Journal of Agrometeorology

(A publication of Association of Agrometeorologists)

ISSN : 0972-1665 (print), 2583-2980 (online)
Vol. No. 28 (1) : 52 - 58 (March - 2026)
https://doi.org/10.54386/jam.v28i1.3193
https://journal.agrimetassociation.org/index.php/jam

Research paper

Impact of climate variability on maize yield in semi-arid region of Tamil Nadu, India

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ABSTRACT

Climate variability poses serious challenges to productivity and food safety in rain-fed semi-arid areas. A study on the impact of Tmax, Tmin, and precipitation on the yield of maize was performed in Ariyalur and Perambalur districts, Tamil Nadu, using historical data from 1985 to 2020 and future projection data from 2021 to 2100 under the Shared Socioeconomic Pathways-SSP2-4.5 climate change scenario. Climate extremes analysis shows the results that there is an increase in warm nights (TN90P), warm days (TX90p), heavy rainfall events (R10mm, R20mm), and shorter dry spells (CDD), reflecting more heat and extreme rainfall in both districts. Temperature is increasing considerably; Max and Min temperatures are projected to rise by 1.5 to 2°C by 2100. Patterns of precipitation are changing, with more frequent moderate rainfall events of 10-20 mm and fewer dry spells. From Ariyalur, in conditions of a rise in minimum temperature by 1°C, there has been a reduction of up to 38.2% in maize yield, and it explained 20-25% of variability in yield. Perambalur experiences a 21.7% yield reduction per 1°C with less intensity. The model from Ariyalur outperforms the one from Perambalur, adjusted R^2 being 0.967 and 0.511, respectively, which suggests that local sites have different sensitivities to climate. The findings from the present research signify the urgent need for adaptive strategies, including heat-tolerant varieties of maize, efficient irrigation, and integrated pest management, which could help mitigate climate risks.

***Keywords**: Climate variability, Maize yield, Multivariate regression, Climate trends, Adaptation strategies*

Climate change is extremely influencing agriculture by changing crop growth cycles, decreasing in crop yields and rise in food insecurity. Due to rise in temperature in affects the crop growth, promote weed and insect attack, which reduce the crop yield. Since, erratic changes in rainfall pattern it aggravates the crop damage and affects the agricultural livelihoods. Worldwide study exposes varied effects – for example, both gains and reduction in rice and soybean yields have been occurred due to climate change (Ray *et al.,* 2019). Climate change has caused a 6.3–21.2% yield reduction in high-yielding crops in Europe, while in China, wheat yields have increased by 14.5% due to increased minimum temperatures (Shi *et al.,* 2021). Various climatic extreme indices have been analysed in India to find out the changing pattern and their impact of agriculture (Lunagaria *et al.,* 2015; Landage *et al.,* 2024). In India, extreme temperatures (1951–2014) have caused yield losses of up to 53% in *kharif* cereals and 63% in wheat (Choudhury & Moulick, 2022). Maize, the primary rain-fed crop in the semi-arid regions of Tamil Nadu, is highly vulnerable to climatic fluctuations. Although most existing studies rely on crop simulation models, regression-based approaches remain underutilised despite their potential to capture location-specific climate–yield relationships more effectively (Ray *et al.,* 2015).

This study addresses this gap by examining the impacts of temperature and precipitation variability on maize yields in Ariyalur and Perambalur districts, Tamil Nadu, using multivariate regression models. To find out the important climatic factors of yield inconsistency also considering for temporal gaps in availability of data, we study historical climate data from 1985–2020 and maize yield data from 2011–2020, complemented by future climate projections for 2021–2100 under the SSP2–4.5 scenario. The aim of this study is to support farmers and policymakers in adopting climate-resilient strategies tailored to local conditions, to ensure sustainable agriculture and food security in this climate-sensitive region.

***Article info - DOI**: https://doi.org/10.54386/jam.v28i1.3193*
Received:10 September 2025; Accepted: 12 December 2025; Published online : 1 March 2026

MATERIALS AND METHODS

Study area

Ariyalur district, spanning 1,949 km² in central Tamil Nadu (10°53'–11°26' N, 78°56'–79°31' E), receives an average annual rainfall of 949 mm, primarily from the northeast (485 mm) and southwest (357 mm) monsoons (Fig. 1). Its clayey soils, classifying from red to yellow, which support maize, a most important crop exposed to heat stress and waterlogging due to poor drainage (Malavath & Mani, 2015). Perambalur district, covering the area around 1,756 km² (10°54'–11°30' N, 78°40'–79°30' E), receives the precipitation 789 mm annually (314 mm southwest, 475 mm northeast monsoons) and features clay loam and sandy soils, increasing maize's vulnerability to water shortages.

