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Changing Rainfall Patterns and Their Impact on Agricultural Sustainability: A Geographical Analysis of Indian Agricultural Regions

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Abstract

Changing rainfall patterns are a significant geographical concern for agricultural sustainability due to the strong inter-linkages of the timing, amount and spatial distribution of monsoon rainfall with crop calendars, soil-water availability, groundwater recharge, rainfed productivity and rural livelihood stability in India. The present paper analyzes the impact of recent variability of rainfall on agricultural sustainability in India. The present paper has adopted a secondary-data, quantitative, longitudinal and spatially orientation research design. Evidence of rainfall has been taken from the India Meteorological Department (IMD) daily gridded rainfall data system and its official monsoon statements while agricultural data have been sourced from Agricultural Statistics at a Glance 2024. The present analysis uses regional southwest monsoon rainfall departures for 2020 to 2024; official all-India land-use and irrigation series for 2000-01 to 2022-23 and food grain yield series for 2005-06 to 2024-25. There are many statistical techniques such as descriptive statistics, coefficient of variation, rainfall-departure diagnostics, Mann-Kendall trend test, Sen's slope estimator, correlation, and simple regression modelling. A constructed Agricultural Sustainability Index (ASI) composite of foodgrain yield, cropping intensity, irrigation coverage, gross irrigation intensity and yield-stability indicators. The findings indicate that between 2020 and 2024, East and Northeast India experienced deficit in the southwest monsoon rainfall for four out of the five years. In contrast, Central India and South Peninsula received surplus rainfall more often. Statistical tests conducted on agricultural indicators reveal a significant increase in total foodgrain yield, cropping intensity, net irrigation ratio and gross irrigation ratio.

Nonetheless, the findings also indicate that the stability of national production is becoming increasingly reliant on irrigation expansion and technical buffers rather than rainfall. The analysis underlines that climate-resilient agricultural planning must graduate from all-India average annual rainfall to harnessing district-level rainfall variability. In addition, rainfall buffer at the irrigation command area level, sensitivity of major crops to vagaries of rainfall, estimate of the area affected by droughts and GIS-based vulnerability mapping must be used for effective agricultural adaptation policy.

Keywords: Rainfall variability; agricultural sustainability; climate change; spatial analysis; India; foodgrain yield; GIS; rainfall anomaly; drought vulnerability.

1. Introduction

Rainfall is one of the most important geographical determinants of agricultural sustainability in monsoon Asia. In India, the importance of rainwater conservation is accentuated by the seasonality of southwest monsoon, the spatial unevenness of rainfall in the agro climatic zones, and the continued dependence of huge parts of agriculture on in-season rainfall. The question is not limited to whether or not annual rainfall is on the rise. Similarly, change in withdrawal, rainy-day distribution, dry-spell concentration, heavy-rain concentration, sub-seasonal break, and change from long-period average are other important aspects. These traits affect sowing decisions, crop-water stress, pest incidence, soil erosion, groundwater recharge, harvest dependability and the capacity of farming systems to stay productive without degradation of ecological resources (IPCC, 2022a; IPCC, 2022b).

The monsoon geography of India is heterogeneous. The same all-India seasonal rainfall number can mask surplus rainfall in Central India, deficits in East and Northeast India, late-season excess in peninsular India, or spatially concentrated excessive fall in the dry zone. The IMD high-resolution daily gridded rainfall product enables us to examine these differences at finer spatial scales; this dataset comes in a 0.25-degree resolution and provides daily rainfall values over India from 1901 to 2024 (India Meteorological Department [IMD], n.d.). Recent IMD annual forecasts display that the 2024 southwest monsoon was above normal at the all-India scale but it has varied substantially at regional levels (IMD, 2025a). The variation is crucial to geographical assessment since risk involved in farming is created through location-specific combinations of exposure to climate, irrigation, cropping pattern, soil, infrastructure and access to the market.

The soil usage system and livelihood of community are agriculture. Assessment of agricultural sustainability merely on production and yield reflects myopic vision. Besides production and yield stability, cropping intensity, irrigation dependence and diversification including cropping pattern, vegetation health impact, water stress situation and vulnerability against weather extremes are equally important to assess the sustainability of agriculture. Irrigation can keep a region's output high but that output may still be unsustainable if groundwater over-extraction or rainfall unreliability or monocropping raises long-term ecological risk. In contrast, if rainfall variability and dry spells, together with heavy rainfall events lead to an

increase, then a rainfed region may be moderately productive but highly vulnerable. According to this study agricultural sustainability is a composite geographical outcome influenced by rainfall, land use, irrigation and crop yield.

Climate-related hazards, such as changing rainfall, drought, flooding, and extreme events are expected to escalate with warmer and with the IPCC (2022b), further, climate risks to agriculture in Asia will also intensify. Recent Studies Focusing on India Find that Variability of Rainfall Affects Crop Production, Intensity of Land Use, the Dynamics of Drought and Resilience of Agriculture in Region-Specific Manner (Chakraborty et al, 2025; Jena, 2025; Nathawat et al, 2025). A tehsil-level assessment conducted by Prabhu and Chitale (2024) also indicates that India is not uniformly experiencing any change in rainfall. While dry regions are getting more rains, agriculturally significant areas like the Indo-Gangetic plain, North East India and the Himalayas are seeing declining or erratic rains during key monsoon months. The need for integrated research involving rainfall variability, agriculture indicators and spatial analysis is shown by the findings.

Research problems in the paper Rainfall and agriculture are discussed over and over again on the basis of broad annual averages or general climate-risk statements without integrating other essential aspects such as rainfall departures, land-use change, irrigation expansion, crop yield trend, spatial vulnerability etc. This creates a gap in geographical scholarship and a gap in agricultural planning methods. Rainfall surpluses at the national scale can produce local crop damage if they occur in heavy, concentrated events. Yield growth at the national scale can mask our increasing dependence on irrigation and other input-intensive buffers. Accordingly, the central issue that arises is how changing rainfall patterns interact with agricultural sustainability indicators across Indian agricultural regions and what does it imply for climate-resilient planning.

The study has the following objectives: First, to examine changes in annual and seasonal rainfall over a period of time in different agricultural regions of India. Second, to analyse the variability in rainfall, rainfall anomaly, frequency of deficit, and regional departure from long period average of rainfall. Third, to study the relationship of variability of rainfall with crop yield stability, cropping intensity and irrigation dependency as sustainability indicators. Fourth, to map and classify rainfall stressed regions in a spatial orientation. Finally, to recommend climate resilient planning for agriculture. The hypotheses behind the study are rise in rainfall variability in select regions, greater rainfall variability will lead to lower yield stability, lower irrigation cover will increase rainfall vulnerability and the presence of spatial clustering in rainfall stressed and agriculturally vulnerable regions.

The value of the Study is based on Climatological, Agricultural and Geological Evidence. This paper considers rainfall not as a singular meteorological variable but as an environmental driver that is unevenly spread out in space and interacts with land-use intensity, irrigation coverage and productivity. The research further provides a repeatable methodological framework for analysts interested in extending the assessment from national and homogeneous-region level to district or tehsil-level GIS modeling using IMD Net CDF rainfall data, district level crop statistics, MODIS NDVI and spatial econometric tools.

2. Review of Literature

2.1 Climate Change and Rainfall Variability

Climate change changed the risk context in which rainfed agriculture operates. According to IPCC (2022a), climate risk is a function of hazards, exposure, vulnerability and adaptive capacity, which is reflected in the key climatic impact drivers (CIDs) on food, water and ecosystem services. In agricultural geography, any variability in the rainfall pattern is not a meteorological issue only. It is involved with land-use planning, rural vulnerability, environmental degradation and development planning. Seasonal rainfall variability in monsoon areas affect the distribution of agricultural risk directly because of well-timed rainfall plants are embedded in calendars at sowing, vegetative, flowering, and grain-filling periods.

The variations in rainfall have relevance in multiple ways. Inter-annual variability alters water availability from year to year. Fluctuaciones de la temporadainfluyenen la siembra de loscultivos y épocas de sequía. The spatial variability causes deficit or surplus rainfall in same season over districts. Alterations in the nature of extreme events will modify the incidence of heavy rainfall days which may affect run-off, erosion, waterlogging, flash floods, cropping lodging. These processes may co-exist. This may happen when a region receives normal seasonal rainfall but also receives damaging dry spells and heavy rainfall. Therefore, climate-sensitive agricultural research should measure both mean rainfall and distributional characteristics.

2.2 Variance in Indian monsoon and agricultural risk.

The southwest monsoon in India is a temporally variable but spatially organised circulation system providing seasonal rainfall causing floods in large parts of the country. Seasonal Rainfall Could Vary a Lot between Years and across Homogenous Regions: IMD Monsoon Report The recent period from 2020 to 2024 has witnessed over-normal all-India monsoon years as well as a below-normal year in 2023, when the rainfall in August was particularly weak in the seasonal distribution (IMD, 2020, 2021, 2022, 2023, 2024). The variations are important for agriculture as the timing of rabi is dependent on monsoon to an extent while the prospects of kharif depends on soil moisture, reservoir storage and groundwater recharge happening due to the monsoon.

