Journal of Agrosystems and Analytics
Volume 1 Issue 1 2026 (Jan-June 2026) | Page No:- 25-33

**RESEARCH ARTICLE**

# Assessment of Climate Change Impact on Sugarcane Productivity in South Gujarat Using the CANEGRO Model

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(*Received 6 January 2026, Accepted 15 March 2026*)

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## Abstract

The study aims to assess the impact of climate change on sugarcane yield attributes in South Gujarat region using bias-corrected General Circulation Model (GCM) projections under SSP245 and SSP585 scenarios. These models were selected based on their accuracy in representing historical climate data and their applicability for future climate projections in the study region. Under SSP585, maximum temperature is projected to rise by 2.4 °C and minimum temperature by over 5.6 °C by the end of the century. Rainfall projections suggest a potential increase of up to 14.50% by 2090. Yield simulations using CANEGRO indicate moderate yield declines (-1% to -2.1%) under SSP245 but substantial reductions (-14% to -15%) under SSP585 due to heat and water stress. Sucrose content also exhibited sharper declines, underscoring the adverse effects of high-emission scenarios. These findings highlight the necessity for climate adaptation and mitigation strategies in sugarcane cultivation.

**Keywords:** GCMs; Climate change; CANEGRO; Sugarcane; Bias correction SSPs

## 1. Introduction

Sugarcane (*Saccharum officinarum*) is an essential crop worldwide, widely utilized in daily life and valued for its economic importance in both food and industrial sectors (Virani *et al.*, 2024). India ranks as the world's second-largest producer of sugar, following Brazil, and its sugar industry is the country's second-largest agro-processing sector (Tyagi *et al.*, 2023). Among the Indian states, Gujarat is the fifth-largest sugarcane-producing state, playing a vital role in the country's sugar industry. Among the districts of Gujarat, most of the sugarcane production occurs in the South Gujarat region.

Increasing temperatures driven by global climate change can significantly influence sugarcane growth, development, and sucrose formation. While sugarcane thrives in an optimal temperature range of 25–35°C, excessive heat stress may hinder photosynthesis, shorten the growing period, and reduce biomass accumulation (Inman-Bamber & Smith, 2005). Research indicates that prolonged exposure to high temperatures can accelerate crop maturity but often results in decreased sucrose concentration, ultimately lowering overall sugar production (Ramesh, 2000). Water availability is essential for sugarcane growth, as it is a highly water-dependent crop. Irregular rainfall patterns and extended drought conditions can hinder tillering, reduce biomass accumulation, and lead to significant yield declines (Silva *et al.*, 2008). On the other hand, excessive rainfall or flooding can adversely affect root development, promote pest and disease outbreaks, and lower sucrose concentration (Junqueira Junior *et al.*, 2020).

Jones *et al.*, (2015) employed the CSM-CANEGRO model to assess the effects of climate change on sugarcane growth and yield under various climate scenarios. Their findings revealed that increasing temperatures could shorten the crop cycle, leading to reduced biomass accumulation and lower sugar yields. Nadeem *et al.,* (2022) used the CSM-CANEGRO model to assess climate change impacts on sugarcane yield and they found that rising temperatures and changing rainfall patterns could reduce yields, but adaptive strategies like adjusted planting dates and deficit irrigation helped mitigate losses. Guhan *et al.,* (2024) used the CSM-CANEGRO model to analyze sugarcane yield under future climate scenarios. They reported significant yield declines in high-emission scenarios due to heat stress and erratic rainfall.

The study primarily aimed to evaluate the impact of climate change on sugarcane productivity using the validated CANEGRO model.

## 2. Data

### *2.1 NASA Global Daily Downscaled Projections (GDDP) CMIP6 dataset*

The NASA GDDP-CMIP6 dataset provides high-resolution daily climate projections based on 34 GCMs from the CMIP6. It offers a spatial resolution of 0.25° × 0.25° (~25 km) globally and includes key climate parameters such as daily maximum temperature (Tmax), minimum temperature (Tmin), and daily precipitation. The dataset spans the historical period from 1950 to 2014 and future projections from 2015 to 2100 under different SSPs scenarios, including SSP245 (moderate emissions) and SSP585 (high emissions).

