

RESEARCH ARTICLE

Integration of Climate and Crop Model to Sustain the Maize Productivity for Efficient Cropping Districts of Tamil Nadu

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ABSTRACT

Global food security was affected by climate change, which causes variations in rainfall and temperature. It brings significant changes in the crop-growing period, leading to a shift in sowing dates from the current sowing dates. This study focuses on maize as a major crop in the Perambalur, Ariyalur, Trichy, and Theni districts of Tamil Nadu and aims to optimize the sowing dates and fertilizer recommendations in the context of climate change. To assess past climate, weather data were obtained from the IMD (India Meteorological Department) gridded dataset, and future climate projections were derived from the CMIP6 global climate models MIROC6 and EC EARTH. The past and future yields were simulated using the DSSAT model, and the adaptation strategies for the base period (1991-2020), near century (2021-2050), and mid-century (2051-2080) were evaluated using the SSP2-4.5 scenario. Adaptation strategies such as different sowing dates (15th September, 30th September, and 15th October) and various fertilizer dosages (75, 100, and 125 per cent of RDF) were evaluated to sustain maize yield. The results showed that the maximum yield was obtained with an early sowing date and a 125% recommended fertilizer dose across all study districts. The EC EARTH model was found to perform better at sustaining maize yield under the projected climate.

Received: 11 Dec 2025

Revised: 14 Feb 2026

Accepted: 17 Feb 2026

Keywords: *Climate change, Maize, DSSAT, MIROC6, EC EARTH.*

INTRODUCTION

Climate change is the single greatest threat to a sustainable future, but addressing the climate challenge also presents a golden opportunity to promote prosperity, security, and a brighter future for all. The IPCC Sixth Assessment Report underlines the need for economic action to make sure that the benefits to the world economy of keeping global warming to 2 °C outweigh the costs of mitigation. Emissions must be cut by at least 43 per cent by 2030 and at least 60

per cent by 2035 relative to 2019 levels to stay within the 1.5 °C goal (IPCC 2023).

The Earth's temperature is expected to rise from 2.5 °C to 4.5 °C by 2100 as greenhouse gas (GHG) emissions continue to increase. Future problems about food security may arise as a result of the rising atmospheric CO₂ concentration, leading to inefficient net carbon absorption by plants, which would reduce crop productivity (Wang et al., 2018). India is one of

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the most vulnerable countries to sea-level rise, with 3.5 crore people potentially suffering from coastal floods every year by the middle of the century. India would see wet-bulb temperatures of 35 °C by the end of the century, especially in cities like Lucknow, Patna, Bhubaneswar, Chennai, Mumbai, Indore, and Ahmedabad, potentially reaching 32–34 °C owing to increased emissions (Vecellio *et al.*, 2023).

By 2050, yields of rice, wheat, pulses, and coarse cereals may decrease by about 9 per cent. If global temperatures continue to rise, maize production in South India might decline by 17 per cent (IPCC 2022). Climate change has adverse effects on Indian Agriculture due to differential variation in yearly precipitation, mean temperature, greenhouse gas emissions, occurrence of heat waves, floods, and droughts, etc., leading to a rise in food insecurity (Raza *et al.*, 2019; Bagale, 2021).

Maize (*Zea mays* L.) is the third most important crop, after rice and wheat, in India. In India, the area under maize cultivation is estimated at 10.7 to 11.5 million hectares, yielding 43.0 million metric tonnes during 2024-2025 (USDA, 2025). The maize crop uses C4 photosynthesis and has very efficient utilization of solar radiation. It is known as the “Queen of Cereals” due to its photo-thermo-insensitive nature and the highest genetic potential for yield (Hulmani *et al.*, 2022). The versatility, nutritional value, and adaptability of maize have made it an important cereal crop in global agriculture.

By 2050, the global population is projected to reach around 10 billion, and global cereal-equivalent food demand is expected to rise by around 10,094 million tonnes in 2030 and 14,886 million tonnes in 2050 (Islam and Winkel 2017). Maize production is expected to reach around 50 million metric tonnes by 2025 to meet the growing population (Sandhu and Irmak, 2019). The yield of rainfed maize is susceptible to climate change, specifically in dry regions. Since the environment is changing daily, there is a need to develop adaptive management strategies to cope with climate change.

