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Research Paper

Assessment of climate change impact on major crops of the southern agroclimatic zone of Tamil Nadu, India

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ABSTRACT

Climate change poses significant risks to crop production, endangering food security and the livelihoods of farmers. The southern agro-climatic zone of Tamil Nadu is particularly susceptible to droughts and floods. This study assessed the future impacts of climate change on crop yields using the DSSAT crop simulation model, with climate projections based on the EC-Earth statistical downscaled model under the SSP2-4.5 scenario for the baseline period (1985–2014) and near-century projections (2021–2050). Projections indicate a 0.4 °C rise in the annual mean maximum temperature and a 7% increase in rainfall. Simulated yields of rice, maize, sorghum, and groundnuts are expected to decline by 5.6%, 2.1%, 8.2%, and 7.6%, respectively, primarily due to heat stress during critical reproductive stages and altered rainfall distribution, which affects crop water availability. In contrast, black gram yield is projected to increase by 4.8%, benefiting from enhanced CO_2 fertilization and improved rainfall during its growing season. The study highlights the significant impact of climate change on agricultural productivity and underscores the urgent need for adaptation strategies, including drought-resistant crop varieties, modified planting calendars, and improved water management techniques, to enhance regional agricultural resilience in Tamil Nadu.

***Keywords**:* Climate change, DSSAT, SSP-2 4.5, Rice, Maize, Sorghum, Groundnut, EC Earth3

Globally, climate change, with an increasing population, negatively impacts food production, particularly in developing and underdeveloped countries (Ullah *et al.,* 2019). Climate variability plays a crucial role in determining the sustainability of agricultural sector growth. According to the IPCC (2022), frequent droughts, scorching heatwaves, devastating floods, and unpredictable monsoons are predicted to severely impact crop yields. Increases in temperature and intensity of rainfall shorten the lifespan of crops, resulting in lower yields and substantial economic losses for farmers (Rahman *et al.,* 2018). Globally, significant yield reductions have been observed in staple crops. For instance, rice production in Southeast Asia has decreased by 8-12% over the past decade, with major grain-producing countries such as China, the Philippines, and Bangladesh facing severe challenges. Climate change impacts crops through multiple mechanisms: increased temperatures accelerate phenological development, particularly during reproductive stages; altered precipitation patterns affect soil moisture availability during critical growth periods, and elevated CO_2 concentrations influence photosynthetic efficiency and water use. These impacts vary significantly by crop type and regional agroclimatic conditions.

To address these impacts, crop simulation models such as DSSAT, APSIM, and INFOCROP have become indispensable for analyzing the effects of climate change on agriculture. These models integrate complex variables, including climate, soil conditions, and management practices, to predict yield variations and develop climate-adaptation strategies. For this study, the DSSAT crop simulation model has been selected due to its extensive validation across diverse agro-climatic zones in India, its comprehensive physiological process modeling capabilities for the specific crops under investigation, and its proven reliability in previous climate impact studies within similar semi-arid regions (Balasubramanian *et al.,* 2022).

Tamil Nadu's semi-arid regions in India represent a

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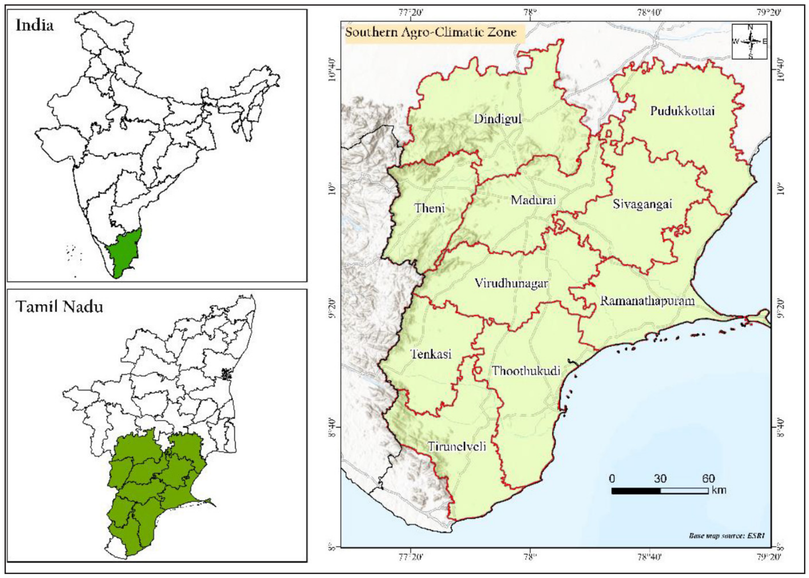