### *2.2 Field experiment data*

The field experiment was conducted at Navsari Agricultural University (NAU) Agronomy Farm, Navsari (latitude 20°57′ N, longitude 72°54′ E, and altitude 12 m above mean sea level). Two sugarcane varieties (CoN 15071 and CoN 13072) were grown on two planting dates (25th January and 25th February) during the two seasons of 2023-24 and 2024-25. Data from the field experiments conducted during the first sugarcane season (2023-24) was used for CANEGRO model calibration while second sugarcane season (2024-25) data were used to validate the CANEGRO model. Figure 1 displays the location of the South Gujarat and the field experimental site, providing essential geographical context for the research.

## 3. Methodology

### *3.1 CANEGRO model calibration and validation*

The calibration process was performed using field data from the 2023–24 sugarcane season. The initial step involved adjusting phenological parameters to align simulated growth stages with observed data. Next, growth and yield parameters were fine-tuned to minimize discrepancies between simulated and actual yield values. The calibration dataset included daily weather variables (temperature, solar radiation, and rainfall), soil properties (texture, bulk density, and moisture retention characteristics), and agronomic management practices (planting dates, irrigation, and fertilizer application). The genetic coefficients of sugarcane cultivars CoN 15071 and CoN 13072 were optimized to enhance model performance. The calibrated genetic coefficient of both cultivars is display in Table 1

The validation process was conducted using independent field data from the 2024–25 season to assess the model predictive capability. Simulated outputs, including cane yield, biomass, and phenology, were compared against observed values using different accuracy assessment metrics. The step-by-step workflow of the model calibration and validation are illustrated in Figure 2.

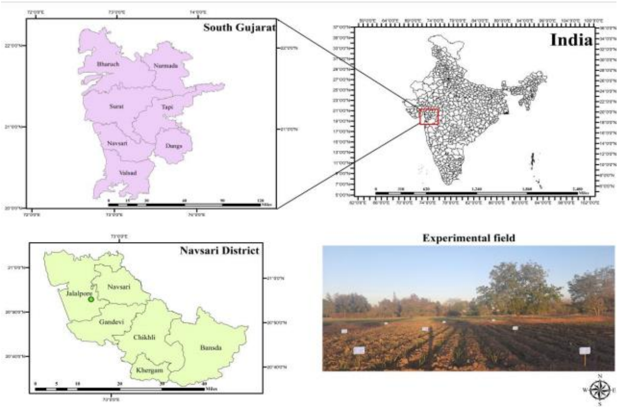


**Fig 1.** Study area and experimental site

## 4. Results and Discussion

### *4.1 Validation of CANEGRO Model*

Model validation is the process of evaluating a model accuracy by comparing its simulated outputs with independent observed data. It ensures the model reliability and predictive capability under different conditions. The independent datasets were collected from the second sugarcane season during the field experiment conducted in the year 2023–24. These datasets included key parameters such as days to emergence, cane yield (t/ha), and aerial dry biomass (t/ha).

The CANEGRO model shows relatively lower accuracy for cane yield during calibration and validation (Figure 3A). Calibration results indicate an MAE of 4.36 t/ha, RMSE of 4.75 t/ha, and MAPE of 4.70%, with an $R^2$ of 0.84 and a D-Index of 0.90. Validation shows an MAE of 5.04 t/ha, RMSE of 6.29 t/ha, and MAPE of 5.70%, with $R^2$ improving to 0.88 but a lower D-Index of 0.77. These results verify CANEGRO sensitivity but indicate limitations in