Findings from a recent study suggest that rainfall changes differ geographically within the sub-district. Many tehsils since 2012-2022 have experienced an increase in southwest monsoon rainfall. Tehsils with reduced rainfall were concentrated in rainfed portions of the Indo-Gangetic plains, northeast India, and the Himalayan region (Prabhu and Chitale, 2024). The study mentions that many tehsils have heavy rainfall events increased. High rainfall is not necessarily a boon for agricultural endeavors; hence, the importance. When rainfall events are short-lived and heavy, the efficiency of soil-water benefit may be less than the total seasonal benefit indicates, especially in landscapes prone to poor drainage and erosion.

2.3 Rainfall Extremes, Droughts, Floods and Crop Yields

The risks of drought and flood are the two sides of the instability of rainfall. The lack of rainfall is reducing the area to be sown, soil moisture, inflow of reservoirs and yield potential of rainfed crops. Heavy rainfall, when concentrated at a time, may damage any standing crop, postpone field operations, increase pest pressure, and post-harvest losses. The impact of agriculture depends on the timing and distribution of rain and not just its amount. Studies at the regional levels confirm that rainfall variability and drought indices are linked with crops. Chakraborty et al. (2025) analyzed IMD and CHIRPS rainfall data with agricultural data for Bankura district, which found that indices like SPI and seasonality index as well as SPI and rainfall ratio are relevant in interpreting crop-production pattern. Jena (2025) in Odisha utilized a panel autoregressive distributed lag model and discovered that the deviation of rainfall exerted negative long-term impacts on different crop yields, implying that weather variations have implications for yield and land use.

Remote sensing research has improved drought and crop-monitoring capacity through the ability to measure vegetation condition, land-surface temperature, and precipitation related stress at high spatial and temporal resolutions. Using Google Earth Engine, MODIS, and CHIRPS, Nathawat et al. (2025) constructed a Standardized Drought Composite Index for Rajasthan and observed severe drought condition on various years between 2010 and 2022. NASA offers various MODIS vegetation index products. NDVI and EVI monthly, 16 days data are available. They can be analysed for vegetation stress during crop seasons (NASA Earthdata, 2021). This proves that rainfall analysis needs to be linked with vegetation health and exposure to droughts rather than it being analysed as a climate variable.

2.4 Sustainability Challenges in Rainfed Agriculture

Rainfed agriculture is particularly vulnerable to rainfall variability due to its production system limited capacity to buffer dry spells or seasonal deficits. Through various methods including irrigation benefit, crop choice, soil and water retention, watershed management, weather based crop insurance market support and advisories access, the impact of change in rainfall is moderated. A region with good irrigation infrastructure can maintain yields during a weak monsoon. A rainfed region that receives the same volume of rainfall deficiency will suffer area diversion, crop loss or a drop in household income. As a result, agricultural sustainability in India should be evaluated based on exposure and adaptive capacity.

Statistics at a Glance 2024 on Agriculture reveals that the net irrigated area and gross irrigated area of India have increased during the present century with net sown area remaining almost stable (Directorate of Economics, Statistics and Evaluation [ESE], 2025). This shows that, increasingly, output growth will depend on multiple cropping and irrigation coverage, not on the expansion of net cultivated area. This shift is a double-edged sword from sustainability standpoint. While irrigation reduces vulnerability to short-term rainfall, it can create new regional inequalities due to ground-water depletion and unequal access to irrigation.

2.5 GIS and Remote Sensing in climate-agriculture studies

The rainfall risk appears to be spatially clustered so a mere administrative average will tend to camouflage the ground reality. Vulnerability maps may be created by joining IMD gridded rainfall, CHIRPS precipitation estimates, MODIS NDVI/EVI, ESA World Cover, Bhuvan land-use products and district crop statistics to district or tehsil boundaries. GIS facilitates the identification of clusters at risk of drought, hotspots experiencing heavy rainfall, areas with low irrigation expansion, zones of varying crop yields, and rainfall departure zones that intersect with socio-economic vulnerability. MODIS vegetation indices that are generated every 16 days at relatively high spatial resolutions are highly relevant for crop-season monitoring (NASA Earth data, 2021).

Spatial statistics further strengthen this work through testing whether vulnerable districts are randomly-dispersed or spatially-clustered. Moran's I is a tool that quantifies global spatial autocorrelation. Also, the Local Indicators of Spatial Association (LISA) highlight high-high, low-low, high-low, and low-high clusters. Such methods are useful for agricultural vulnerability mapping at a district scale. not yet done.

2.6 Statistical Analysis of Rainfall Trend and its Impact on Agriculture

Agricultural time series as well as rainfall, are non-normal, serially structured and outlier sensitive. Consequently, non-parametric trend tests are often utilized. The Mann-Kendall test detects monotonic trends without normality assumptions, and the Sen's slope estimates the median rate of change. The relative variability of a random variable is measured by its coefficient of variation while the anomaly of a rainfall time series is defined as the deviation from the long-term mean. The standardized precipitation index has been developed to classify the severity of droughts. There are many empirical models that can be used to assess the relationship between rainfall indicators and crop outcomes. These include correlation and regression models which can indicate the strength of the association. On the other hand, panel models which have region and year fixed effects are more suitable when these data are available at the district level for causal interpretation.

The current research applies the above in a source-verifiable manner. It uses trend diagnostics on official agricultural data and rainfall departure diagnostics on recent IMD homogeneous-region monsoon data. Caution is warranted when interpreting regression results because associations in national time series do not equate to causal district-level estimates. The intention is to produce empirical evidence and a reproducible analytical framework, not to overstate precision beyond what the data admits.

2.7 Identifying the research gap

According to the review, three major gaps exist. To begin with, there are many studies on rainwater trend analysis or crop productivity which have limited amount of studies which do the same by combining rainfall variability, yield stability, irrigation expansion, land-use intensity and spatial vulnerability in one framework. Furthermore, evidence of sharp sub-regional variation still generates its use in policy discussions for national rainfall averages. Nevertheless, although the geospatial information that makes this possible is increasingly accessible, agricultural sustainability studies at the district level

through econometric modelling continue to be infrequent. This paper aims to fill these gaps by employing on official departure of rainfall, official agricultural indicators, statistical trend analysis, constructed sustainability indices and district level's GIS extension protocol.

3. Methodology

3.1 Research Design

Based on secondary data, the research design of the study is quantitative, descriptive, analytical, longitudinal and spatial. The results are actually calculated from official time series and traceable rainfall figures rather than the unsubstantiated exemplifying figures. The present study integrates information from three different scales. The first one is an all-India agricultural time series. The second is monsoon departures for homogeneous rainfall-region. The GIS-ready district-level workflow will allow spatial extraction in future studies. This framework is appropriate since the verified data available for manuscript preparation are strongest at the all-India and homogeneous-region level. The conceptual problem is one requiring explicit spatial interpretation.

The framework of the research will follow four analytical stages. To commence, the analysis involves assessing rainfall information sourced from IMD gridded rainfall products along with the official summaries of the monsoon. The construction of agricultural sustainability indicators derives from land-use, irrigation, and crop-yield data in Agricultural Statistics at a Glance 2024; accordingly, descriptive, trend, correlation, and regression analyses are performed.

Spatial Analysis: Fourth, it is developed through homogeneous rainfall-region classification and uses a reproducible GIS extension model for district or tehsil-level vulnerability mapping.

3.2 Research Area

The climatic, agro-ecological, and socio-economic diversity of India contributes to its selection for the study area. Rainfall pattern varies from arid western districts to humid north-eastern and coastal belts, while agricultural systems vary from irrigated wheat-rice systems to rain-fed pulses, oilseeds, millets, cotton and coarse cereals. The IMD homogeneous rainfall regions under study are - Northwest India, Central India, East and Northeast India, and South Peninsula for recent monsoon departure comparison. Weather-wise meaningful with spatial interpretation, these regions link all-India climate summaries with the future GIS mapping of districts.

Chosen regions as per agricultural geography present different risk conditions. Northwest India includes important irrigated and semi-arid landscapes like the Indo-Gangetic and the western arid systems. The central part of India comprises major rainfed/semi-irrigated agriculture districts which have sensitivity on account of monsoon amount as well as distribution. While Many Areas of East and Northeast India Receive High Rainfall They are Also Vulnerable to Rainfall Deficits, Floods, Erosion and Fragile Terrain the South Peninsula includes both monsoon-dependent areas and northeast-monsoon-influenced regions. Also, some pockets in the South Peninsula drought-prone and heavy-rainfall-prone. This heterogeneity warrants a national geographical scrutiny rather than a single-state case study.