Fig. 1: Study area map

critical case study due to their dependency on agriculture and susceptibility to climate variability. The state experiences diverse weather patterns, influenced by the southwest and northeast monsoons, which lead to frequent droughts and floods. Existing studies have examined specific districts or single crops, such as rice in the Cauvery Delta (Geethalakshmi *et al.,* 2011) and groundnut in coastal districts (Ramachandran *et al.,* 2017). However, multi-crop assessments in the Southern Agro-Climatic Zone (SACZ) remain limited, creating a significant knowledge gap in understanding the differential impacts of climate change across various crops within the same region (Saravanakumar *et al.,* 2022). Recent research indicates a 30% increase in drought frequency over the past three decades, significantly impacting food grain productivity in this vulnerable region.

This study aims to comprehensively assess the impacts of climate change on multiple food grain crops (rice, maize, sorghum, groundnut, and black gram) in Tamil Nadu's SACZ. By focusing on diverse land-use systems and soil types, this research offers a comprehensive perspective on climate impacts, addressing the identified research gap in multi-crop climate vulnerability assessments. The findings will inform stakeholders, including farmers and policymakers, in formulating targeted climate adaptation strategies and enhancing resilience in agriculture, thereby ensuring sustainable food production in this vulnerable region. Specifically, the results will enable policymakers to prioritize resources for the most susceptible crops and districts while providing farmers with crop-specific adaptation recommendations tailored to local conditions.

MATERIALS AND METHODS

The Southern Agro-Climatic Zone (SACZ) of Tamil Nadu includes ten districts: Tenkasi, Tirunelveli, Ramanathapuram, Thoothukudi, Virudhunagar, Sivagangai, Theni, Dindigul, Madurai, and Pudukkottai, spanning 8281.72 sq. km between 10.787°N and 79.1378°E (Fig. 1). The region is bounded by the Western Ghats to the west and the Bay of Bengal to the east, exhibiting distinct agro-climatic variability. Rainfall ranges from 600 to 800 mm annually, predominantly during the Northeast monsoon (October-December), with temperatures varying between 24°C (minimum) and 35°C (maximum). SACZ contributes 32% of Tamil Nadu's food grain production, relying primarily on rain-fed agriculture, which makes it highly vulnerable to climate variability. Small and marginal farmers account for 78% of the farming community, with landholdings averaging 0.8–1.2 hectares.

Daily temperature and rainfall datasets were obtained from the Indian Meteorological Department (IMD) for bias correction. The EC-Earth3 model was chosen for downscaling CMIP6 projections using PyClim-SDM due to its proven reliability in Tamil Nadu (Balu *et al.,* 2023). Quantile mapping was applied for bias correction, and validation was performed using RMSE and correlation metrics. Downscaled data were generated at a 25 × 25 km resolution, deemed appropriate for agricultural impact assessments based on previous studies.

Field experimentation and calibration

A field trial was conducted across eight agricultural research stations in the southern region of Tamil Nadu under the Tamil Nadu Agricultural University. Rice experiments were conducted at four locations: the Rice Research Station, Ambasamudram (8.7056°N, 77.4511°E); the Agricultural Research Station, Paramakudi (9.5425°N, 78.5901°E); Vaigaidam (9.675°N, 77.8708°E); and the Madurai Agricultural College and Research Station (10.150°N, 78.783°E). Maize trials were conducted at the Maize Research Station, Vagarai (10.950°N, 77.933°E), and the Agricultural Research Station (ARS) Kovilpatti (9.283°N, 77.950°E). Black gram experiments were conducted at the National

Table 1: Leading crop varieties used in SACZ of Tamil Nadu

Sl. No	Crop	variety	Duration (days)	Cropping Season
1	Rice	CO 51, ASD 16, ADT 43, Anna 4	105-100, 110-115, 100- 105, 105-110	June - July, August - September
2	Maize	CO 6	105- 110	September – October
3	Sorghum	K 12	95 - 100	September – October
4	Black gram	VBN 6	65 - 70	January - March
5	Groundnut	CO 6, TMV 13	125 – 130, 100 - 105	November – December, January - February