The sowing date has a major influence on crop development and yield because of variations in environmental conditions over time and space. Optimal sowing times can greatly enhance crop yields and help crops better adapt to current cropping systems (Choudhury *et al.*, 2021; Iizumi and Ramankutty, 2015). (Tandisau and Muhammad, 2009) state that

maize develops well when nutrients are supplied in adequate amounts to meet the plant’s requirements throughout its growth, which is particularly important for high-yielding superior varieties. Nitrogen (N) is a key nutrient for corn plants. It is essential for the development of vegetative structures such as leaves, stems, and roots, thereby making it vital for overall plant growth (Sutedjo, 2002). Additionally, the extensive use of hybrid maize varieties, which are highly responsive to fertilization, has increased demand for fertilizers, especially nitrogen-containing fertilizers. According to (Rahim and Halima,2013), corn requires large amounts of N fertilizer, it takes 20–30% in its growth phase.

The World Climate Research Programme (WCRP) organised the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6). CMIP is evolving into an integrated framework for organising a number of individual Model Intercomparison Projects (MIPs), such as EC-Earth and MIROC6. To secure achievable yields amid changing climatic conditions and to avoid the expense and duration of lengthy field experiments required to study long-term climate variability, a robust, widely accepted, and validated crop model can serve as a valuable tool (Holzworth *et al.*, 2014 and Jones *et al.*, 2003). The CERES-Maize module in DSSAT provides a greater ability to predict how the crop will respond to changes in weather, soil, water, and management. It can mimic crop development and yield by using dynamic interactions between photosynthetic output, dry matter build-up and allocation, and physiological processes (MacCarthy *et al.*, 2012). Therefore, the present study was designed and executed with the aim of identifying the optimal sowing window and fertilizer dosage for maize to attain sustainable yield.

MATERIALS AND METHODS

Study area

The identified most efficient cropping zones for maize are Theni, Perambalur, Dindigul, Salem, Trichy, Ariyalur, Erode, and Tiruppur (Abinaya *et al.*, 2022) (Fig.1). Among the efficient cropping zones, Perambalur, Ariyalur, Trichy, and Theni were selected for the present study since the date of sowing was common for these districts.

Perambalur district, located at 11.2266° N and 78.9288° E, covers a total area of 175,736 hectares, of which 102,418 hectares are under cultivation. The predominant soil types

in the region are red loamy and black soils. The district receives an average annual rainfall of 908 mm. In 2021–2022, maize was cultivated on 67,183 hectares, yielding a total of 601,209 tonnes.

Ariyalur district, situated at 11.2399° N and 79.2902° E, encompasses a total area of 193,398 hectares, of which approximately 97,359 hectares are designated as net sown area. The region receives an average annual rainfall of 954 mm and is mainly characterized by red loamy soils. The area and production of Ariyalur were 18,130 ha and 1,08,614 tonnes, respectively, in 2021–2022.

Trichy district lies between 11.0346° N and 78.5661° E and spans a total geographical area of 440,383 hectares. Of this, 160,159 hectares are used as net sown area. The region receives an average annual rainfall of 880.2 mm, and the predominant soil type is red sandy soil. The area and production of Trichy were 18,339 ha and 1,53,672 tonnes, respectively, in 2021–2022.

Theni district, located at 9.9330° N, 77.4702° E, covers a total area of 324,230 hectares, with 107,560 hectares under cultivation. The district receives an average annual rainfall of 829.8 mm. Red loam

soil is the dominant soil type. In 2021–2022, Theni had 6,032 hectares under cultivation, resulting in a production of 39,726 tonnes.

Weather Data

The India Meteorological Department provided the maximum, minimum temperature, and precipitation datasets at the daily scale with spatial resolutions of 1° by 1° and 0.25° by 0.25°, respectively, and they were downloaded for a 30-year base period (1991–2020). Recent studies carried out by (Sandeep *et al.*, 2017; Anil and Anand Raj, 2022; Vinod and Agilan, 2022; Shetty *et al.*, 2023) has used the IMD dataset as a base period for the Coupled Model Intercomparison Project (CMIP).