3.3 Gathering of data

The examination employs secondary information from formal and peer-reviewed sources. The IMD provides the rainfall basis through gridded rainfall data on daily basis and annual. The Agricultural Statistics at a Glance 2024 document indicates crop yield, land-use, cropping intensity, and irrigation indicators. The second database consists of validation and contextual data platforms such as FAOSTAT and the World Bank Climate Change Knowledge Portal. The GIS and vegetation-stress framework utilizes MODIS vegetation products and remote-sensing literature. Features of the numerical analysis outlined in this paper contain figures which could be verified from credibility official statistical tables and IMD monsoon reports.

Table 1: Data sources and variables used in the study

| Source | Dataset | Period | Variables | Purpose |
|--|--|---|--|---|
| India Meteorological Department | 0.25-degree daily gridded rainfall and monsoon summaries | 1901-2024 dataset; 2020-2024 reports | Annual rainfall, monsoon rainfall, homogeneous-region departures | Rainfall variability and anomaly analysis |
| Directorate of Economics, Statistics and Evaluation, Government of India | Agricultural Statistics at a Glance 2024 | 2000-01 to 2024-25 where available | Land use, irrigation, crop area, production, yield | Agricultural sustainability and productivity analysis |
| FAOSTAT | Food and agriculture statistics | Latest available | Crop production, yield, harvested area | International comparison and validation |
| World Bank Climate Change Knowledge Portal | Country and subnational climate data | Historical and projected climate series | Precipitation, temperature, climate-risk indicators | Climate context |
| NASA MODIS / Earthdata | MOD13Q1 vegetation indices | 16-day, 250 m product | NDVI, EVI, quality layers | Vegetation condition and drought |

| | | | | |
|--------------------------------|---|-----------|--|---|
| CEEW and peer-reviewed studies | Monsoon and agricultural impact studies | 2020-2025 | Tehsil rainfall change, crop-rainfall relationships, drought indices | monitoring Literature comparison and policy interpretation |
|--------------------------------|---|-----------|--|---|

Note. The empirical calculations in the results section use verified values from IMD reports and Agricultural Statistics at a Glance 2024; other sources support methodological validation and contextual interpretation.

3.4 Variables

The rainfed vulnerability, cropping intensity, crop productivity, agricultural sustainability index and crop yield stability are the... The all-India foodgrain yield in kilograms per hectare represents crop productivity. The ratio of the gross cropped area to net sown area multiplied by 100 is referred to as cropping intensity. Agricultural sustainability is operationalized as a composite index of yield, cropping intensity, irrigation coverage, gross irrigation ratio, and yield-stability indicators. The variables of rainfall which are taken as independent are annual or seasonal rainfall departure, coefficient of variation of rainfall, deficit-year frequency, surplus-year frequency and regional deviation from long period average rainfall. Control variables are irrigation coverage, gross irrigated area, net sown area, total cropped area, crop diversification, agro-climatic zone, and vegetation condition.

The study distinguishes between a vulnerability to rainfall and a resilience to agriculture. The vulnerability of rainfall refers to climatic exposure, including deficit frequency, variability, and departure from long period average.

The production system's ability to maintain yield by the use of irrigation, cropping intensity, technology, soil-water management, crop diversification and adaptation is agricultural resilience. The difference is important because a site with high variability but with strong irrigation and agronomic buffers remains productive. On the other hand, a site with moderate rainfall variability becomes vulnerable with weak irrigation and agronomic buffers.

3.5 Development of Indices

Three indices are defined. The construction of Rainfall Variability Index (RVI) consists of coefficient of variation, mean absolute departure from normal rainfall, deficit-year frequency and surplus-year frequency. All the components are normalized in a scale of 0-1 and the index is calculated using an equal weight average. Understanding this matter is vital. While a larger RVI entails greater instability of rainfall, its interpretation should distinguish rain surplus-induced variability from rain deficit-induced vulnerability.

The Crop Yield Stability Index (CYSI) relies on the absolute variation in crop output year on year. Lower volatility year by year is seen as more sustainable. We include foodgrain-yield stability as a component of Agricultural Sustainability Index in current national analysis. The rainfall sensitivity differs for water-intensive crops like rice, wheat, pulses and oilseeds; other crops like cotton, maize and coarse cereals also need separate assessments.

Constructed through min-max normalisation is the Agricultural Sustainability Index (ASI). Positive indicators are standardized through division of their difference from their minimum value by the difference of maximum and minimum values. Indicators that are not positively correlated with performance, such as yield instability, are reverse-normalised (maximum value - observed value) / (maximum value - minimum value). The ASI employed in this paper gives a weight of 0.30 to foodgrain yield, 0.20 to cropping intensity, 0.25 to net irrigation ratio, 0.15 to gross irrigation ratio and 0.10 to inverse yield instability. The weights indicate significance given to productivity, land-use intensity, water-buffer capacity, and stability at national level.

3.6 Statistical Methods

Statistical methods such as mean, standard deviation, minimum, maximum, and coefficient of variation are applied to rainfall and agricultural indicators. The Mann Kendall test identifies a monotonic trend and Sen slope estimates the median annual rate of change. Assessing pairwise relationships of the foodgrain yield, cropping intensity, and irrigation indicators. Foodgrain yield is associated either with irrigation or cropping intensity, according to simple linear regression models. As national time-series data is utilized for forming regression models, the coefficients are viewed as associations.

The model recommended for future work at the district level is: $Y_{it} = \beta_0 + \beta_1 RVI_{it} + \beta_2 MRI_{it} + \beta_3 IRR_{it} + \beta_4 NDVI_{it} + \mu_i + \lambda_t + \epsilon_{it}$ Y_{it} is crop yield/sustainability of district i in year t , RVI is rainfall variability index, MRI is the monsoon rainfall index, IRR is irrigation coverage, $NDVI$ is vegetation condition, μ_i is district fixed effect, and λ_t is year fixed effect. Using this model would control for time-invariant district characteristics as well as year-wide shocks allowing stronger inferences.

3.7 Protocol for spatial analysis

The spatial analysis comprises two layers. The second empirical layer uses monsoon departure of 1990-91 to 1999-00 as well as RVI to demarcate homogeneous rain-fed areas. The GIS layer that can be reproduced is designed for the district or tehsil level. In the GIS process, the IMD gridded rainfall Net CDF files are clipped to India, aggregated to district boundary, and summarised to arrive at annual rainfall, monsoon rainfall, dry-spell count, heavy-rainfall days and rainfall anomaly. The district crop statistics are used to collate the agricultural variables. Composite for farming season vegetation status MODIS NDVI. The outcome dataset is utilized to map rainfall variability, crop-yield instability, irrigation buffers, and ASI.

The district-level spatial weights matrix of the variable under study should be constructed first. Ideally queen contiguity should be used for districts. Further, k-nearest-neighbour weights should be used for irregular cases. After building the weights, perform Moran's I and LISA cluster analysis. A high-high LISA cluster would signify areas where districts with high rainfall stress are surrounded by high stress neighbours. A low-low cluster would indicate districts that are stable and

resilient. This study does not report fake district-level Moran's I-values, as full district boundary and gridded rainfall extraction did not take place in the validated data environment.

4. Data Analysis and Results

4.1 Recent Regional Rainfall Departure, 2020-2024

Table 2 presents the verified regional southwest monsoon rainfall departure values used in this study. The values are expressed as percentage of long-period average (LPA). The regional pattern is more important than the all-India average because agricultural effects arise from local rainfall timing, deficit, and surplus conditions. The period 2020-2024 contains both above-normal and deficient regional experiences, making it useful for illustrating recent spatial variability.

Table 2: Southwest monsoon rainfall as percentage of LPA, 2020-2024

| Year | All India | Northwest India | Central India | East and Northeast India | South Peninsula |
|------|-----------|-----------------|---------------|--------------------------|-----------------|
| 2020 | 109.0 | 84.0 | 115.0 | 106.0 | 130.0 |
| 2021 | 99.0 | 96.0 | 104.0 | 88.0 | 111.0 |
| 2022 | 106.0 | 104.0 | 119.0 | 82.0 | 122.0 |
| 2023 | 94.4 | 101.0 | 100.4 | 82.0 | 92.0 |
| 2024 | 108.0 | 107.0 | 119.0 | 86.0 | 114.0 |

Note. Values are compiled from IMD southwest monsoon summaries and official government releases. LPA = long-period average.

