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Research Article

Potential Impacts of Future Climate Changes on Crop Productivity of Cereals and Legumes in Tamil Nadu, India: A Mid-Century Time Slice Approach

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Climate change is a terrible global concern and one of the greatest future threats to societal development as a whole. The accelerating pace of climate change is becoming a major challenge for agricultural production and food security everywhere. The present study uses the midcentury climate derived from the ensemble of 29 general circulation models (GCMs) on a spatial grid to quantify the anticipated climate change impacts on rice, maize, black gram, and red gram productivity over Tamil Nadu state in India under RCP 4.5 and RCP 8.5 scenarios. The future climate projections show an unequivocal increase of annual maximum temperature varying from 0.9 to 2.2°C for RCP 4.5 and 1.4 to 2.7°C in RCP 8.5 scenario by midcentury, centered around 2055 compared to baseline (1981–2020). The projected rise in minimum temperature ranges from 1.0 to 2.2°C with RCP 4.5 and 1.8 to 2.7°C under RCP 8.5 scenario. Among the monsoons, the southwest monsoon (SWM) is expected to be warmer than the northeast monsoon (NEM). Annual rainfall is predicted to increase up to 20% under RCP 4.5 scenario in two-third of the area over Tamil Nadu. Similarly, RCP 8.5 scenario indicates the possibility of an increase in rainfall in the midcentury with higher magnitude than RCP 4.5. Both SWM and NEM seasons are expected to receive higher rainfall during midcentury under RCP 4.5 and RCP 8.5 than the baseline. In the midcentury, climate change is likely to pose a negative impact on the productivity of rice, maize, black gram, and red gram with both RCP 4.5 and RCP 8.5 scenarios in most places of Tamil Nadu. The magnitude of the decline in yield of all four crops would be more with RCP 8.5 over RCP 4.5 scenario in Tamil Nadu. Future climate projections made through multi-climate model ensemble could increase the plausibility of future climate change impact assessment on crop productivity. The adverse effects of climate change on cereal and legume crop productivity entail the potential adaptation options to ensure food security.

1. Introduction

Agriculture plays a safekeeping role in food security and rural trades in large parts of the world [1]. The interaction between climate change and agriculture is a critical concern because the world's food production capabilities are under constraint due to a rapidly growing population [2]. Climate change triggered anxiety among everyone in the world because it endangers agriculture and food security [3]. Food security for the rapidly growing population is a critical concern due to the serious threat that climate change poses to agriculture [4–7]. Scientists and planners are concerned because this could jeopardize their efforts to achieve food security [4]. Climate change has the potential to alter the crop yield (both positively and negatively), as well as the types of crops cultivated in certain places, through affecting irrigation water availability, solar radiation levels that affect plant growth, and pest prevalence [4]. Overall, persistent changes in climate could disturb the crop production and have more potential to determine crop productivity.

Impacts of climate change on agriculture are increasing with time, posing substantial impacts in low-latitude (tropical), low-income countries of sub-Saharan Africa, South Asia, and Latin America that have less adaptive capacity [8–11]. Though some crops gain beneficial effects from climate change in some regions of the world, the comprehensive impacts of climate change are expected to be negative on agriculture. Many assessments indicated that despite some adaptation practices followed by the farmers being beneficial, the negative effect of climate change in low-latitude countries situated in the tropical regions may still be considerable [8]. In developing countries, agricultural productivity is badly affected due to devastating environmental changes [12]. The anticipated climate change and the enhancement of greenhouse gas may increase the crop productivity over Northwestern Europe and reduce the crop productivity in the Mediterranean area [13].

Global atmospheric CO_2 concentrations and air temperature are expected to increase considerably by 2050 and beyond [11]. Although water deficits are expected to rise, there is larger uncertainty in rainfall anticipated for different regions and time periods. The rise in temperature and carbon dioxide (CO_2) could improve the yield of some crops in some places. However, to realize these advantageous effects, water availability, soil moisture, nutrient levels, and other essential conditions need to be met. Elevated CO_2 levels can increase plant growth, but increase in temperature, water, and nutrient constraints may counteract the positive influence of CO_2 on crop growth and productivity. Climate change-induced changes in frequency and severity of extreme weather events and uncertainty in rainfall patterns are detrimentally affecting the agricultural crops [14]. The production of major crops has decreased owing to the elevated temperature, and it is likely to reduce further with increased climatic severity around the world at the end of this century [15].

To understand the impact of climate change, the future climate is projected using climate models under different climate change scenarios. A climate change scenario is defined by Fischer [16], and these scenarios are highly useful tools for scientific evaluation, learning about complex system's behavior, and policymaking. IPCC has developed a set of new emission scenarios termed as representative concentration pathways (RCPs). There are four RCP scenarios: RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, and the number attached to each RCP scenario reflects a specific radiative forcing by the year 2100. Zhou and Wang [17] studied the impact of future climate change on the yield potential of rice and maize under the RCP 4.5 scenario by using 30 GCMs. Dissimilar GCM projections and various RCPs were used in more rigorous and precise climate change effect assessment studies as indicated by Araya et al. [18] and Tebaldi and Knutti [19]. In southwestern Ethiopia, Araya et al. [18] simulated the influence of climate change on maize yield under high and moderate RCP scenarios using 20 distinct GCMs.

Quite a lot of researchers have used diverse methodological approaches to investigate the effects of climate change on the range of crops for their yield productivity. They have employed either biophysical models based on processes or economic and statistical models [20–23]. Crop simulation and other autoregressive models have been widely used to investigate the effects of abiotic pressures on diverse crops, including long-term variations in surface temperatures, CO_2 emissions, and rainfall [24–26]. Vijayakumar et al. [27] projected the increasing trend of rainfall and temperature pattern for the eastern coastal region of India while using CMIP5 models in different RCP scenarios during the near (2011–39), mid (2040–69), and late (2070–99) centuries, respectively. Kourat et al. [28] assessed the future climate change impact on rainfed wheat and revealed that as the concentration of CO_2 is higher under RCP 8.5 than under RCP 4.5, the predicted rise in wheat yield is substantially greater. Pu et al. [29] explored the occurrence of a desirable association between maize yield and changes of precipitation besides showing an undesirable association with temperature under two RCPs. However, rice shows a desirable correlation with the changes of precipitation under RCP 4.5. Islam et al. [30] opined that due to the effects of climate change, global yields of chief food crops, namely, maize, rice, wheat, and soybean, would be around 25% lower by 2050.

Owing to changing climate, the likely rise of extreme weather events will have negative impacts on the production of cereal crops in Ethiopia [31–33]. The results of the various studies have shown large inconsistencies in the magnitude and sometimes in the direction of the climate change impact on crops as some studies projected a 20–43% decline in maize yield [34–36], and other studies predicted the increase in maize yield by 2–51% [31, 32, 34]. The possible reasons for these discrepancies might stem from the consideration of a low number of climate model projections in each of the studies.

In confronting climate change, agricultural decision making becomes a challenging task because of the uncertainties linked with impact assessments. Most of the studies assessed the climate change impact on crop yields using specific or a few number of climate model projections without considering the uncertainty in the climate change projections. Therefore, it is important to use the future climate derived from the ensemble of multiple climate models to reduce the uncertainty in the climate change impact assessment. In the present research, we used the future climate generated through the ensemble of 29 climate models for projecting the changes in climate and assessing its impact on crop productivity.

Climate change and its consequences on various crops are not uniformly distributed in space. Scientific pieces of evidence on the spatial sensitivity of a range of crops under the same multi-modelensemble-projected plausible climatic conditions in a region could be helpful for a better understanding of how the different crops respond to the same future climate projections and also to know the future suitability of various crops in that region with a high level of confidence. We focused on the two important cereal crops, namely, rice and maize, and two pulse crops, namely, red gram and black gram, which have food and nutritional security values and are also majorly grown in Tamil Nadu. We assessed the potential biophysical impact of climate change on selected crops and also evaluated the varied magnitude of spatial responses of rice, maize, red gram, and black gram to the climate projected using a common multi-model ensemble scheme for all four crops under both RCP 4.5 and RCP 8.5 scenarios for midcentury. The objectives of this paper are (i) to reduce the uncertainties in future climate change projection and (ii) to unravel the spatial and differential effects of climate change on the productivity of cereals and legumes.

