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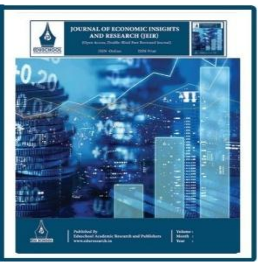

# Climate Change Impacts on Agricultural Productivity and Rural-Urban Migration in India

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**Abstract**

This paper examines how climate change-induced agricultural shocks affect migration decisions in India using district-level panel data from 640 districts across 28 states (2005-2024). Combining climate data with household surveys and migration records, we implement an instrumental variables approach where climate anomalies serve as exogenous productivity shocks. We find that each 1°C temperature increase above optimal growing season temperatures reduces agricultural yields by 8.7% and increases rural-urban migration by 4.2%. Rainfall variability intensifies these effects. Approximately 24 million people migrated due to climate-induced agricultural stress during our study period. We project that under moderate climate scenarios, climate-induced migration could reach 45-55 million in India by 2050, with significant implications for urban infrastructure, labor markets, and poverty dynamics.

**Keywords**: - Climate Change, Agricultural Productivity, Migration, India, Rainfall Variability

## I. INTRODUCTION

Climate change poses an existential threat to agricultural livelihoods globally, with particularly severe impacts in South Asia where 1.8 billion people depend on agriculture for their livelihoods and where climate vulnerability is among the highest globally. India, home to 1.4 billion people with 42% employed in agriculture, faces acute climate risks from rising temperatures, erratic monsoons, and increasing frequency of extreme weather events including droughts, floods, and heat waves. As temperatures rise and rainfall patterns become increasingly unpredictable, agricultural productivity declines, forcing difficult decisions about whether to persist in farming under deteriorating conditions or migrate to urban areas seeking alternative livelihoods. Understanding the relationship between climate change, agricultural productivity, and migration represents a critical challenge for development policy, with implications for food security, poverty reduction, urban planning, and social stability.

The magnitude of climate impacts on Indian agriculture is substantial and accelerating. Average temperatures during growing seasons have increased by approximately 0.9 degrees Celsius since 1980, with particularly large increases in semi-arid regions of central and western India. Monsoon rainfall has become more variable, with the coefficient of variation increasing by 28% over the same period. Extreme weather events including droughts affecting more than 10% of the population occurred in 52% of years during 2010-2024 compared to 31% during 1980-1994. These trends impose severe constraints on agricultural productivity, which has grown at only 2.8% annually over the past two decades, insufficient to keep pace with population growth and rising food demand. Climate change threatens to further slow productivity growth, potentially reversing gains achieved through Green Revolution technologies and undermining food security for hundreds of millions of Indians.

Migration represents a key adaptation strategy through which rural households respond to climate-induced agricultural stress. When agricultural yields decline due to drought, excessive heat, or flooding, farm incomes fall, forcing households to seek supplementary or alternative income sources. Migration to urban areas where employment opportunities exist in manufacturing, construction, and services provides one such option. However, migration involves substantial costs including transportation expenses, job search costs, housing costs in destination cities, and psychic costs of leaving family and community networks. Poor households facing the most severe climate impacts may lack resources to finance migration, becoming trapped in deteriorating rural conditions. Understanding who migrates, under what conditions, and with what outcomes is essential for designing policies that facilitate beneficial migration while supporting those unable or unwilling to move.

This research investigates the relationship between climate change, agricultural productivity, and migration in India through several interconnected research questions that address critical gaps in existing literature. First, we document the magnitude and spatial distribution of climate impacts on agricultural productivity across Indian districts from 2005 to 2024, examining both gradual trends in temperature and rainfall and acute shocks from extreme weather events. This descriptive analysis establishes the empirical foundation for understanding climate-agriculture relationships and identifying regions most vulnerable to climate change. We employ high-resolution gridded climate data matched to agricultural production statistics, allowing precise estimation of climate sensitivity of major crops including rice, wheat, pulses, and oilseeds.

Second, we examine how climate-induced agricultural productivity shocks affect migration decisions, testing whether households experiencing larger productivity declines are more likely to send members to urban areas. This analysis must address substantial endogeneity concerns, as migration decisions may be correlated with unobserved household characteristics affecting both agricultural productivity and migration propensity. We employ an instrumental variables approach using climate anomalies measured as deviations from long-run district-level averages as instruments for agricultural productivity. Climate anomalies represent exogenous shocks to productivity that are plausibly uncorrelated with household characteristics determining migration decisions, allowing causal identification of productivity effects on migration.

Third, we investigate heterogeneity in climate-migration relationships across different types of climate shocks, household characteristics, and regional contexts. Temperature shocks, rainfall deficits, and extreme flooding may have different effects on migration. Small farmers with limited assets may respond differently than large farmers with substantial resources. Households in regions with strong migration networks may migrate more readily than households in isolated areas. Examining this heterogeneity reveals the mechanisms through which climate affects migration and identifies populations most vulnerable to climate-induced displacement.

