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PADDY YIELD RESPONSE TO AGRICULTURAL DROUGHT STRESS IN THE NORTHERN HILLY REGION OF CHHATTISGARH INDIA

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ABSTRACT

This study investigates the impact of agricultural drought on paddy yield in the Northern Hilly Region of Chhattisgarh over a 25-year period (1998–2022). Using the Agricultural Standardized Precipitation Index (aSPI12) computed via DrinC software, drought severity was classified into mild, moderate, severe, and extreme categories. Frequency distribution and spatial mapping revealed a marked increase in drought events after 2009, with the 2009–2010 period registering an extreme drought (aSPI12 < -2.5). Annual yield deviations showed a strong inverse relationship with aSPI12 values, indicating the direct effect of moisture stress on rice phenology and productivity. Box–Cox transformation was applied to normalize yield data due to non-normal distribution identified through the Shapiro–Wilk test. Findings suggest persistent drought vulnerability across the region, with yield reductions varying by severity level and spatial extent. The integration of aSPI12 into early warning and agro-advisory systems can enhance preparedness and resilience in rainfed rice cultivation across this climatically sensitive region.
***Keywords*:** Agricultural Drought, aSPI12, Paddy Yield, DrinC, Frequency Mapping, Rainfed Rice, Northern Hilly Region, NHZ.

Introduction

Drought is recognized as one of the most pervasive and economically disruptive natural hazards, exerting profound adverse effects on the agricultural sector. It manifests in multiple typologies, each reflecting a unique dimension of the drought phenomenon. Meteorological drought pertains to anomalies in climatic variables, chiefly precipitation deficits and temperature deviations, which collectively initiate the onset of drought conditions. In contrast, hydrological drought represents the downstream impacts on surface and groundwater resources, including reduced streamflow's, declining reservoir levels, and depleted aquifers. Of particular concern to crop science and food security is agricultural drought, often termed vegetation or soil moisture drought, which directly influences plant water uptake, physiological processes, and overall crop performance. The identification and characterization of drought remain inherently complex due to its gradual onset, indistinct boundaries, and highly variable spatial and temporal dynamics. Consequently, the development of precise and timely drought monitoring tools is indispensable for proactive management, mitigation planning, and the formulation of region-specific adaptation strategies.

Emerging research underscores a troubling expansion in drought-vulnerable regions across India, particularly in the post-1997 period. Contemporary assessments estimate that drought-exposed areas have surged by nearly 57%, a trend attributed to the combined effects of climate variability, land-use changes, and anthropogenic stress on water systems. In recent years, over one-third of India's administrative districts have experienced four or more drought events, affecting an estimated 50 million individuals annually through diminished agricultural outputs, food insecurity, and rural livelihood disruptions. The period between 2020 and 2022 was particularly alarming, with two-thirds of the nation's landmass encountering drought episodes of varying intensity. This widespread exposure has resulted in India being listed in the Global Drought Vulnerability Index, signalling the international recognition of the nation's ecological and economic susceptibility. The cumulative economic toll is equally stark drought-related losses have contributed to a 2% to 5% decline in Gross Domestic Product (GDP) over the two-decade span from 1998 to 2017, as reported by the United Nations Convention to Combat Desertification (UNCCD, 2022). These figures highlight the urgency of enhancing drought preparedness through improved forecasting systems, early warning mechanisms, and resilient agroecological planning tailored to regional climatic stressors.

Recent assessments by the Government of India have reported a significant decline in the net sown area under major Kharif season crops, including rice (*Oryza sativa* L.), pearl millet [*Pennisetum glaucum* (L.) R. Br. emend Stuntz], sorghum [*Sorghum bicolor* (L.) Moench], maize (*Zea mays* L.), groundnut (*Arachis hypogaea* L.), and soybean [*Glycine max* (L.) Merr.], over recent growing seasons. The contraction in cultivated area has been quantified at approximately 5% to 20%, accompanied by a corresponding reduction in total crop output ranging from 5% to 7%. These declines are predominantly attributed to the increasing frequency and severity of climatic stressors, most notably meteorological and agricultural drought, which have emerged as critical abiotic constraints in India's monsoon-dependent agricultural systems. The cascading impacts of such climatic aberrations are multidimensional, compromising the resilience of food production systems, destabilizing national food supply chains, and intensifying economic precarity among smallholder farmers. This is particularly evident in rainfed agroecosystems, where the absence of supplemental irrigation makes crop yields highly sensitive to intra-seasonal rainfall variability. The resultant crop failures trigger a series of socio-economic repercussions, including income losses, price volatility, and increased indebtedness, thereby amplifying rural agrarian distress (Gautam *et al*., 2014).