2. Materials and Methods

2.1. Study Site. Tamil Nadu is designated as a study area consisting of 32 districts, and it lies in the southern most part of the Indian subcontinent and covers an area of about 1,30,058 km^2. Geographically, it is located between 8°4′35.5″ to 13°33′44.8″N latitude and 76°13′32.6856″ to 80°20′ 48.4872″E longitude. Tamil Nadu has a tropical climate and receives an average annual rainfall of 987 mm. Tamil Nadu is different from the rest of the states in India as it gets a major share of its rains from the northeast monsoon during October to December (48%), followed by the southwest monsoon from June to September (32%). The major soil types of Tamil Nadu are red loam, laterite, black, alluvial, and saline soils. Red loam covers a large part of the state especially the central districts of the state. It is one of the water-starved southern states in India and has a total geographical area of 13 million ha with a cultivable area of 7 million ha. Rice, maize, black gram, and red gram are the major food crops grown in Tamil Nadu and occupy an area of 18.5, 3.25, 4.26, and 0.61 lakh ha, respectively. Crop production in the state is greatly affected by climate variability and climate change.

2.2. Climate Data

2.2.1. Baseline Climate. Gridded rainfall data at a spatial resolution of 0.25×0.25 degrees obtained from the India Meteorological Department (IMD) were utilized to investigate the historical rainfall variability of climate over Tamil Nadu. Maximum and minimum temperatures were calculated using district-level IMD data in daily time steps from 1981 to 2020. The DSSAT model's weather generator tool, which used maximum and minimum temperatures as input, was used to create solar radiation data for crop simulations. To understand the climatology, annual and seasonal ranges of climate variables were derived and their percent contribution to annual rainfall was worked out. Descriptive statistics were also worked out to understand the climatic variability in time and space.

2.2.2. Climate Projections. Future climate projections were created using 29 GCMs suggested in IPCC's fifth assessment report, by utilizing the "mean and variability" approach, in which the mean monthly changes, as well as the magnitude of variability, were applied to the daily baseline weather record under RCP 4.5 and RCP 8.5 for midcentury time slices, centered around 2055 (2041–2070). The ensemble of all 29 models was taken to finally develop the future climate over Tamil Nadu. Four parameters were retrieved from future scenario simulations, namely, solar radiation (W m^{-2}), maximum temperature (°C), minimum temperature (°C), and rainfall (mm). The absolute change in maximum temperature and minimum temperature from the base period to that of midcentury was captured. Similarly, for rainfall, the percent change was computed.

2.3. Crop Model Description. Crop models are increasingly used to quantify the impact of future climate change on crop yield including the effect of increases in both temperature and CO_2 concentration [9]. The impact of climate change on crops' productivity was assessed using Decision Support System for Agrotechnology Transfer (DSSAT), a dynamic crop simulation model. The CERES (Crop Environment Resource Synthesis) model embedded in DSSAT [37] was used to assess the impact of climate change on rice and maize. Similarly, for red gram and black gram, the CROPGRO model embedded in DSSAT was used. CERES and CROPGRO are process-based models that run on a daily time step and operate based on water, nitrogen, carbon, and energy balance principles for stimulating the growth and development of the plants. They simulate crop growth, development, and yield of specific cultivars as a function of soil characteristics, weather, and crop management practices [38]. CERES and CROPGRO can be replaced with CERES and CROPGRO [39, 40]. In addition to the good predictability of high temperature effects [24, 41, 42], these models are also very much capable of capturing the leaf and canopy assimilation responses to CO_2 as noticed in soybean [43–46]. DSSAT considers the factors like root growth distribution function and lower limit of soil water availability to model drought situations. Root growth distribution function deals with the access and extraction of the soil water by the plants, and the lower limit of soil water availability is defined as the limit below which roots cannot draw the water from the soil [20]. Drought stress is programmed in the CERES and CROPGRO modules as a function of the actual to potential transpiration ratio and its influences on photosynthesis and grain filling rate [47]. The comprehensive modelling features of DSSAT make it a perfect choice to study climate change impacts on cereals and pulse crops.

2.4. Biophysical Modelling: DSSAT Crop Model. DSSAT requires data on weather, soil profiles, genetic coefficients, and crop management details for simulating the growth and productivity of crops. The details of the input parameters used in the DSSAT model are described below.

Weather input file: for examining the biophysical impact of climate change on crop production, the baseline and future climate data were exported as weather files in the DSSAT 4.7.5 crop simulation model [48]. The weather data were converted into DSSAT weather file format using Weatherman tool available in DSSAT. The corresponding projected CO_2 concentration of 499 ppm for RCP 4.5 and 571 ppm for RCP 8.5 was used in the DSSAT model to include the CO_2 fertilization effects over the midcentury (2041–2070).

Soil input file: the soil database for Tamil Nadu at a 1 : 50,000 scale obtained from the Department of Remote Sensing and GIS of Tamil Nadu Agricultural University (TNAU) was utilized to create soil files. The profile details as required in DSSAT were extracted from the above database using ArcGIS and were fed into S Build tool in DSSAT to create soil files.

Crop management file: the crop management files were created using a standard package of practices suggested in the crop production guide of TNAU for the study crops. The details of the experimental conditions and field characteristics such as weather station name, soil description details, planting geometries, irrigation and water management, and fertilizer management details were given through X Build tool in DSSAT.

In rice field experiments, 21-day-old seedlings were pulled out from the nursery and transplanted in the main field at the rate of two seedlings per hill by adopting a spacing of 15 × 10 cm. We maintained 2 cm of water up to seven days after transplanting. After the establishment stage, irrigation was provided to maintain the cyclic submergence to a depth of 5 cm from planting up to 10 days prior to harvest. As per the recommendation of TNAU crop production guide, 150 : 50 : 50 of N, P_2O_5, K_2O kg ha^{-1} fertilizer was applied during the crop period. The phosphatic fertilizer was applied completely as basal, nitrogen, and potash fertilizers were applied in four equal splits at basal, active tillering, panicle initiation, and flowering stage.

In maize field experiments, the field was uniformly leveled and ridges and furrows were prepared with a spacing of 60 cm. The maize seeds were dibbled at the rate of one seed hill^{-1} by adopting an intrarow spacing of 25 cm. The recommended fertilizer dose of 250 : 75 : 75 of N : P : K kg ha^{-1} was applied in the form of urea, super phosphate, and muriate of potash, respectively. The full dose (100%) of P and K was applied as basal in the sowing lines of maize. Nitrogen was applied in four splits with 25 % basal, 50 % top dressing at 25 DAS, and 25 % top dressing at 45 DAS (Crop Production Guide, TNAU). Irrigation was provided immediately after sowing, and life irrigation was provided on the third day. Subsequent irrigation was provided as and when necessary.

For red gram, the land was prepared to fine tilth and the beds and channels were formed. Seeds were dibbled in the beds with a spacing of 120 × 30 cm. The recommended dose of all fertilizers (25 : 50 : 25 of N : P : K kg ha^{-1}) was applied basally before sowing in the form of urea, SSP, and Muriate of potash. Irrigation was done immediately after sowing, 3rd day after sowing, at the bud initiation stage, and at 50% flowering and pod development stages. For black gram, the seeds were dibbled in the beds by adopting 30 × 10 cm spacing, and the fertilization was done with 25 kg N, 50 kg P_2O_5, and 25 kg K_2O per hectare as a basal application before sowing. We irrigated the field immediately after sowing, followed by life irrigation on the third day. Subsequent irrigation was provided at intervals of 7 days. We avoided water stagnation at all stages of the crop.

Genetic coefficient file: genetic coefficients were estimated based on the data obtained from the field experiments of TNAU. The genetic coefficients in the DSSAT model that influence the occurrence of developmental stages were obtained iteratively by manipulating the relevant coefficients to achieve the best possible match between the simulated and observed number of days to phenological events and yield of the test cultivars and used for simulations.

DSSAT model setup was done by creating the necessary input files as described above, and the productivity of cereal and legume crops under baseline and future climatic conditions was simulated. The baseline and future crop productivity was extracted from the DSSAT output files and used for assessing the potential impact of future climate change on the productivity of rice, maize, red gram, and black gram crops. The consecutive research steps followed to achieve the objectives are indicated in the schematic diagram (Figure 1).

2.5. Estimating the Future Yield Changes under Different Climate Scenarios. The impact of projected future climate on crops was assessed by calculating the changes in yield between baseline and the future climate scenarios. The changes in crop yield were calculated during the midcentury period (2041–2070) relative to the baseline period (1981–2020) as follows:

$$\text{change in yield} = \frac{\left(Y_f - Y_b\right)}{Y_b}, \quad (1)$$

where Y_f is the yield under future climate and Y_b is the yield under the baseline climate.