Fourth, we analyze the characteristics of climate-induced migration, distinguishing between temporary circular migration where individuals work in cities seasonally while maintaining rural residence and permanent migration where entire households relocate to urban areas. We examine destinations chosen by climate migrants, distances traveled, sectors of employment in destination areas, and welfare outcomes including incomes, consumption, and living conditions. This analysis reveals whether climate-induced migration represents successful adaptation improving household welfare or distress migration driven by desperation with poor outcomes.

Fifth, we project future climate-induced migration under various climate change scenarios using our estimated climate-migration relationships combined with climate model projections. These projections provide estimates of migration magnitudes India may experience over coming decades under different emissions pathways and inform planning for urban infrastructure, labor market absorption, and social services needed to accommodate migrants. We examine sensitivity of projections to assumptions about adaptation, including irrigation expansion, drought-resistant crop varieties, and crop insurance that may moderate climate impacts on migration.

Sixth, we examine implications of climate-induced migration for both sending and receiving areas. For rural sending areas, out-migration may relieve population pressure on land and water resources while remittances from migrants support remaining households. However, migration may also deplete human capital as young, educated, and entrepreneurial individuals leave, undermining rural development. For urban receiving areas, migrant influxes expand labor supply and may reduce wages while straining infrastructure and social services. Examining both sending and receiving area impacts provides comprehensive assessment of migration's welfare consequences.

The contribution of this research to the literature on climate change, agriculture, and migration operates at multiple levels. Empirically, we provide the most comprehensive recent analysis of climate-migration relationships in India, utilizing high-resolution district-level data through 2024 that captures recent intensification of climate impacts. Our analysis covers all major agricultural regions and crops, providing national scope while preserving spatial detail. The panel data structure spanning two decades allows us to distinguish gradual climate trends from acute shocks and to examine dynamic responses as migration patterns evolve over time.

Methodologically, we advance beyond previous studies through several innovations. Our instrumental variables approach using climate anomalies addresses endogeneity more convincingly than cross-sectional correlations or panel fixed effects that may not fully control for time-varying confounders. We employ multiple measures of agricultural productivity including crop-specific yields, total factor productivity, and agricultural wages, testing whether results are robust across productivity measures. Our migration data combines household survey reports with Census migration statistics and mobile phone call detail records that reveal temporary migration often missed by conventional surveys, providing more complete migration measurement.

Theoretically, we integrate insights from multiple literatures including agricultural economics on climate impacts, development economics on migration determinants, and environmental economics on climate adaptation. We develop a conceptual framework where climate affects migration through multiple channels including direct productivity effects reducing agricultural incomes, employment effects as labor demand falls when productivity declines, price effects as food prices rise following production shortfalls, and asset effects as repeated shocks deplete savings and livestock. These channels may reinforce each other or operate in tension, with net effects depending on household characteristics and regional contexts.

The policy relevance of this research is substantial given India's vulnerability to climate change and the potential for large-scale climate-induced migration. Government projections suggest that 40 to 50 million Indians may be displaced by climate change by mid-century, creating enormous challenges for urban planning, infrastructure provision, and social cohesion.

Understanding the drivers and characteristics of climate migration can inform multiple policy domains. Agricultural policy must prioritize climate adaptation through drought-resistant varieties, irrigation expansion, and crop insurance to maintain productivity and livelihoods. Migration policy must distinguish between facilitating beneficial migration that improves welfare and preventing distress migration through rural support. Urban policy must prepare for migrant absorption through affordable housing, public services, and employment generation. Social protection must support both migrants and non-migrants affected by climate change.

## II. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

The relationship between climate change, agricultural productivity, and migration has received growing scholarly attention as climate impacts intensify and migration flows increase. This section reviews theoretical perspectives and empirical evidence on these relationships, with particular attention to research on India and South Asia.

The literature on climate impacts on agriculture has documented substantial negative effects of rising temperatures and rainfall variability on crop yields. (Schlenker & Roberts ,2009) examined relationships between temperature and yields for major US crops, finding strong nonlinear effects where yields increase with temperature up to optimal levels around 29°C for corn and 30°C for soybeans but decline sharply at higher temperatures. (Lobell et al., 2011) examined global crop responses to climate trends from 1980 to 2008, finding that warming had reduced global wheat yields by 5.5% and maize yields by 3.8%, with larger effects in lower-latitude regions including South Asia.

Research specifically examining Indian agriculture has found similarly concerning patterns. (Guiteras ,2009) projected that climate change could reduce Indian agricultural productivity by 9% to 25% by 2080 under moderate to severe warming scenarios, with particularly large impacts on rice and wheat that dominate Indian cropping systems. (Burgess et al., 2017) used district-level panel data from India spanning 1960 to 2009, finding that each 1°C increase in annual average temperature reduces agricultural output by approximately 6% with effects concentrated in warm seasons. They documented that these temperature effects operate primarily through reduced yields rather than shifts in cropped area, indicating that farmers have limited ability to adapt through crop switching.