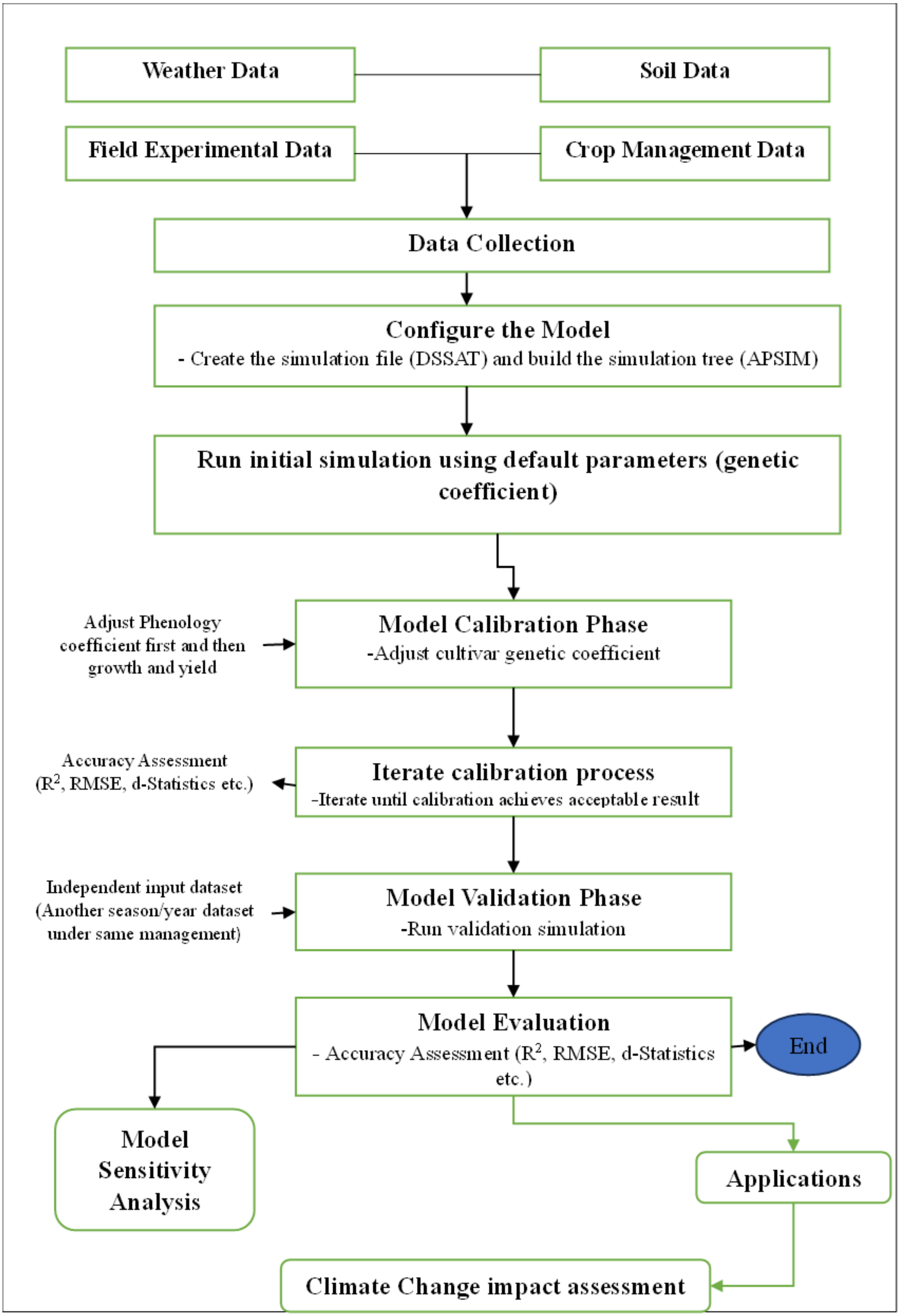


**Fig 2** Workflow of CANEGRO Simulation Model

**Table 1** Calibrated genetic coefficients of sugarcane cultivars

| Parameter | Category | Default | Calibrated Genetic Coefficient | |
|---|---|---|---|---|
| | | CP 88-1762 | CON15071 | CoN13072 |
| **MaxPARCE (G)** | Biomass accumulation | 5.70 | 10.90 | 11.60 |
| **APFMX (G)** | Biomass partitioning | 0.880 | 0.990 | 0.980 |
| **STKPFMAX (G)** | | 0.700 | 0.980 | 0.990 |
| **SUCA (G)** | Sucrose accumulation | 0.580 | 0.820 | 0.840 |
| **TBFT (N)** | | 25.0 | 26.0 | 26.0 |
| **LFMAX (N)** | Canopy - leaves | 12.0 | 13.0 | 13.0 |
| **MXLFAREA (G)** | | 360.0 | 600.0 | 620.0 |
| **MXLFARNO (N)** | | 15.0 | 15.0 | 15.0 |
| **LER0 (N)** | | 0.250 | 0.250 | 0.250 |
| **PI1 (P)** | Leaf phenology | 69.0 | 97.0 | 99.0 |
| **PI2 (P)** | | 169.0 | 199.0 | 195.0 |
| **PSWITCH (P)** | | 18.0 | 18.0 | 18.0 |
| **TDELAY (N)** | Tiller phenology | 50.0 | 50.0 | 50.0 |
| **TAR0 (N)** | | 0.020 | 0.020 | 0.020 |
| **POPTT16 (P)** | | 13.30 | 11.30 | 13.30 |
| **TTPLNTEM (N)** | Phenology | 80.0 | 250.0 | 270.0 |
| **TTRATNEM (N)** | | 30.0 | 50.0 | 50.0 |