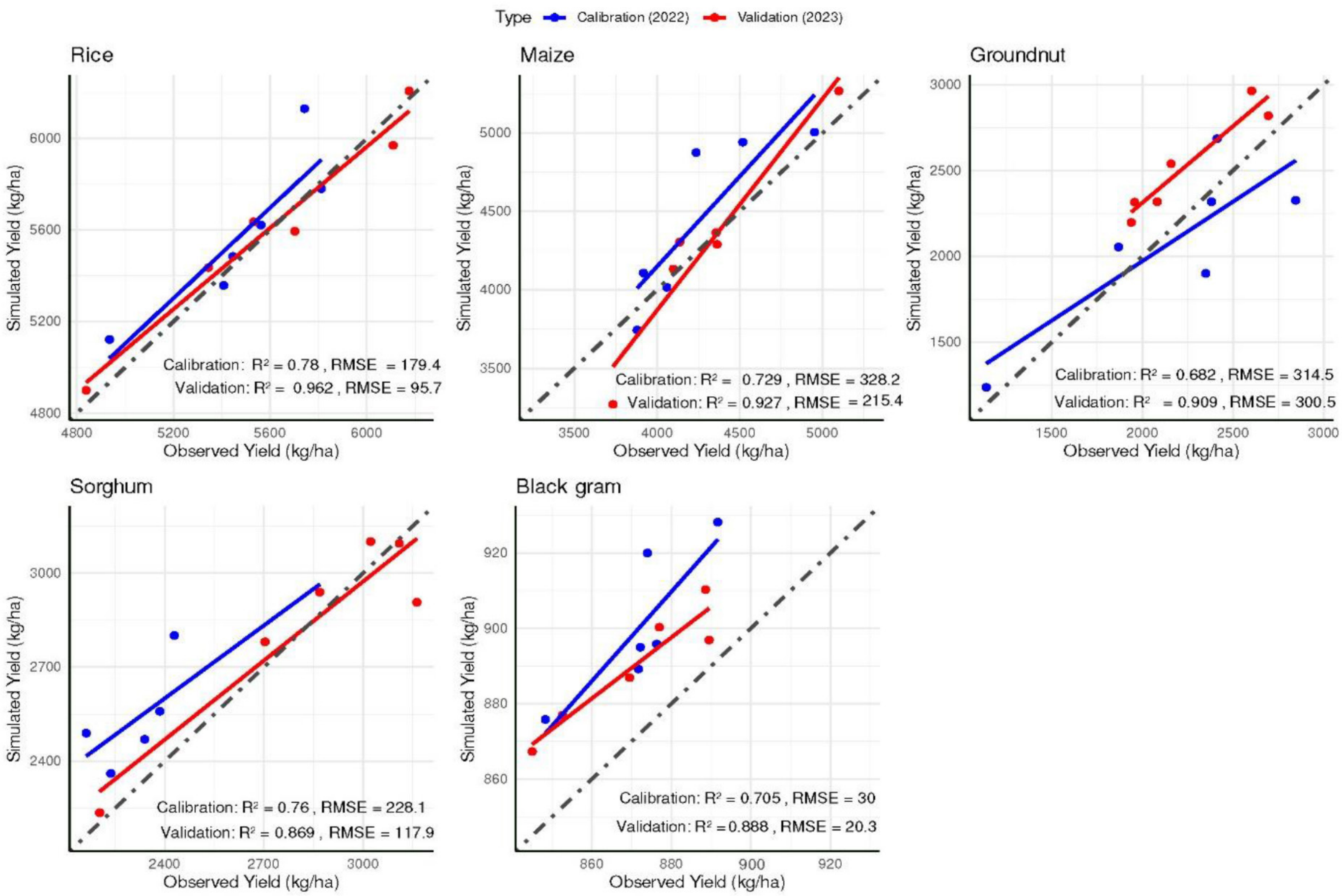

Fig. 2: Calibration and validation of major crop yield in the GENCALC module of DSSAT

Pulse Research Station, Vamban (9.5085°N, 78.0998°E), and the Regional Research Station (RRS), Aruppukottai (10.5111°N, 78.8745°E). Groundnut trials took place at the Dryland Agricultural Research Station, Chettinad (10.1597°N, 77.6892°E), as well as at the ARS, Kovilpatti (10.2207°N, 78.7807°E) and RRS, Aruppukottai (10.5111°N, 78.8745°E)." Sorghum experiments were conducted at the Agricultural Research Station, Chettinad, and the RRS, Aruppukottai. Crop cultivation was recorded annually, and detailed data was collected on crop growth parameters, phenology, and harvest at each experimental site. Genetic crop coefficients were calibrated using DSSAT's GENCALC tool, integrating weather, soil, and crop management data. Soil properties, including organic carbon, bulk density, and pH, were analyzed using DSSAT's S-Build tool, with soil profiles stratified into six layers based on agronomic significance.