Historical climatological evidence further corroborates the persistent nature of drought as a systemic threat to Indian agriculture. A comprehensive historical analysis by Ghosh and Jana (1993) revealed that, between 1870 and 1990, drought recurrence was especially pronounced during the 1901–1925 period, during which 29 out of the 35 meteorological sub-divisions in India experienced severe to extreme drought conditions. These historical patterns not only underscore the long-term susceptibility of Indian agroecosystems to interannual climatic fluctuations but also highlight the structural inadequacy of existing adaptive frameworks to absorb hydrometeorological shocks. The continued prevalence of drought spanning both historical and contemporary timelines necessitates the urgent institutionalization of climate-resilient policy interventions, including the deployment of early warning systems, risk-informed cropping strategies, and index-based drought diagnostics such as Agricultural SPI (aSPI). These tools offer scalable, location-specific solutions for quantifying drought severity, facilitating agronomic decision-making, and minimizing productivity losses in India's increasingly climate-vulnerable agroecological landscapes.

Research by Mahesh *et al*. (2018) highlights the climatic dependency of agriculture in Chhattisgarh, where the average annual rainfall is approximately 1400 mm, with nearly 90% of this precipitation received during the southwest monsoon season (June–September). This high seasonal concentration of rainfall makes the region's agrarian systems particularly vulnerable to temporal variations in monsoonal activity, especially in rainfed agro-ecosystems, which constitute a substantial portion of the state's cultivated area. In such systems, even short-term water deficits during critical phenological stages such as tillering, flowering, and grain filling can significantly constrain crop productivity. Rice (*Oryza sativa* L.), the dominant rainfed crop in Chhattisgarh, is traditionally cultivated through broadcast sowing at the onset of monsoon rains. Farmers commonly grow long-duration rice varieties, which require more than 140 days to complete their life cycle, typically flowering in mid-October and reaching maturity by mid-November. However, as the southwest monsoon begins to retreat by mid-September, these rice crops often encounter terminal drought stress during their reproductive and grain-filling phases. This late-season water scarcity imposes substantial physiological stress, reducing grain yield and quality, and represents a recurrent challenge for paddy cultivation in upland areas of the state.

Complementing this agronomic understanding, the study by Das *et al*. (2009) underscores the magnitude of vulnerability in Chhattisgarh to episodic droughts. The 2002–2003 drought, cited as one of the most severe in the state's climatic history, severely disrupted the agricultural economy and affected all 16 administrative districts, thereby marking 100% spatial coverage of drought impact across the state. The worstaffected regions included Raipur, with 13 drought-hit tehsils, followed by Durg (11 tehsils) and Surguja (9 tehsils). The widespread spatial extent and severity of the drought highlighted the acute sensitivity of the state's monsoon-dependent agrarian systems to climate anomalies. These findings emphasize the urgent need for early-season drought monitoring, adaptive varietal selection, and the integration of tools like the agricultural Standardized Precipitation Index (aSPI) to enable timely interventions, support sustainable water management, and build long-term climate resilience in the region's rice-based farming systems.

In view of the recurring threat of climate-induced agricultural drought in India and the high dependency of rice cultivation on monsoonal rainfall, the present study focuses on evaluating the Paddy Yield Response to Agricultural Drought Stress in the Northern Hilly Region of Chhattisgarh for the period spanning 1998 to 2022. This upland agroclimatic zone, characterized by rainfed paddy cultivation, is especially vulnerable to terminal drought stress, as long-duration rice varieties often face water scarcity during the reproductive and grain-maturation stages due to the early retreat of the southwest monsoon. To monitor agricultural drought conditions effectively, this study will employ the 12-month Agricultural Standardized Precipitation Index (aSPI12), calculated using the DrinC (Drought Indices Calculator) software. DrinC facilitates multi-scalar drought assessment and enables detailed year-wise categorization of drought intensity into mild, moderate, severe, and extreme classes.