| **CHUPIBASE (N)** | | 1050.0 | 1050.0 | 1050.0 |
| **SER0 (N)** | | 0.140 | 0.140 | 0.140 |
| **TT_POPGROWTH (N)** | | 600.0 | 500.0 | 550.0 |
| **LG_AMBASE (N)** | Lodging | 220.0 | 220.0 | 220.0 |

predictive performance (Parmar *et al.*, 2019; Bhengra *et al.*, 2016).

For aerial dry biomass (Figure 3B), CANEGRO achieved $R^2$ values of 0.77 (calibration) and 0.80 (validation), with RMSE decreasing from 4.51 t/ha to 1.26 t/ha. The D-Index improved from 0.51 to 0.87, and MAPE reduced from 12.90% to 4.00%, confirming enhanced validation accuracy (Singh *et al.*, 2018). For days to emergence (Figure 3C), CANEGRO performed well in calibration ($R^2 = 0.97$, MAE = 2.00, RMSE = 2.55, MAPE = 6.87%) but declined during validation ($R^2 = 0.39$, RMSE = 2.60, D-Index = 0.65). Reduced bias (MBE: -2.00 to -0.25) suggests some improvement, but weak validation performance raises concerns about model generalization (Parmar *et al.*, 2019; Singh *et al.*, 2018). The above results indicate that the CANEGRO model performs satisfactorily in both calibration and validation stages, verifying its reliability for further applications in assessing climate change impacts on sugarcane productivity.