Agriculture is the major occupation in both districts, and the important crops grown in the area are maize, paddy, groundnut and sugarcane (Muthumurugan *et al.,* 2021). The yield of maize is directly impacted by changes in climate and soil features; hence region-specific adaptation strategies are required. Climatic parameters and derived indices were interpreted in relation to the maize growing season prevalent in the semi-arid region of Tamil Nadu, extending from sowing to harvest during the principal cultivation window. This alignment ensured that climatic variability was examined in the context of crop phenology and yield formation stages

Data and analysis

The daily temperature and rainfall data with a resolution of 1 km × 1 km and 25 km × 25 km, respectively, from the year 1985 to 2020 were sourced from the India Meteorological Department. The above data were utilised for the study due to the impressive resolution and accuracy in indicating local variations. For understanding future projections from the year 2021 to 2100, the SSP2-4.5 scenario from CMIP6 was used, which indicates a moderate radiative forcing of 4.5 W/m² by the year 2100 (O'Neill *et al.,* 2016), and to ensure accuracy, the bias correction against IMD observations using quantile mapping, helping to decrease methodical faults (Lange, 2019). Data were divided into four periods for analysis: Historical (1985–2020), Near-Century (2021–2050), Mid-Century (2051–2080), and End-Century (2081–2100).

The climate variability assessment employed standard extreme weather indices recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI). These included consecutive dry days (CDD, days), consecutive wet days (CWD, days), total precipitation (PRCTOT, mm), heavy rainfall days (R10mm, days; R20mm, days), very wet day precipitation (R95p, %), extremely wet day precipitation (R99p, %), maximum 1-day rainfall (RX1day, mm), maximum 5-day rainfall (RX5day, mm), diurnal temperature range (DTR, °C), cold night frequency (TN10p, %), warm night frequency (TN90p, %), minimum temperature extremes (TNn, TNx, °C), warm day frequency (TX90p, %), and maximum temperature extremes (TXn, TXx, °C). These indices were used to characterize climatic variability influencing maize yield.

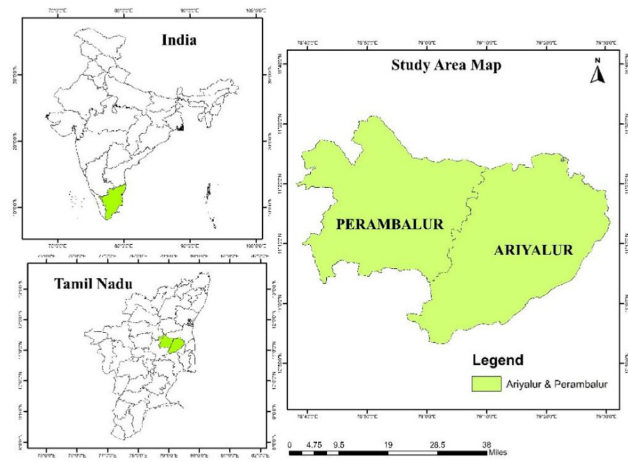

Fig. 1: Study area

The temporal trends in annual and seasonal maximum temperature (Tmax), minimum temperature (Tmin), and rainfall were evaluated using the non-parametric Mann-Kendall (MK) test, which was chosen for its robustness to evaluate non-normal time-series data (Mann, 1945) and Sen's slope estimator was used to quantify the median trend magnitude. Statistical significance was assessed at $p < 0.05$.

Climate extremes analysis

Climpact2 package in R is used to analyze climate extremes (Alexander & Herold*,* 2016), calculating 17 indices (Lunagaria *et al.,* 2015; Landage *et al.,* 2024). Of these, nine were rainfall indicators, including consecutive dry days (CDD), consecutive wet days (CWD), total yearly rainfall (PRCPTOT), days with at least 10 mm (R10mm) or 20 mm (R20mm) of rain, the heaviest 1-day (Rx1day) and 5-day (Rx5day) totals, very wet days (R95p), and extremely wet days (R99p). The other eight dealt with temperature and included: diurnal temperature range (DTR), warm days (TX90p), cool nights (TN10p), warm nights (TN90p), coldest night (TNn), warmest night (TNx), coldest day (TXn), and warmest day (TXx). The baseline period we compared our results to was 1985–2014-with the limitation on data availability-and projected changes for the three periods, that is, 2021–2050, 2051–2080, and 2081–2100.