The computed aSPI12 values will be used to determine the number of drought events and their severity distribution across the 25-year period. These drought classifications will then be examined in relation to recorded paddy yield fluctuations, enabling a contextual understanding of how varying degrees of agricultural drought stress have influenced yield outcomes in the region. This investigation aims not at modeling or forecasting but rather at characterizing the historical drought landscape using aSPI-based monitoring to support the development of drought contingency planning, varietal advisories, and strategic interventions for upland rice farming in Chhattisgarh. The integration of DrinC-based aSPI monitoring into agroecological assessments offers a scalable, field-oriented tool for future drought preparedness and policy decision-making.

Materials and Methods

Study area and Data collection

The study was conducted for the Northern Hilly Region of Chhattisgarh, focusing on the period 1998 to 2022. Daily gridded weather data was obtained from the India Meteorological Department (IMD), with rainfall at 0.25° × 0.25° resolution and temperature (Tmax, Tmin) at 1.0° × 1.0° resolution. This dataset was used for drought index calculation. Corresponding agricultural data on paddy including annual production (kg) and area sown (ha) from 1998 to 2022 was sourced from the Directorate of Economics and Statistics, under the Department of Agriculture and Farmers Welfare. These datasets supported the assessment of agricultural drought and its impact on paddy yield.

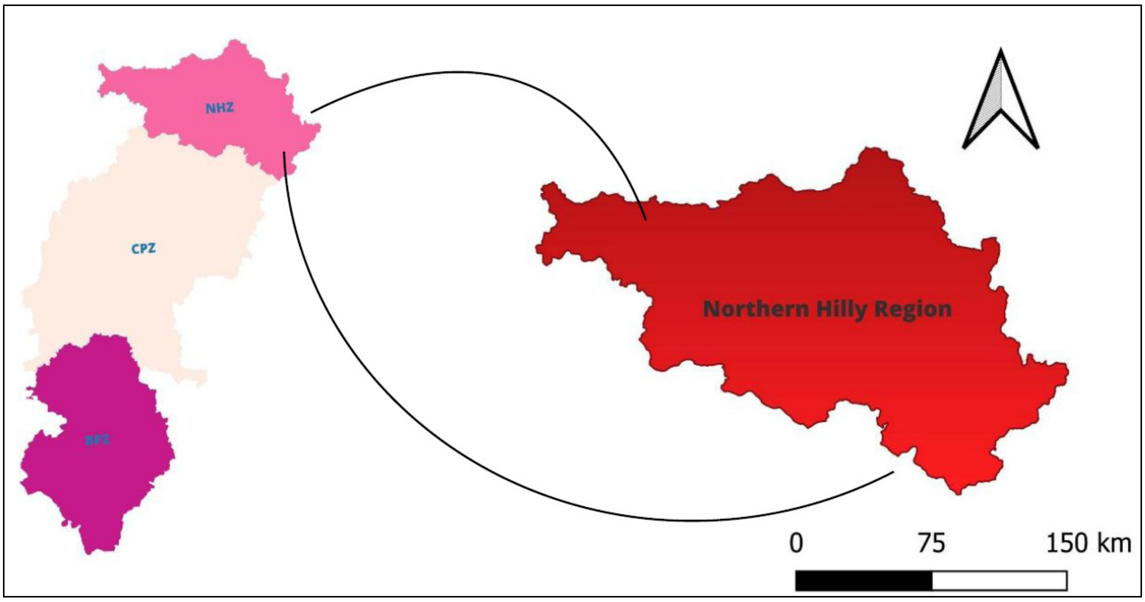

Fig. 1 : Study Area Map of Northern Hilly Region

Transformation techniques are widely used in time series analysis to eliminate systematic variations or non-stationary trends, thereby enabling a more accurate interpretation of the underlying data structure. While a variety of transformation methods have been proposed in the literature, comprehensive evaluations of their consistency and effectiveness in capturing long-term agronomic yield patterns remain limited. This gap is particularly relevant in drought-related research, where the non-stationary behavior of yield time series poses significant challenges in the objective identification and attribution of drought impacts (Kumar *et al.*, 2024). In the present study, paddy yield time series data (1998–2022) for the Northern Hilly Region of Chhattisgarh was analyzed. To stabilize variance and enhance interpretability, the Box-Cox transformation was applied using the XLSTAT software, serving as a preparatory step for subsequent drought impact assessment.