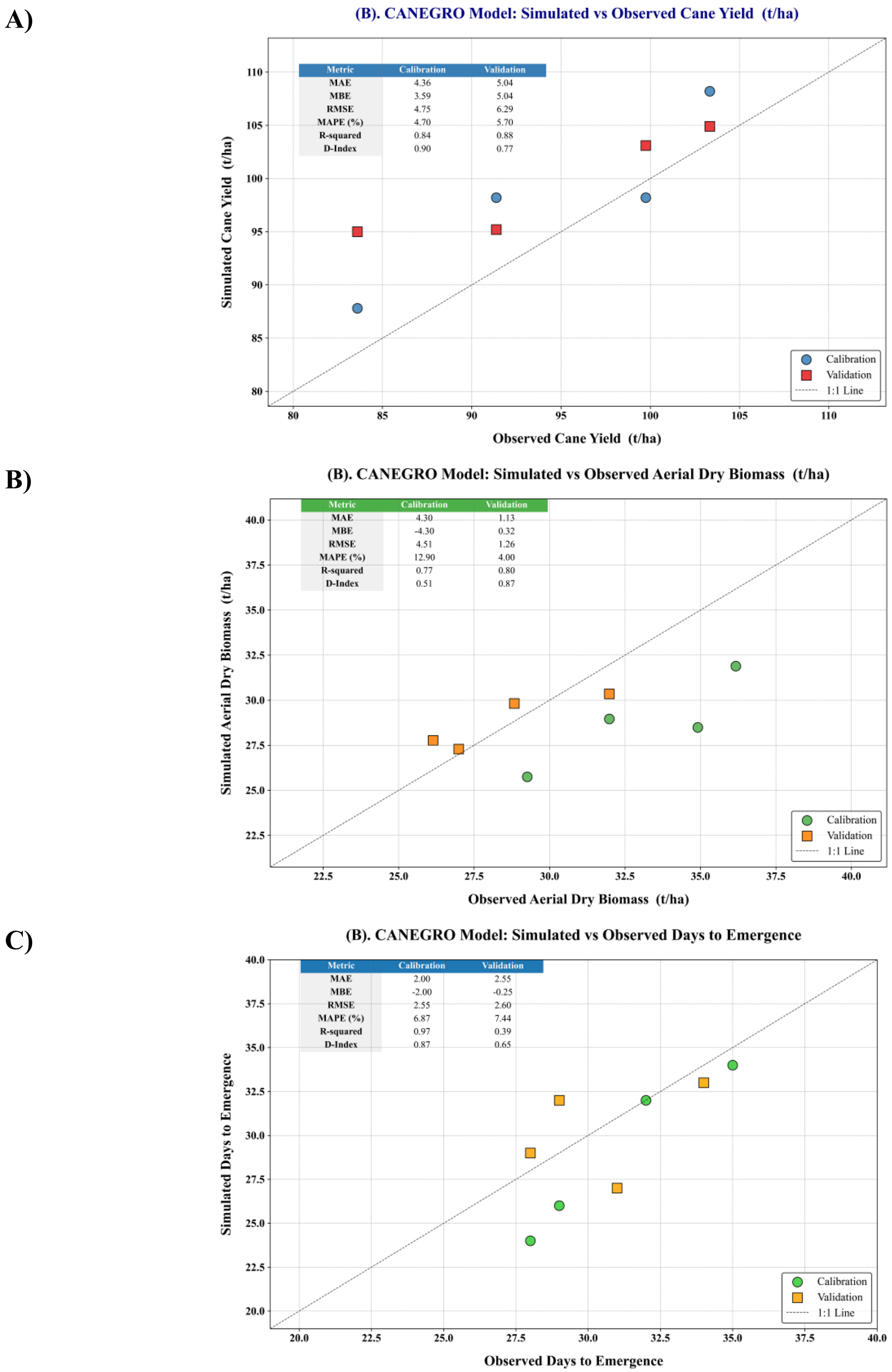
### *4.2 Sensitivity Analysis of CANEGRO model*

Before assessing the impact of climate change projections on sugarcane productivity using the CANEGRO model, it is essential to first evaluate the model sensitivity to changes in key climatic parameters. This ensures a better understanding of how variations in temperature, solar radiation, and $CO_2$ levels influence sugarcane growth and yield, allowing for more accurate impact assessments. In this study, we assess the sensitivity of temperature on cane yield, as displayed in Figure 4.

The CANEGRO model reveals a steeper and more pronounced sensitivity to temperature changes. Yield initially increases at −2 °C and −1 °C, showing average improvements of 4.49% and 4.32%, respectively. However, the decline in yield begins more sharply with positive temperature increments, reaching an average decline of 31.35% at +6 °C. The findings align well with the studies of Verma *et al.*, (2023) and Sonkar *et al.*, (2020). These results demonstrate the CANEGRO model sensitivity to changes in climatic parameters, further supporting its use in assessing the impact of climate change projections on sugarcane productivity under SSP scenarios.

### *4.3 Projected Climate Change Impact on Sugarcane Yield Parameters*

Decade-wise deviations in projected climate data (Tmax, Tmin, and rainfall) from baseline values under SSP245 and SSP585 scenarios were analyzed to assess their impact on sugarcane yield parameters using the calibrated and validated CANEGRO model.



| Metric | Calibration | Validation |
|---|---|---|
| MAE | 4.36 | 5.04 |
| MBE | 3.59 | 5.04 |
| RMSE | 4.75 | 6.29 |
| MAPE (%) | 4.70 | 5.70 |
| R-squared | 0.84 | 0.88 |
| D-Index | 0.90 | 0.77 |

| Metric | Calibration | Validation |
|---|---|---|
| MAE | 4.30 | 1.13 |
| MBE | -4.30 | 0.32 |
| RMSE | 4.51 | 1.26 |
| MAPE (%) | 12.90 | 4.00 |
| R-squared | 0.77 | 0.80 |
| D-Index | 0.51 | 0.87 |

| Metric | Calibration | Validation |
|---|---|---|
| MAE | 2.00 | 2.55 |
| MBE | -2.00 | -0.25 |
| RMSE | 2.55 | 2.60 |
| MAPE (%) | 6.87 | 7.44 |
| R-squared | 0.97 | 0.39 |
| D-Index | 0.87 | 0.65 |