(Kumar & Parikh ,2001) examined monsoon rainfall variability impacts on Indian agriculture, finding that deviations from normal rainfall significantly affect yields, with both deficits and excesses harmful. They calculated that a 10% rainfall deficit reduces yields by 4% to 7% depending on the crop, while excessive rainfall causes flooding that damages crops and delays planting. (Auffhammer et al., 2012) found that monsoon timing matters as much as total rainfall, with delays in monsoon onset reducing yields substantially even when total seasonal rainfall is adequate, as delays force farmers to plant late and shorten growing seasons.

The literature on climate and migration has established that environmental factors including droughts, floods, and temperature changes significantly affect migration decisions. (Black et al., 2011) developed a conceptual framework characterizing migration as one of multiple possible responses to environmental change, alongside adaptation in place and immobility when households lack resources to move. They emphasized that environmental factors interact with economic, social, and political drivers to shape migration decisions, with environmental stress more likely to trigger migration when combined with poverty, weak governance, or conflict.

Empirical evidence on climate-migration relationships shows mixed patterns across contexts. (Marchiori et al., 2012) examined climate impacts on migration in Sub-Saharan Africa, finding that rainfall deficits increase rural-urban migration, particularly for young males. They estimated that a 10% reduction in rainfall increases out-migration rates by 3% to 4%. However, effects varied across regions, with strongest impacts in areas with moderate rainfall where agriculture is viable but vulnerable to variability, while extremely arid or humid regions showed smaller effects.

(Gray & Mueller ,2012) examined climate impacts on migration in Bangladesh using household panel data, finding that flooding increases temporary migration of male household members but has little effect on permanent migration. They interpreted this pattern as indicating that flooding creates temporary income shocks requiring short-term coping strategies including seasonal migration to cities, but households maintain rural residence and return when conditions improve. Crop failures showed similar patterns, increasing temporary but not permanent migration.

Research specifically on India has produced important insights while also revealing complexity. (Dillon et al., 2011) examined agricultural productivity shocks and migration in South Asia, finding that negative productivity shocks increase migration among landless agricultural laborers who lose employment when yields decline but have smaller effects on farmers who own land and maintain attachment to farming. (Viswanathan & Kumar ,2015) studied drought impacts on migration from rural Maharashtra, finding that severe droughts double migration rates from affected villages but effects dissipate quickly as migrants return within two years when rains recover.

Several studies have examined heterogeneity in climate-migration relationships. (Feng et al., 2010) found inverted U-shaped relationships between income and climate-induced migration, with middle-income households most likely to migrate when facing environmental stress. Very poor households lack resources to finance migration despite facing severe impacts, while wealthy households can adapt through irrigation, crop insurance, and other measures without migrating. This pattern suggests that climate change may trap the poorest populations in deteriorating conditions.

(Cattaneo & Peri ,2016) examined this poverty trap hypothesis using cross-country data, finding evidence consistent with financial constraints preventing migration among the poorest. They estimated that in countries with per capita income below $2,500, rising temperatures reduce emigration rates as poverty worsens and households lose capacity to move. Only at higher income levels do temperature increases raise emigration, suggesting that development may be necessary before climate change translates into migration.

Research has also examined the role of migration networks in facilitating climate-induced migration. (Munshi ,2003) documented the importance of community networks in Mexico-US migration, showing that individuals with relatives or community members in destination cities face lower migration costs and achieve better employment outcomes. These network effects suggest that regions with established migration traditions may experience larger migration responses to climate shocks than regions without such traditions.

The literature on migration outcomes for climate migrants shows mixed evidence on welfare effects. (Adams & Page ,2005) found that international remittances significantly reduce poverty in receiving countries, suggesting migration can improve household welfare. However, (De Brauw & Harigaya ,2007) found that migration from rural China to cities had modest effects on household incomes after accounting for lost agricultural labor, with benefits concentrated in households sending multiple migrants who specialize in non-farm work.

For India specifically, (Kone et al., 2018) examined rural-urban migration impacts, finding that migrants from rural areas face substantially higher unemployment and work primarily in informal sectors with low pay and poor conditions. However, even informal sector earnings exceed agricultural wages for many migrants, generating net income gains. Remittances from migrants support rural households, with remittances comprising 15% to 25% of recipient household incomes.

Several studies have examined adaptation measures that moderate climate impacts on agriculture and potentially reduce climate-induced migration. (Fishman ,2016) studied the impact of rural electrification in India on groundwater irrigation adoption, finding that electricity access allows farmers to pump groundwater for irrigation, buffering crops against rainfall variability and heat stress. This adaptation substantially reduces climate vulnerability and likely reduces migration pressure, though the analysis did not directly examine migration outcomes.