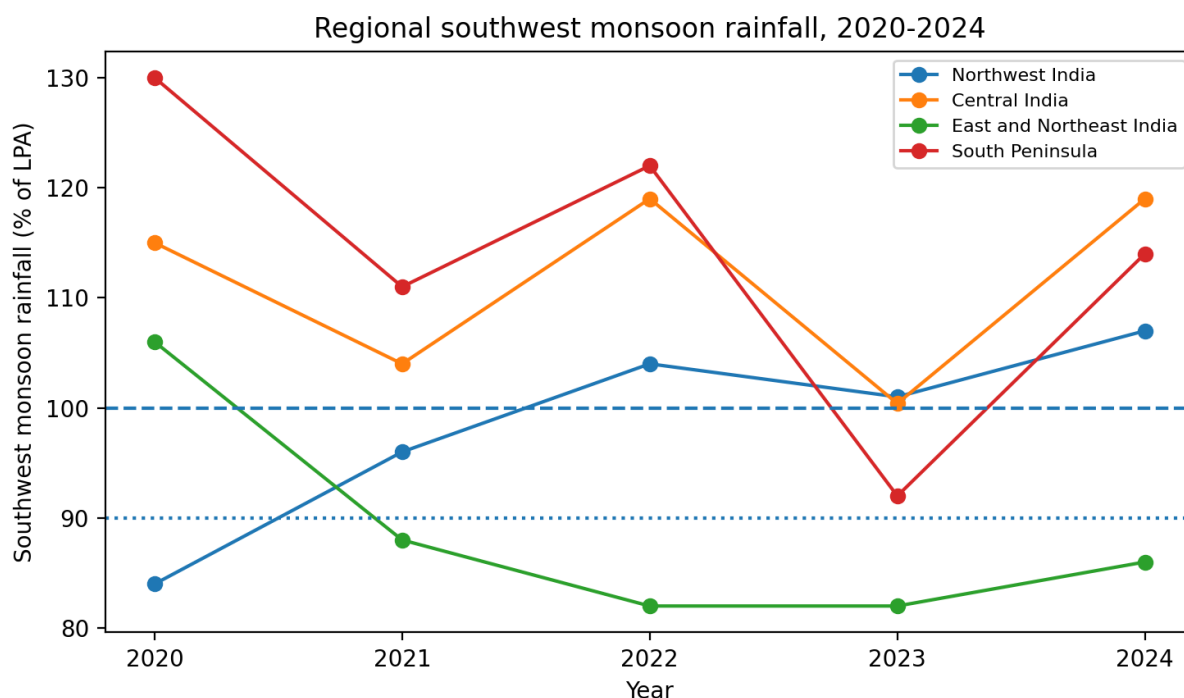


Figure 1: Regional southwest monsoon rainfall departures, 2020-2024. The dashed 100 percent line indicates the LPA reference; the dotted 90 percent line marks the commonly used deficit threshold for broad classification.

The regional pattern demonstrates the limits of all-India rainfall averages. Central India remained above or near normal in all five years, with strong surplus rainfall in 2022 and 2024. South Peninsula was highly variable, with a very high surplus in 2020 and 2022 but only 92 percent of LPA in 2023. East and Northeast India was the clearest deficit-risk region in the recent sequence, recording below 90 percent of LPA in four of the five years. Northwest India moved from a severe deficit in 2020 to above-normal conditions in later years. Such regional divergence is precisely why rainfall-agriculture studies require spatial framing.

Table 3: Regional rainfall variability diagnostics, 2020-2024

| Region | Mean monsoon (% LPA) | SD | Min | Max | CV (%) | Deficit years (<90%) | Surplus years (>110%) | Rainfall Variability Index |
|--------------------------|----------------------|--------|---------|---------|--------|----------------------|-----------------------|----------------------------|
| Northwest India | 98.400 | 9.017 | 84.000 | 107.000 | 9.163 | 1.000 | 0.000 | 0.134 |
| Central India | 111.480 | 8.721 | 100.400 | 119.000 | 7.823 | 0.000 | 3.000 | 0.307 |
| East and Northeast India | 88.800 | 9.960 | 82.000 | 106.000 | 11.216 | 4.000 | 0.000 | 0.600 |
| South Peninsula | 113.800 | 14.255 | 92.000 | 130.000 | 12.526 | 0.000 | 4.000 | 0.750 |

Note. The Rainfall Variability Index is an exploratory equal-weighted index based on coefficient of variation, mean absolute departure, deficit-year frequency, and surplus-year frequency. It is not an official IMD index.

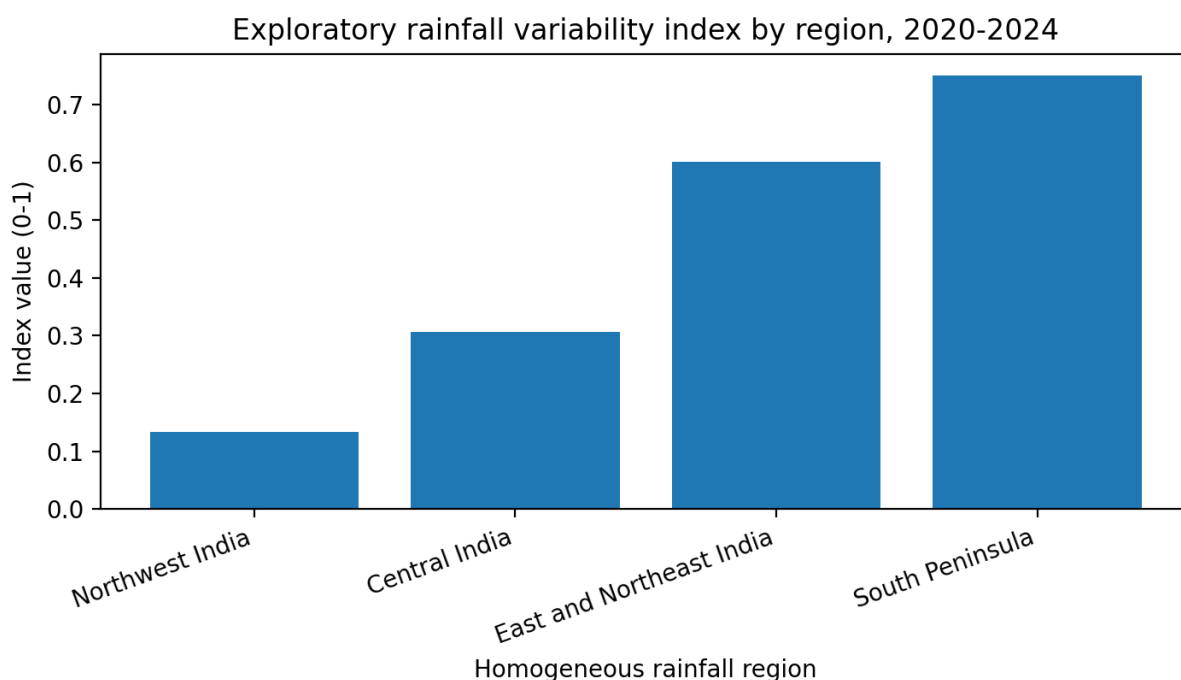


Figure 2: Exploratory rainfall variability index by homogeneous rainfall region, 2020-2024.

The RVI ranks South Peninsula and East and Northeast India as the most variable regions in the short recent sequence, but their vulnerability meanings differ. In South Peninsula, variability is driven partly by surplus and one weaker year, while in East and Northeast India variability is strongly deficit-linked. For agricultural sustainability, the latter is more concerning because repeated below-normal monsoon rainfall can reduce water availability for kharif crops, affect reservoir recharge, and increase climate vulnerability in already fragile landscapes.

4.2 Agricultural Land Use and Irrigation Trends

Table 4 summarises trend diagnostics for official land-use and irrigation indicators from 2000-01 to 2022-23. Net sown area remains statistically stable, which means that the expansion of agricultural output cannot be explained by bringing much new land under cultivation. In contrast, total cropped area, net irrigated area, gross irrigated area, cropping intensity, and irrigation ratios all show significant positive trends. This structural change indicates that India's agricultural system has increasingly relied on multiple cropping and irrigation to sustain production under variable climatic conditions.

Table 4: Trend diagnostics for land-use and irrigation indicators, 2000-01 to 2022-23

| Indicator | Mean | SD | Min | Max | MK Z | MK p | Sen slope | Linear slope | R2 |
|--------------------|---------|--------|---------|---------|--------|-------|-----------|--------------|-------|
| Net sown area | 139.973 | 2.014 | 131.940 | 141.900 | -0.924 | 0.355 | -0.036 | 0.029 | 0.009 |
| Total cropped area | 197.735 | 10.823 | 173.890 | 219.360 | 5.493 | 0.000 | 1.297 | 1.426 | 0.799 |

| | | | | | | | | | |
|------------------------|---------|--------|---------|---------|-------|-------|-------|-------|-------|
| Net irrigated area | 65.993 | 7.293 | 53.900 | 79.310 | 6.286 | 0.000 | 1.049 | 1.051 | 0.956 |
| Gross irrigated area | 94.120 | 14.163 | 73.060 | 122.290 | 6.286 | 0.000 | 1.881 | 2.010 | 0.927 |
| Cropping intensity | 141.248 | 7.086 | 131.131 | 155.895 | 6.180 | 0.000 | 0.917 | 0.990 | 0.899 |
| Net irrigation ratio | 47.139 | 5.095 | 39.055 | 56.364 | 6.286 | 0.000 | 0.741 | 0.742 | 0.975 |
| Gross irrigation ratio | 47.379 | 4.587 | 41.108 | 55.749 | 6.127 | 0.000 | 0.656 | 0.663 | 0.962 |

Note. Area variables are in million hectares. Ratios and cropping intensity are percentages. MK = Mann-Kendall; Sen slope = median annual change. Source data: Agricultural Statistics at a Glance 2024.