**Fig 3** Calibration and validation results of the CANEGRO models for **A).** Cane yield, **B).** Aerial dry biomass, and **C).** Days to emergence

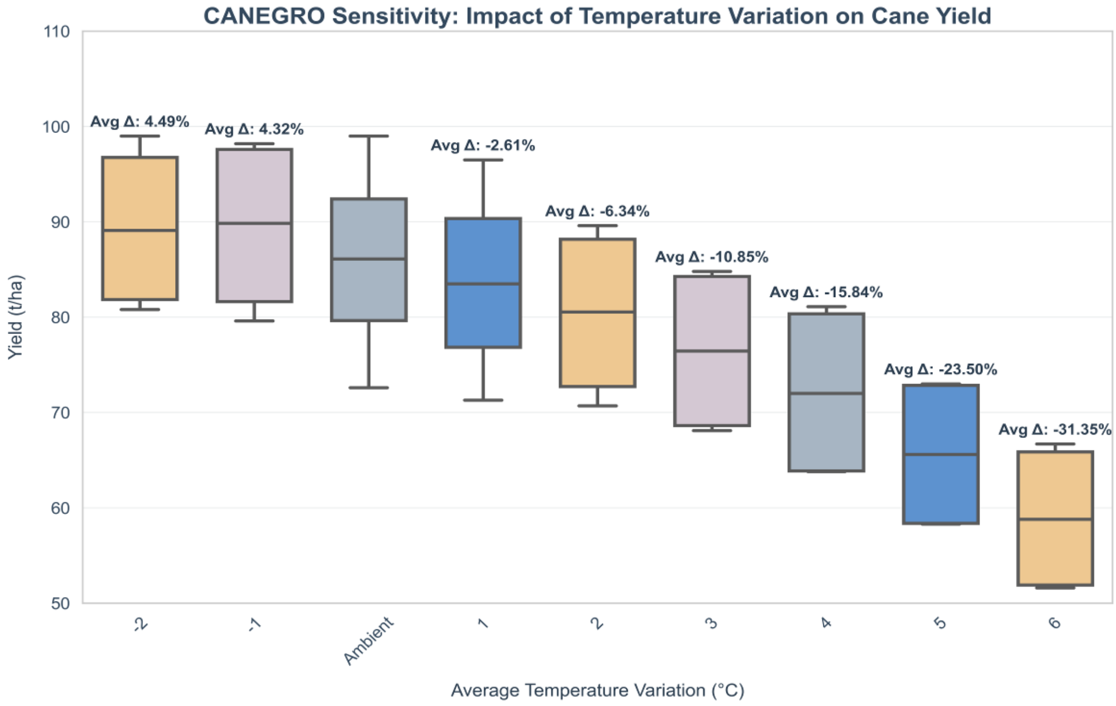


**Fig 4** CANEGRO sensitivity of sugarcane yield (t/ha) to temperature variation

#### 4.3.1 *Cane yield (t/ha)*

The projected changes in sugarcane yield under SSP245 and SSP585 scenarios for two varieties, CoN15071 and CoN13072, are presented in Figure 5A. The results indicate a declining trend in cane yield across both scenarios, with more severe reductions observed under SSP585 due to higher temperature stress and greater rainfall variability.

For variety CoN15071, yield reductions remain relatively moderate under SSP245, with losses ranging from approximately -1% to -2.1% throughout the century. However, under SSP585, a more pronounced decline is observed, especially after 2070, where yield decreases sharply, reaching nearly -14% to -15% by 2091–2100. This suggests that under high-emission scenarios, excessive temperature increases and water stress could significantly limit crop growth and productivity. Similarly, for variety CoN13072, the trend follows a comparable pattern, with yield losses under SSP245 stabilizing between -2% and -2.3% over time. In contrast, SSP585 shows a much steeper decline, with losses exceeding -13% by the end of the century. This suggests that both cultivars are equally vulnerable to high-emission climate conditions, requiring adaptation strategies to mitigate future productivity declines. Nadeem *et al.*, (2022) revealed that the CANEGRO model projected a decline in cane yield ranging from 15.31% to 22.57% under different GCMs during the mid-century (2039–2069).

