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Climate Change and Agricultural Productivity: A System GMM Approach using District-level Data

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ABSTRACT

Background: This study investigates the impact of climate change on rice productivity in Jharkhand, India, with a focus on temperature fluctuations and rainfall patterns. It highlights the risks associated with maximum temperatures during critical growth stages for rice, while minimum temperatures can benefit growth. The study also underscores the challenges posed by water scarcity, as agriculture in Jharkhand heavily relies on rainfed systems.

Methods: The current study employs secondary district-level data collected from different sources and applies the system GMM approach for empirical estimation.

Result: The findings indicate that both temperature and rainfall have a significant influence on rice yields. The results suggest that policymakers should account for district-level heterogeneity when designing climate adaptation strategies. Enhancing irrigation coverage and efficiency, as well as converting fallow land into arable land, are identified as key measures to mitigate climate-related risks and improve farm income.

Key words: Climate, Drought, Productivity, Rice, System GMM.

INTRODUCTION

Climate change is now indisputable and has become a global challenge (IPCC, 2007). Climate change increases the frequency, intensity and duration of precipitation, leading to persistent droughts and floods (IPCC, 2007; Palei *et al*., 2024). However, every sector of the economy is being influenced by climate change. However, agriculture faces the main threat from climate change, as the temperature and rainfall are the critical inputs in crop production. Hence, the most significant risk is associated with this sector (Deschene and Greenstone, 2007; Pawar *et al*., 2025). Furthermore, the interaction between climate and agriculture is crucial for achieving food security and reducing poverty (Kavi Kumar, 2011; Kumar and Upadhyay, 2019). Researchers and experts predict that developing nations face greater adverse effects due to their reliance on agriculture and limited resources to manage these challenges (Mendelsohn, 2009).

Among crops, rice serves as the primary staple food for most people in India (Bandyopadhyay *et al*., 2024). Rice cultivation spans approximately 44 million hectares in India, primarily during the *kharif* season. Out of that, around 40 per cent of rice-growing areas are rainfed, which is characterised by wide fluctuations leading to drought and flood and hence the loss of productivity in the country (Birthal *et al*., 2015; Kalmani *et al*., 2025). Additionally, the distribution of rainfall and temperature is asymmetric, meaning that spatial variations in climatic conditions exist across Indian states, which in turn influence agricultural productivity. For instance, specific regions or states demonstrate an increasing rainfall trend, whereas others exhibit a decreasing trend (Padakandla, 2016; Kumar *et al*., 1992; Shukla *et al*., 2023). Likewise, the East Coast, West Coast and peninsular regions experience an increase in the frequency of hot days, although Northern India displays minimal change (Government of India, 2010). This indicates that significant climatic changes occur within India's geographical boundaries (Gurugnanam *et al*., 2010; Manickam *et al*., 2012; Padakandla, 2016). Kishore *et al*. (2015) assess the efficacy of the fuel subsidy program (2008) in response to the persistent droughts in Bihar over the past decade. The evaluation reveals that the program is ineffective due to inadequate implementation. Guntukula *et al*. (2020) assess the impact of precipitation and temperature on the primary pulses grown in Telangana, India. This study finds that rainfall harms pulse productivity. Numerous studies (Padakandla, 2016; Guntukula *et al*., 2020) examine the regional dimensions of climate change in Indian states. However, empirical research on the Jharkhand region remains limited, as it continues to function as an agrarian economy. Approximately 76% of its population resides in rural areas and 66.85% of the total labour force is engaged in agriculture and allied activities for their livelihood (Jharkhand Economic Survey, 2017-18). However, the sectoral share of agriculture has ranged from 12.2% to 15.5% in GSVA at constant prices since 2015-16,

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highlighting the low productivity of agriculture in Jharkhand (Jharkhand Economic Survey, 2023-24). The Department of Agriculture notes that the state falls short of approximately 14% of its food grain and about 70% of its fruits (Jharkhand Action Plan on Climate Change, 2014). Jharkhand remains one of the most vulnerable and food-insecure states, with around 10% of the population facing seasonal food grain shortages (Preparatory Survey on Initiative for Horticulture Intensification by Micro Drip Irrigation in Jharkhand, 2014).