3. Results

3.1. Current Climate. The normal annual maximum temperature of Tamil Nadu averaged over a period of 1981 to 2020 was found to be 32.5°C, and it varied from a minimum of 29.0°C (Cuddalore) to a maximum of 33.9°C (Karur) with a standard deviation of 1.5°C. Spatial variations of maximum and minimum temperatures and rainfall for the two crop growing seasons, namely, southwest monsoon (SWM) season and northeast monsoon (NEM) season, are presented in Figure 2. Among the seasons, during SWM, Tamil Nadu

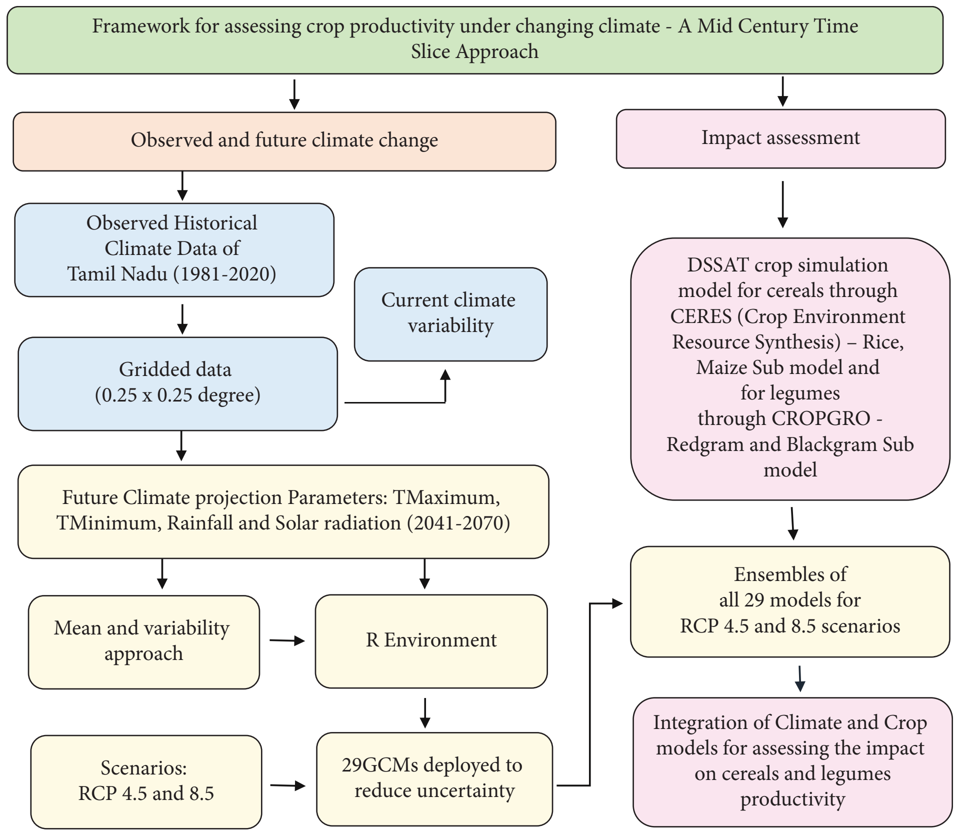

Figure 1: Framework for assessing the impact of climate change on productivity of cereals and legumes.

witnessed maximum temperature from 27.5°C (Cuddalore) to 35.3°C (Ariyalur, Villupuram, Karur, Vellore, Nagapattinam, Trichy, Perambalur, and Thanjavur) with a standard deviation of 2.5°C, while the northeast monsoon witnessed a variation from 27.7°C (Cuddalore) to 31.2°C (Kanyakumari) with a standard deviation of 1.1°C. The annual minimum temperature was found to be 22.7°C, and it varied from a minimum of 18.8°C to a maximum of 24.4°C with a standard deviation of 1.7°C. Among the seasons, SWM had variation ranging from 19.6 to 25.8°C, while NEM varied from 18.0 to 23.2°C. SWM had the highest standard deviation of 1.9°C, and the NEM had the standard deviation of 1.6°C.

The mean annual rainfall of Tamil Nadu was found to be 930 mm; it varied from a minimum of 276 mm to a maximum of 1647 mm with a standard deviation of 322 mm. Among the seasons, NEM had the highest amount of rainfall (460 mm) followed by SWM (322 mm) and HWP (117 mm), and the least was during CWP (32 mm). Among the monsoons, SWM rainfall ranged from 67 to 703 mm while NEM varied from 99 to 992 mm. The standard deviation was highest for NEM (214 mm) compared to SWM (154 mm). The mean number of rainy days per annum for Tamil Nadu was 58 days with a standard deviation of 15 days and ranged from 23 to 86 days. Among the monsoons, NEM had a normal period of about 25 rainy days while SWM had 22 rainy days. NEM witnessed a variation ranging from 8 to 43 days while SWM varied between 6 and 41 days.

3.2. Future Climate Projection. Maximum temperature was projected to increase by all the models studied for all the locations over Tamil Nadu (Figure 3). The climate models under RCP 4.5 projected 0.9 to 2.2°C increase in annual temperature by midcentury. The lowest increase was projected over Vellore by both the scenarios while the highest increase was projected over Krishnagiri. With RCP 8.5 scenario, an increase of 1.4 to 2.7°C in maximum temperature is expected.

Seasonal variation in climate projections (Figure 3) indicated that during SWM, with RCP 4.5, the lowest increase in maximum temperature was projected over Tiruvannamalai (0.9°C), while the highest increase was projected over Perambalur (1.6°C), and with RCP 8.5, an increase of 1.5°C (Kanyakumari) to 2.5°C (Krishnagiri) is projected during the midcentury time scale (Figure 3). As far as NEM is concerned, increase in maximum temperature is projected for RCP 4.5 ranging from a lowest value in Ariyalur (1.0°C) to a highest value in Dharmapuri (2.2°C), and for RCP 8.5, the projected increase is from 1.3°C (Thoothukkudi, Thanjavur, Sivagangai, Ramanathapuram, Perambalur, and Madurai) to 2.9°C (Dharmapuri). Minimum temperature was projected to increase for all the locations over Tamil Nadu (Figure 3). The climate models under RCP 4.5 projected 1.0°C (Ariyalur) to 2.2°C (Dharmapuri) increase in annual minimum temperature by midcentury. With RCP 8.5 scenario, an increase of 1.8°C (Chennai) to 2.7°C (Krishnagiri) is expected. Seasonal variation in minimum temperature (Figure 3) indicated that

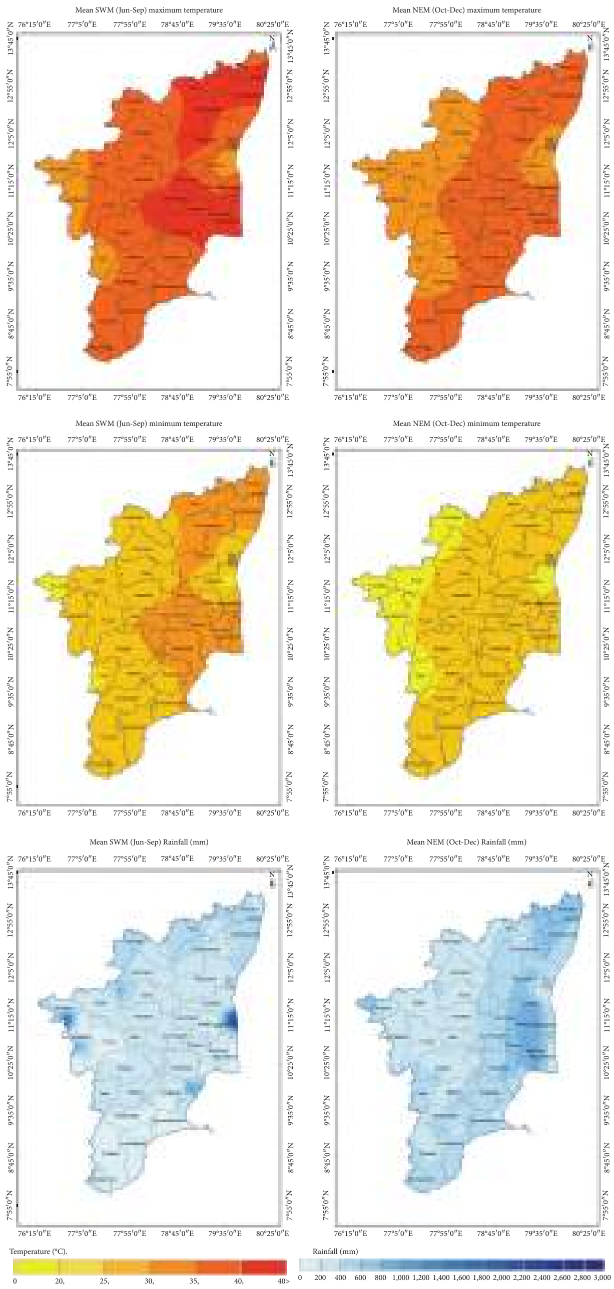

Figure 2: Spatial variation of maximum and minimum temperatures (°C) and rainfall (mm) over Tamil Nadu (mean of 1981–2020).

