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Short communication

Climate change impact on pigeon pea (*Cajanus cajan*) yield in Maharashtra and Karnataka: A panel regression approach

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Pigeon pea (*Cajanus cajan*), also known as tur or red gram, is a vital pulse crop of India, ranking second after gram in acreage and production. It contributes significantly to food and nutritional security, particularly for low-income households. India produces nearly 80% of the world's pigeon pea, primarily under rain-fed conditions in semi-arid regions where yield performance depends heavily on monsoon variability (Ghritlahre *et al.*, 2022). However, pigeon pea yields are increasingly threatened by climate variability. Erratic rainfall, temperature extremes, and delayed monsoon onset disrupt crop growth stages, causing yield fluctuations of 15–25% across major producing regions (Patil *et al.*, 2018; Mishra *et al.*, 2017). Studies by Raju *et al.*, (2014) and Khedikar *et al.*, (2023) identified rainfall distribution and sowing time as key determinants of pigeon pea productivity. Similarly, Musokwa & Mafongoya (2021) emphasized rainfall timing and drought resilience. Nevertheless, most existing analyses are either state-level, short-term, or simulation-based. Despite pigeon pea's economic and nutritional importance, there is limited long-term, district-level evidence quantifying how rainfall, temperature, and other climatic factors affect yield under rain-fed conditions in India. This study fills this gap using a 56-year (1966–2022) district-level panel dataset for major pigeon pea-producing regions of Maharashtra and Karnataka, applying a random effects regression approach to estimate the influence of key climatic variables on yield outcomes.

The analysis focuses on five leading pigeon pea-producing districts—Bidar, Kalaburagi (Gulbarga) and Vijayapura (Bijapur) of Karnataka, and Buldhana, and Wardha of Maharashtra states (Fig. 1). These districts contribute nearly one-third of India's total pigeon pea output. Located in the semi-arid Deccan plateau (17°–21°N, 75°–79°E), they are characterized by vertisol soils, annual rainfall between 650 and 950 mm, and temperatures ranging from 15°C to 42°C. Pigeon pea in the study region is typically cultivated during the

monsoon (kharif) season, with sowing occurring during June–July and harvesting extending from December to February depending on varietal duration and regional agro-climatic conditions.

Data and methodology

The panel dataset (1966–2022) on yield (kg ha⁻¹) and area (ha) were obtained from the Directorate of Economics and Statistics, Government of India (DES, 2023). The daily rainfall (mm) gridded data (0.25° × 0.25°) & temperature (°C) gridded data (1° × 1°) were obtained from India Meteorological Department (IMD) gridded data. The monthly wind speed (m s⁻¹) & cloud cover (%) were obtained from ERA5 Reanalysis (ECMWF). Climatic variables such as rainfall and temperature were interpreted in relation to the crop growing period to understand their influence on pigeon pea productivity. While aggregated datasets were used for panel regression modeling, the interpretation of climate–yield relationships was undertaken within the agronomic context of the crop season.

The monsoon onset date was computed for each district using the Cumulative Rainfall Deviation (CRD) method, a standard approach aligned with IMD protocols (Singh *et al.*, 2020). The formula used is as follows:

$$S(d) = \sum_{t=1st\ May}^d [R(t) - Pc]$$

Where: S(d): Cumulative rainfall deviation at day d; R(t): Observed rainfall at time t; Pc: Average daily precipitation over the year. The monsoon onset date is identified as the day immediately following the lowest value of S(d), representing the transition from pre-monsoon dry conditions to active rainfall. This method was applied annually from 1966 to 2022 for each district to construct a

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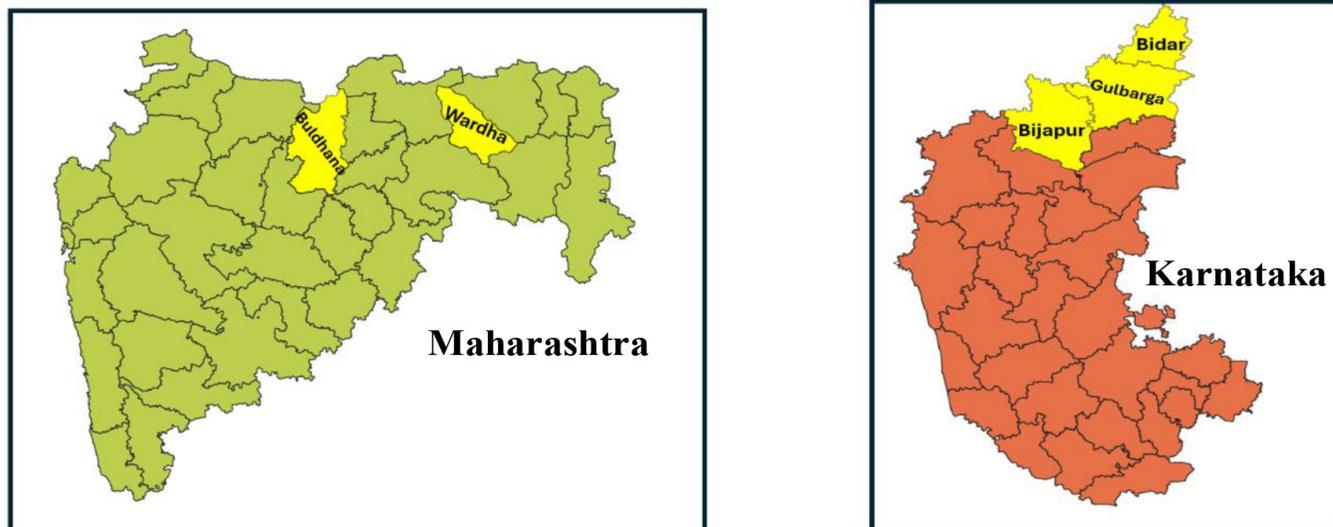


Fig. 1: Study area maps of key pigeon pea-producing districts of Karnataka and Maharashtra

continuous variable for regression analysis.