#### 4.3.2 *Aerial dry biomass (t/ha)*

The projected changes in aerial dry biomass for sugarcane varieties CoN15071 and CoN13072 under SSP245 and SSP585 scenarios are depicted in Figure 5B. The results indicate a gradual decline in biomass accumulation over time, with more pronounced reductions under SSP585 due to higher temperatures and increased climate variability. The aerial dry biomass for both varieties, CoN15071 and CoN13072, shows a moderate decline under SSP245, with reductions ranging from approximately -2% to -4.2% throughout the century. However, under SSP585, biomass losses become significantly higher, particularly after 2070, reaching nearly -11% by 2091–2100. The similar response of both varieties suggests that higher temperatures and changing rainfall patterns negatively impact overall biomass production, reducing the plant's ability to accumulate sufficient energy for optimal growth.

#### 4.3.3 *Sucrose weight (t/ha)*

The projected changes in aerial dry biomass for sugarcane varieties CoN15071 and CoN13072 under SSP245 and SSP585 scenarios are depicted in Figure 5C. The projected sucrose weight for sugarcane varieties CoN15071 and CoN13072 shows a consistent declining trend across future decades, with significantly greater reductions under SSP585 compared to SSP245. Under

SSP245, sucrose weight losses remain moderate, ranging between -2.5% to -13% throughout the century. However, under SSP585, the decline is more severe, particularly after 2070, with losses reaching nearly -20% to -22% by 2091–