during SWM, with RCP 4.5, the lowest increase in minimum temperature was projected over Ariyalur (1.0°C), while the highest increase was projected over Krishnagiri (1.8°C), and with RCP 8.5, an increase of 1.9°C (Thanjavur) to 2.6°C (Perambalur) is projected during the midcentury. As far as NEM is concerned, increase in minimum temperature projected for RCP 4.5 ranges from a lowest value in Thanjavur (1.4°C) to a highest value in Perambalur (2.3°C), and for RCP 8.5 scenario, the projected increase is from 1.9°C (Kanyakumari) to 2.5°C (Krishnagiri, Perambalur, and Thiruvallur).

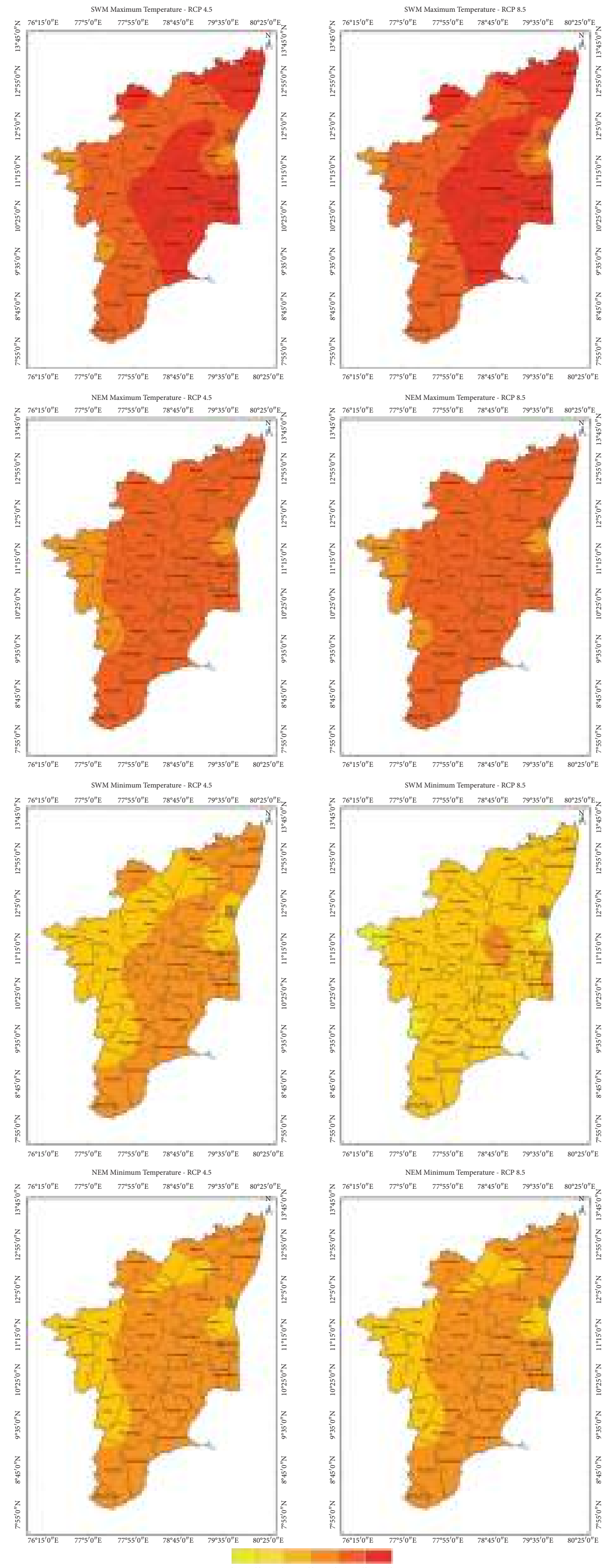

Figure 3: Multi-climate model ensemble projection of maximum and minimum temperatures (°C) for RCP 4.5 and RCP 8.5 scenarios for the midcentury.

Table 1: Spatial representation of change in annual and seasonal rainfall over Tamil Nadu for the midcentury time period.

Percent change in rainfall	Percentage of grids in RCP 4.5					Percentage of grids in RCP 8.5				
	Annual	CWP	HWP	SWM	NEM	Annual	CWP	HWP	SWM	NEM
−81 to 100	—	23	—	—	—	—	—	—	—	—
−61 to 80	—	25	—	—	—	—	—	4	—	—
−41 to −60	—	23	—	—	—	—	—	28	—	—
−21 to −40	—	14	—	—	—	—	2	30	—	—
0 to −20	2	8	39	6	2	21	8	36	1	2
1 to 20	77	4	39	85	86	26	34	1	45	33
21 to 40	21	2	1	9	11	50	13	1	46	64
41 to 60	—	2	14	—	1	3	21	—	2	1
61 to 80	—	—	7	—	—	—	14	—	6	—
81 to 100	—	—	—	—	—	—	2	—	—	—
Above 100	—	—	—	—	—	—	8	—	—	—

Ensemble value of 29 global climate model predictions for rainfall over Tamil Nadu for RCP 4.5 and RCP 8.5 during midcentury is presented as percent departure from the baseline period (Table 1 and Figure 4). Annual rainfall, under RCP 4.5 scenario, is projected to increase up to 20% in 77% of the grids, while in 21% of the grids, it is expected to increase from 20 to 40%; similarly, RCP 8.5 scenario also indicates that there is a possibility for increase in rainfall in the midcentury.

During SWM season, with RCP 4.5 scenario, only nine percent grids had increase in rainfall from 21 to 40%, and 85% of grids show an increase in rainfall from 1 to 20%; however, six percent of grids indicate the possibility for reduction in rainfall up to 20%. In respect of RCP 8.5 scenario, during SWM season, about 45% of grids had an increase in rainfall from 1 to 20% followed by 46% of grids with 21 to 40% increase, and minimum of 2 and 6% of grids had 41 to 60 and 61 to 80% increase in rainfall. In the case of NEM, the increase in rainfall is expected to be 1 to 20 percent in 86 percent of grids, 21 to 40 percent in 11 percent of grids, and 41 to 60 percent in 1 percent of grids under RCP 4.5 scenario. For RCP 8.5 scenario, 98 percent of grids are expected to have an increase in rainfall with 1 to 20 percent increase in 33 percent of grids, 21 to 40 percent increase in 64 percent of grids while only 1 percent of grids showed 41 to 60 percent increase in rainfall. A decrease in rainfall up to 20 percent was projected in 2 percent grids (Table 1 and Figure 4).

3.3. Impact of Climate Change on Cereals and Pulses over Tamil Nadu

3.3.1. Cereal Crops

(1) Genetic Coefficients of Cereal Crops. Crop simulation model DSSAT was calibrated for rice cultivar ADT 43 and for maize cultivar CO(M)H-6 using the field experimental data carried out at TNAU, Coimbatore. Data collected from six dates of sowing experiments in each of the crops were used for developing genetic coefficient. The calibrated genetic parameters of rice and maize cultivar used in the DSSAT model are presented in Table 2.

(2) Spatial Variability in Rice Productivity

(a) *Current Climate*

Rice productivity in Tamil Nadu for the baseline varied spatially between 1594 $^{-1}$ and 4631 kg·ha^{-1}. Rice productivity was more than 4000 kg·ha^{-1} in Thiruvarur (4564 kg·ha^{-1}), Tiruchirappalli (4444 kg·ha^{-1}), Thanjavur (4230 kg·ha^{-1}), Theni (4139 kg·ha^{-1}), Nagapattinam (4120 kg·ha^{-1}), and in the Nilgiris (4110 kg·ha^{-1}) districts (Figure 5). Virudhunagar, Chennai, Ariyalur, Tirunelveli, Karur, Perambalur, Coimbatore, Salem, Kancheepuram, Sivagangai, and Pudukkottai districts registered the rice productivity between 3000 and 3659 kg·ha^{-1}. Districts like Namakkal, Vellore, Dharmapuri, Tirupur, Madurai, Krishnagiri, Kanyakumari, and Erode registered the productivity from 2000 to 3000 kg·ha^{-1}. The remaining districts had very low rice productivity (1758 to 1995 kg·ha^{-1}).

