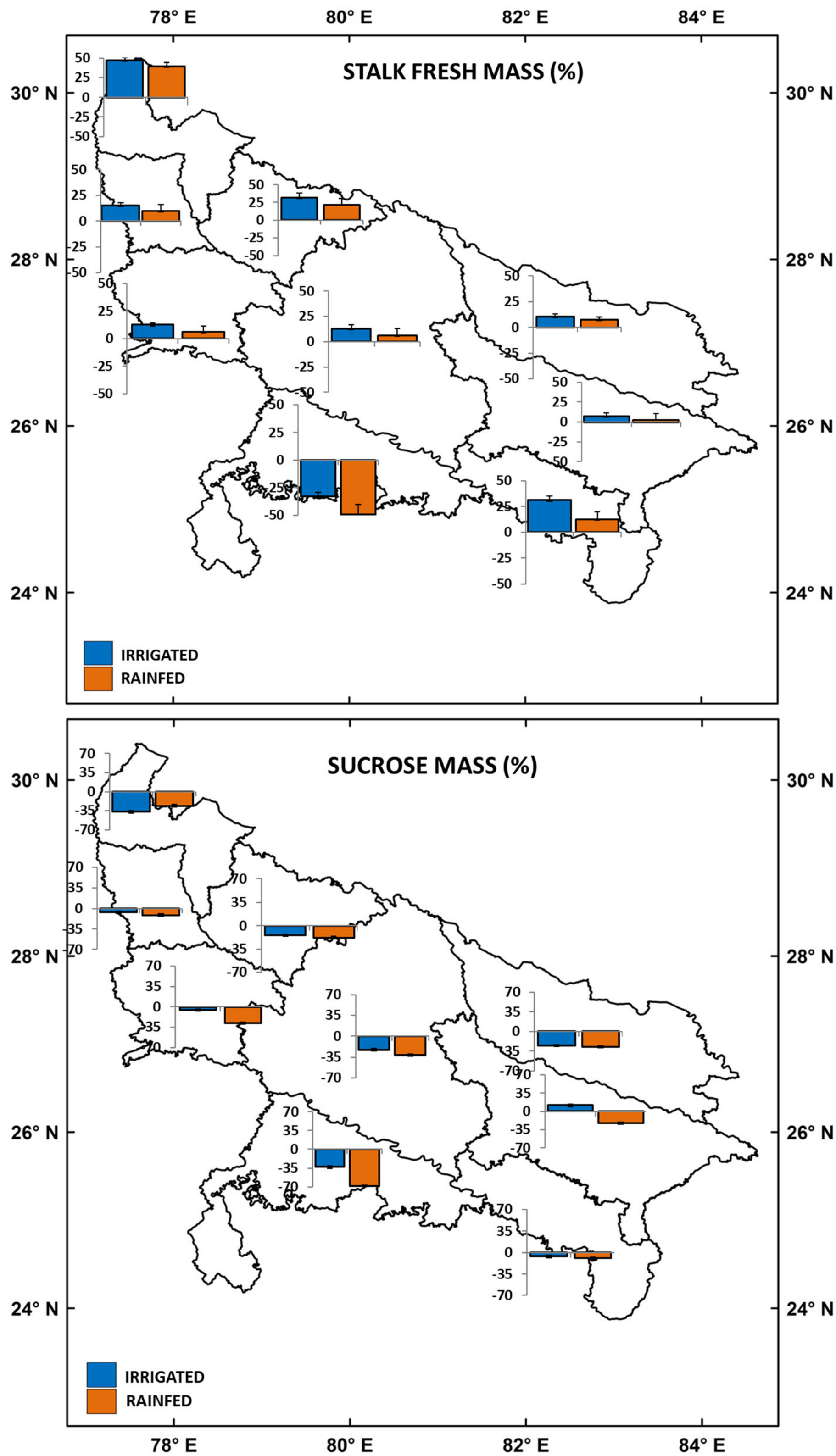


Fig. 3 Simulated change in SM (%) due to the combined effect of temperature and CO_2 under the irrigated and rainfed conditions

sugarcane productivity will be positively affected under future climate change. Sugarcane requires an optimal rainfall during vegetative phase failure which can cause decreased growth. As there is some certainty that the temperature and CO_2 will increase in the future, the unsubstantial increase in rainfall will act as a limiting factor for Uttar Pradesh sugarcane yield and sucrose mass as visible in Figs. 4 and S4. The low-temperature requirement during the ripening period (12–14 °C) is required for the enrichment of sucrose (Fageria and Moreira 2011). This could be the reason that our study area observed a decline in sucrose mass under RCP 4.5 that showed an increase in maximum and minimum temperature over the period of 2040–2060. Higher temperature may further cause the change of sucrose into fructose and glucose and increased photorespiration that may cause reduction in sugar accumulation (Binbol et al. 2006; Gawander 2007). An increase in sugarcane yield due to CO_2 fertilization (+ 520 ppm) was limited to midcentury (RCP 4.5) in Tamil Nadu (Ramachandran et al. 2017). Sugarcane growth as well as yield was significantly

Fig. 4 Change in irrigated and rainfed SFM (%) and SM (%) under RegCM4–RCP4.5 climate scenario (2041–2060) in comparison with the baseline over the nine agro-climatic zones of Uttar Pradesh



influenced by spatial variation of climatic parameters at all growth stages (Samui et al. 2014).