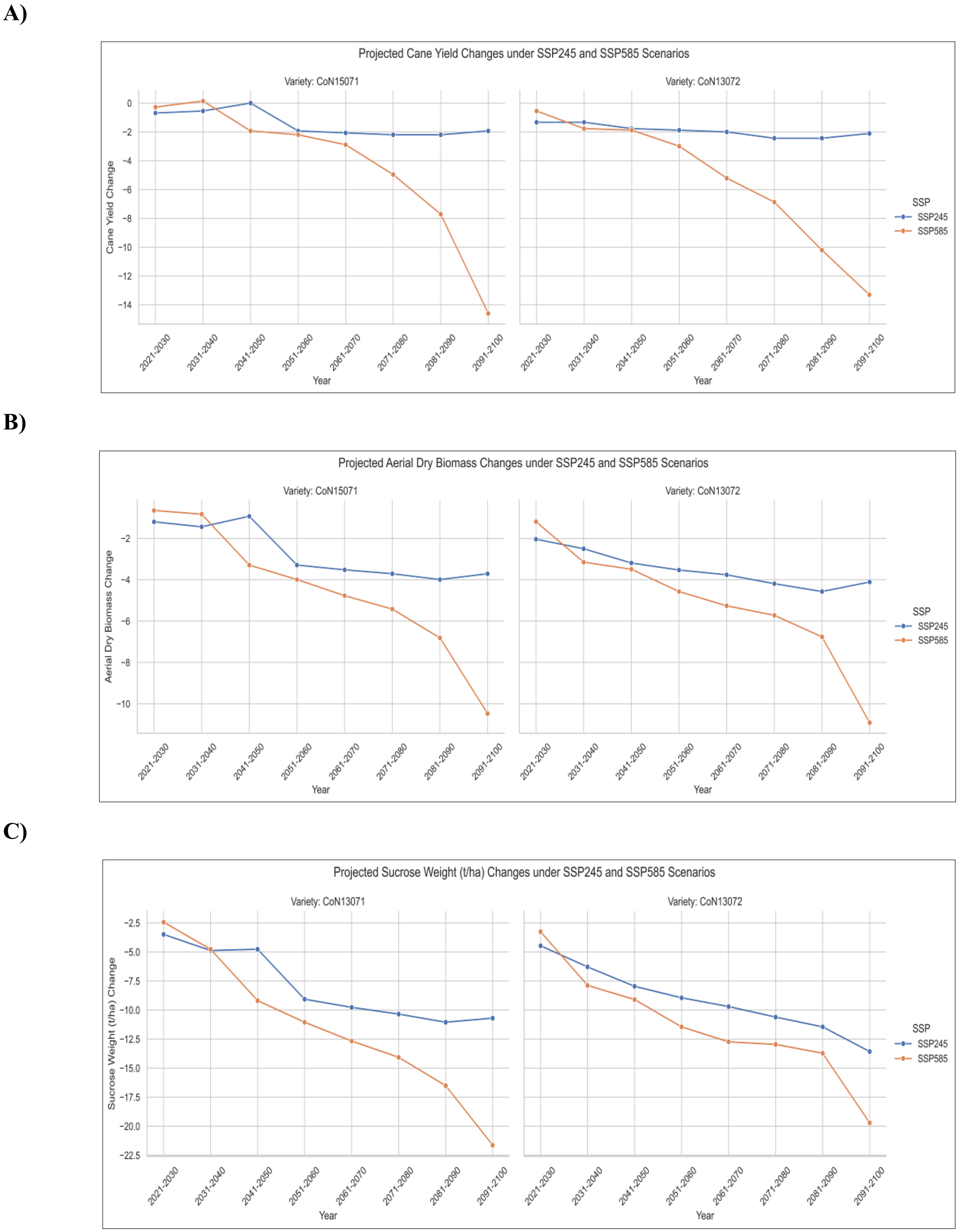


**Fig 5** Projected **A).** Cane yield, **B).** Aerial dry biomass, and **C).** Sucrose weight changes for sugarcane varieties under SSP245 and SSP585 scenarios

2100.

The steeper reduction under SSP585 highlights the adverse impacts of higher temperatures and increasing climate variability, which can shorten the crop growth cycle, reduce photosynthetic efficiency, and impair sucrose accumulation. These trends suggest that prolonged exposure to heat stress and erratic rainfall patterns may negatively impact the biochemical pathways responsible for sucrose synthesis (Mehdi *et al.,* (2024), ultimately leading to reduced sugar recovery and lower economic returns for farmers. Jaiswal *et al.,* (2023) used the CANEGRO-Sugarcane model to assess climate change impacts on sugarcane production. They concluded that rising future temperatures will accelerate plant growth but reduce sucrose content.

## 5. Conclusion

This study provides a comprehensive assessment of the potential impacts of climate change on sugarcane productivity in South Gujarat under the SSP245 and SSP585 scenarios. The findings reveal that rising temperatures and shifting rainfall patterns could significantly influence sugarcane yield, underscoring the vulnerability of the crop to future climate change.

Our results highlight the necessity of integrating climate-resilient agricultural practices to mitigate the adverse effects of climate change. Furthermore, this study emphasizes the crucial role of bias correction in enhancing the reliability of climate projections, ensuring more accurate impact assessments. By combining robust climate modeling with advanced crop simulation techniques, we contribute to a deeper understanding of climate risks in sugarcane production. Moving forward, developing region-specific adaptation strategies, and leveraging advanced crop simulation models will be essential for sustaining sugarcane productivity in a changing climate, ultimately supporting food security and agricultural sustainability in South Gujarat and beyond.

## Acknowledgments

We extend our gratitude to colleagues and researchers whose valuable insights contributed to this study. We acknowledge the availability of climate data from Data Source, e.g., CMIP6, IMD, NASA, as well as the DSSAT-CANEGRO model developers for their contributions to crop modeling. Lastly, we express our appreciation to our families and peers for their encouragement throughout this research.

## Declarations

### Author's Contribution

**Neeraj Kumar**: Conceptualization, Methodology, Data Collection, Processing, and Analysis, CANEGRO model calibration and validation. **H. B. Virani:** Writing - Original Draft, Visualization. **V. B. Virani:** Writing - Original Draft.

### Funding Statement

This research was conducted without external financial support, reflecting the independent efforts and commitment of the authors.

### Data Availability

The datasets generated and/or analysed during the current study are available in a publicly accessible repository.

### Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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