(b) *Future Climate*

Spatial variability in rice productivity during midcentury for RCP 4.5 and RCP 8.5 during SWM and NEM seasons is presented in Figure 6. During southwest monsoon season (June–September) coinciding with Kharif season, the productivity is expected to have 10 to 15% yield reduction with RCP 4.5, and in the same period with RCP 8.5, up to 30% yield reduction is expected. Though the reduction is found in almost all the districts, it is more pronounced in the major rice growing districts such as Thanjavur and Nagapattinam.

The same study for the northeast monsoon (Rabi season) indicates that there is an expected increase in rice yield up to 15% with RCP 4.5 in few districts (Karur, Perambalur, Trichy, Coimbatore, and Namakkal), and a very small decrease up to 5% is expected in Dindigul district and 15% decrease is expected in Thanjavur, Thiruvarur, Ramanathapuram, Tirunelveli, Virudhunagar, and Tenkasi districts. In Nagapattinam, Erode, Tiruppur, and Theni districts, 10% decrease in rice production is expected. In other districts, 5% decrease in rice productivity is expected. With RCP 8.5, only Madurai district shows positive

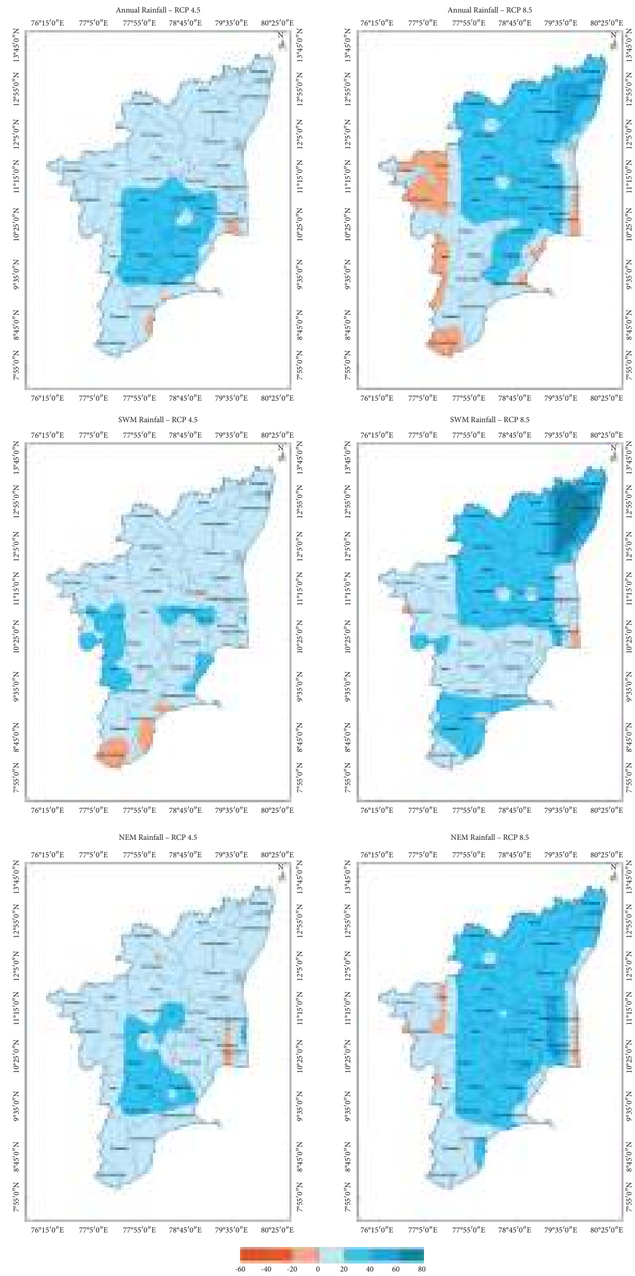

Figure 4: Multi-climate model ensemble projection of rainfall deviation (%) for RCP 4.5 and RCP 8.5 over baseline.

Table 2: Genetic coefficients of rice and maize cultivars.

Crop	P1	P2	P2R	P5	P2O	G1	G2	G3	G4	PHINT
Rice: ADT 43	483	—	53.5	348	12	55.8	0.240	1	1	—
Maize: CO(M)H-6	295	0.510	—	840	—	—	635	8.30	—	39.0

Note: P1: thermal time between the emergence of seedling and end of juvenile phase (denoted as degree days over a base temperature of 8°C); P2R: rate to which development (expressed as days) is stalled for each hour rise in photoperiod beyond the longest photoperiod at which development takes at a maximum extent (which is deemed to be 12.5 hours); P5: thermal time from commencement of grain filling (3 to 4 days after flowering) in rice and beginning of silking in maize to attainment of physiological maturity (denoted as degree days over a base temperature of 8°C); P2O: critical photoperiod or the maximum day length (in hours) at which the development happens at a maximum rate. Higher the P2O - developmental rate is decelerated; G1: potential spikelet number coefficient, generally, the value is 55; G2: single grain weight (g) under appropriate growing conditions in rice; maximal number of kernels/ plant in maize; G3: tillering coefficient comparative to IR64 cultivar under optimum conditions (scaler value). In rice, a higher tillering cultivar can have coefficient greater than 1.0; in maize Kernel filling rate at the linear grain filling phase and under ideal conditions (mg/day); G4: temperature resistant coefficient. In normal environment it is usually 1.0; PHINT: phylochron interval; it is give as thermal time (degree days) between subsequent leaf tip appearances.

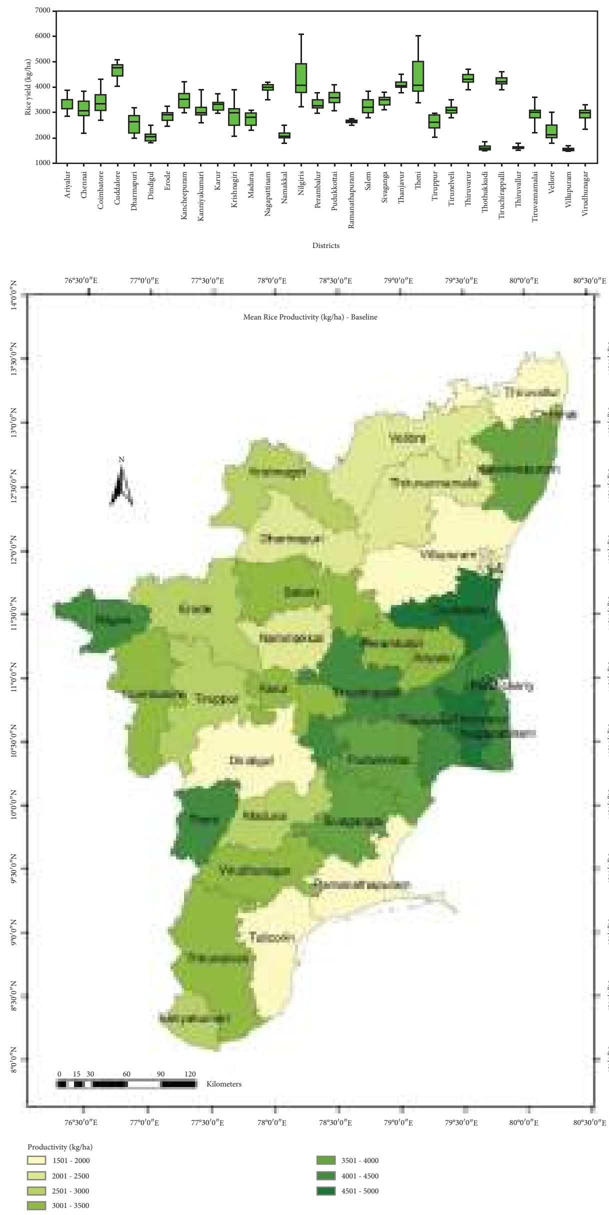

FIGURE 5: Current climate variability on rice productivity over Tamil Nadu (baseline period).

deviation in rice productivity and rest of the districts are projected to have negative deviation in rice productivity from 10 to 40%.