Maize yield impact modelling

District-wise maize yield data (kg ha^{-1}) for the years 2011–2020 were procured from the Department of Economics and Statistics, Tamil Nadu. Multiple linear regression models were developed for Ariyalur and Perambalur to quantify climate impacts on maize yield. To address variability, a common problem in agricultural yield data demonstrating inverse responses to environmental stressors, and stabilize variance, yield was log-transformed (Box & Cox*,* 1964).

$$Log(Yield) = \beta_0 + \beta_1 * Rainfall_c + \beta_2 * (Rainfall_c)^2 + \beta_3 * Tmax_c + \beta_4 * CDD\_c + \beta_5 * Var + \beta_6 * Pest\_c + \beta_7 * RX5\_c + \beta_8 * TNx\_c + \varepsilon$$

where Yield is maize yield (kg ha^{-1}), β are coefficients, ε is the error term, and predictors include centered climate variables

Table 1: Mann-Kendall (MK) test of temperature and rainfall in the past and future projected periods in Ariyalur and Perambalur districts

Period	Ariyalur		Perambalur	
	MK Statistics	p-value	MK Statistics	p-value
		Maximum temperature (Tmax)		
Historical	2.10	0.035	2.40	0.018
Near Century	1.60	0.10	1.90	0.06
Mid Century	2.90	0.003	3.439	0.0006
End Century	0.586	0.557	2.20	0.028
		Minimum temperature (Tmin)		
Historical	5.70	1.14×10^{-8}	4.80	3×10^{-6}
Near Century	3.90	0.0001	3.20	0.001
Mid Century	4.20	<0.0001	3.60	0.0003
End Century	3.60	0.0003	3.10	0.002
		Rainfall		
Historical	18.91	0.30	15.09	0.43
Near Century	-10.78	0.60	-6.49	0.73
Mid Century	0.41	0.91	-12.50	0.76
End Century	-11.27	0.74	-5.37	0.95

(Rainfall_c: total seasonal rainfall; Tmax_c: mean maximum temperature; CDD_c: consecutive dry days; RX5_c: maximum 5-day rainfall; TNx_c: maximum minimum temperature) and agronomic factors (Var: use of hybrid variety [1 = yes, 0 = no]; Pest_c: pest management intensity). To improves coefficient interpretability and reduce multicollinearity imposed due to strong correlations among climate indices, centering has been used to all ongoing forecasting variables.

The climate variables were selected due to known biophysical connections to maize phenology and yield formation. These are Tmax and TNx reflect heat stress during development phases; rainfall and RX5 affect water availability during critical growth stages; and CDD captures drought stress (Lobell *et al.,* 2011). As important feasible inputs that are known to alter climate sensitivity, agricultural variables (variety type and pest control) have been included (Muthumurugan *et al.,* 2021). Variance inflation factors (VIF) and correlation analysis ($|r| < 0.7$ threshold) were used to screen the initial candidate predictors, and collinear terms were removed step-by-step. To reduce multicollinearity, predictors were centered on themselves. Ordinary least-squares methods were utilized to fit the predictions, and leave-one-out cross-validation (LOOCV), adjusted R^2, the F-statistic ($p < 0.05$), and root mean square error (RMSE) were used for evaluating performance. Multicollinearity was evaluated using variance inflation factors (VIF), where VIF > 10 denoted significant collinearity. To ensure model stability and prevent biased coefficient estimates, RX5_c was removed from the Perambalur model because of its near-perfect collinearity with Rainfall_c (VIF > 15). Linearity, normality, and homoscedasticity have been verified by diagnostic plots (Q-Q, residual vs. fitted) (Dhanya *et al.,* 2022).

RESULTS AND DISCUSSION

Climate variability analysis

The present study assesses temporal shifts in climate variability maximum temperature (Tmax), minimum temperature (Tmin), and precipitation in Ariyalur and Perambalur districts from 1985 to 2100. Future climate data for the years 2021–2100 were obtained from the SSP2-4.5 scenario (O'Neill *et al.,* 2016). The Mann–Kendall (MK) trend test was useful to distinguish variations in Tmax and Tmin across four periods: Historical (1985–2020), Near-Century (2021–2050), Mid-Century (2051–2080), and End-Century (2081–2100). The results specify rising trends in both Tmax and Tmin in the two districts (Table 1), though statistical significance varies. For Tmax, MK statistics range from 0.586 ($p = 0.557$; non-significant) in the End-Century for Ariyalur to 3.439 ($p = 0.0006$; significant) in the Mid-Century for Perambalur. Tmin exhibits stronger warming, with the highest MK statistic of 5.708 ($p = 1.14 \times 10^{-8}$; highly significant) in the Historical period for Ariyalur.