In this context, this study assesses the impact of climate on agricultural productivity, specifically rice productivity, in the agrarian economy of Jharkhand, India, utilising district-wise data. Rice serves as the primary *kharif* crop, cultivated across over 60 per cent of the cropped area. Most of the prior literature (Birthal *et al*., 2015; Padakandla, 2016; Birthal *et al*., 2021), which utilises district-wise data, has employed static panel data models, specifically the Fixed Effects (FE) and Random Effects (RE) models. We anticipate that last year's agricultural output may affect current year production through multiple channels, potentially resulting in a biased result and an endogeneity issue. Hence, we prefer the System GMM model over FE and RE models to estimate the dynamic relationship between climatic factors and agricultural yield. This technique removes the individual unobserved heterogeneity among the districts. It also addresses the endogeneity issue by using an instrumental variable. It accounts for heteroscedasticity and serial correlation (Roodman, 2009).

The layout of the current study is as follows. The upcoming section deals with data and methodology, which explores the data and their sources, as well as the econometric tools applied to analyse the data. The following section presents the results and discussion. The last section 'conclusion' summarises the paper and highlights the main findings and limitations.

MATERIALS AND METHODS

The present study is based on secondary, district-wise data for the main *Kharif* crop in Jharkhand, *i.e*., rice, as well as climatic factors such as minimum temperature, maximum temperature and rainfall and non-climatic factors like the area under rice cultivation, irrigated area and fertiliser consumption. Fig 1 presents a map of Jharkhand, India, which comprises 24 districts. Out of these, 22 are selected for this study based on the availability of data.

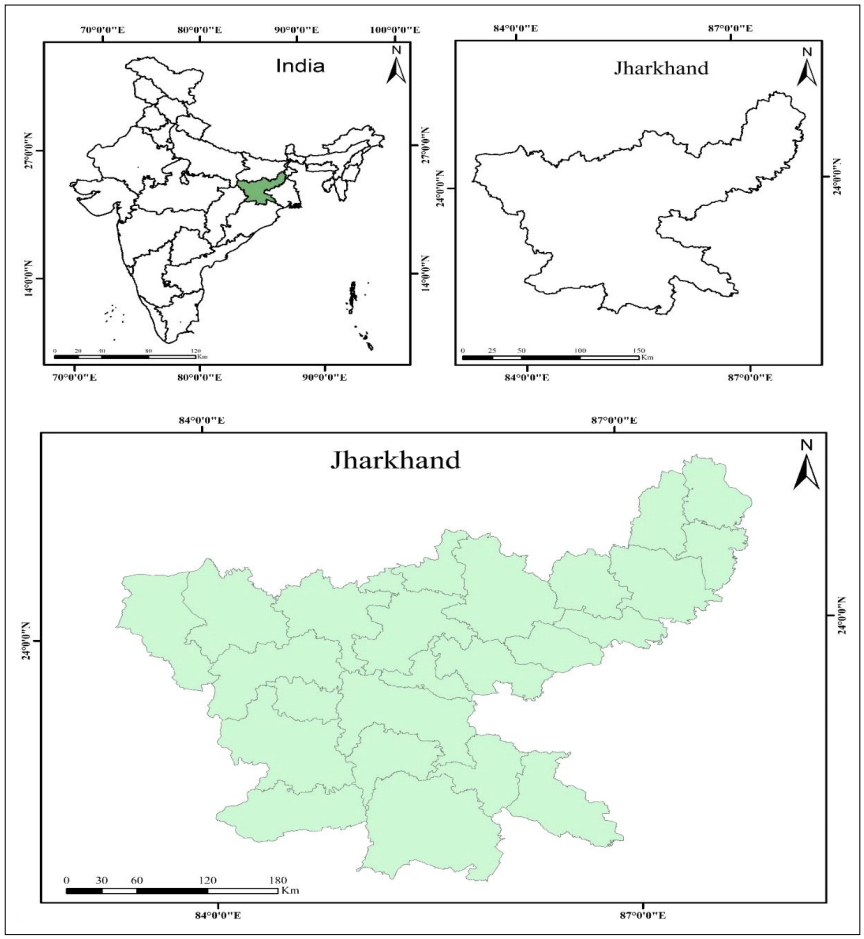


Fig 1: Map of Jharkhand and India.