(3) Spatial Variability in Rainfed Maize Productivity

(a) *Current Climate*

Maize crop is mainly grown during northeast monsoon season as a rainfed crop. Spatial variation in rainfed maize productivity simulated using DSSAT model over Tamil Nadu for the current climate (mean productivity of 1981–2020) and change in the productivity during midcentury with RCP 4.5 and RCP 8.5 are presented in Figure 7. From the analysis, it could be noticed that there is high spatial variability in rainfed maize productivity over Tamil Nadu and it ranged between 5161 and 2046 kg·ha^{-1} with an average productivity of 3958 kg·ha^{-1}. Mean productivity of more than 5000 kg ha^{-1} was noted in 5 grid points spread near to the Western Ghats and near the coastal region. Out of 182 grids, 81 grids located along the east coast region and southern region registered the mean productivity between 4000 and 5000 kg·ha^{-1}. Around 51 grids spread in the northeastern, northwestern, and southern regions recorded the productivity of 3500 to 4000 kg·ha^{-1}. Most of the western and southern regions (36 grids) produced the yield between 3000 and 3500 kg·ha^{-1}. Yield lower than 3000 kg·ha^{-1} (2500 to 3000 kg·ha^{-1}) and yield below 2500 kg·ha^{-1} were noticed in six and three grids, respectively, spread in different parts of the state (Figure 7).

(b) *Future Climate*

Results indicate that under RCP 4.5 scenario, DSSAT predicted increase and decrease in maize yield with varying magnitude for the five different future climatic conditions over Tamil Nadu (Figure 7). Overall, in most places of Tamil Nadu, negative impact of climate change on maize productivity during midcentury is expected. The deviation in maize productivity showed (−) 38 to (+) 60% during the midcentury for RCP 4.5, while in case of RCP 8.5 scenario, (−) 24 to (+) 35% deviation in maize yield was predicted.

(4) Genetic Coefficients of Legume Crops. The cultivar used for the present investigation is black gram CO6. Genetic coefficients calculated and used in the study are as follows (Table 3).

(5) Spatial Variability in Legume Crop Productivity. Productivity of black gram and red gram for the current climate and future climate (midcentury for both the RCP 4.5 and RCP 8.5) is presented in Figure 8. Higher productivity of pulses was noticed in western districts of Tamil Nadu and in northeastern districts of Tamil Nadu. Pulses are very sensitive to increase in temperature and in both the pulses, productivity declined under both the future climate scenarios, namely, RCP 4.5 and in RCP 8.5. The magnitude of decrease in yield was higher with RCP 8.5.

4. Discussion

4.1. Current Climate Variability. Climate change has surfaced as one of the major environmental issues as a result of its successive effect on food security. The climate of Tamil Nadu has many regional variations expressed in the pattern temperature and rainfall and the degree of wetness or dryness. The inland areas that are close to the western ghat region are exhibiting relatively lower maximum and minimum temperatures compared to coastal Tamil Nadu. This is because the ocean takes much longer to heat and to cool than the land and higher heat capacity of the water keeps the coastal area warmer than the inland [49].

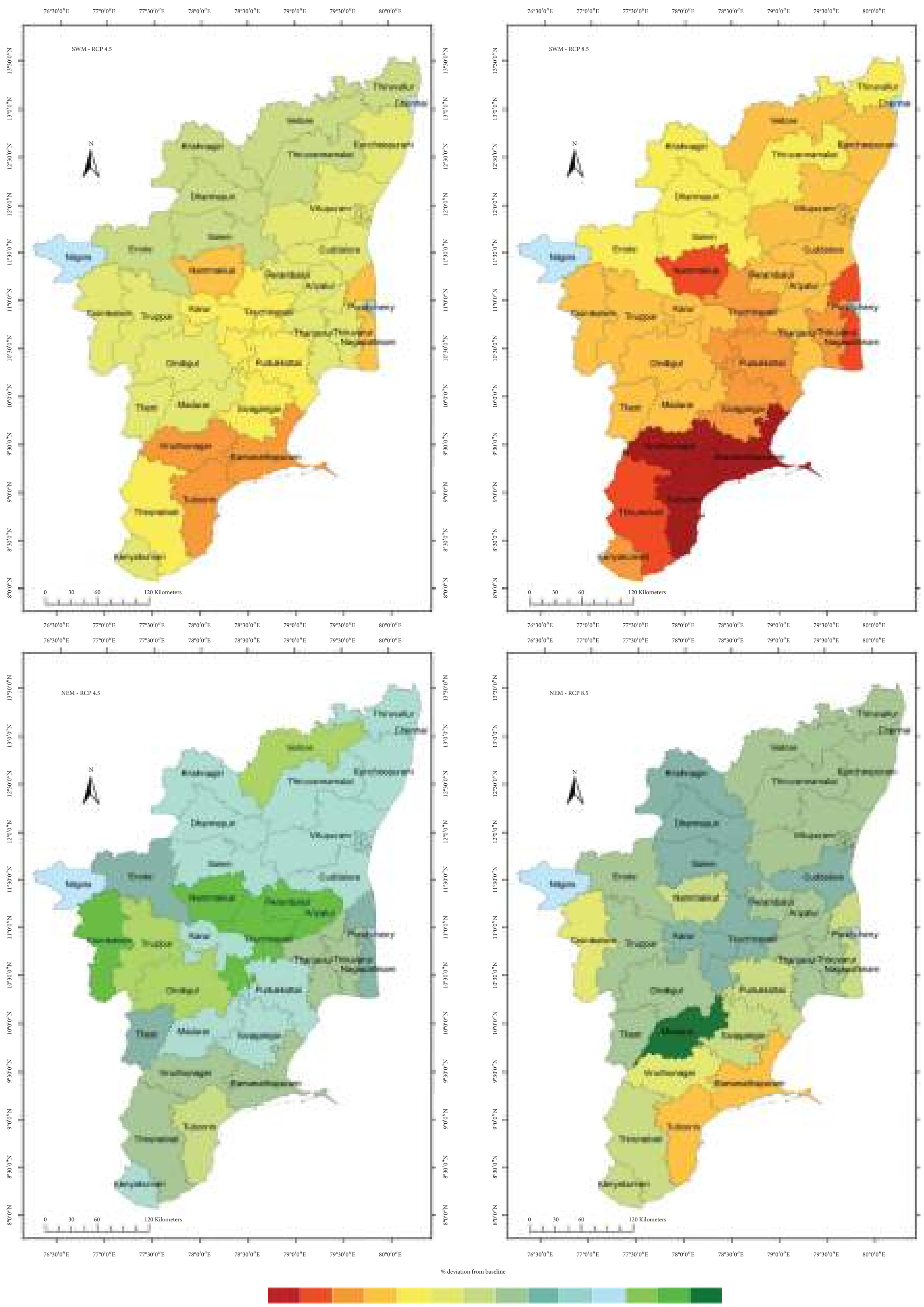

FIGURE 6: Spatial variability in rice productivity under multi-model ensemble climate projection during midcentury for RCP 4.5 and RCP 8.5 during SWM and NEM seasons.