Climate Data

CMIP6 global climate model data were collected from NASA Earth Exchange Global Daily Downscaled Projections at a resolution of 0.25°x0.25° for maximum temperature, minimum temperature, and rainfall. Among the General Circulation Models (GCMs), MIROC6 and EC-Earth; the SSP2-4.5 scenario (+4.5 Wm⁻²; medium forcing, middle-of-the-road pathway, and updates the RCP4.5 pathway) was chosen for the contemporary study. The future climate projection was

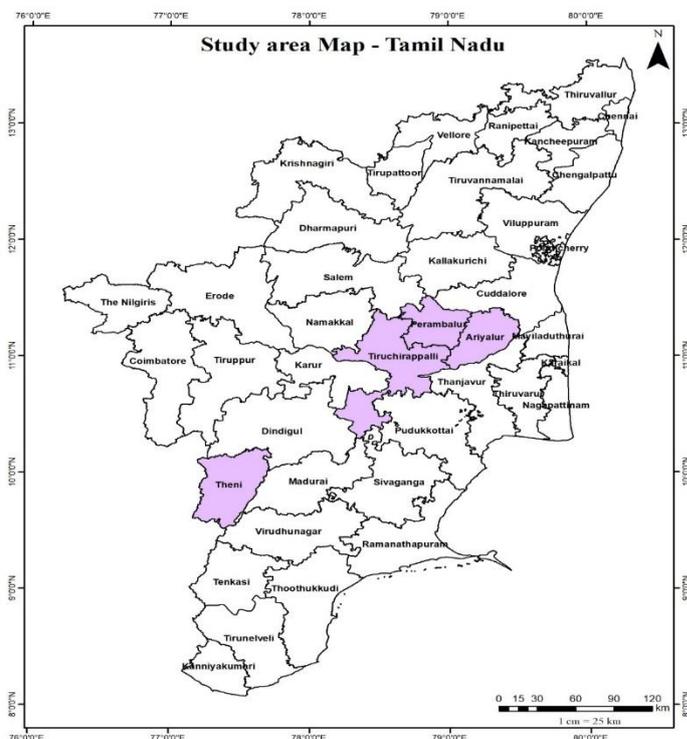


Fig.1 Study area map

done for two time periods: near-century (2021-2050) and mid-century (2051-2080). Previous analyses conducted by Anil *et al.*, (2021); Anil and Anand Raj (2022); Reddy and Saravanan (2023) showed that this model was best for precipitation and temperature projections. The variation in minimum temperature across the study districts between the models was meagre, and the influence of minimum temperature on crop yield was not assessed.

Soil Data

District-level soil data were obtained from a comprehensive database containing soil characteristics for 623 Indian districts, sourced from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP) soil database and maps (Bhattacharyya *et al.*, 2011). Using the 27 Generic Soil Profiles outlined by Koo and Dimes (2013), appropriate soil profiles were assigned to each district based on soil texture, rooting depth, and organic carbon content, which serves as an indicator of soil fertility. The HC27 soil profiles, extensively used in crop modelling at both regional and global scales (Muller and Robertson 2014; Nelson *et al.*, 2009), were utilized as input files in the 'S Build' tool to create soil files for the DSSAT model.

Crop Data

Maize COHM6, a 110-day crop of parentage UMI 1200 x UMI 1230. It is grown in both rainfed and irrigated conditions. Crop management information, such as sowing date, spacing, planting depth, planting population, fertilizer dosage, and irrigation schedule, is taken from the crop production guide 2020. The crop management file (XFile) allows the model inputs to be simulated for each experiment, replicating the field situation under the assumption of pest- and disease-free conditions.

Adaptation Strategies

In previous studies, different adaptation strategies had been adopted to minimize the impact of future climate change. The adaptation strategies include different sowing dates (Akshaya *et al.*, 2023; Boomiraj *et al.*, 2010; Lashkari *et al.*, 2012; Rao *et al.*, 2016), increased fertilizer dosage (Pramod *et al.*, 2017; Rao *et al.*, 2022), and irrigation scheduling (Ma *et al.*, 2017). However, in the present study, the adaptation strategies were tested using two different climate models to respond to changes in sowing data (DOS) and fertilizer dosage. The normal sowing date (September 30th) was set based on information gathered from

the farmers. The early DOS was fixed as September 15th, and the late DOS was fixed as October 15th. The fertiliser dosages given are the recommended dosage (RDF), 75% RDF, and 125% RDF.