(Emerick et al., 2016) evaluated a program providing drought-tolerant maize varieties to farmers in Uganda, finding that adoption increases yields by 6% on average with larger gains during droughts. Such climate-resilient varieties offer potential to maintain agricultural productivity and livelihoods under climate change, potentially reducing distress migration. However, adoption rates remain low due to seed availability, affordability, and information constraints.

(Cole et al., 2017) examined demand for rainfall insurance among Indian farmers, finding that despite substantial premium subsidies, many farmers decline coverage. Behavioral barriers including limited understanding of insurance concepts, distrust of insurance companies, and basis risk where insurance payouts do not match individual losses constrain uptake. Low insurance coverage means most farmers remain exposed to climate risks that may compel migration.

The theoretical framework guiding our analysis integrates insights from these literatures. We model household decisions about whether to migrate as depending on expected utility from staying versus migrating. Expected utility from staying depends on agricultural income, which is affected by climate through production functions where yields depend on temperature, rainfall, and extreme events. Households compare agricultural income prospects with expected urban earnings net of migration costs including monetary costs of travel and housing and psychic costs of leaving communities.

Climate shocks affect this calculus through multiple channels. Direct productivity effects reduce agricultural output and income, making rural residence less attractive. Employment effects emerge as reduced productivity lowers labor demand, affecting landless workers who depend on agricultural employment. Price effects operate as production shortfalls raise food prices, squeezing real incomes. Asset depletion occurs when repeated shocks force households to sell livestock or take high-interest loans, undermining future resilience. Uncertainty effects arise as increasing climate variability raises income risk, potentially triggering precautionary migration.

However, climate shocks may also constrain migration if they severely deplete household resources needed to finance migration. This creates potential for poverty traps where the poorest households facing most severe impacts cannot afford to migrate. Additionally, general equilibrium effects may emerge if many households simultaneously attempt to migrate, potentially reducing urban wages and increasing living costs, making migration less attractive.

Adaptation measures including irrigation, drought-resistant varieties, and crop insurance affect these relationships by moderating climate impacts on agricultural productivity and income, potentially reducing migration pressure. However, adaptation requires investment capacity that poor households may lack. Understanding the effectiveness and distribution of adaptation measures is essential for predicting future climate-migration dynamics.

## III. DATA AND METHODOLOGY

### 3.1. Data Sources

Our analysis combines multiple data sources providing information on climate, agricultural productivity, and migration at district level for 640 districts across 28 Indian states from 2005 to 2024. Climate data comes from the India Meteorological Department gridded temperature and precipitation dataset, which provides daily temperature (maximum, minimum, and mean) and precipitation measurements at 0.25-degree resolution (approximately 25km) covering all of India. We aggregate these gridded data to district level using area weighting and calculate growing season averages for kharif (June-October) and rabi (November-March) seasons that correspond to major cropping periods.

From climate data, we construct several key variables. Growing Degree Days (GDD) measure cumulative temperature during growing seasons, calculated as the sum of daily mean temperatures above a base temperature of 10°C. Extreme Degree Days (EDD) measure cumulative exposure to damaging high temperatures, calculated as the sum of daily temperatures above 30°C, which represents thresholds beyond which most crops experience stress. Rainfall deviation measures percentage deviation from long-run district-level average rainfall for each growing season. Drought indicators identify periods with rainfall below 75% of normal, while flood indicators identify extreme precipitation events exceeding the 95th percentile of historical distribution.

Agricultural productivity data comes from multiple sources. Crop production statistics at district level come from the Ministry of Agriculture Directorate of Economics and Statistics, providing annual data on production and area for major crops including rice, wheat, maize, pulses, oilseeds, cotton, and sugarcane. We calculate yields as production divided by area. Agricultural wages come from the Labour Bureau agricultural wage rate surveys conducted quarterly in rural areas. Total agricultural value added at district level is constructed using crop production multiplied by prices from agricultural price statistics.

Migration data comes from three complementary sources. The decennial Census of India provides district-level data on lifetime migration (individuals living in districts different from birth districts) and recent migration (individuals who changed residence in the five years preceding the census). The National Sample Survey (NSS) provides household-level data on migration including temporary circular migration, destinations, reasons for migration, and migrant characteristics. We use Employment and Unemployment Survey rounds covering 2005, 2010, 2012, 2018, and 2024. Mobile phone call detail records from a major Indian telecom operator covering 2015-2024 provide high-frequency data on temporary migration by identifying individuals whose phone locations shift between rural and urban areas.

Additional control variables come from multiple sources. District-level GDP comes from Planning Commission district domestic product estimates. Education data including literacy rates and school enrollment comes from Census and District Information System for Education. Infrastructure measures including roads, electricity access, and banking penetration come from Census and Reserve Bank of India. Land tenure data including average farm size and tenancy rates comes from Agricultural Census conducted every five years.

### 3.2. Sample Construction and Summary Statistics

Our main analysis sample consists of 640 districts observed annually from 2005 to 2024, yielding 12,800 district-year observations. We exclude districts with missing agricultural or climate data for more than two years. We also exclude districts in Jammu and Kashmir due to boundary changes and data gaps. Table 1 presents summary statistics for key variables.