Table 1 shows that Crop yield and non-climatic inputs data are sourced from ICRISAT and the Directorate of Economics and Statistics, Government of India. Monthly rainfall data are obtained from India-WRIS (Water Resource Information System), which compiles water-related data from various sources, including IMD. In contrast, Monthly maximum and minimum temperature data are gathered from NASA Power (satellite data), as satellite temperature data are considered superior to weather station data (Mendelsohn, 2009). This is because weather stations are widely dispersed, with some states having only two or three stations. We have converted these monthly maximum and minimum temperatures into average maximum and minimum temperatures during the rice-growing season (*Kharif*) and monthly rainfall into cumulative rainfall for the *Kharif* season.

Previous literature suggests a static panel data model, *e.g.,* Fixed Effects and Random Effects models. They are based on the strict assumption of exogeneity. Once this assumption is breached, these models might not be effective. In determining the functional link between agricultural inputs and outputs, we posit that the previous year's output may affect current-year production through multiple channels within the agricultural sector. For instance, the High price of a particular crop in the previous year has the potential to increase the production of the given crop in the current year. Incorporating lagged values of the regressand as explanatory factors may lead to endogeneity. To resolve this endogeneity problem, we utilise a dynamic panel data model, specifically the Generalised Method of Moments (GMM) popularised by Arellano and Bond (1991), which employs lag values of the dependent variable as instruments to address endogeneity. These lag-dependent variables are highly correlated with the endogenous variable in the equation. However, they are uncorrelated with the error term. Later, Arellano and Bover (1995) and Blunder and Bond (1998) extended this approach. They suggest that a set of equations should be established. One equation must be presented in level form, while the other should be in difference form. The lagged level of the dependent variable should serve as an instrument for the difference equation. In contrast, the lagged first differences of the regressand should be utilised as an instrument for the equation in levels. This equation set is referred to as System GMM (Roodman, 2009; Blundell and Bond, 2023). The application of system GMM significantly improves efficiency and mitigates finite sample bias (Blundell and Bond, 2023).

This technique necessitates the presence of AR (1) due to the incorporation of a lagged dependent variable among the explanatory variables, while AR (2) must be absent as the first post-estimation criterion, complemented by the Hansen test of over-identifying restrictions as the second criterion for the applicability of GMM. The Hansen test null hypothesis, H_0, asserts that the overidentifying constraints are legitimate. This should not be disregarded.

The final model of this study, after including the lag dependent variables, will be:

$$\ln_Rice\ yield_{it} = \alpha_0 + \alpha_1 MaxT_{it} + \alpha_2 MinT_{it} + \alpha_3 RF + \alpha_4 Area_{it} + \alpha_5 Fertiliser_{it} + \alpha_6 Irrigation + \alpha_7 \ln_Rice\ yield_{i,t-i} + \mu_i + \varepsilon_{it} \quad ...(1)$$

Where Rice yield is measured in kg per hectare. i is a cross-sectional unit, representing a district and t is the year. So, rice yield in kg per hectare in the i^{th} district and in the t^{th} year. MaxT is the average maximum temperature of the Kharif season, MinT is the minimum temperature of the same period and RF is the cumulative rainfall during the rice-growing period. Area is the total area under rice cultivation. Fertiliser is the fertiliser consumption in the given season and irrigation is the irrigated area under cultivation. γ_i is the district fixed effect and captures the effects of district-specific time-invariant factors and ε_{it} is the error term.