These results are in line with national studies that show a steady rise of approximately 0.2°C per decade in India (Kothawale *et al.,* 2010) predictions that say there will be an extra 1.5–2°C warming by the end of the century under SSP2-4.5. Perambalur exhibits an ongoing rise in Tmax during the Mid-Century, suggesting an increased risk of heat stress, whereas Ariyalur experiences a more significant increase in Tmin, which could increase nighttime respiration losses and impact maize pollination efficiency (Lobell *et al.,* 2011; Geetha & Srivastava, 2019).

In generally, Ariyalur seems to be more affected by changes in rainfall, while Perambalur seems to be more affected by extreme temperatures during the day. These geographical variations are due to differences in the way the soil holds moisture, how high it is, and how much water is used for irrigation. This demonstrates how essential it is to have adaptation strategies that are specific to each district.

Climate extremities analysis

Climate extremes indices for rainfall (CDD, CWD,

Table 2: Climate extremes under different SSP scenarios of Ariyalur and Perambalur

Index (Units)	Ariyalur				Perambalur			
	Baseline	Near century	Mid century	End century	Baseline	Near century	Mid century	End century
CDD (days)	78	75	70	62	85	87	85	81
CWD (days)	10	14	15	16	9	12	13	14
PRCTOT (mm)	1051.6	1385.4	1383.4	1569.9	912.2	1189.8	1210.1	1317.5
R10mm (days)	31	46	46	52	27	41	42	46
R20mm (days)	16	22	23	27	13	20	21	23
R95p (%)	296.5	275.9	285.0	344.6	245.5	233.7	247.8	271.5
R99p (%)	106.8	74.1	74.9	115.7	84.0	54.8	74.2	88.1
RX1day (mm)	97.4	65.7	65.8	74.9	81.6	60.2	64.8	70.4
RX5day (mm)	198.9	181.4	187.8	205.2	160.0	150.9	158.5	170.7
DTR (°C)	9.4	7.6	7.7	7.5	9.9	8.2	8.2	8.1
TN10p (%)	10.3	18.3	4.8	2.7	10.3	18.0	4.6	2.4
TN90p (%)	10.4	2.6	8.8	20.2	10.4	2.9	11.8	20.0
TNn (°C)	18.6	19.1	20.0	20.5	18.1	18.2	19.2	19.6
TNx (°C)	28.1	31.2	32.4	32.5	27.8	31.0	32.2	32.6
TX90p (%)	10.4	4.5	12.8	16.3	10.4	4.9	12.7	16.3
TXn (°C)	26.0	26.6	27.5	27.4	26.0	26.7	27.5	27.5
TXx (°C)	39.3	40.6	41.4	41.7	39.6	40.8	41.7	41.9

PRCTOT, R10mm, R20mm, R95p, R99p, Rx1day, Rx5day) and temperature (DTR, TN10p, TN90p, TNn, TNx, TX90p, TXn, TXx) were evaluated using Climpact for historical (1985–2020) and projected periods: Near-Century (2021–2050), Mid-Century (2051–2080), and End-Century (2081–2100) (Table 2).

According to the analysis, both districts have seen a general rise in annual rainfall over the course of the century, which is a sign of wetter future conditions under SSP2–4.5. Shorter dry spells and better moisture availability for maize are offered by the slight decline in consecutive dry days and the increase in the frequency of moderate rainfall events (10–20 mm). The rainfall gradient of central Tamil Nadu is consistent with the fluctuating patterns of extreme precipitation indices, with Ariyalur usually recording higher magnitudes than Perambalur. These anticipated shifts indicate more water availability, but they also raise the risk of flooding during severe storms.

Consistent rise is demonstrated by temperature-related indices; both districts have fewer diurnal variations in temperature and more frequent warm nights. Stronger nighttime warming (an increase in TNx) is seen in Ariyalur in particular, which can shorten grain-filling times and worsen respiratory stress. Similarly, yield losses due to heat warming have also been described in semi-arid areas of India, by Dhanya *et al.,* (2022) and Ray *et al.,* (2015). This denote that even minor increases in minimum temperature extensively affect the yields of maize.