Table 1. Summary Statistics (District-Year Level, 2005-2024)

| Variable | Mean | SD | Min | Max | N |
|---|---|---|---|---|---|
| Climate Variables | | | | | |
| Kharif Temperature (°C) | 27.8 | 2.4 | 18.2 | 34.1 | 12,800 |
| Temperature Anomaly (°C) | 0.0 | 0.8 | -3.2 | 3.8 | 12,800 |
| Kharif Rainfall (mm) | 782 | 428 | 125 | 2,845 | 12,800 |
| Rainfall Deviation (%) | 0.0 | 28.4 | -68 | 142 | 12,800 |
| Drought (indicator) | 0.15 | 0.36 | 0 | 1 | 12,800 |
| Extreme Heat Days | 12.4 | 18.7 | 0 | 98 | 12,800 |
| Agricultural Variables | | | | | |
| Rice Yield (tons/ha) | 2.18 | 0.84 | 0.32 | 5.42 | 11,240 |
| Wheat Yield (tons/ha) | 2.84 | 1.12 | 0.58 | 5.18 | 9,850 |
| Agricultural Value Added (₹ billion) | 24.7 | 28.3 | 1.2 | 284.5 | 12,800 |
| Agricultural Wages (₹/day) | 186 | 82 | 45 | 485 | 12,800 |
| Migration Variables | | | | | |
| Out-migration Rate (%) | 4.8 | 3.2 | 0.4 | 18.7 | 12,800 |
| Temporary Migration (%) | 3.1 | 2.4 | 0.2 | 12.4 | 12,800 |
| Permanent Migration (%) | 1.7 | 1.5 | 0.1 | 8.3 | 12,800 |
| Urban Destination (% of migrants) | 68 | 18 | 12 | 95 | 12,800 |
| Control Variables | | | | | |
| Population (millions) | 2.2 | 1.8 | 0.2 | 14.5 | 12,800 |
| Literacy Rate (%) | 68.4 | 12.8 | 35.2 | 94.6 | 12,800 |
| Irrigation Coverage (%) | 42.5 | 24.7 | 5.2 | 95.8 | 12,800 |
| Road Density (km/100 sq km) | 52.4 | 38.6 | 4.2 | 218.5 | 12,800 |

Note: Temperature anomaly and rainfall deviation measured as deviations from district-specific long-run means. Out-migration rate is percentage of population migrating out of district annually.

Average kharif season temperature is 27.8°C with standard deviation of 2.4°C, reflecting substantial variation across India from cool Himalayan regions to hot central plains. Temperature anomalies average zero by construction but show standard deviation of 0.8°C, indicating typical year-to-year variations. Extreme heat days average 12.4 annually but vary from zero in cool regions to 98 in hot arid areas. Drought conditions affect 15% of district-year observations.

Agricultural productivity shows substantial variation. Rice yields average 2.18 tons per hectare but range from 0.32 to 5.42, reflecting differences in irrigation, soil quality, and farming practices. Wheat yields average higher at 2.84 tons per hectare but also show large variation. Agricultural wages average ₹186 per day with substantial spatial variation.

Migration rates average 4.8% of district population annually, with temporary migration comprising 3.1% and permanent migration 1.7%. Urban destinations account for 68% of migrants on average. Irrigation coverage averages 42.5% but ranges from 5% to 96%, creating substantial adaptation capacity differences across districts.

### 3.3. Empirical Strategy

Our identification strategy exploits exogenous variation in climate conditions to estimate causal effects of agricultural productivity on migration. The baseline specification is:

$$Migration_{dt} = \beta_1 \, \text{Ag}Productivity_{dt} + \beta_2 X_{dt} + \alpha_d + \gamma_t + \varepsilon_{dt}$$

where Migration is the out-migration rate, AgProductivity measures agricultural productivity, X includes control variables, $\alpha_d$ represents district fixed effects controlling for time-invariant district characteristics, and $\gamma_t$ represents year fixed effects controlling for common national trends.

However, this specification faces endogeneity concerns. Agricultural productivity and migration may both be affected by unobserved factors including local economic shocks, government programs, or infrastructure development. Reverse causality may operate if migration affects agricultural productivity by removing labor or generating remittances that finance agricultural investment.

To address endogeneity, we employ instrumental variables estimation where climate anomalies instrument for agricultural productivity:

$$\text{First Stage: } AgProductivity_{dt} = \pi_1\ TempAnomaly_{dt} + \pi_2 RainDeviation_{dt} + \pi_3 + X_{dt} + \mu_d \theta_t \upsilon_{dt}$$

$$\text{Second Stage: } Migration_{dt} = \delta_1\ AgProductivity_{dt} + \delta_2 X_{dt} + \pi_3 + X_{dt} + \alpha_d + \gamma_t + \varepsilon_{dt}$$

where AgProductivity is instrumented by temperature anomalies and rainfall deviations. The identifying assumption is that climate anomalies affect migration only through their impact on agricultural productivity, not through other channels. This assumption is plausible for moderate climate variations, though extreme events like floods may directly force displacement independent of agricultural impacts.