RESULTS AND DISCUSSION

Table 2 and 3 present the descriptive statistics and correlation matrices for the variables included in the current study. Table 2 presents the descriptive statistics of the selected variables in the current study. It shows a significant fluctuation in the rice yield during the study period. Similarly, rainfall during the rice-growing period also exhibits significant variations, ranging from 392.82 mm (far below the average rainfall) to 2385.56 mm (far above the normal rainfall during the season).

Table 3 shows that the values of correlation range from -1 to +1. Positive and high values of correlation

Table 1: Data description.

Variables	Source	Description
Rice yield	ICRISAT	KG per hectare
Rice area	ICRISAT	1000 hectares
Irrigation	ICRISAT	Crop-wise irrigated Area (1000 hectares)
Fertilizer	ICRISAT	*Kharif* fertiliser use (ton)
Temp max	NASA POWER	Degrees Celsius (°C). Average maximum temperature during *Kharif* (Jun-Sep)
Temp min	NASA POWER	Degrees Celsius (°C). Average minimum temperature during *Kharif*
Total RF	INDIA WRIS	Millimetre (mm). Cumulative rainfall during the *Kharif* season.

Sources: Author's compilation.

Table 2: Summary statistics.

Variable	Observation	Mean	Std. Dev.	Min	Max
Rice yield	454	1708.18	720.027	89	7370
Rice area	454	74.4817	246.318	0.85	3050
Rice irrigation	383	2314.48	4258.29	1000	25780
Fertiliser	454	74.0358	118.546	0	696.518
Temp max (°C)	462	35.1913	1.35755	31.4175	38.1475
Temp min (°C)	462	23.1472	1.05766	20.47	25.415
Total RF (mm)	462	1003.93	255.558	392.82	2385.56

Source: Author's calculation.

Table 3: Correlation matrix.

Variables	Rice yield	Rice area	Irrigation	Fertiliser	Temp max	Temp min	Total RF
Rice yield	1						
Rice area	0.1058	1					
Irrigation	0.0413	-0.0438	1				
Fertiliser	-0.0434	-0.1012	0.0122	1			
Temp max	-0.2814	-0.1738	0.2238	0.1206	1		
Temp min	-0.0345	-0.2136	-0.0097	-0.0567	0.5552	1	
Total RF	0.2171	-0.0348	-0.2006	-0.1431	-0.2595	0.0825	1

Source: Author's calculation.

Table 4: Unit root and cointegration test.

Variables	Level	1st difference
Ln rice yield	-8.4808***	
Rice area	4.6012	-10.5512***
Temp max	-11.7266***	
Temp min	-10.008***	
Total RF	-10.3493***	
Irrigation	-6.3354***	
Fertiliser	-3.678***	
Westerlund cointegration test		
Variance ratio	7.4155***	

Source: Author's calculation.

Note: ***, ** and * denote significance levels of 1%, 5% and 10%, respectively.

coefficients imply that the concerned variables are moving in the same direction. In contrast, negative values of correlation coefficients mean that the two variables are moving in opposite directions. It also shows that any two variables do not indicate a high positive or negative correlation, which may lead to a collinearity problem.

Table 4 presents the result of the IPS (Im, Pesaran and Shin) unit root test. It is the first-generation unit root test applied to check the stationarity of the data, which is necessary to avoid spurious relationships. The null hypothesis of this test indicates that the variable has a unit root, implying that if the null hypothesis is rejected at a certain level of significance, then the variable is stationary by differencing. The results indicate that all variables are stationary at the 1% level except the Rice area, which is stationary at the first difference. Therefore, System GMM is appropriate because it can substantially reduce the bias by employing relevant stationary restrictions on initial conditions (Wani *et al*., 2024; Asiamah *et al*., 2024). We have also conducted the Westerlund cointegration test, which suggests that a cointegrating relationship exists among the variables employed in the model.