Crop simulation and economic impact

The DSSAT v4.8 CERES and CROPGRO modules simulated crop yields under baseline (1985–2014) and future (2021–2050) conditions under the SSP2-4.5 scenario. The model's selection of alternatives was based on its established accuracy in simulating responses of tropical crops. The gridded yield change has been interpolated using ArcGIS to enhance resolution clarity. Relative yield change was assessed to quantify climate-induced impacts on significant crops. This methodological approach integrates climate projections, crop modeling, and economic assessment to comprehensively evaluate the impacts of climate change on SACZ agriculture, providing a foundation for targeted adaptation measures.

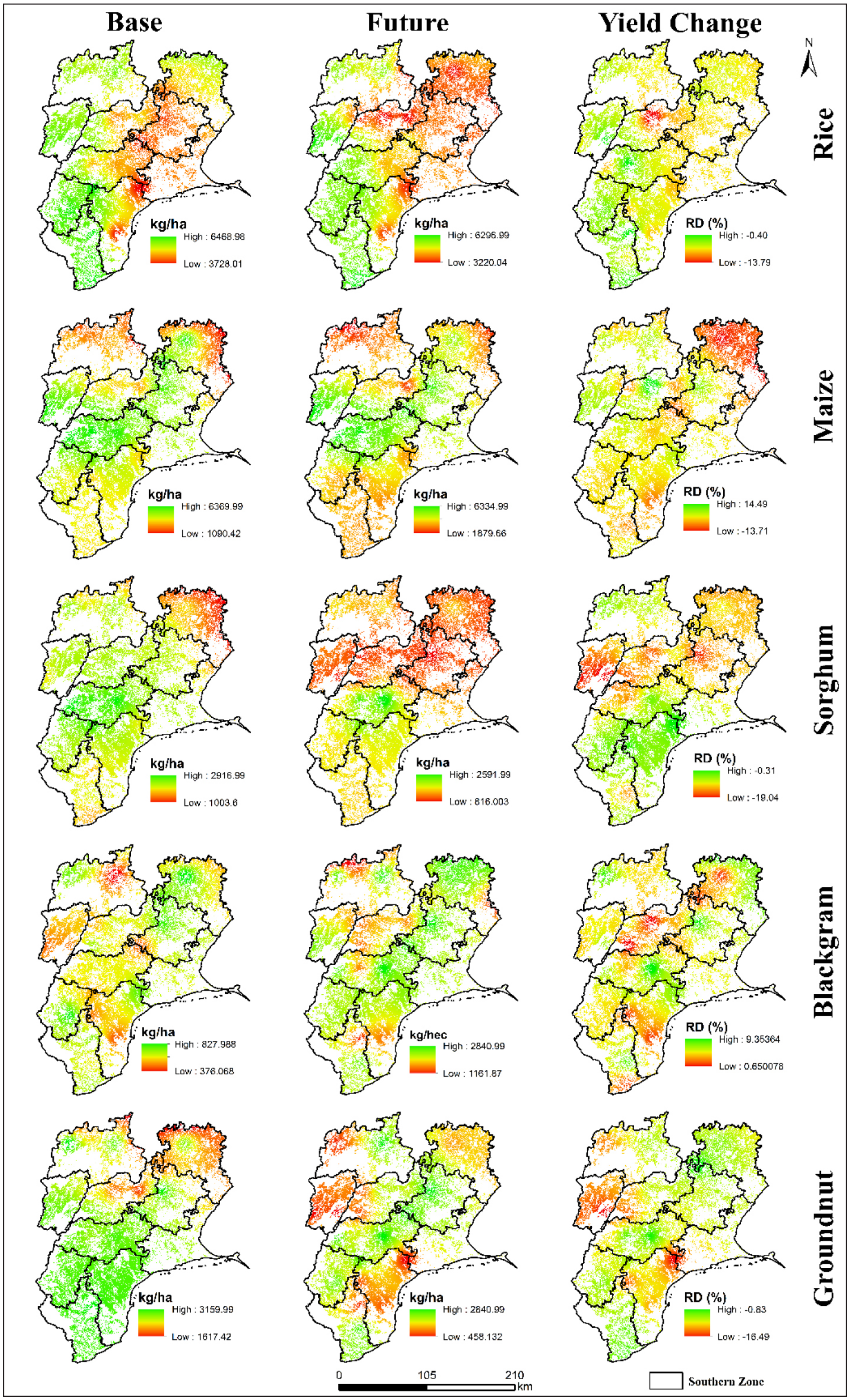

Fig. 3: Spatial variation of crop yield (baseline and projected) and its percentage change over major crops in SACZ