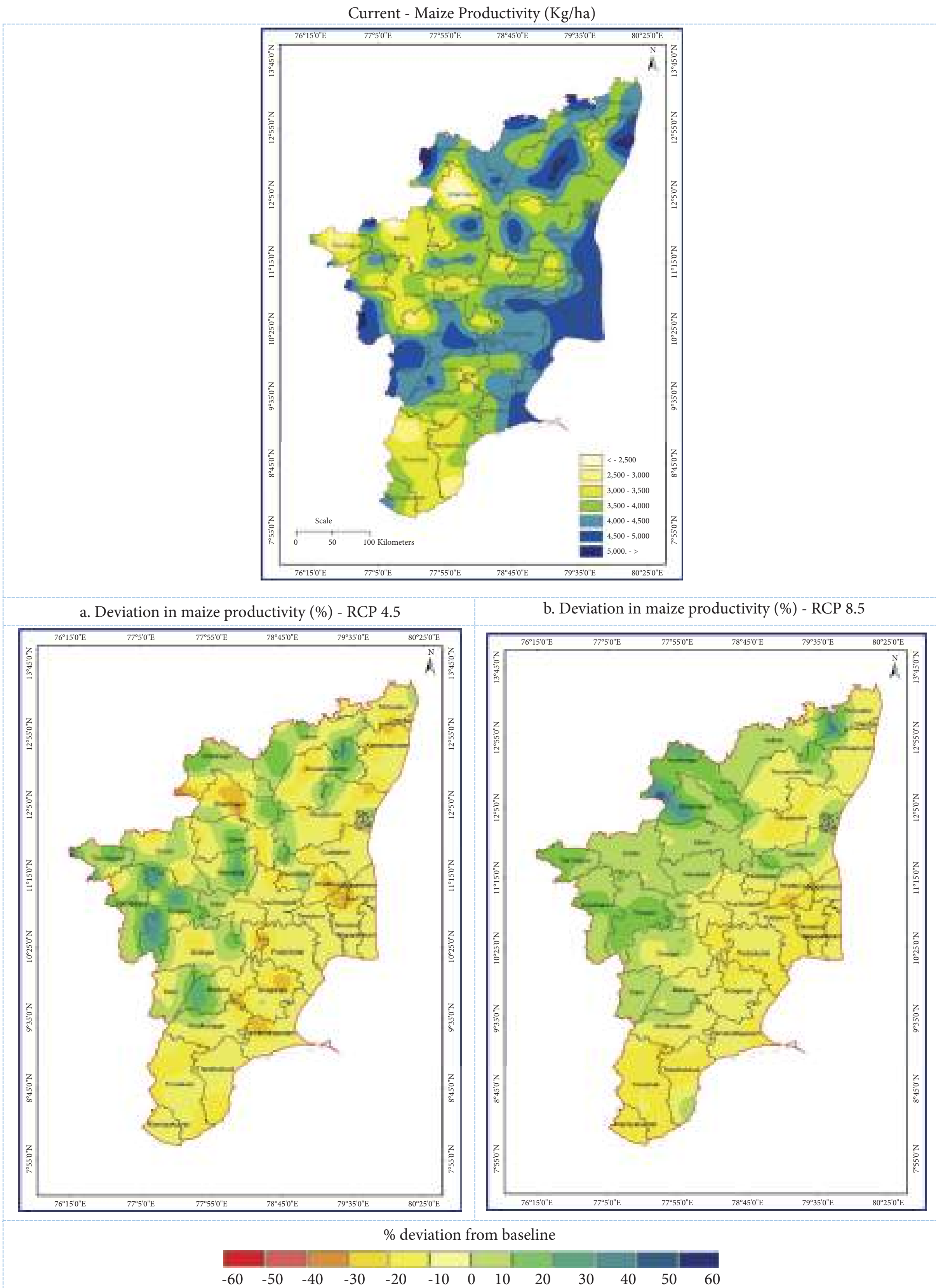

Figure 7: Spatial variability in rainfed maize productivity under current climate and multi-model ensemble climate projection for future climate scenarios (RCP 4.5 and RCP 8.5). (a) Deviation in maize productivity (%): RCP 4.5. (b) Deviation in maize productivity (%): RCP 8.5.

Table 3: Genetic coefficients of black gram CO6 and red gram CO(RG)6.

Coefficient	Black gram CO 6	Red gram CO(RG)6	Coefficient	Black gram CO 6	Red gram CO(RG)6	Coefficient	Black gram CO 6	Red gram CO(RG)6
CSDL	11.9	12.94	FL-LF	7.073	20.87	SFDUR	2.788	39.6
PPSEN	0.394	0.1	LFMAX	90.09	50.1	SDPDV	3.702	2
EM-FL	15.23	37.5	SLAVR	565.8	400	PODUR	1.478	10.3
FL-SH	3	10.4	SIZLF	300	301.4	THRSH	82	76.2
FL-SD	7.046	16.5	XFRT	0.98	0.9	SDPRO	0.3	0.224
SD-PM	21.84	19.02	WTPSD	0.037	0.24	SDLIP	0.065	0.015

CSDL: critical short day length under which reproductive development continues without the effect of daylength (for short day plants) (hour); PPSEN: slope of the relative growth response to photoperiod with time (positive for short day plants) (1/hour); EM-FL: time from plant emergence to appearance of flower (R1) (photothermal days); FL-SH: time from first flower to first pod (R3) (photothermal days); FL-SD: time from first flower to first seed (R5) (photothermal days); SD-PM: time from first seed (R5) to physiological maturity (R7) (photothermal days); FL-LF: time from first flower (R1) to end of leaf expansion (photothermal days); LFMAX: maximum rate of leaf photosynthesis at 30°C, 350 vpm CO_2, and high light (mg CO_2/m^2-s); SLAVR: specific leaf area of the cultivar under ideal growth conditions (cm^2/g); SIZLF: largest size of full leaf (three leaflets) (cm^2); XFRT: maximal fraction in daily growth that is partitioned to seed and shell; WTPSD: highest single seed weight (g); SFDUR: duration of seed filling for pod cohort at optimum growth conditions (photothermal days); SDPDV: average seed/pod under standard growing conditions (#/pod); PODUR: time required by a cultivar to attain final pod load under standard conditions (photothermal days); THRSH: Threshing percentage. The maximum ratio of (seed/(seed+shell)) at maturity, causes seeds to stop growing as their dry weight increases until shells are filled in a cohort. SDPRO: protein fraction in seeds (g-protein/g-seed); SDLIP: oil fraction in seeds (g-oil/g-seed).

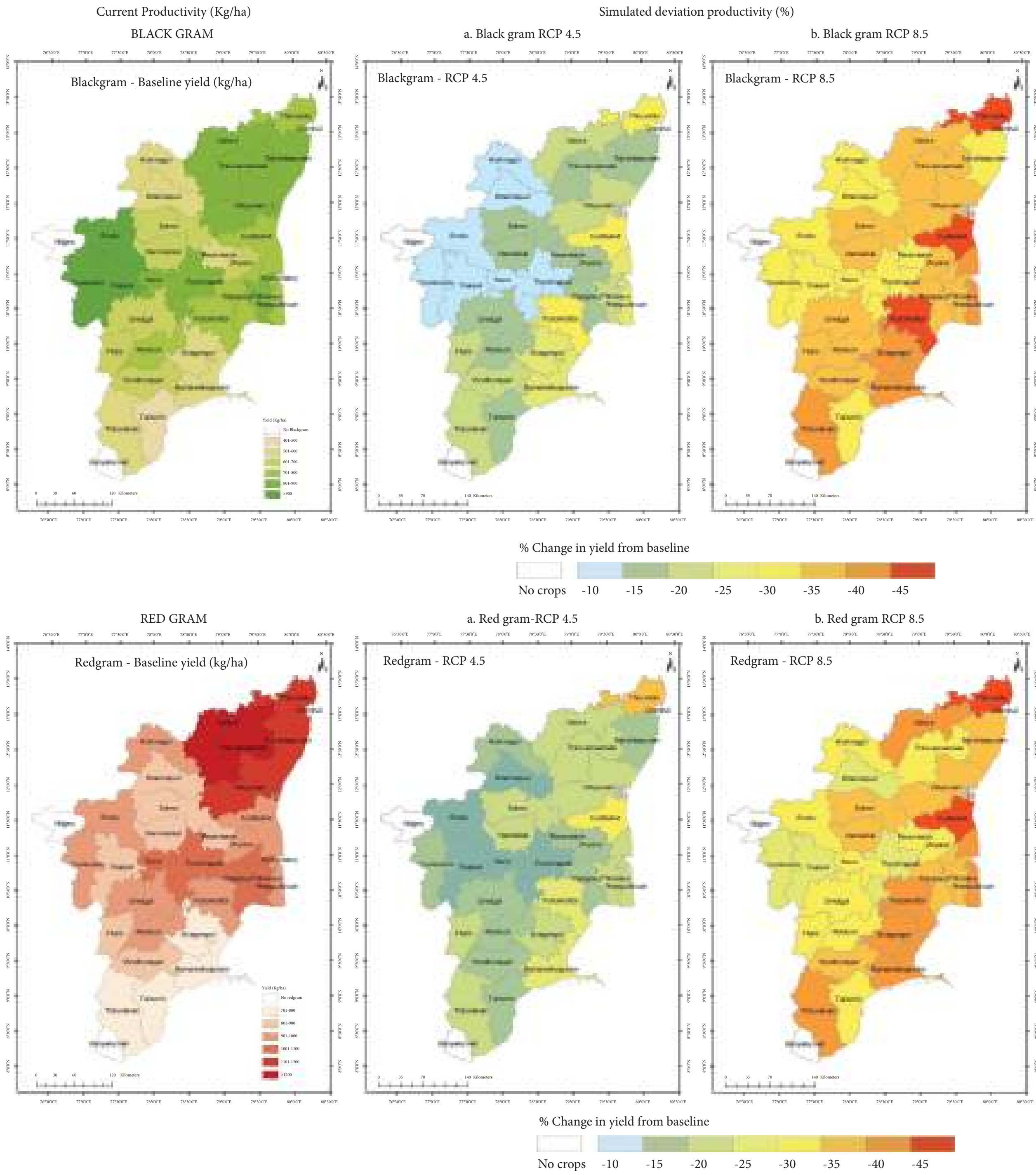

FIGURE 8: Spatial variability in black gram and red gram productivity under multi-model ensemble climate projection during current and future climate scenarios (RCP 4.5 and RCP 8.5).