We plot the rice yield per hectare in Fig 2, the average maximum temperature in Fig 3, the average minimum temperature in Fig 4 and the total rainfall of the rice-growing season, *i.e*., *Kharif*, in Fig 5, during the study period to understand their behaviour. Fig 2 illustrates a graphical representation of rice yield, accompanied by a trend line. It exhibits a considerable fluctuation with a positive trend, implying an increase in the rice yield over the year. Fig 3 and 4 present the average maximum and minimum temperatures, along with their respective trends. Both figures show an increasing trend, indicating that the average maximum and minimum temperatures of the rice *Kharif* season are rising in the Jharkhand region. In contrast, Fig 5, *i.e*., *Kharif* season rainfall, shows a decreasing trend, leading to recurring droughts in various parts of the state. This analysis aligns with the economic survey report, which notes a rainfall deficiency of around 27% in the state (Jharkhand Economic Survey, 2023-24).

Table 5 presents the results of the one-step and two-step GMM systems, following the approach outlined by Roodman (2009). The dependent variable is used in a log to reduce the fluctuations. Table 5 shows that the lag-dependent variable has a positive effect on the current year's Yield and this effect is significant at the 1% level in both models.

The coefficient of average maximum temperature is (-0.1057) in one-step GMM and (-0.096) in two-step system GMM and both are significant at the one per cent level in both models. This implies that a one-degree Celsius increase in maximum temperatures will decrease rice yields by nine per cent, given that no adaptive measures are taken.

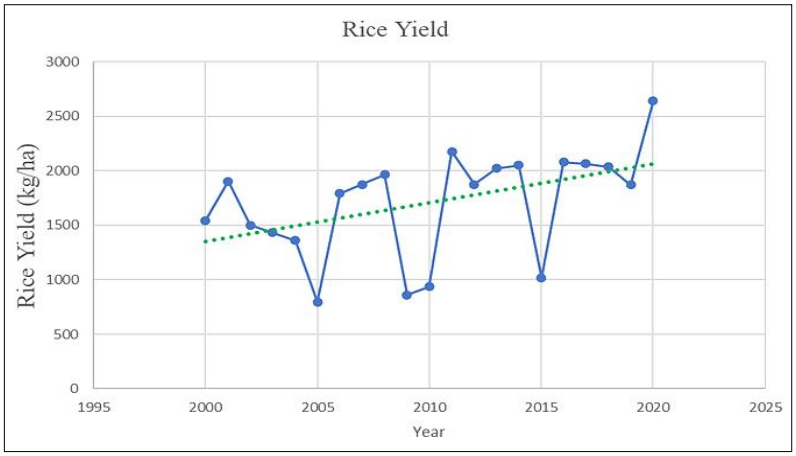


Fig 2: Rice yield (kg/ha).

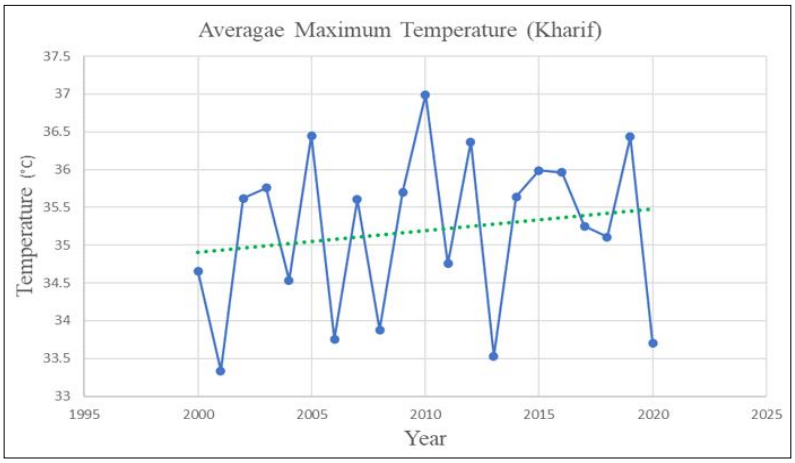


Fig 3: Average maximum temperature of the *kharif* season.