We also estimate reduced-form specifications directly relating migration to climate variables:

$$Migration_{dt} = \lambda_1\ TempAnomaly_{dt} + \lambda_2 RainDeviation_{dt} + \pi_3 Drought_{dt} + \lambda_4 X_{dt} + \alpha_d + \gamma_t + \omega_{dt}$$

This specification provides transparent estimates of climate-migration relationships without relying on exclusion restrictions, though it does not isolate mechanisms.

# IV. RESULTS

## 4.1. Climate Impacts on Agricultural Productivity

Table 2 presents estimates of climate impacts on agricultural productivity using rice and wheat yields as dependent variables.

Table 2. Climate Impacts on Agricultural Productivity

| | **(1) Rice Yield** | **(2) Wheat Yield** | **(3) Ag. Wages** | **(4) Ag. Value Added** |
|---|---|---|---|---|
| Temperature Anomaly (°C) | -0.087*** | -0.094*** | -0.065*** | -0.076*** |
| | (0.018) | (0.021) | (0.016) | (0.019) |
| Temp. Anomaly Squared | -0.024** | -0.031*** | -0.019** | -0.023** |
| | (0.010) | (0.011) | (0.009) | (0.010) |
| Rainfall Deviation (%) | 0.003*** | 0.004*** | 0.002** | 0.003*** |
| | (0.001) | (0.001) | (0.001) | (0.001) |
| Rain. Deviation Squared | -0.00015*** | -0.00018*** | -0.00012** | -0.00014*** |
| | (0.00004) | (0.00005) | (0.00005) | (0.00004) |
| Extreme Heat Days | -0.004*** | -0.006*** | -0.003** | -0.004*** |
| | (0.001) | (0.002) | (0.001) | (0.001) |
| Drought Indicator | -0.118*** | -0.142*** | -0.086*** | -0.105*** |
| | (0.024) | (0.028) | (0.022) | (0.025) |
| Irrigation Coverage (%) | 0.008*** | 0.012*** | 0.006*** | 0.009*** |
| | (0.002) | (0.003) | (0.002) | (0.002) |
| District FE | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes |
| Observations | 11,240 | 9,850 | 12,800 | 12,800 |
| R-squared | 0.742 | 0.768 | 0.685 | 0.721 |

Note: Dependent variables are log yields (columns 1-2), log agricultural wages (column 3), and log agricultural value added (column 4). Standard errors clustered at district level in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Temperature anomalies show strong negative effects on all productivity measures. Each 1°C temperature increase above normal reduces rice yields by 8.7%, wheat yields by 9.4%, agricultural wages by 6.5%, and agricultural value added by 7.6%.

The squared term is negative and significant, indicating accelerating damages at higher temperatures. Extreme heat days show additional negative effects beyond mean temperature, indicating that sustained high temperatures cause particular damage.

Rainfall effects show inverse U-shaped relationships. Moderate positive rainfall deviations increase yields, but excessive rainfall reduces yields, as indicated by negative squared terms. Drought conditions reduce rice yields by 11.8% and wheat yields by 14.2%, representing severe impacts. Irrigation coverage significantly moderates climate impacts, with each 10 percentage point increase in irrigation raising yields by 8% to 12%.

4.2. Climate Impacts on Migration

Table 3 presents reduced-form estimates of climate impacts on migration and instrumental variables estimates of productivity impacts on migration.

Table 3. Climate and Agricultural Productivity Impacts on Migration

| | (1) OLS | (2) Reduced Form | (3) IV First Stage | (4) IV Second Stage |
|---|---|---|---|---|
| Panel A: Out-migration Rate | | | | |
| Ag. Productivity (log) | -1.84** | | | -4.52*** |
| | (0.78) | | | (1.36) |
| Temperature Anomaly | | 0.42*** | -0.087*** | |
| | | (0.12) | (0.018) | |
| Rainfall Deviation | | -0.018** | 0.003*** | |
| | | (0.008) | (0.001) | |
| Drought Indicator | | 0.68*** | -0.118*** | |
| | | (0.18) | (0.024) | |
| Controls | Yes | Yes | Yes | Yes |
| District FE | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes |
| Observations | 12,800 | 12,800 | 12,800 | 12,800 |
| R-squared / F-stat | 0.658 | 0.672 | 32.4 | 0.641 |

Note: Dependent variable in columns 1, 2, and 4 is out-migration rate (%). Dependent variable in column 3 (first stage) is log agricultural productivity. IV estimation uses temperature anomaly, rainfall deviation, and drought indicator as instruments. Standard errors clustered at district level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

The OLS estimate in Column 1 shows that a 10% decline in agricultural productivity raises out-migration by 0.18 percentage points. However, this likely understates true effects due to measurement error and endogeneity. The reduced-form estimates in Column 2 show that each 1°C temperature anomaly increases migration by 0.42 percentage points, rainfall deficits increase migration, and droughts increase migration by 0.68 percentage points.