Impact of climate parameters on maize yield

The regression analysis shows that the relationship between climate and the yield of maize varies significantly between the two districts and the regression coefficients results were tabulated in the Table 3. The multiple regression analysis indicated limited explanatory strength of the selected climatic variables under the fitted model framework. Except for TNx (centered) in Ariyalur district, most predictors did not exhibit statistically meaningful contributions to yield variability, suggesting complex climate–crop interactions beyond the present model specification.

The Ariyalur district has a stronger model fit with an R^2 value of about 0.97. This indicates a more reliable and climate-sensitive yield response compared to Perambalur district, which has an R^2 of roughly 0.51. This difference in model fit highlights the fundamental variations in factors that impact the yield limit between the districts. In contrast to Perambalur district, where improved irrigation, lighter soil, and better agronomic management practices may buffer climatic impacts (Ramachandran *et al.,* 2025), the heavier clay soil with poor drainage and higher nighttime humidity in Ariyalur district amplifies the temperature-induced physiological stress, leading to greater yield reduction.

The estimated 38% decline in maize yield per 1 °C increase in maximum minimum temperature (TNx) in Ariyalur — derived from the significant coefficient $\beta = -0.482$ ($p = 0.025$) using $(\exp(\beta) - 1) \times 100\%$ (Table 3) — is larger than the 10–15% reductions reported by Lobell *et al.,* (2011) for mean temperature effects across tropical maize systems. This stronger response is consistent with evidence that night-time warming disproportionately increases respiratory losses in tropical maize (Kettler *et al.,* 2022), particularly under rainfed, low-input conditions prevailing in Ariyalur. The 95% confidence interval corresponds to an approximate 20–55% yield

Table 3: Multivariate regression model performance for maize prediction over Perambalur and Ariyalur

Predictor	Perambalur	Ariyalur
Rainfall (centered)	$9.54 \times 10^{-5} \pm 4.84 \times 10^{-4}$	$-8.75 \times 10^{-4} \pm 3.15 \times 10^{-4}$
Rainfall² (centered)	$-5.52 \times 10^{-7} \pm 9.61 \times 10^{-7}$	$-5.00 \times 10^{-7} \pm 3.32 \times 10^{-7}$
Tmax (centered)	–0.178 ± 0.536	0.299 ± 0.194
CDD (centered)	0.00829 ± 0.00341	–0.00538 ± 0.00466
Variety (Var = 1)	–0.831 ± 0.551	–0.471 ± 0.233
Pest_centered	0.0350 ± 0.0204	0.0233 ± 0.00934
RX5 (centered)	— (excluded due to collinearity)	0.00358 ± 0.00115
TNx (centered)	–0.244 ± 0.143	–0.482 ± 0.078 * (p = 0.025)
(Intercept)	9.191 ± 0.417 ***	8.717 ± 0.198 ***
Adjusted R²	0.511	0.967
Residual Std. Error	0.377 (df = 3)	0.112 (df = 2)

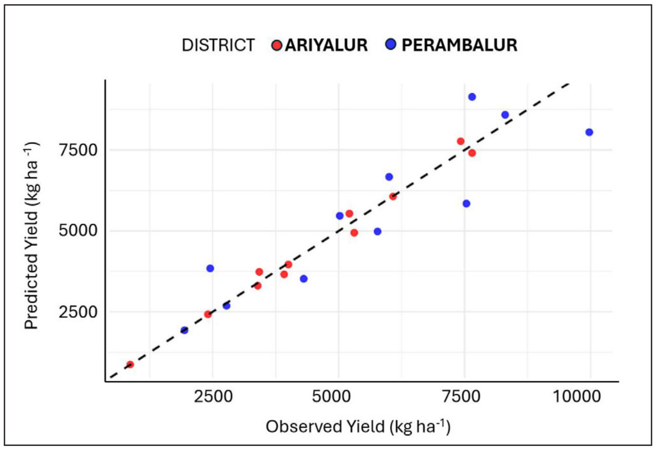

Fig. 2: Observed and predicted maize yield of Ariyalur (R^2=0.993, RMSE=231 kg ha^{-1}) and Perambalur (R^2=0.853, RMSE=1074 kg ha^{-1})

reduction per 1 °C, a range that includes values reported for extreme minimum temperature impacts in South Asian maize systems Lobell *et al.,* (2011)