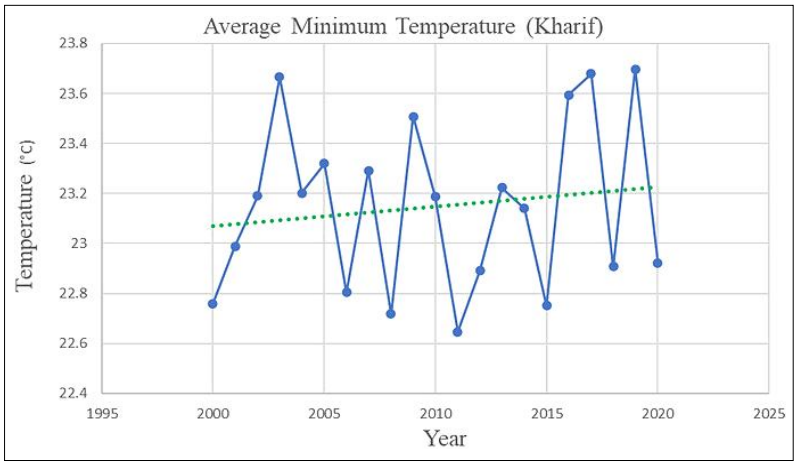


Fig 4: Average minimum temperature of *kharif* season.

This finding aligns with previous studies by Birthal *et al*. (2014); Mendelsohn *et al*. (2009) and Padakandla (2016). The coefficient of minimum temperature is positive, indicating that an increase in the average minimum temperature during the *Kharif* season benefits rice production and enhances productivity. This result is statistically significant at the 10% level in the one-step model only. This finding is consistent with Birthal *et al*. (2021).

The rainfall coefficient is positive and statistically significant at the 1% level in both models, indicating that rainfall helps increase rice productivity. However, the effect size is small, possibly reflecting Jharkhand's soil characteristics, which have low water retention capacity (Preparatory Survey on Initiative for Horticulture Intensification by Micro Drip Irrigation in Jharkhand 2014), thus limiting the potential benefits of rainfall for rice plants. The coefficient of rice irrigation is positive and significant, aligning with the findings of Birthal *et al*. (2015), which suggest that productivity increases with irrigation. However, its effect size is also tiny, likely due to Jharkhand's low irrigation facilities. Only around 14.5% of the cropped area in the state is irrigated, which is far below the national average of approximately 47% (Economic Survey, 2021-22). The remaining two variables, rice-cropped area and fertiliser, are insignificant in both models. However, a time series plot of rice-cropped area shows an increasing trend.

The negative coefficient of average maximum temperature highlights losses due to heat stress, aligning with the previous literature. Conversely, the effect of average minimum temperature and rainfall reflects the productivity gain from favourable moisture and thermal conditions. More importantly, the positive and significant coefficient of irrigation demonstrates that adaptation through irrigation helps minimise the detrimental effects of excess heat, which indicates that optimal irrigation can reduce the vulnerability associated with climate change.

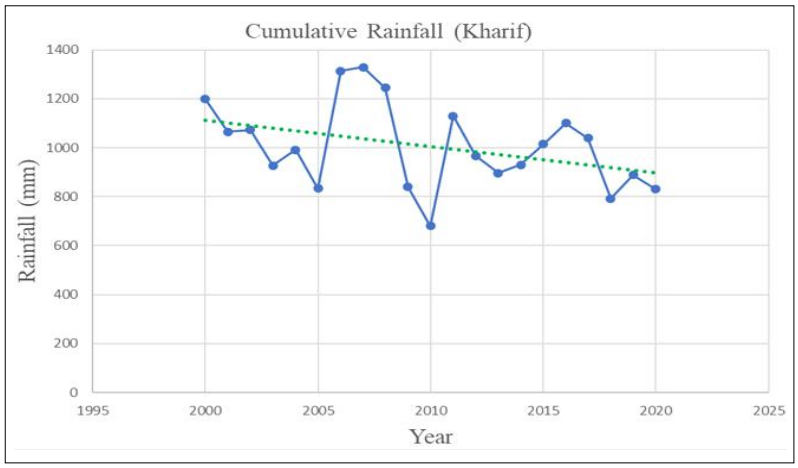


Fig 5: *Kharif* season rainfall.