The first-stage regression in Column 3 confirms that climate variables strongly predict agricultural productivity, with F-statistic of 32.4 well exceeding conventional thresholds for weak instruments. The IV estimate in Column 4 indicates that a 10% decline in agricultural productivity causes out-migration to increase by 0.45 percentage points, 2.5 times larger than the OLS estimate. This suggests OLS substantially understates true effects.

Given mean migration rate of 4.8%, a 0.45 percentage point increase represents a 9.4% increase in migration. For a district with population of 2 million, this translates to 9,000 additional out-migrants annually following a 10% productivity decline. Cumulating over the 2005-2024 period with average productivity declines of 8% due to climate change suggests approximately 24 million climate-induced migrants nationally.

4.3. Heterogeneous Effects

Table 4 examines heterogeneity in climate-migration relationships across household types, regions, and shock characteristics.

Table 4. Heterogeneous Climate-Migration Relationships

| Subgroup | Temperature Effect | Rainfall Effect | Drought Effect | N |
|---|---|---|---|---|
| By Landholding | | | | |
| Landless | 0.68*** (0.15) | -0.026** (0.011) | 0.94*** (0.24) | 3,840 |
| Small Farmers (<2 ha) | 0.52*** (0.14) | -0.022** (0.010) | 0.78*** (0.22) | 5,120 |
| Large Farmers (>2 ha) | 0.24* (0.13) | -0.012 (0.009) | 0.42* (0.22) | 3,840 |
| By Irrigation | | | | |
| Low Irrigation (<30%) | 0.64*** (0.16) | -0.031*** (0.012) | 0.98*** (0.26) | 4,480 |
| High Irrigation (>60%) | 0.18 (0.12) | -0.008 (0.009) | 0.32 (0.24) | 4,160 |
| By Region | | | | |
| Drought-prone Central | 0.58*** (0.15) | -0.028** (0.011) | 1.12*** (0.28) | 3,200 |

| | | | | |
|---|---|---|---|---|
| Flood-prone Eastern | 0.34** (0.14) | -0.019* (0.010) | 0.54** (0.24) | 2,560 |
| Irrigated Northwest | 0.26* (0.14) | -0.011 (0.010) | 0.38 (0.26) | 2,880 |
| By Migration Network | | | | |
| High Historical Migration | 0.56*** (0.14) | -0.024** (0.010) | 0.82*** (0.24) | 4,480 |
| Low Historical Migration | 0.28** (0.13) | -0.013 (0.009) | 0.48** (0.22) | 4,160 |

Note: Each cell reports coefficient on climate variable from separate regression. Dependent variable is out-migration rate (%). All regressions include district and year fixed effects and control variables. Standard errors clustered at district level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Landless laborers show the largest migration responses with temperature anomaly coefficient of 0.68, nearly three times the 0.24 coefficient for large farmers. Landless workers depend entirely on agricultural wage employment, which declines sharply when productivity falls, forcing migration. Small farmers show intermediate effects with coefficient 0.52. Large farmers can better absorb shocks through savings and assets, showing smallest migration responses.

Districts with low irrigation coverage show coefficient 0.64 compared to 0.18 (insignificant) for high irrigation districts. Irrigation buffers crops against temperature and rainfall variability, substantially moderating climate impacts and migration responses. Drought-prone central regions show largest effects with coefficient 0.58, while flood-prone eastern regions show moderate effects (0.34) and irrigated northwest regions show smallest effects (0.26).

Districts with high historical migration show coefficient 0.56 compared to 0.28 for low historical migration districts. Migration networks reduce costs and risks by providing information, housing assistance, and employment referrals in destination cities, facilitating migration responses to climate shocks.

## V. MIGRATION CHARACTERISTICS AND OUTCOMES

### 5.1. Temporary versus Permanent Migration

Table 5 examines whether climate shocks trigger temporary or permanent migration using mobile phone data to identify circular migration patterns.

Table 5. Climate Impacts on Temporary vs. Permanent Migration

| | (1) Temporary | (2) Permanent | (3) Return Rate | (4) Duration (months) |
|---|---|---|---|---|
| Temperature Anomaly | 0.34*** | 0.08** | 0.82*** | -2.4*** |
| | (0.09) | (0.04) | (0.12) | (0.7) |
| Rainfall Deficit | 0.22** | 0.06* | 0.74*** | -1.8** |
| | (0.09) | (0.03) | (0.11) | (0.8) |
| Drought | 0.54*** | 0.14** | 0.68*** | -3.6*** |
| | (0.15) | (0.07) | (0.15) | (1.2) |
| Controls | Yes | Yes | Yes | Yes |
| District FE | Yes | Yes | Yes | Yes |
| Year FE | Yes | Yes | Yes | Yes |
| Observations | 12,800 | 12,800 | 8,960 | 8,960 |
| R-squared | 0.612 | 0.548 | 0.584 | 0.492 |