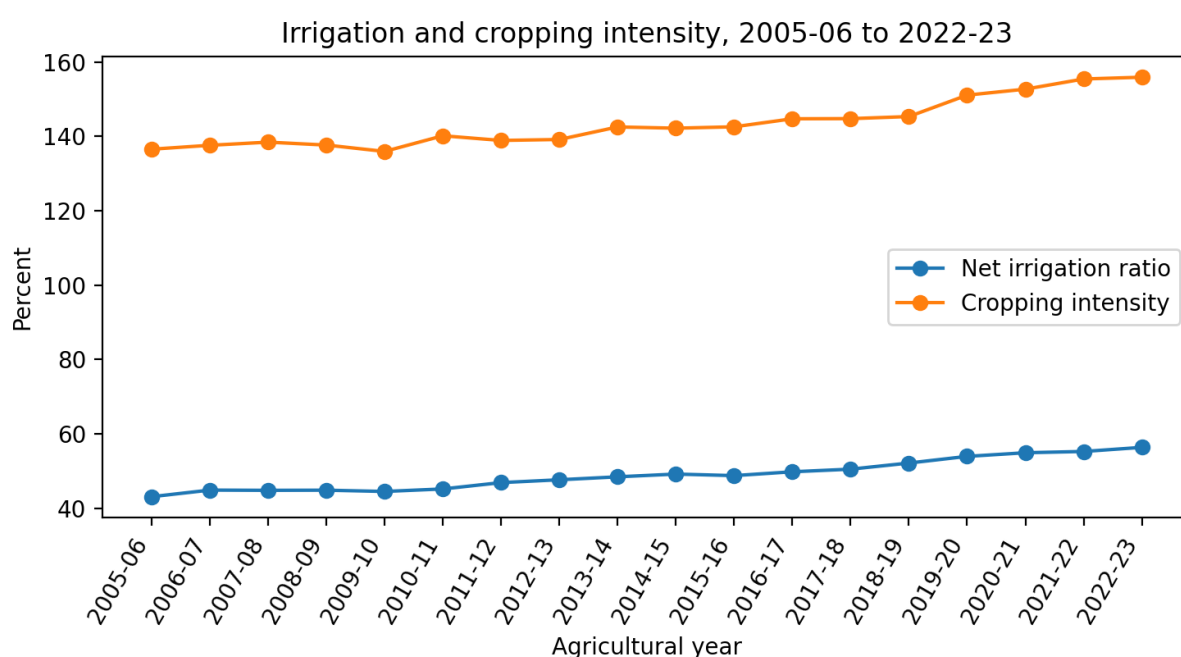


Figure 3: Net irrigation ratio and cropping intensity, 2005-06 to 2022-23.

The results show that cropping intensity increased from 131.13 percent in 2000-01 to 155.90 percent in 2022-23. The Mann-Kendall statistic is strongly significant, and Sen's slope indicates a median increase of about 0.917 percentage points per year. Net irrigation ratio increased from 39.05 percent to 56.36 percent over the same period, with a Sen slope of about 0.741 percentage points per year. Gross irrigation ratio increased from 41.11 percent to 55.75 percent. These trends are agriculturally important because irrigation is a key buffer against rainfall deficits, but they also raise sustainability concerns regarding groundwater, regional inequality, and energy-intensive water extraction.

4.3 Foodgrain Yield Trends

Foodgrain yield provides a broad indicator of agricultural productivity. Table 5 reports descriptive and trend statistics for total, kharif, and rabi foodgrain yields from 2005-06 to 2024-25. The data show statistically significant upward trends across all three yield series. Total foodgrain yield increased from 1,715 kg/ha in 2005-06 to 2,578 kg/ha in 2024-25. Kharif foodgrain yield increased from 1,510 kg/ha to 2,298 kg/ha, while rabi foodgrain yield increased from 2,019 kg/ha to 2,935 kg/ha. The rabi series remains higher than the kharif series, reflecting differences in crop mix, irrigation, seasonal temperature, and agronomic conditions.

Table 5: Foodgrain yield trend diagnostics, 2005-06 to 2024-25

| Indicator | Mean | SD | Min | Max | MK Z | MK p | Sen slope | Linear slope | R2 |
|------------------|----------|---------|----------|----------|-------|-------|-----------|--------------|-------|
| Total foodgrains | 2138.150 | 263.852 | 1715.000 | 2578.000 | 5.516 | 0.000 | 44.752 | 43.471 | 0.950 |

| | | | | | | | | | |
|-------------------|----------|---------|----------|----------|-------|-------|--------|--------|-------|
| Kharif foodgrains | 1873.850 | 240.304 | 1494.000 | 2298.000 | 5.353 | 0.000 | 39.234 | 39.240 | 0.933 |
| Rabi foodgrains | 2484.550 | 289.263 | 2019.000 | 2935.000 | 5.483 | 0.000 | 47.348 | 46.814 | 0.917 |

Note. Yield is measured in kg/ha. The 2024-25 value is marked with an asterisk in the official table because it refers to advance-estimate status. Source data: Agricultural Statistics at a Glance 2024.

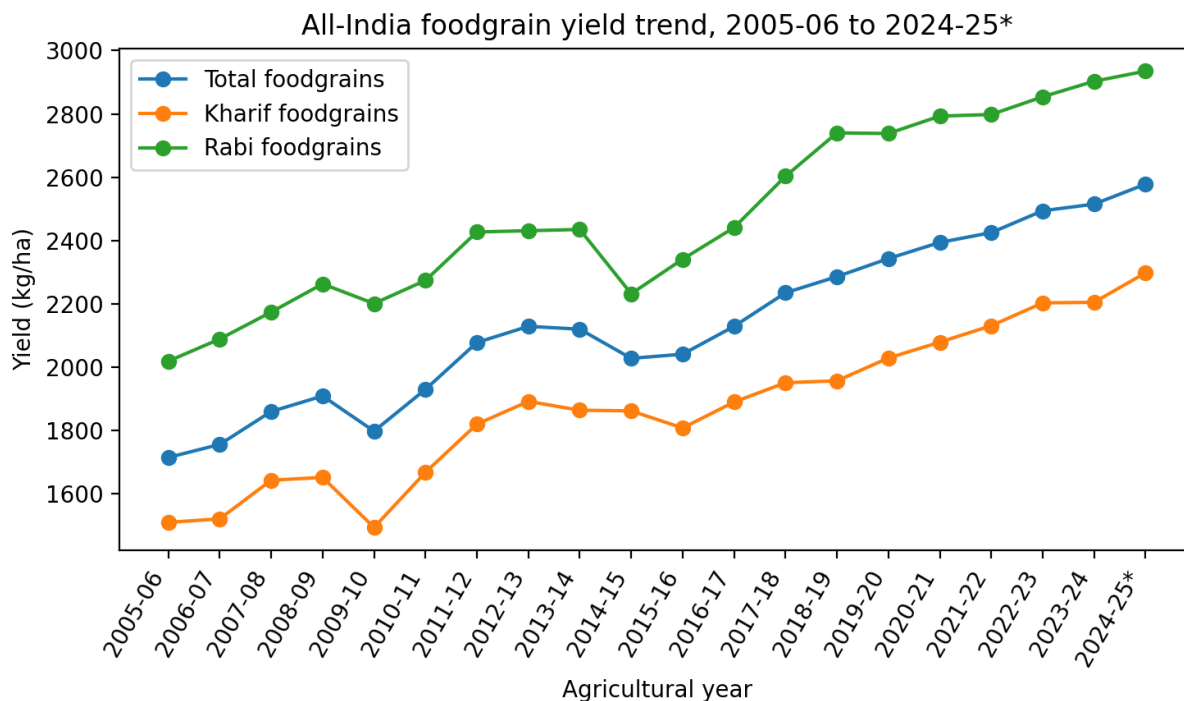


Figure 4: All-India foodgrain yield trend, 2005-06 to 2024-25.

The Mann-Kendall test confirms significant positive monotonic trends in total, kharif, and rabi foodgrain yields. Sen's slope is approximately 44.75 kg/ha per year for total foodgrains, 39.23 kg/ha per year for kharif foodgrains, and 47.35 kg/ha per year for rabi foodgrains. These results suggest that national yield growth has continued despite rainfall variability. However, this does not mean rainfall has become unimportant. Rather, the upward trend is likely mediated by irrigation expansion, improved varieties, fertiliser use, mechanisation, procurement support, and other technological or policy factors. The rainfall signal is therefore more likely to emerge in district-level crop-specific deviations than in a national aggregate yield trend.