RESULTS AND DISCUSSION

Climate change impact on crop yield

The impact of climate change on crop yields (Rice, Maize, Sorghum, Groundnut, and Black gram) was simulated under the SSP2 4.5 climate scenario using the DSSAT crop model for the Southern Agro-Climatic Zone (SACZ) during the baseline period (1985–2014) and the near-century period (2021–2050). This section presents a comparative analysis of the projected yield changes across different crops and regions, addressing model uncertainties, validation, and potential adaptation strategies. The model's performance was validated using observed yield data from 2022 and 2023 obtained from the Tamil Nadu Agriculture Department to ensure reliability in the projections (Fig. 2).

Rice yield simulated in the CERES-Rice module of DSSAT under future climate change scenarios indicates substantial variations across the study region throughout the 21st century. The *ASD 16* rice variety, cultivated in the Tenkasi and Tirunelveli districts, and the *Anna 4* variety, predominantly grown in the Virudhunagar, Sivagangai, Ramanathapuram, and Thoothukudi districts, are expected to face yield reductions within the same range. Likewise, CO-51, primarily cultivated in the Madurai, Theni, and Dindigul districts, is anticipated to exhibit comparable yield losses. The ADT 43 rice variety, commonly grown in the Pudukkottai district, is also projected to experience yield declines of 4-11%. These variations in projected yield changes are spatially represented in Fig. 3a. The sensitivity of rice to rising ambient temperatures, as highlighted by the CERES-Rice model simulations, underscores the potential severity of yield impacts under elevated temperature conditions. In SACZ, the rice yield in the Tirunelveli, Tenkasi, Dindigul, and Theni districts indicates a minimal yield loss of 2.34 to 4.5%. In contrast, the yield in Madurai is expected to decline by 14.79%. The overall projected change in rice yield is expected to be reduced by 5.6% in SACZ. The critical phenological phases of rice, including panicle initiation and the milky stage, play a significant role in growth and development. The results indicate that projected rainfall would be very low in the panicle initiation stage (Guo *et al.,* 2021), which could lead to water stress. At the same time, excessive rainfall (201 mm) during the harvest stage, which corresponds to maturity, may result in lodging and deterioration of grain quality, contributing to yield declines in both inland and coastal districts of SACZ (Bhuvaneswari *et al.,* 2014).

The future projection on maize yield in CERES-Maize indicates that under the SSP2 4.5 scenario, DSSAT predicts a decrease in maize yield with varying magnitudes across SACZ. The spatial distribution of relative changes in maize yield is illustrated in Fig. 3. The projected maize yield for SACZ exhibited a higher variation among districts. The results indicate an overall decline of approximately 1.6%, with the districts of Theni, Madurai, and Dindigul exhibiting a positive change of 2.3%, while the districts of Ramanathapuram, Sivagangai, Tenkasi, Tirunelveli, and Virudhunagar show negative yield changes. High temperatures have a severe impact on maize yield, accelerating crop maturity and reducing the duration of grain filling. Climate change is likely to negatively impact maize yields in Tamil Nadu over the coming decades due to rising temperatures and changes in precipitation patterns, which will increase the frequency and severity of drought stress. A more recent study by Krishnan *et al.,* (2019) projected the potential impacts of climate change on maize yield in Tamil Nadu up to 2050 using a crop simulation model. Temperature increases could negatively impact the 469 mm of total rainfall received during crop growth, contributing to a decline in maize yield during the near-century period. The study found that increasing temperature and precipitation variability could reduce maize yield in the region by up to 15%, reinforcing the need for adaptation strategies such as heat-tolerant maize varieties and improved irrigation scheduling.