Thus, an increase in irrigation by 21% is required for the subsequent increase in yield in the 2050s (Knox et al. 2010) and 10–20% over the end of the century (Schulze and Kunz 2010). An increase of 4–20% in cane yield over South Africa, Australia and Brazil (2100s) was observed with varied sucrose yield (− 33 to + 13%) by Singels et al.

(2014). The relative increase in cane yield (irrigated: 14%; rainfed: 15%) but a decrease in sucrose content was also reported by Jones et al. (2015), primarily due to increased rate for simulated maintenance respiration, increased assimilate demand for structural growth and little response of photosynthesis to increased temperature. The results varied across different zones in terms of spatial heterogeneity and magnitude of change. Our findings are consistent with other studies made at the global scale mostly over Brazil, South Africa, Australia, China and Pakistan, the major sugarcane growing regions of the world. We found an increased stalk fresh mass under the irrigated and rainfed conditions for all the RCP scenarios (Fig. S5) and impact assessment study, but a decreased sucrose mass for the same scenario was observed. In addition, the increase in stalk fresh mass and decrease in sucrose mass were specifically lower/higher in the rainfed condition. This must also be considered that the results are cultivar specific and should not be generalized for India as a whole, as genetic coefficient and phenological stages are climate and area specific (Vu et al. 2009).

The limitations of the present study include that the simulations for future scenario were made under assumptions that the population size and cane area under cultivation remain the same. Also, apart from climatic factors the yield is highly variable on exposure to drought, flood, heat and cold waves. Further, the CANEGRO-Sugarcane model did not consider the impact of pest infections, weeds and diseases on a crop. Moreover, the widely acceptance of the CANEGRO-Sugarcane model is based on the previous results where it could generate the yield and other plant characteristics with much reliability. Therefore, scientists and policy makers to plan the mitigation and adaptation strategies as desired could use the findings from the present study.

There is an increased demand in international market as a major source of biofuel; the global interest is shifted to sugarcane and its response to climate change. Thus, the study recommends as per the findings, which is the development of cane variety with higher water use efficiency without compromising for the sucrose quality and quantity. This may be done through the existing classical breeding process or the use of new and advanced biotechnological tools. As may be the case, the present potential sites for sugarcane production may turn unsuitable or into climate risk areas making it unsuitable for future production. Further, the areas currently possessing low potential may be favorable for future cultivation. As was observed in our study, the zones that possess dry sub-humid to arid climate type observed the maximum reduction in sucrose mass in all the scenarios. The use of improved irrigation technology and proper irrigation scheduling for decreasing water loss, land grading, development of verities is heat- and drought-tolerant and change in classical agronomic practices like change of sowing date, crop residue retention and nutrient management and disease and pest control.

Conclusion

The study showed an increasing trend in maximum (decreasing in some zones) and minimum temperature and rainfall over all agro-climatic zones during baseline period of 1971–2000. In the future (2040–2060), this region will experience an increase in annual maximum and minimum temperature and rainfall. The CANEGRO-Sugarcane model was used to analyze the impact of the temperature and CO_2 on sugarcane SFM and SM, which showed a declining SM particularly in rainfed condition across the zones. Similarly, the impact assessment based on different combinations of temperature and CO_2 showed an increase in the stalk fresh mass but reduced the sucrose mass where more negative impact was observed for rainfed crop. In the projected RCP 4.5 scenario, SFM was projected to increase by 3–39% (rainfed) and 7–47% (irrigated), whereas SM was projected to decrease by 9–69% (rainfed) and 6–37% (irrigated) in 2040–2060 relative to 1971–2000 across the zones. However, the magnitude of change in SFM and SM largely depended on the locations and RCM data. The climate condition directly or indirectly has been affected and will be affecting the sugarcane crop. The present study provides the insight and understanding for the sugarcane crop under changing climate scenario. The existing adaptation and management strategies should be improved, and the development of new and potential varieties will help offset the adverse impacts for the sustainable sugarcane cultivation and to maintain the sugar production. A support in the form of insurance, policy and market incentives from government will be required to enhance national and international sugarcane trade and to assist sugar industry to face the threats from climate change.

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Author Contributions GS has done sugarcane crop modeling and data analysis and prepared the manuscript. NS has done data analysis and helped in manuscript preparation. RKM designed research and manuscript modification. KKS provided his help in manuscript modification. AG helped in manuscript and text modification.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Research Involving Human Participants and/or Animals There is no involvement of any human participants and/or animals.

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