Tamil Nadu receives relatively less rainfall during the southwest monsoon because of its geographical location in the leeward side of the Western Ghats. The southwest monsoon winds are blocked from blowing over the state by the Western Ghats, and the moisture-laden winds lose their moisture on the western slopes of the Western Ghats resulting in little rainfall over Tamil Nadu during this season. However, Tamil Nadu receives good amount of rainfall during northeast monsoon as the northeast trade winds blow from sea to land. The Cauvery delta and the coastal plains of Tamil Nadu are hit by strong rain-bearing storms during northeast monsoon season, while the inland areas in the eastern side of the Western Ghats receive comparatively lesser rainfall [50, 51].

4.2. Future Climate Projections. Future climate projections indicate increase in both maximum and minimum temperature with higher confidence [49, 50]. Major reason for projected increase in temperature is attributed to increase in concentration of greenhouse gases in the atmosphere as a result of anthropogenic activities such as burning fossil fuels, deforestation, and emission from livestock sector and rice paddies [52]. With RCP 8.5 scenario, more warming is expected compared to RCP 4.5, owing to the level of expected greenhouse gas concentration in the atmosphere [53, 54]. As temperatures rise and the air becomes warmer, hydrological cycle is expected to get altered with more moisture evaporating from land and water into the atmosphere resulting in increased rainfall activity over the state. Among the two monsoon seasons, higher increase in rainfall is expected during the northeast monsoon, which is the primary rainy season. Normally, during northeast monsoon, the rainfall activity is due to formation of low-pressure systems in the Bay of Bengal [51]. In the future warmer climate with the increased hydrological activity, there may be more extreme weather events with increased intensity in rainfall.

5. Genetic Coefficients of Cereals and Pulses

A set of parameters that define the genotype × environment interaction is expressed as genetic coefficient. They quantitatively express the response of a particular cultivar to various environmental factors. In case of two cereals, namely, rice and maize, thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) indicates a vast difference. In case of rice, it is much higher because the crop is being transplanted and it enters into transplantation shock, requiring more thermal time in the initial stages to move to the subsequent phenophases. In contrast, thermal time from beginning of grain filling (3 to 4 days after flowering) to physiological maturity (expressed in degree days above a base temperature of 8°C) in rice is much smaller compared to maize. In case of maize, invariably, this phase gets completed in approximately 30 days, whereas the period from silking to physiological maturity in maize is higher because of the longer duration required for this stage of the crop growth. Also, in pulses, all the coefficients studied showed a greater difference between black gram and red gram due to the inherent variability in crop stature and difference in time taken to attain different physiological stages and also change in the yield attributing characters.

5.1. Impact of Climate on Crop Productivity. Rice productivity in Tamil Nadu for the past 30 years (baseline climate) varied widely. The productivity is high in the Cauvery delta zone due to introduction of high yielding rice varieties responsive to high dose of fertilizers coupled with improved package of practices evolved by agricultural scientists, besides congenial climate that prevails in the region for rice growth and productivity. The inland regions in the state exhibit medium level productivity, and the dry air with relatively lesser RH in this region might be the reason for reduced levels of rice yields. Year to year variation in yield is very high in the Nilgiris as a result of weather prevailing in that district. Only limited area is under paddy in the Nilgiris; however, it experiences extreme weather conditions such as intense rainfall as well as very low temperatures. Similarly, Theni district, located at the foot hills of the Western Ghats in southern part of Tamil Nadu also expressed high yield variability due to the inherent weather variations that occur during the rice growing seasons.

The future rice yield productivity is projected to decline in both southwest and northeast monsoon seasons due to change in temperature as well as precipitation patterns [55, 56]. With the RCP 4.5 scenario, the yield reduction is predicted to be lesser compared to RCP 8.5 scenario. Higher increase in temperature must have negatively influenced the rice productivity by reducing the crop duration as well as altering the physiological processes [57, 58]. When the two rice growing seasons, namely, Kharif coinciding with southwest monsoon and Rabi coinciding with northeast monsoon, were compared, the reduction was much higher during the Kharif season. They might be attributed to the higher temperatures that prevail over Tamil Nadu during the southwest monsoon season. During the northeast monsoon season, which is the major rainy season of Tamil Nadu, the prevailing temperatures are relatively cooler and increase in temperature has lesser negative impact on rice productivity [50].

Rainfed maize is grown during the northeast monsoon season, and the productivity varies between 5161 and 2046 kg·ha^{-1}. Higher productivity is noticed near the Western Ghats and coastal regions which may be attributed to receiving relatively higher quantum of rainfall in these regions. Maize requires 500 mm of water to complete its life cycle successfully, and the critical stages for water are tasseling, silking, and early dough stages during which if there is any scarcity for water, the yield will get reduced to a greater extent. Lower yield in the southern region is mainly because of uncertainty in rainfall and also poor distribution of rainfall during growing season [45, 48, 59].

Future prediction on maize yield indicates that under RCP 4.5 scenario, DSSAT predicted increase and decrease in maize yield with varying magnitude over Tamil Nadu. Wherever there is mild temperature in the current condition, the increase in temperature shows advantageous yield increase in future times. In the southern part of Tamil Nadu, the prevailing temperatures during the crop growing season are exceeding 30°C during day time and 23°C during night time. The effects of increased temperature exhibit a larger impact on grain yield than on vegetative growth because of the increased minimum temperatures. These effects are evident in an increased rate of senescence which reduces the ability of the crop to efficiently fill the grain [60].

Pulse crops are mainly grown as rainfed crops, and they are highly heat sensitive [61, 62]. Inadequate and erratic rainfall, abrupt rise in temperature, and untimely drought pose a threat to pulse production [63–67]. Other problems like salinity resulting from high temperature and reduced rainfall also reduce pulse productivity.

6. Conclusions

According to the results of the present study, the temperature over Tamil Nadu is increasing with time. However, the rainfall indicates higher spatial variability with different magnitudes of increase in rainfall. Results clearly indicate that all the study crops could suffer yield reduction under future climate. With both RCP 4.5 and RCP 8.5 scenarios, negative change was witnessed in the productivity of all the crops over the majority of places in Tamil Nadu. Our analysis using the multi-model ensemble approach facilitated the robust estimation of the impact of climate change on four crops. The results of the study could be used for evaluating the uncertainty in the climate change impact assessment associated with the use of a single or few climate projections. This study provides comprehensive spatial and temporal-based analysis evidence on the sensitivity of different crops to climate change. The results conspicuously indicate the varied spatial and temporal response of study crops under climate change which can help identify the hotspots of a particular crop to the climate change. Results also emphasize the need for proper targeting of adaptation measures in the identified areas to maintain economically acceptable yields under future climates. This assessment result could serve as a basis for the policymakers to better understand the consequences of climate change on various crops over a region and to make informed decision making to sustain crop productivity. The results also enable policymakers to make investment plans on the potential adaptation strategies for various crops to reduce the negative impact of climate change on crop production and build the resilience of smallholder farmers in tropical crop growing environments.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

This paper has been carved out from the study "Causal Factors Influencing Agricultural Land Use Patterns in Central Tamil Nadu" funded by Tamil Nadu State Land Use Research Board, State Planning Commission, Government of Tamil Nadu.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

RG and VG were responsible for conceptualization and methodology. RG and KB were responsible for software. RG was responsible for validation. SP, MR, MD, and KB were responsible for formal analysis. RG, RKG, RR, and KS were responsible for investigation. SP and MR were responsible for resources. VG was responsible for data curation and original draft preparation. MD and KS were responsible for review and editing. VG, RKG, and RR were responsible for supervision. RKG and RR were responsible for project administration and funding acquisition. All authors have read and approved the manuscript for publication.

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