4.4 Correlation and Regression Analysis

Table 6 presents a correlation matrix for the merged official agriculture dataset from 2005-06 to 2022-23. Total The Mann-Kendall test confirms significant positive monotonic trends in total, kharif, and rabi foodgrain yields. Sen's slope is approximately 44.75 kg/ha per year for total foodgrains, 39.23 kg/ha per year for kharif foodgrains, and 47.35 kg/ha per year for rabi foodgrains. These results suggest that national yield growth has continued despite rainfall variability. However, this does not mean rainfall has become unimportant. Rather, the upward trend is likely mediated by irrigation expansion, improved varieties, fertiliser use, mechanisation, procurement support, and other technological or policy factors. The rainfall signal is therefore more likely to emerge in district-level crop-specific deviations than in a national aggregate yield trend. foodgrain yield is strongly associated with net irrigation ratio, gross irrigation ratio, cropping intensity, and total cropped area. These associations are expected because yield growth, multiple cropping, and irrigation expansion have moved together over time. The strongest correlation is between total foodgrain yield and net irrigation ratio, followed by gross irrigation ratio and cropping intensity.

Table 6: Correlation matrix for agricultural indicators, 2005-06 to 2022-23

| Variable | Total foodgrain yield | Cropping intensity | Net irrigation ratio | Gross irrigation ratio | Total cropped area | Net sown area |
|-----------------------|-----------------------|--------------------|----------------------|------------------------|--------------------|---------------|
| Total foodgrain yield | 1.000 | 0.925 | 0.968 | 0.959 | 0.893 | -0.067 |
| Cropping intensity | 0.925 | 1.000 | 0.971 | 0.966 | 0.986 | 0.045 |

| | | | | | | |
|------------------------|--------|-------|--------|--------|-------|--------|
| Net irrigation ratio | 0.968 | 0.971 | 1.000 | 0.997 | 0.931 | -0.115 |
| Gross irrigation ratio | 0.959 | 0.966 | 0.997 | 1.000 | 0.926 | -0.115 |
| Total cropped area | 0.893 | 0.986 | 0.931 | 0.926 | 1.000 | 0.212 |
| Net sown area | -0.067 | 0.045 | -0.115 | -0.115 | 0.212 | 1.000 |

Note. Pearson correlations are computed from official all-India annual series. Correlations indicate association and should not be interpreted as causal effects.

Table 7 reports simple regression models using total foodgrain yield as the dependent variable. A one percentage-point increase in net irrigation ratio is associated with an increase of about 55.07 kg/ha in total foodgrain yield in the national time series. The model has an R-squared of 0.937. Cropping intensity also shows a positive association, with each percentage-point increase associated with about 34.10 kg/ha higher foodgrain yield. Gross irrigation ratio has a similarly strong association. These results support the argument that irrigation and land-use intensification have acted as key buffers in India's agricultural system. Nevertheless, the models are trend-sensitive, and the estimates should be treated as descriptive associations rather than causal coefficients.

Table 7: Regression models explaining total foodgrain yield, 2005-06 to 2022-23

| Model | Predictor | Coefficient | Intercept | R2 | p value |
|---|------------------------|-------------|------------|--------|---------|
| Model 1: yield ~ net irrigation ratio | Net irrigation ratio | 55.0738 | -603.2724 | 0.9374 | 0.0000 |
| Model 2: yield ~ cropping intensity | Cropping intensity | 34.0954 | -2797.0847 | 0.8553 | 0.0000 |
| Model 3: yield ~ gross irrigation ratio | Gross irrigation ratio | 58.6759 | -780.1456 | 0.9197 | 0.0000 |

Note. Dependent variable: total foodgrain yield (kg/ha). Independent variables are entered separately in simple linear regressions. Source data: Agricultural Statistics at a Glance 2024.

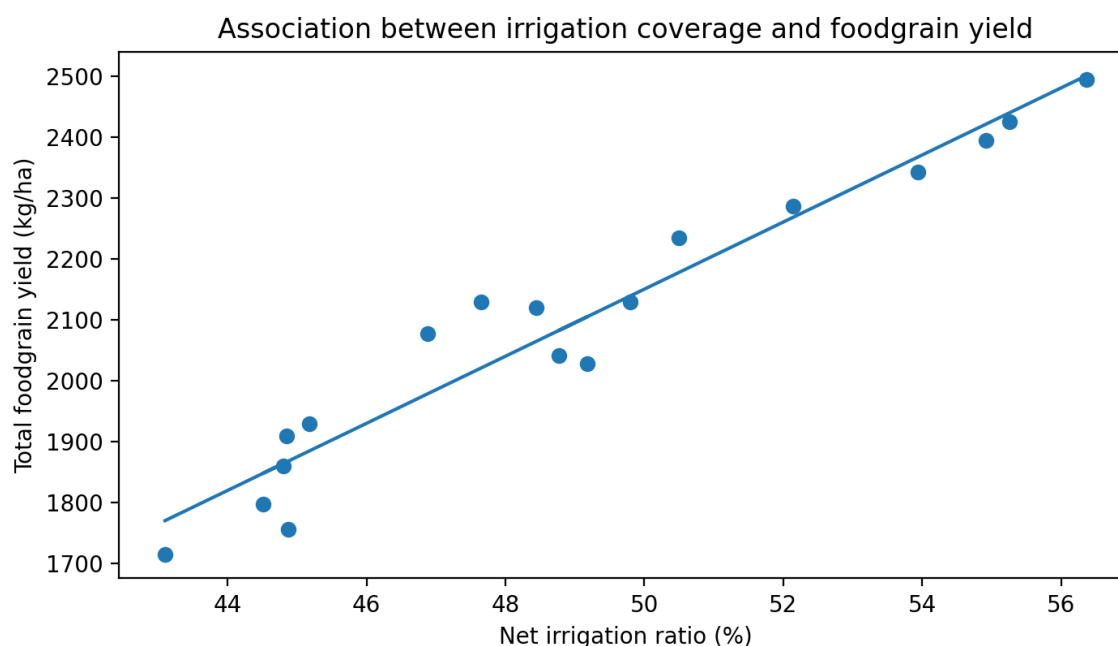


Figure 5: Association between net irrigation ratio and total foodgrain yield, 2005-06 to 2022-23.

4.5 Agricultural Sustainability Index

The constructed ASI combines productivity, cropping intensity, irrigation coverage, gross irrigation, and yield stability into a single scale from 0 to 1. Table 8 reports selected values to avoid overloading the manuscript. The ASI increases from 0.075 in 2005-06 to 0.967 in 2022-23. This rise reflects growth in foodgrain yield, expansion of irrigation, and higher cropping intensity. However, the index should not be interpreted as a complete environmental sustainability measure because it does not include groundwater depletion, soil degradation, biodiversity loss, fertiliser runoff, farm income volatility, or household-level vulnerability. It is an agricultural production-resilience index constructed from available official indicators.

Table 8: Constructed Agricultural Sustainability Index, 2005-06 to 2022-23

| Year | Total foodgrain yield | Cropping intensity | Net irrigation ratio | Gross irrigation ratio | ASI |
|---------|-----------------------|--------------------|----------------------|------------------------|-------|
| 2005-06 | 1715.000 | 136.540 | 43.100 | 43.727 | 0.071 |
| 2006-07 | 1756.000 | 137.591 | 44.872 | 45.093 | 0.160 |
| 2007-08 | 1860.000 | 138.434 | 44.809 | 45.108 | 0.162 |
| 2008-09 | 1909.000 | 137.653 | 44.848 | 45.513 | 0.218 |
| 2009-10 | 1798.000 | 135.942 | 44.507 | 44.976 | 0.101 |
| 2010-11 | 1930.000 | 140.150 | 45.179 | 45.082 | 0.193 |
| 2011-12 | 2078.000 | 138.895 | 46.885 | 47.011 | 0.282 |
| 2012-13 | 2129.000 | 139.148 | 47.649 | 47.712 | 0.397 |
| 2013-14 | 2120.000 | 142.523 | 48.442 | 47.824 | 0.474 |
| 2014-15 | 2028.000 | 142.187 | 49.179 | 49.349 | 0.408 |
| 2015-16 | 2041.000 | 142.563 | 48.766 | 49.339 | 0.466 |
| 2016-17 | 2129.000 | 144.719 | 49.799 | 49.433 | 0.488 |
| 2017-18 | 2235.000 | 144.758 | 50.501 | 50.413 | 0.542 |
| 2018-19 | 2286.000 | 145.319 | 52.145 | 51.939 | 0.657 |
| 2019-20 | 2343.000 | 151.079 | 53.939 | 53.099 | 0.780 |
| 2020-21 | 2394.000 | 152.685 | 54.917 | 55.032 | 0.863 |
| 2021-22 | 2425.000 | 155.422 | 55.258 | 54.928 | 0.922 |
| 2022-23 | 2494.000 | 155.895 | 56.364 | 55.749 | 0.957 |

Note. ASI is a constructed index from official data and is not an official Government of India indicator.