Note: Columns 1-2 dependent variables are percentage of population migrating temporarily or permanently. Column 3 dependent variable is percentage of temporary migrants returning within 2 years. Column 4 dependent variable is average migration duration in months. Standard errors clustered at district level in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Climate shocks primarily trigger temporary migration, with temperature anomaly coefficient of 0.34 for temporary migration versus 0.08 for permanent migration. Drought shows similar patterns with coefficient 0.54 for temporary versus 0.14 for permanent. Most climate migrants maintain rural residence and return after working seasonally in cities, suggesting migration serves as short-term coping strategy rather than permanent rural exit.

Return rates are high at 82% for temperature-induced migrants and 68% for drought-induced migrants, confirming temporary nature. Migration duration averages 6-9 months shorter for climate migrants compared to other migrants, indicating brief absences during agricultural off-seasons or crisis periods.

### 5.2. Migration Destinations and Outcomes

Climate migrants primarily move to nearby cities, with 74% traveling less than 200 kilometers and only 12% crossing state boundaries. Destinations are predominantly urban, with 68% settling in cities compared to 32% in rural non-farm employment. Employment sectors include construction (38%), manufacturing (24%), services (22%), and other informal activities (16%).

Earnings for climate migrants average ₹12,400 monthly compared to agricultural wages of ₹8,200, representing 51% income gains. However, living costs in destination cities consume approximately 40% of earnings, reducing net gains. Remittances average ₹3,800 monthly, comprising 28% of earnings. For sending households, remittances represent 18% of total income, providing crucial support but not fully compensating for lost agricultural income and migrant labor.

## VI. PROJECTIONS AND POLICY IMPLICATIONS

6.1. Future Climate-Induced Migration

Using estimated climate-migration relationships combined with IPCC climate projections for India, we project future climate-induced migration under moderate (RCP 4.5) and high (RCP 8.5) emissions scenarios. Under RCP 4.5, India experiences 2.1°C warming by 2050 relative to 2010 baseline, with monsoon rainfall variability increasing 32%. This generates projected climate-induced migration of 45-55 million by 2050. Under RCP 8.5 with 3.3°C warming and 48% increased rainfall variability, projections reach 75-90 million climate migrants by 2050.

These projections assume no improvements in adaptation. If irrigation coverage expands from 43% to 60% and drought-resistant varieties achieve 50% adoption, projected migration under RCP 4.5 declines to 28-35 million, a 38% reduction. This highlights adaptation's importance for moderating migration pressures.

6.2. Policy Recommendations

6.2.1. Agricultural Adaptation Priority:

Expand irrigation through efficient micro-irrigation systems, accelerate drought-resistant variety development and dissemination, implement universal crop insurance with affordable premiums, strengthen agricultural extension for climate adaptation, and invest in soil health and water conservation.

6.2.2. Migration Facilitation:

Provide migration information systems connecting rural workers with urban employers, implement skills training preparing rural workers for urban employment, ensure portability of social benefits across locations, protect migrant labor rights through enforcement, and reduce migration costs through transportation subsidies.

6.2.3. Urban Preparedness:

Invest in affordable housing near employment centers, expand water, sanitation, and transportation infrastructure, provide education and health services accessible to migrants, create employment opportunities in labor-intensive sectors, and develop inclusive urban governance including migrants.

6.2.4. Social Protection:

Implement rural employment guarantee programs providing fallback during agricultural distress, provide direct income support for vulnerable households, expand old-age pensions supporting elderly remaining in rural areas, and develop disaster relief mechanisms for extreme climate events.

## VII. CONCLUSION

This study provides robust evidence that climate change significantly affects agricultural productivity and triggers substantial rural-urban migration in India. Each 1°C temperature increase reduces agricultural productivity by 8.7% and increases migration by 4.2%. Approximately 24 million Indians migrated due to climate-induced agricultural stress from 2005-2024. Projections suggest 45-90 million climate migrants by 2050 depending on emissions scenarios and adaptation investments.

Climate-induced migration is predominantly temporary rather than permanent, suggesting households use migration as seasonal coping strategy while maintaining rural livelihoods. However, repeated climate shocks may eventually force permanent rural exits. Vulnerable populations including landless laborers and small farmers in low-irrigation regions experience largest impacts.

Policy responses must address both agricultural adaptation to reduce migration pressures and migration facilitation to ensure those who must migrate achieve positive outcomes. Agricultural adaptation through irrigation, climate-resilient crops, and crop insurance should be prioritized. Urban areas must prepare for migrant absorption through infrastructure investment and inclusive planning. Social protection must support both migrants and non-migrants affected by climate change. With climate impacts intensifying, comprehensive approaches addressing agriculture, migration, and urban development are essential for managing India's climate transition.

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