RESULT AND DISCUSSION

Temperature variation during SWM

During the southwest monsoon season (SWM), in the base period, the highest maximum temperature is recorded in Perambalur district (34.2 °C), and the lowest maximum temperature is recorded in Theni district (31.6 °C).

Ariyalur recorded the highest maximum temperatures of 34.8 °C (MIROC6) and 35.4 °C (EC-EARTH) in the near century, and 35.2 °C (MIROC6) and 36.0 °C (EC-EARTH) in the mid-century.

Theni recorded the lowest maximum temperature of 33.1 °C (MIROC6) & 29.1 °C (EC-EARTH) in the near century and 33.2 °C (MIROC6) & 29.5 °C (EC-EARTH) for mid-century. (Fig. 2a)

Temperature variation during NEM

During the northeast monsoon season (NEM), during the base period, the highest maximum temperature is recorded in Trichy district (31.2 °C), and the lowest maximum temperature is recorded in Theni district (30.2 °C).

The highest maximum temperature for the near-century was recorded in Trichy at 32.5 °C (MIROC6) and in Perambalur at 30.7 °C (EC-EARTH), whereas for mid-century, Trichy reaches 32.8 °C with MIROC6, and both Perambalur and Ariyalur reach 31.1 °C in the EC-EARTH model.

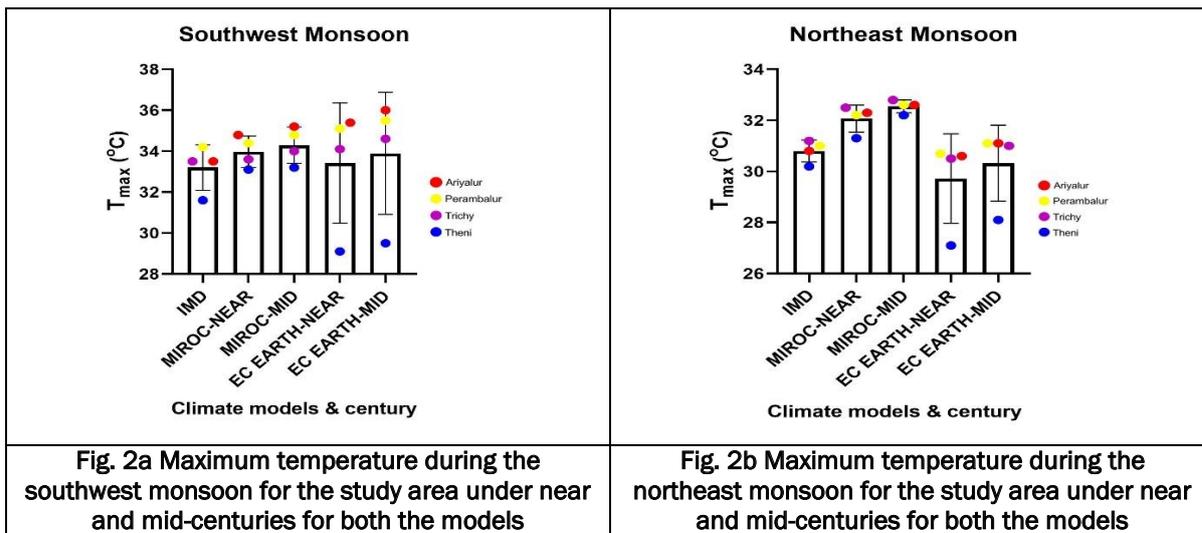
Theni recorded the lowest maximum temperature of 31.3 °C (MIROC6) & 27.1 °C (EC-EARTH) in the near future and 32.2 °C (MIROC6) & 28.1 °C (EC-EARTH) for mid-century. (Fig. 2b)

Rainfall variation during SWM and NEM

In SWM season, during the base period, the highest rainfall is in Theni (503 mm), and the lowest rainfall is in Perambalur (376 mm).

Theni has recorded the highest rainfall in both, in near century, it received rainfall of 675mm (MIROC6) & 505 mm (EC-EARTH), and in the mid-century, it was 566 mm (MIROC6) & 618 mm (EC-EARTH)

The lowest rainfall was recorded in Ariyalur: 451mm (MIROC6) & 400 mm (EC-EARTH) in the near century, whereas in the mid-century, the



lowest was recorded in Ariyalur (452 mm) for MIROC6 and Trichy (410 mm) for EC-EARTH. (Fig. 3a)

In the NEM season, during the base period, the highest rainfall reaches in Perambalur (554 mm), and the lowest rainfall reaches in Ariyalur district (403 mm).