. This unusually high sensitivity of maize to high-temperature stress could be attributed to the combined effect of thermal and moisture stress; thus, increased night-time temperature increases respiration losses while wet soil conditions impede root aeration and nutrient uptake (Geetha & Srivastava, 2019). Similar compound stress responses were reported by Prasanna *et al.,* (2021) over the Indo-Gangetic Plains, where night-time warming, in combination with poor drainage, resulted in yield losses of 25–35%, falling between our estimates for Ariyalur and Perambalur. The relatively weaker temperature response in Perambalur can be explained by the fact that the soils are sandy loams with better drainage, thereby less synergistic stress due to waterlogging.

The insignificance of several climatic predictors in the regression model of Perambalur does not imply their lack of agronomic significance but rather stresses the limitations of the model arising out of small sample size, collinearity, and unmeasured management factors such as fertilizer use, pest control, and selection of hybrid varieties (Ray *et al.,* 2015). These limitations are clear from Fig. 2, which shows scattered observed-predicted yield patterns, with much larger deviations in Perambalur than the close clustering observed in Ariyalur. For this reason, while Ariyalur seems dominated by a temperature-driven yield response, the productivity in Perambalur is influenced more by rainfall timing, soil type, and farm-level adaptive practices.

Overall, the patterns have observed really highlight that minimum temperature is the key climatic factor affecting maize production in the semi-arid regions of Tamil Nadu. The yield losses experienced here are more significant than most regional and global estimates indicate, suggesting that localised maize systems are becoming increasingly vulnerable to nighttime temperature increases. This clearly highlights the need to consider and predict extreme climate conditions, such as high minimum temperatures and heavy rainfall, more precisely when preparing district agricultural planning

Both districts face the prospect of future warming and unstable rainfall, and when these factors are evaluated together, the impacts will be severe. In Ariyalur, maize yield plummets mostly from heat stress, while in Perambalur, the yield varies more with rainfall patterns and soil type. These results are in line with other broader studies (Lobell *et al.,* 2011; Dhanya *et al*., 2022; Geetha & Srivastava, 2019). The most important fact is that this district-level detail paves the way for creating site-specific solutions like clearing drainage channels in Ariyalur district to improve water availability to face heat stress and using moisture-saving methods in Perambalur district.

LIMITATIONS OF THE STUDY

The regression framework applied in this study represents an exploratory assessment of climate–yield relationships. Several climatic indices exhibited limited statistical contribution within the fitted model, indicating the complexity of maize response to climatic variability. Alternative modeling approaches, including step-wise regression or advanced predictive techniques, may improve explanatory strength. Further crop stage-specific climate analysis may also refine interpretation in future investigations.

CONCLUSION

This study shows that Ariyalur and Perambalur districts of Tamil Nadu have different unique characteries in terms of climate sensitivity. An increase in minimum temperature by 1°C in Ariyalur district is expected to cause maize loss of about 38.2%, highlighting the importance of site- specific adaptation strategies. On the other hand, Perambalur is an area that is more prone to rainfall variation, but is relatively less sensitive to temperature changes, hence the district requires site specific management approaches.

Although the sample sizes for each regression model were limited, the consistent significance of the temperature-related predictors indicates that the identified relationships are robust. These findings provide a strong empirical foundation for climate-resilient interventions such as heat-tolerant maize hybrids, precision irrigation, and improved soil-moisture conservation in semi-arid regions. These district-level differences reinforce the need for climate adaptation policies that are sensitive to local conditions. When integrated, insights from studies like ours can contribute to more effective and forward-looking agricultural planning under Tamil Nadu's shifting climate

ACKNOWLEDGEMENT

We thank the Department of Agriculture, Government of Tamil Nadu, for providing the data. We sincerely acknowledge Dr. Ahamed Ibrahim S N, Senior Scientist, Centre for Climate Change and Disaster Management (CCCDM), Anna University, for his valuable support in the modelling framework, data validation, and statistical analysis.

Funding: No funding was received for this work

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability: Data will be made available on request

Author's contribution: **B. R. Easwari**: Original draft, Investigation, Formal analysis, Conceptualisation, **Pavithrapriya S**: writing, climate analysis and validation, **A. Ramachandran**: Writing – review & editing, Methodology, **K. Palanivelu:** Writing – review & editing, Supervision

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