Sorghum, a staple in dryland agriculture, was simulated using the CERES-Sorghum module in DSSAT. The K-12 sorghum cultivar was used to analyze phenology, growth, and yield changes for the baseline period (1985–2014) and the near-century (2021-2050) under SSP2 4.5. The spatial distribution of sorghum yield change is depicted in Fig. 3. The Theni district in SACZ exhibits a higher yield loss compared to other districts. Future temperature increases may accelerate phenological development, reducing grain-filling duration and yield. Elevated temperatures may also exacerbate evaporation and evapotranspiration rates, leading to water shortages (Ammaiyappan *et al.,* 2023). Climate change is likely to have a significant negative impact on groundnut yield in the southern agro-climatic zone of Tamil Nadu, primarily due to rising temperatures and changing precipitation patterns, leading to more frequent and severe drought stress.

Groundnut yield was simulated using the CROPGRO module of DSSAT, and the results indicate an overall decline of approximately 12.17% over the past century. Higher temperatures are expected to adversely affect groundnut productivity by shortening crop duration and altering physiological processes. In the Theni district, groundnut yield is projected to decline by 14.52%, making it one of the most affected districts in the region. Theni, despite receiving the highest rainfall in the zone due to its location in the Western Ghats, experiences increased soil moisture stress during critical growth stages, resulting in reduced yields. Similarly, the Dindigul district is expected to experience a 13.55% decline in yield, mainly due to temperature-induced changes in crop phenology. On the other hand, the Ramanathapuram district, which is highly dependent on rainfall for irrigation, is projected to witness a 7.2% decline in groundnut yield. Being highly vulnerable to climate change, farmers in this region predominantly follow a single-cropping pattern, making them particularly susceptible to temperature and rainfall variability. The ideal maximum temperature for groundnut cultivation is 30°C; however, during critical growth stages, such as flowering, pegging, and pod filling, the projected temperature is expected to rise to 32°C. Increased temperatures during these stages are likely to accelerate phenological development, leading to early flowering (Wang *et al.,* 2015) and faster crop senescence, resulting in poor seed filling due to increased assimilate demand under yield-limiting conditions. Regarding relative yield change, the western parts of the SACZ, including Theni and Dindigul, are expected to experience the highest yield reductions due to high-temperature stress. At the same time, some eastern regions may see slight improvements in yield under the SSP2 4.5 climate change scenario. Given that significant parts of Theni and Dindigul lie within the Western Ghats, where high rainfall influences soil moisture conditions, these factors collectively contribute to variations in groundnut yield across the region.

Pulses are crucial in maintaining a healthy agricultural ecosystem by naturally converting atmospheric nitrogen into a form usable by plants. This process, known as biological nitrogen fixation, enhances soil fertility and reduces dependency on synthetic fertilizers. Among pulses cultivated in the Southern Agro-Climatic Zone (SACZ) of Tamil Nadu, black gram occupies the largest cultivable area and accounts for the largest production compared to Red, Green, Horse, and Bengal gram. It is primarily grown during the winter season, from January to February. This study used the VBN 6 black gram variety to simulate yield projections under the SSP2 4.5 climate scenario for the baseline period (1985-2014) and the near-century period (2021-2050).

The spatial yield projections for black gram under SSP2 4.5 during the near-century period are illustrated in Fig. 3. The results indicate a projected 8.14% increase in black gram yield, primarily attributed to extended soil moisture availability resulting from an increase in rainy days. While this enhanced soil moisture can benefit crop growth, it also introduces potential risks. Excessive rainfall may create favorable conditions for fungal diseases, root rot, and pest infestations, which could offset the expected yield benefits. Furthermore, prolonged soil saturation may lead to nutrient leaching and reduced aeration, which can adversely impact plant growth. Future adaptation strategies should focus on enhancing drainage systems, developing crop varieties with resistance, and implementing integrated pest and disease management to sustain productivity under changing climatic conditions (Pavithrapriya *et al.,* 2023).

CONCLUSION

EC Earth, the AR6 climate model, was used as input for the DSSAT crop simulation model to simulate crop yields in the southern agro-climatic zone. Farmers in this region predominantly rely on rainfed agriculture. The intensified rainfall, primarily attributed to unprecedented monsoon patterns, has a significant impact on agriculture in the southern agro-climatic Zone of Tamil Nadu. In recent years, there has been considerable uncertainty about rainfall throughout the south zone, which is affecting crop production. According to the findings, the simulated yields of Rice, maize, sorghum, and Groundnut are projected to decline by 8.37%, 4.74%, 13.03%, and 12.17%, respectively. The study's inference to address these challenges and minimize yield loss through site-specific adaptive measures should be prioritized.

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