In near century, the highest rainfall was recorded in Perambalur at 664 mm (MIROC6) &569 mm (EC-EARTH). In contrast, for the mid-century it was recorded in Perambalur at 600 mm (MIROC6) and Ariyalur at 644 mm (EC-EARTH).

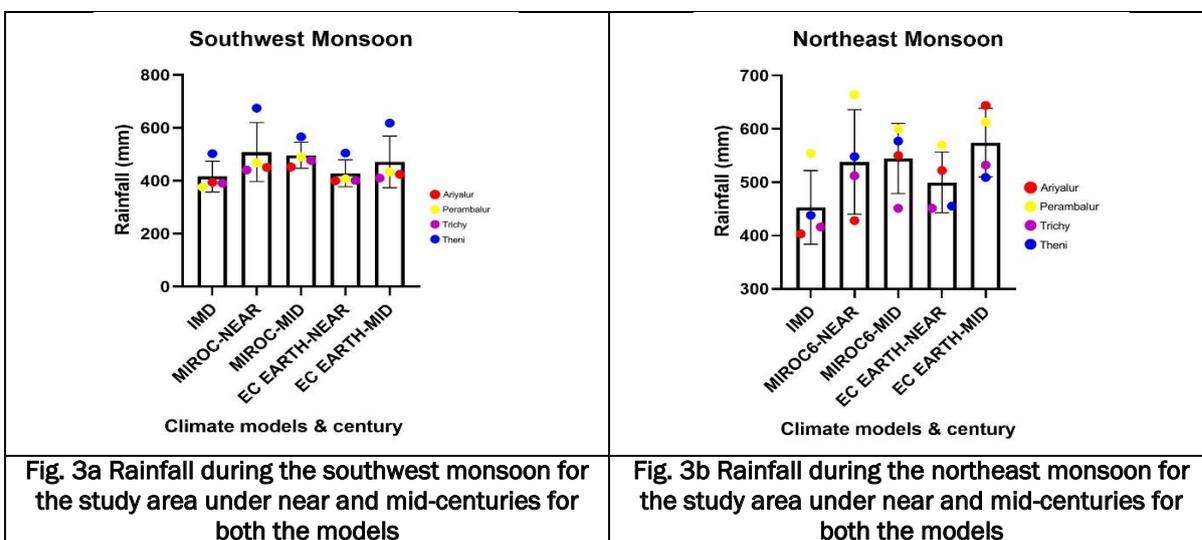
The lowest rainfall in the near future was observed in Ariyalur (428 mm) under the MIROC6 model, and in Trichy (451 mm) under the EC-EARTH model. For the mid-century period, Trichy receives the least rainfall

(451 mm) according to MIROC6, while Theni records the most rainfall (509 mm) under the EC-EARTH model. (Fig. 3b)