Table 5: Results for one-step and two-step GMM model.

Explanatory variables	One-step system GMM	Two-step system GMM
ln rice yield (L1)	0.1525*** (0.04350)	0.14099** (-0.05685)
Temp (Max)	-0.1057*** (-0.02435)	-0.09644*** (-0.02248)
Temp (Min)	0.0542* (-0.03056)	0.04944 (-0.05614)
Total rainfall	0.00094*** (-0.00012)	0.00093*** (-0.0001)
Rice irrigation	0.000022*** (-0.00000418)	0.00002*** (-0.00000552)
Fertiliser cons	0.0002 (0.0002)	0.0004 (-0.00032)
Rice area	-0.0003 (-0.00107)	0.0005 (-0.0017)
Constant	7.6331*** (-1.1384)	7.4980*** (-1.464)
AR (1)	0.005	0.005
AR (2)	0.155	0.218
Hansen test	0.169	0.169
No of instrument	14	14
No of group	22	22

Note: Standard errors are reported in parentheses. Note: ***, ** and * denote significance levels of 1%, 5% and 10%, respectively. It is worth noting that both models suggest that high temperatures harm rice yield, whereas minimum temperatures, rainfall and irrigation have a positive impact on rice yield.

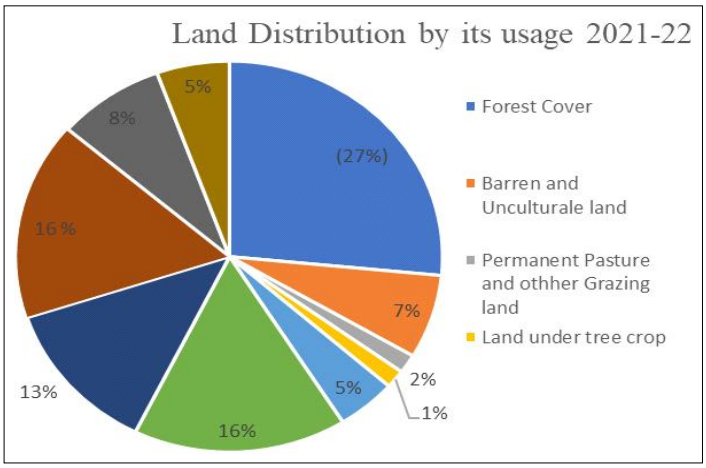


Fig 6: Land distribution.

Table 6: Regression result of DOLS (Robustness check).

Variables	Coefficients (DOLS)	Standard error
Temp (Max)	-0.1395***	0.03193
Temp (Min)	0.07999**	0.03193
Total rainfall	.00079***	0.00012
Rice irrigation	0.00013*	0.00000753
Fertiliser consumption	0.00021	0.00025
Rice area	-0.00056	0.0008
Constant	9.599***	0.91738
R-squared	0.261	
Adjusted R-squared	0.2444	

Source: Author's calculation.

It is important to note from the result that irrigation turns out to be an important adaptive measure which mitigates the harmful impact of climate stress. However, the larger area of rice cultivation in Jharkhand exhibits adaptation constraints. Rice is highly water-intensive, while the observed decline in rainfall in the state, combined with minimal irrigation infrastructure, constitutes a serious risk to sustaining rice cultivation. These limitations disproportionately affect marginal and small-scale farmers, who constitute the majority of the agricultural population and often lack adequate adaptive capacity. The decline in water availability for irrigation may be a significant factor in the expansion of fallow land over time, which can exacerbate the seasonal food shortage in the state. Hence, the empirical evidence on the role of irrigation as an adaptive measure should be carefully interpreted considering these structural constraints, which indicate that adaptation benefits are unevenly distributed among the farmers and largely depend on access to water.