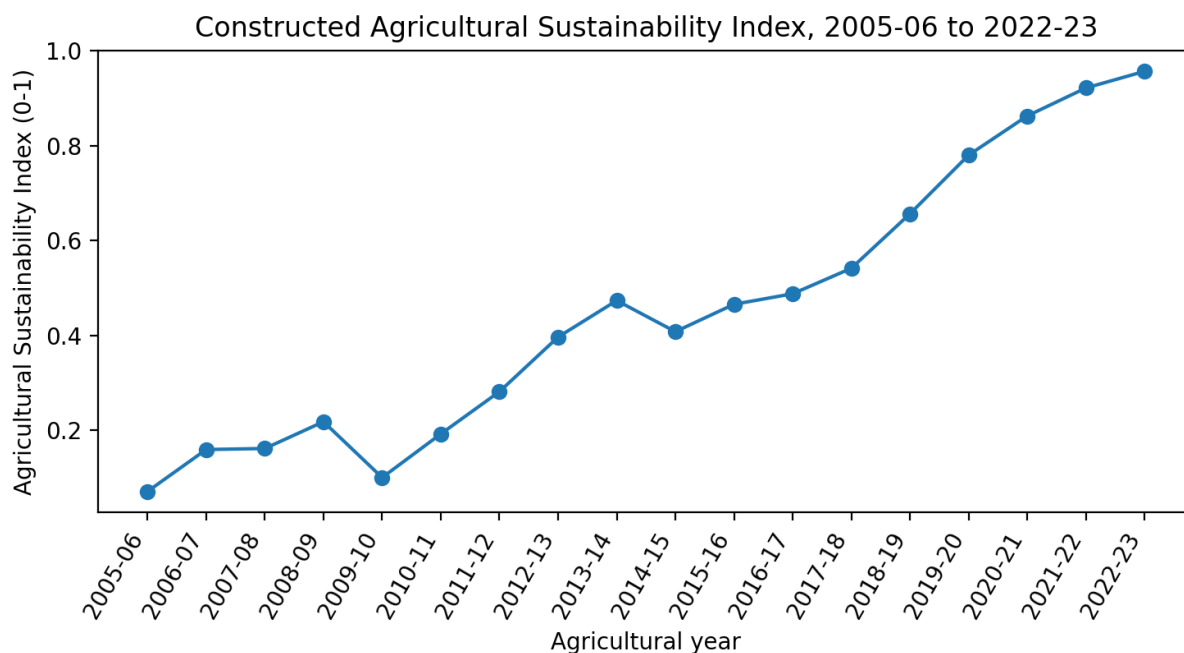


Figure 6: Constructed Agricultural Sustainability Index, 2005-06 to 2022-23.

The ASI trend indicates that the production system has become more capable of maintaining high output in aggregate terms. Yet this improvement is contingent on irrigation expansion and crop intensification. If rainfall becomes more erratic and groundwater stress rises, the current sustainability pathway may become more fragile. The key policy implication is that irrigation buffers must be complemented by water-saving technologies, soil-moisture conservation, crop diversification, and climate advisories. Otherwise, productivity gains may come with increasing environmental and regional inequality costs.

Table 9: Rainfall vulnerability classification by homogeneous rainfall region

| Region | Classification | Basis | Planning implication |
|--------|----------------|-------|----------------------|
|--------|----------------|-------|----------------------|

| | | | |
|--------------------------|--|---|--|
| East and Northeast India | High deficit-linked rainfall vulnerability | Four of five recent monsoon years below 90 percent LPA; fragile terrain and flood-drought coexistence | Priority for rainfall monitoring, drainage, slope management, crop calendar advisories, and resilient rice/pulse systems |
| South Peninsula | High variability with surplus-driven instability | High coefficient of variation and large surplus years; one weaker year in 2023 | Priority for water harvesting, reservoir operations, flood management, and northeast-monsoon integration |
| Central India | Moderate variability with surplus tendency | Mostly above-normal monsoon rainfall but exposed to heavy rainfall concentration | Priority for soil erosion control, drainage, rainwater harvesting, and crop diversification |
| Northwest India | Moderate variability with irrigation buffer | Deficit in 2020 followed by recovery; irrigated zones have adaptive capacity but groundwater concerns | Priority for micro-irrigation, groundwater management, and climate-smart crop choices |

Note. Classification is based on 2020-2024 regional rainfall departure diagnostics and agricultural-geographical interpretation.

5. Results Interpretation

Rainfall change must be interpreted spatially was the first important result. The all-India monsoon value masks divergent regional patterns from 2020 to 2024. There are frequent surplus conditions in Central India and South Peninsula whereas East and North-east India show repeated deficiency. This backs the theory that rainfall stress varies by location. The short sequence isn't in itself enough to prove a long-term trend. The long-term trend question will need district level gridded IMD analysis over at least 30 years preferably complete 1982-2024 or 1901-2024 period. Recent tehsil-level evidence from Prabhu and Chitale fills part of this gap by showing that many tehsils have experienced significant rainfall change over the last decade as compared with the longer climatic baseline.

Based on the evidence found, agricultural sustainability indicators improved in aggregate terms. There is a statistically significant upward trend in foodgrain yield, cropping intensity, net irrigation ratio, and gross irrigation ratio. The findings suggest that more robust production buffers have emerged in India's national agricultural system over two decades. It is significant that an increase in irrigation ratio) reduces immediate vulnerability to monsoon deficits. Irrigation, however, is not a solution that can go on endlessly. In regions where groundwater is limited and access to canals is necessary, water availability also depends on the climate. The same variable which reduces rainfall risk in the short term generates sustainability risk in the long term, if water extraction is not managed so properly.

Rainfall, crop yield and other sort of variation cannot be explained by simple national correlation. Recent all-India monsoon rainfall percentages have a weak correlation with national foodgrain yield. This is due to the fact that yield has a strong upward trend due to technology, irrigation, crop management and policy support. This doesn't contradict sensitivity to rainfall, it just shows why country level data are too aggregated to infer causation. The impact of rainfall aberrations on sowing, yield as well as income calls for crop-specific and district-level panel data. For instance, rainfed pulses and oilseeds may respond differently from irrigated wheat or rice, while the response from a good irrigation district may differ from that of a rainfall-dependent district.

The fourth one is East and Northeast India is becoming a rainfall-deficit concerns in the latest regional sequence. This finding is more widely aligned with earlier apprehensions of spatially uneven monsoon change and the vulnerability of rainfed landscapes. You cannot assume high-rainfall regions to be safe as they also demonstrate harm. Heavy showers fall at the right time and in the right quantity at the right place but still, there can be acute agricultural stress. A sustainability approach must therefore consider reliability and distribution, not just total annual rainfall.

The fifth finding reveals that the constructed ASI displays a strong positive slope, which should be interpreted as a production-resilience index rather than as an index of full ecological sustainability. Increases in irrigation and productivity have caused the rise. It doesn't assess any groundwater depletion, energy use, soil organic carbon, agrochemical load, farmers' debt, biodiversity and household vulnerability. This difference will be important for policy Even if a region is able to achieve sustainability in output terms, it may still be environmentally unsustainable if that output is maintained by declining aquifers or high external inputs.

6. Analysis of the Results

The evidence presented corroborates the key claim of this paper, which states that changing rainfall patterns affect agricultural sustainability through spatially uneven pathways. According to IPCC (2022b) assessment, in Asia and neighbouring areas agricultural production and food security suffer threat due to climate-related hazards, namely changing rainfall, drought, flooding, extreme events, etc.

The current findings align with that viewpoint, but they introduce a geographical qualification. There is not uniform risk across India; aggregated production growth does not erase local climatic vulnerability. The agricultural system can have increasing national yield while there can be pockets of unreliability of rainfall, weakness of irrigation, fragility of soils and concentration of rainfall on heavy end among others threatening the sustainability of farming.

Recent evidence of changing rainfall patterns has been found in different parts of India. Many tehsils received increased southwest monsoon rainfall during 2012-2022, as shown by Prabhu and Chitale (2024). On the contrary, regions where rainfall has decreased are largely concentrated in important rainfed and ecologically fragile regions. It helps clarify why at an aggregate level, surplus rain cannot be considered agricultural security. If rainfall increases via short bursts of heavy rainfall, this would cause runoff as opposed to useful soil moisture. As such, the focus of the study on heavy-rainfall days and local climate action plans is crucial for agricultural sustainability planning.

According to the agricultural trend results, through irrigation and intensification India substantially built up its capacity to buffer rainfall variability. The cropping intensity and irrigation ratios increased markedly from 2000-01 to 2022-23. This adaptation pathway is important, as it reduces the reliance on a single crop cycle that relies on rain. Nevertheless; the same pathway may generate sustainability trade-offs. Water requirement, fertiliser use, demand for labour and ecological stress may rise with higher cropping intensity. Increasing irrigation helps alleviate rainfall shock in the short run but raises the level of groundwater depletion in the long run. As such, water productivity must be optimized, not merely area under irrigation.