Adaptation Strategies to Sustain Maize Yield

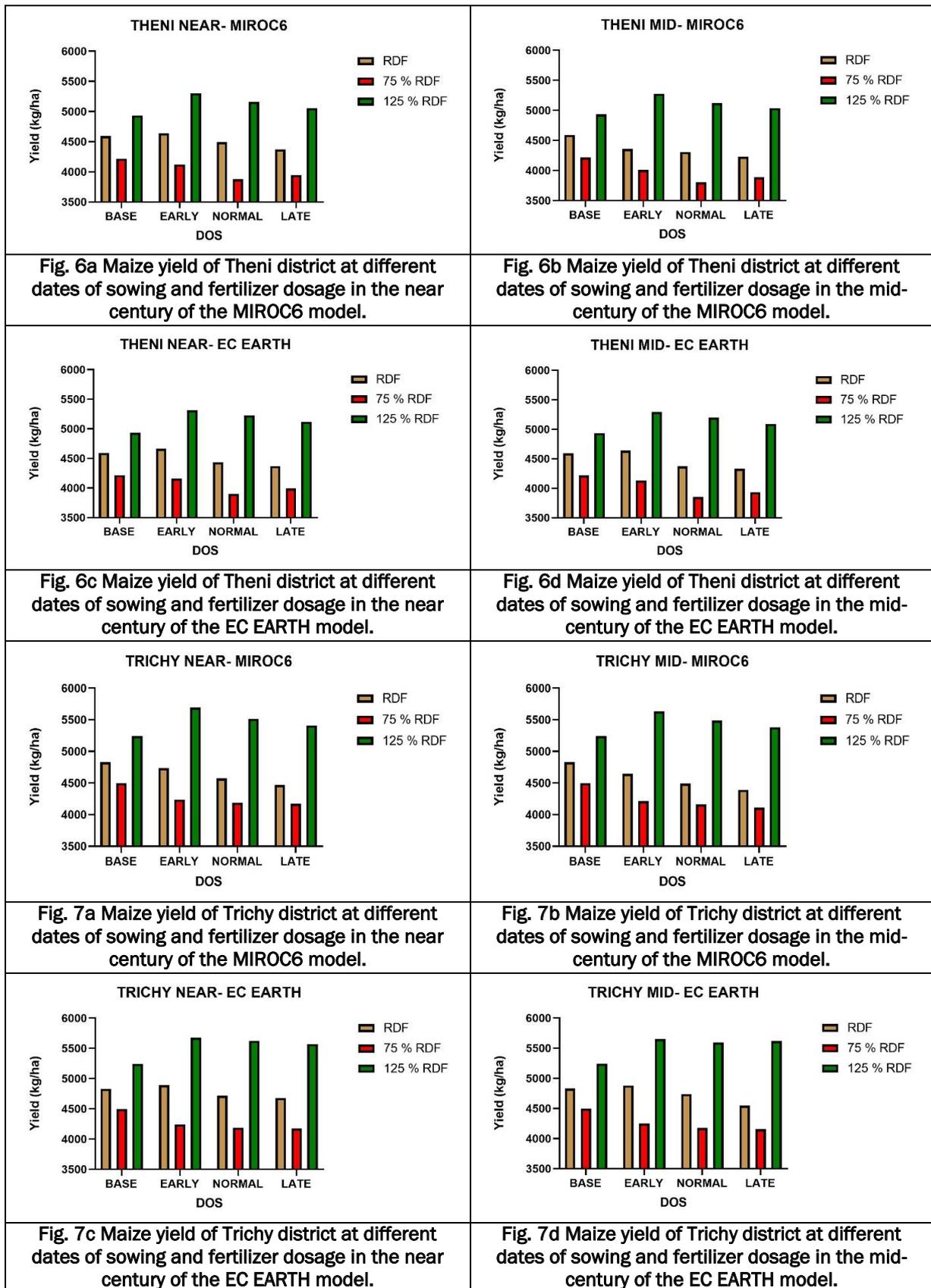
In Perambalur district, among the different dates of sowing and fertilizer applications, the highest yield was obtained with early DOS + 125% RDF, which was 8.3 & 7.9% (MIROC6) and 8.8 & 8.1% (EC EARTH), higher than the base yield (5137 kg/ha) for near and mid-century, respectively. (Fig. 4a-d)

In Ariyalur, the highest yield was obtained in early DOS + 125% RDF, at 8.0% (MIROC6) and 7.2% (EC EARTH), which were higher than the base yield (4755 kg/ha) for near and mid-century, respectively. (Fig. 5a-d)





<p>Fig. 4a Maize yield of Perambalur district at different dates of sowing and fertilizer dosage in the near century of the MIROC6 model.</p>	<p>Fig. 4b Maize yield of Perambalur district at different dates of sowing and fertilizer dosage in the mid-century of the MIROC6 model.</p>
<p>Fig. 4c Maize yield of Perambalur district at different dates of sowing and fertilizer dosage in the near century of the EC EARTH model.</p>	<p>Fig. 4d Maize yield of Perambalur district at different dates of sowing and fertilizer dosage in the mid-century of the EC EARTH model.</p>
<p>Fig. 5a Maize yield of Ariyalur district at different dates of sowing and fertilizer dosage in the near century of the MIROC6 model.</p>	<p>Fig. 5b Maize yield of Ariyalur district at different dates of sowing and fertilizer dosage in the mid-century of the MIROC6 model.</p>
<p>Fig. 5c Maize yield of Ariyalur district at different dates of sowing and fertilizer dosage in the near century of the EC EARTH model.</p>	<p>Fig. 5d Maize yield of Ariyalur district at different dates of sowing and fertilizer dosage in the mid-century of the EC EARTH model.</p>