A percentile-based classification system was employed to categorize annual rainfall distribution and used as a dummy variable. Rainfall years were classified into three categories: Deficient rainfall (annual rainfall below the 25th percentile); Normal rainfall (between the 25th and 75th percentiles) and Excessive rainfall (above the 75th percentile). To capture the effect of extreme heat events, a dummy variable was created based on the upper 20th percentile of the temperature distribution. If the maximum temperature for a year exceeded the 80th percentile, it was classified as a “Bad Temperature Shock”, and the dummy variable was coded as one. If not, the dummy was coded as zero.

Four regression specifications were estimated using Python (Stats models 0.14) under a random effects (RE) framework validated by the Hausman test (Hausman, 1978). The statistical significance was evaluated at *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.10$ thresholds. The parameters of four models are given below;

Model 1: Model was developed using rainfall, temperature and onset of monsoon

Model 2: Model 1+ rainfall distribution (deficient, normal, excessive) as dummies

Model 3: Model 2+ Temperature shock (top 20% hottest years) dummy variable

Model 4: Model 3 + wind speed and cloud cover

The estimated model is: $Y_{it} = \alpha + \beta_1 R_{it} + \beta_2 T_{it} + \beta_3 M_{it} + \beta_4 X_{it} + \epsilon_{it}$ where Y_{it} is the yield (kg ha^{-1}) for district i in year t , denotes rainfall, temperature, and monsoon onset.

Impact of climate on pigeon pea yield

Regression results (Table 1) identify rainfall as the most influential climatic determinant of pigeon pea yield. Each

additional millimeter of rainfall increased yield by 0.84 kg ha^{-1} ($p < 0.01$), while excessive rainfall reduced it by $\sim 200 \text{ kg ha}^{-1}$ ($p < 0.01$). Delayed monsoon onset reduced yield by $1.7 \text{ kg ha}^{-1} \text{ day}^{-1}$, consistent with (Khedikar *et al.*, 2023), who observed that early sown crops outperform late ones. Temperature had a non-linear effect: moderate warming enhanced productivity ($15\text{--}25 \text{ kg ha}^{-1}$), while heat shocks reduced yield by 95 kg ha^{-1} , a finding like those of (Patil *et al.*, 2018; Mishra *et al.*, 2017). Wind speed showed a strong negative influence (-216 kg ha^{-1} ; $p < 0.05$), likely due to mechanical stress and increased evapotranspiration. Conversely, cloud cover improved yield ($+895 \text{ kg ha}^{-1}$; $p < 0.05$), reducing canopy heat stress. Overall, the findings align with previous regional studies (Musokwa & Mafongoya, 2021; Raju *et al.*, 2014) replicated three times, was used. Soil water tension was measured at 20, 50, and 120 cm within plots. The highest and lowest soil water tension was recorded at 20 m and 120 m respectively. Combined biomass and grain yield were significantly different: pigeonpea + maize (5513 kg ha^{-1}) and provide robust long-term empirical evidence on climate-yield sensitivity in rain-fed pigeon pea systems.

The results revealed that rainfall is the most critical driver, with well-distributed precipitation enhancing yield whereas excessive rainfall reduced yield. Temperature exhibited a threshold effect—moderate warmth improved yield but extreme heat caused yield losses. Delayed monsoon onset and high wind speed negatively influenced yield, while cloud cover contributed positively by reducing canopy heat stress. These findings confirm the high climate sensitivity of rain-fed pigeon pea systems and emphasize the importance of rainfall distribution, timely sowing, and temperature thresholds in shaping yield outcomes. Further refinement using crop period-specific climatic datasets would strengthen predictive interpretation of climate change impacts on pigeon pea yield.

Policy Implications: Developing heat- and flood-tolerant cultivars, improving drainage infrastructure, and promoting early sowing aligned with monsoon forecasts are key strategies for climate adaptation in semi-arid regions.

Table 1: Random effects regression results (Dependent variable: pigeon pea yield in kg ha⁻¹)

Variable	Model 1	Model 2	Model 3	Model 4
Rainfall	0.843*** (0.114)	0.569*** (0.133)	0.588*** (0.138)	0.255*** (0.092)
Temperature	2.247 (1.592)	12.838 (8.371)	15.601*** (4.996)	24.818* (12.78)
Monsoon onset date	-1.745** (0.699)	-1.776** (0.749)	-1.163 (0.762)	-0.929 (0.702)
Wind speed	—	—	—	-215.93** (93.73)
Cloud cover	—	—	—	894.74** (375.94)
Bad temp. shock (Dummy)	—	—	-95.34* (49.83)	—
Normal rainfall (Dummy)	—	117.81*** (40.81)	—	—
Excessive rainfall	-196.41*** (63.65)	—	-198.40*** (64.79)	—
R-squared	0.83***	0.82***	0.83***	0.83***

Values in parentheses are robust standard errors. Significance levels: ***p < 0.01, **p < 0.05, *p < 0.10

Limitation: The analysis utilized aggregated climatic datasets within a panel regression framework. While this approach captures broader climate–yield associations, crop stage-specific weather variability may provide additional precision in understanding pigeon pea productivity responses. Future studies incorporating seasonally disaggregated climate parameters are recommended.

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