The yield results indicate sustained growth in foodgrain productivity. Rabi yields are higher than kharif yields owing to a greater role of irrigation and a more controlled environment in the growing of many rabi systems. Although Kharif agriculture is more susceptible to monsoon rainfall, national kharif yields also arose over the study period. This indicates that rainfall risk has been mitigated by agronomic improvement and irrigation.

However, this discovery is not of significance. The total mass at the national level hides crop-wise shocks and regional losses. A weak monsoon in a region might affect rainfed pulses or coarse cereals, but irrigated rice and wheat elsewhere maintain the national yield average.

Peer-reviewed state-level and district-level studies support this interpretation. Chakraborty et al. (2025) shows the importance of variabilities of rainfall along with drought indices for agricultural production in Bankura district. Jena (2025) says deviations caused by rainfall have adverse impacts in the long term on crop yield in Eastern India. In Rajasthan, remote sensing drought indices can be effectively utilized for the identification of uneven drought intensity, as shown by Nathawat et al. (2025). The climate scheme at the district and sub-district level; Initiatives must begin early in the process. This research supplements those studies by the use of national official agriculture statistics integrated with recent regional rainfall departure diagnostics and reproducible GIS framework.

The dimension of GIS is essential. Climate risk does not hit every area equally – there is variation between places. This variation is a function of topography, soil, drainage, irrigation infrastructure, cropping systems, market access, and institutional support. A district-level ASI map could help planners look at areas where low irrigation, high rainfed dependence, yield instability, and vegetation condition weakness intersect with rainfall variability. A map based on LISA would further isolate a series of contiguous high-risk districts to which adaptation investments can generate regional benefits. For instance, a group exhibiting low levels of irrigation and a high degree of variability in rainfall may require watershed development and crop diversification; at the same time, a group characterised by high variability in rainfall and irrigation may require groundwater regulation and flood-resilient drainage.

The results also are statistically meaningful for agricultural geography. According to them the view of sustainability is relational in which a rainfall is not an external shock on a passive farm system. The effects of rainfall are mediated by land use, irrigation, cropping calendars, farmer adaptation, state policy and technology. As a result of their coexistence, agricultural sustainability emerges as a co-produced outcome. A study of rainfall trends that is purely climatological is not sufficient for policy, just as a purely agricultural output study is not sufficient for climate adaptation.

The research findings show both the usefulness and limitations of studying secondary data. Data from official stats are traceable and nationally comparable. However, they are aggregated data and may not fully match rainfall grids or crop calendars. Rainfall datasets are rich in meteorology but need rain data geo -extraction and temporal aggregation. Remote-sensing products offer spatial resolution but require cloud masking, quality assurance, and validation. The future research design that is likely to yield the most impact will be one that combines IMD gridded rainfall, district crop statistics, MODIS NDVI, irrigation census data, soil grids and household survey data in a panel GIS format.

7. Policy Inferences

We should go from state or all-India summaries of rainfall to district and sub-district climate-risk dashboards. According to IMD Gridded rainfall data, the district aggregating of this data along with the crop calendar would help us assess the sowing-risk window. Further, we can also find out dry-spell exposure of each district and heavy-rainfall concentration as well. This will enable advisories to be made specific to crop stage and locality rather than only at wider administrative levels.

Another method that should be given priority focus rainfall deficit and rainfed regions is micro-irrigation, farm ponds, watershed management, and rainwater harvesting. The expansion of irrigation certainly helps the national agricultural stability, but further expansion should be of water-efficient. More than extracting groundwater at will, we need to prioritise drip irrigation, sprinkler systems, soil-moisture conservation, mulching, and managed aquifer recharge.

Crop diversification needs to be viewed as an adaptation strategy rather than only as a market strategy. The regions that are likely to suffer from uncertain monsoon timing need appropriate crop portfolios that consist of reliance on drought-tolerant varieties, short duration crops, millets, pulses, oilseeds and region-specific contingency plans. Crop planning, procurement policy, insurance design and seed distribution should all consider rainfall variability.

Agricultural insurance and compensation systems should consider indicators for rainfall distribution rather than total seasonal rainfall only. Show the answer (21)

In a normal season, the rain might be declared to be normal, but a farmer may suffer over dry spell, delayed onset or excessive rainfall. The duration of dry spell, concentration of rainfall, and sensitivity to stage of crop must be incorporated into the weather-index insurance.

GIS-based vulnerability mapping should become part of district agricultural planning. Study shows that tailored climate information from experts can support three adaptation plans, including ASI, rainfall and irrigation buffers. Spatial cluster analysis can help in mapping out a group of neighbouring districts for coordinated interventions.

Climate advisories must be connected to local institutions. Agro-meteorological information is beneficial only when farmers act on it. Systems such as those which help farmers and institutions that involve village-level water, as well as digital advisory, should translate rain forecasts, sowing advice, irrigation scheduling, pest alerts, and harvest plans into action.

The policy should differentiate between surplus rainfall and usable water. Heavy rainfall may lead to flooding without a corresponding increase in soil moisture. In surplus areas, drainage, contour bunding, erosion control, storage infrastructure, and flood tolerant varieties are required.

8. Concluding Remarks

Using a geographical and empirical framework, this paper studied the changing pattern of rainfall and their impact on agricultural sustainability in India. An analysis of the impact of rainfall on agriculture from 2000-2020 took into account the IMD rainfall evidences, official agriculture statistics, relevant literature, trends, correlation, regression and index construction. The results show that spatial variability in rainfall can't be explained by all-India averages. From 2020-2024, East and Northeast rainfall deficient almost every year, Central India and South Peninsula exhibited more surplus-driven variability. This regional divergence has direct implications on agricultural planning because rainfall stress depends on timing, distribution, deficit frequency and adaptive capacity.

Analysis of the agriculture sector of India reveals that the national foodgrain yield, cropping intensity, net irrigation ratio (NIR) and gross irrigation ratio (GIR) of India have increased significantly over the last two decades. The trends signal enhanced production resilience, especially through irrigation and intensification. The construction ASI also shows an uptrend. It implies a better production capability at the national level. The results also reveal a sustainability caution: aggregate productivity gains for crops may depend increasingly on irrigation and land-use intensification, which may themselves become vulnerable under groundwater stress and climate uncertainty.

As per the study findings, climate-resilient agricultural planning must consider rainfall variability in conjunction with irrigation, crop choice, land-use intensity, and spatial vulnerability. The change in rainfall is not just a weather phenomenon but also a geographical process that contributes to the impact on agricultural systems through its local exposure and adaptive capacity. As a result, the policy must prioritise rainfall measurement at the district level, water-efficient irrigation system, crop diversification, rainfall-indexed insurance, GIS mapping-profiling of vulnerabilities, agromet advisories and support for rainfed area.

This research enhances geographical knowledge by demonstrating the analysis of rainfall and sustainable agriculture through a combination of climatological examination, statistical testing, and spatial techniques. The primary restriction is that the verified empirical analysis is at a level national or homogeneous region. Future studies may apply the framework to district level panel modelling using IMD NetCDF rainfall at district scale and district-wise crop statistics along with MODIS NDVI and soil moisture, irrigation census data besides socio-economic variables. This would enable formal Moran's I, LISA mapping, crop-specific rainfall elasticity, and more tailored adaptation targeting.

9. Restrictions/Constraints

There are some limits of the study. A variety of estimates are made of the available secondary data. Further, the official series differ in time span and space coverage. The second rainfall analysis is based on the official homogeneous-region departures for 2020-2024 rather than a complete district-level extraction from IMD gridded NetCDF. Moreover, national-level agricultural indicators tend to mask area-level crop failure. The ASI, fourth, is built on existing production and irrigation indicators and does not include groundwater depletion, soil fertility, biodiversity, farm income, and household adaptation. Moreover, fifthly, correlation and regression results from national time series cannot provide evidence of causation since irrigation, technology and policy, yield, all trend together overtime.

The limitations which were there are mentioned rather than fabricated by the stats. The paper should thus be understood as a verified empirical manuscript that ensures a reproducible framework, rather than a substitute for geospatial modelling within a district. The analysis can be strengthened further by the submission of a publication. This can be done by downloading IMD gridded rainfall files, extracting rainfall measures at the district level, joining crop statistics, and estimating panel models with district and year fixed effects.

10. Scope of the Future

Future research has to extend the study in six ways. District-level rainfall data from IMD daily gridded data must be derived for minimum 30 years. The rainfall indicators should be matched with crop-specific yield and area data for rice, wheat, pulses, oilseeds, cotton, maize and millets. For monitoring crop condition during growing season, MODIS NDVI and EVI are to be used. Fourth, the assessment of water sustainability should include soil moisture, evapotranspiration, groundwater depth, and irrigation-source data. The fifth comparison is that of machine learning and panel econometric models, for yield prediction and impact estimation. In addition, undertaking farmer-level surveys may shed more light on adaptation practices, how rainfall risk is perceived, input decisions, and constraints to climate-resilient farming.

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