<p>Fig. 8a Maize GDD of Perambalur district at different dates of sowing and fertilizer dosage in the near century of the MIROC6 model.</p>	<p>Fig. 8b Maize GDD of Perambalur district at different dates of sowing and fertilizer dosage in the mid-century of the MIROC6 model.</p>
<p>Fig. 8c Maize GDD of Perambalur district at different dates of sowing and fertilizer dosage in the near century of the EC EARTH model.</p>	<p>Fig. 8d Maize GDD of Perambalur district at different dates of sowing and fertilizer dosage in the mid-century of the EC EARTH model.</p>
<p>Fig. 9a Maize GDD in Ariyalur district at different dates of sowing and fertilizer dosages in the near century of the MIROC6 model.</p>	<p>Fig. 9b Maize GDD of Ariyalur district at different dates of sowing and fertilizer dosage in the mid-century of the MIROC6 model.</p>
<p>Fig. 9c Maize GDD of Ariyalur district at different dates of sowing and fertilizer dosage in the near century of the EC EARTH model.</p>	<p>Fig. 9d Maize GDD of Ariyalur district at different dates of sowing and fertilizer dosage in the mid-century of the EC EARTH model.</p>



<p style="text-align: center;">THENI NEAR- MIROC6</p>	<p style="text-align: center;">THENI MID- MIROC6</p>
<p>Fig. 10a Maize GDD of Theni district at different dates of sowing and fertilizer dosage in the near century of the MIROC6 model.</p>	<p>Fig. 10b Maize GDD of Theni district at different dates of sowing and fertilizer dosage in the mid-century of the MIROC6 model.</p>
<p style="text-align: center;">THENI NEAR- EC EARTH</p>	<p style="text-align: center;">THENI MID- EC EARTH</p>
<p>Fig. 10c Maize GDD of Theni district at different dates of sowing and fertilizer dosage in the near century of the EC EARTH model.</p>	<p>Fig. 10d Maize GDD of Theni district at different dates of sowing and fertilizer dosage in the mid-century of the EC EARTH model.</p>
<p style="text-align: center;">TRICHY NEAR- MIROC6</p>	<p style="text-align: center;">TRICHY MID- MIROC6</p>
<p>Fig. 11a Maize GDD of Trichy district at different dates of sowing and fertilizer dosage in the near century of the MIROC6 model.</p>	<p>Fig. 11b Maize GDD of Trichy district at different dates of sowing and fertilizer dosage in the mid-century of the MIROC6 model.</p>
<p style="text-align: center;">TRICHY NEAR- EC EARTH</p>	<p style="text-align: center;">TRICHY_ MID- EC EARTH</p>
<p>Fig. 11c Maize GDD of Trichy district at different dates of sowing and fertilizer dosage in the near century of the EC EARTH model</p>	<p>Fig. 11d Maize GDD of Trichy district at different dates of sowing and fertilizer dosage in the mid-century of the EC EARTH model</p>

For Theni, the highest yield was obtained in early DOS + 125% RDF, which was 7.4 & 6.9% (MIROC6) and 7.7 & 7.2 % (EC EARTH) higher than the base yield (4937 kg/ha) for near and mid-century, respectively. (Fig. 6a-d)

In Trichy, the highest yield was obtained in early DOS + 125% RDF, which was 8.6 & 7.5% (MIROC6) and 8.3 & 7.8 % (EC EARTH) higher than the base yield (5243 kg/ha) for near and mid-century, respectively (Fig. 7a-d)

Between the two models, for both near- and mid-century, the highest yield was obtained with early DOS + 125% RDF. The sowing date has a significant influence on crop growth and yield due to environmental variations over time and space. (Sankar *et al.*, 2023) concluded that among different sowing windows, early sowing achieved the highest yield. (Futo, 2003) experienced that the increasing fertilizer rate stimulated the photosynthetic activity and Leaf Area Index (LAI). (Csajboket *al.*,2005; El Hallof *et al.*, 2006) measured the highest photosynthetic activity at N 120+PK fertilizer dose in the average of maize hybrids.