We conduct post-estimation checks required for the Generalised Method of Moments (GMM), including (1) testing for autocorrelation of order one and two and (2) the Hansen test for overidentifying restrictions. The AR test suggests the presence of an AR(1) process and the absence of an AR(2) process and the Hansen test confirms the validity of the overidentifying restrictions.

Land utilisation in Jharkhand is also significant. 34% of the state's geographical area is fallow land, as shown in Fig 6, which could be cultivated, a figure much higher than the net sown area of 16%. Historical data show an increasing trend in fallow land and a decreasing trend in net sown area from 1980-81 to 2006-07 (Preparatory Survey on Initiative for Horticulture Intensification by Micro Drip Irrigation in Jharkhand, 2014).

The government has initiated various programs to cultivate fallow land. However, accelerating these efforts is essential, given the high dependence of a large population on agriculture.

To check the robustness of the current study, we apply the dynamic ordinary least squares (DOLS) method. Table 6 presents the results of the dynamic ordinary least squares method (DOLS). We report the R^2 and adjusted R^2 to evaluate the goodness of our results. This technique also validates the relationship among the variables in the study. The coefficient of average maximum temperature is negative and significant at the 1% level, indicating the harmful impact of maximum temperature, as shown in this model. Similarly, as observed in our primary analysis, the coefficients for minimum temperature and total rainfall are positive and significant at the 5% and 1% levels, respectively. Rice area under irrigation is significant at the 10% level.

CONCLUSION

Jharkhand experiences erratic rainfall and temperature fluctuations that significantly impact agricultural productivity. This study examines the effects of climate change (Using temperature and rainfall data) on rice yield in Jharkhand, using district-wise secondary data from 2000 to 2020. Applying the system GMM approach enables dynamic panel data analysis, effectively addressing potential endogeneity caused by lagged dependent variables within the explanatory variables, which might otherwise bias the

results. Findings indicate that high average maximum temperatures harm rice productivity, while minimum temperatures improve growth. A positive correlation exists between monthly rainfall and rice yields, underscoring the importance of a sufficient water supply during the rice-growing season. In the past two decades, rainfall in Jharkhand has decreased, exacerbating drought conditions and potentially leading to an increase in fallow land (Land Degradation, Desertification and Drought in Jharkhand, 2024). Farmers can employ several adaptation techniques to mitigate the negative impacts of drought, including adjusting planting schedules, altering input mixtures, utilising more resilient crop varieties and enhancing irrigation and fertiliser application. This study demonstrates that irrigation is a significant adaptive strategy for mitigating the impacts of climate change in the state. However, Jharkhand lags behind the national average in terms of area under irrigation. The study recommends enhancing irrigation facilities, improving existing irrigation systems and promoting micro-irrigation to increase water productivity (Birthal *et al*., 2015). Additionally, the policymakers need to promote drought-resistant crops and horticulture, which require less water and are more drought-tolerant, as this could reduce vulnerability among small and marginal farmers in the state. The state has significant potential for horticulture, with the area under horticultural crops exceeding the national average (Preparatory Survey on Initiative for Horticulture Intensification by Micro Drip Irrigation in Jharkhand 2014). These measures would help mitigate climate variability risks, improve farm income and address seasonal food insecurity in the state.

This study was unable to address the impact of alternative adaptation techniques, such as adjusting planting dates or modifying input mixtures, on reducing climate-induced losses due to data unavailability. Future studies may examine the effects of various adaptive measures farmers implement and provide optimised recommendations for policymakers.

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Disclaimers

The opinions and findings drawn in this article are the authors' own and may not necessarily reflect those of the organisations with which they are affiliated. The authors disclaim any liability for any direct or indirect losses stemming from the use of this content; however, they are accountable for the accuracy and completeness of the information presented.

Conflict of interest

The authors affirm that they have no conflicts of interest relevant to the publication of this article. The study's design, data collection, analysis, publication decision and manuscript preparation were all unaffected by funding or sponsorship.

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