For the Perambalur district, the highest growing degree days ($^{\circ}\text{C-d/d}$) were obtained in early DOS + 125% RDF, which were 17.0 & 16.8 (MIROC6) and 17.2 & 17.0 (EC EARTH), respectively, higher than the base yield (16.8) for near and mid-century, respectively (Fig. 8a-d).

For Ariyalur district, the highest growing degree days ($^{\circ}\text{C-d/d}$) were obtained in early DOS + 125% RDF, which were 16.84 & 16.74 (MIROC6) and 17.1 & 16.82 (EC EARTH), respectively, higher than the base yield (16.59) for near and mid-century, respectively (Fig. 9a-d).

For the Theni district, the highest growing degree days ($^{\circ}\text{C-d/d}$) were obtained in early DOS + 125% RDF, which were 16.74 & 16.30 (MIROC6) and 16.78 & 16.71 (EC EARTH), respectively, higher than the base yield (16.67) for near and mid-century, respectively (Fig. 10a-d).

For the Trichy district, the highest growing degree days ($^{\circ}\text{C-d/d}$) were obtained in early DOS + 125% RDF, which were 17.16 & 16.74 (MIROC6) and 17.05 & 16.78 (EC EARTH), respectively, higher than the base yield (16.89) for near and mid-century, respectively (Fig. 11a-d).

The increase in yield at early sowing dates was due to higher heat accumulation, and this relationship was also substantiated by many authors (Naveen *et al.*, 2020), who found that greater heat-unit accumulation with longer phenophase duration in early sowing increased yield in green gram, and vice versa. (Hemalatha *et al.*, 2013), who found that higher accumulation of heat units increased maize yield, and vice versa. Early sowing increased the duration of the crop and accumulated more heat units, viz., GDD, HTU, PTU, RTD, and HUE, due to a longer phenophase than in other sowing windows (Shankar *et al.*, 2023).

CONCLUSION

Assessing the effects of climate change on maize yields is essential for developing adaptation strategies to mitigate its impacts and ensure food security. Maize yield would be reduced in the future if adaptation strategies were not implemented. Adaptation options varied quantitatively by location and season. As a result, breeding cultivars with phenology adapted to changed scenarios similar to those of current varieties is required. Plant breeders should consider phenological variation among maize genotypes when developing varieties for future climate change scenarios. In both models across the study area, early DOS + 125% RDF has a higher yield than the others. This study has the potential to quantify future spatiotemporal changes in maize yield and to identify adaptation strategies to mitigate the negative effects of climate change.

ACKNOWLEDGEMENT

We thank the Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore, for providing support to carry out the research.

Funding and Acknowledgment:

The authors received no financial support for the research, authorship, and/or publication of this article.

Ethics Statement:

This study was conducted using publicly available dataset sources. It did not involve human participants, animals, or any form of personal data. Therefore, ethical approval was not required.

Originality and Plagiarism:

The authors confirm that this manuscript is an original work and has not been published previously, nor is it under consideration for publication elsewhere.

All sources of data, concepts, and previously published material have been properly cited and acknowledged. The manuscript has been prepared in accordance with ethical academic standards, and plagiarism in any form has been strictly avoided.

Consent for Publication:

All authors have read and approved the final version of the manuscript and consent to its submission and publication in the journal.

Competing Interests:

The authors declare that they have no known financial or non-financial competing interests that could have influenced the work reported in this manuscript.

Data Availability:

The study utilized publicly available datasets. Observed gridded meteorological data were obtained from the India Meteorological Department (IMD). Future climate projections were derived from Global Climate Models (GCMs) participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) framework.

Author Contributions:

Kokilavani S: Conceptualization, methodology development, drafting the initial manuscript, and overall coordination of the research work; data interpretation and review.

Akshaya S: Data curation, analysis, visualization, and preparation of figures and tables.

Dheebakaran Ga: Data processing, statistical analysis, and support in result interpretation.

Boomiraj K: Overall supervision, review and editing of the manuscript, and project guidance.

Sathyamoorthy N.K: Critical review, technical inputs, and manuscript editing.

Santhoshkumar B: Methodology refinement, data analysis, visualization, drafting of sections of the manuscript, and editing support.

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