Mathematical Frameworks for Computing Drought Index

A wide range of drought indices have been developed for the effective identification and quantification of drought conditions across different temporal and spatial scales. Among these, the Agricultural Standardized Precipitation Index (aSPI), as proposed by Tigkas *et al.* (2019), has gained prominence for assessing agricultural drought by incorporating precipitation anomalies relevant to crop-specific growing periods. In the present study, the gamma probability distribution function was utilized to model long-term precipitation data, providing the statistical foundation for computing aSPI values and facilitating the standardization of precipitation time series for drought classification.

For the aSPI, the cumulative probability distribution is transformed into a normal distribution through the approximation of Eq (1) (Tigkas *et al.*, 2019) (McKee *et al.*, 1993)

$$aSPI = -\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right), 0 < H(x) \leq 0.5 \quad (1)$$

$$where\ t = \sqrt{ln\frac{1}{H(x)^2}} \quad (2)$$

$$aSPI = \left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right), 0.5 < H(x) \leq 1.0 \quad (3)$$

$$where\ t = \sqrt{ln\frac{1}{1-H(x)^2}} \quad (4)$$

and c_0=2.515517, c_1=0.802853, c_2=0.010328, d_1=1.43278, d_2=0.189269, d_3=0.001308

Determination of the index of drought

Using the DrinC software, the Agricultural Standardized Precipitation Index (aSPI) was computed for a 12-month timescale, enabling the detection of long-term agricultural drought events. Prior to index computation, the software was supplied with monthly aggregated data on precipitation (P), maximum temperature (Tmax), and minimum temperature (Tmin), which were derived from daily meteorological records. The standardized formulation of aSPI, as noted by Guttman *et al*. (1999), ensures spatial and temporal comparability, thereby allowing the estimation of drought frequency and severity across agroclimatic contexts. The classification of drought severity levels based on aSPI values follows the established thresholds proposed by Tsakiris *et al.* (2007) and Proutsos and Tigkas (2020). These thresholds, summarized in Table 1, enable the categorization of drought conditions into mild, moderate, severe, and extreme classes, providing a structured framework for drought impact assessment.

Table 1 : Classification of the indices SPI, aSPI, RDI, eRDI

SPI, aSPI, RDI & eRDI (Dimensionless)	Category
>= 2.00	Extremely wet
1.5 to 1.99	Severely wet
1.0 to 1.49	Moderately wet
0.0 to 0.99	Mildly wet
0.0 to -0.99	Mild drought
-1.00 to -1.49	Moderate drought
-1.50 to 1.99	Severe drought
<=-2.00	Extreme drought

Results and Discussion

Monitoring of Agricultural Droughts at a 12-Month Timestep

The assessment of agricultural drought severity over a 25-year period (1998–2022) in the Northern Hilly Region of Chhattisgarh using the aSPI12 index reveals a distinct temporal pattern of increasing drought frequency and intensity. As shown in Figure 2, the region has experienced recurrent mild drought conditions, interspersed with more intense events such as moderate, severe, and extreme droughts. The early years of the series, from 1998–1999 to 2007–2008, were characterized primarily by alternating mild drought and mild wet conditions, with aSPI12 values fluctuating moderately between –0.93 and +1.32.

These suggest that while drought events did occur, they were of limited severity and relatively short duration.

However, the onset of 2009–2010 marks a critical hydrometeorological turning point, with the aSPI12 index plunging to –2.68, indicating an extreme drought year. This was followed by a severe drought in 2010–2011 (aSPI12 = –1.82) and a cluster of moderate drought years, particularly between 2013–2015, where the index remained below –1.00. This sequence underscores a shift toward prolonged and intensified agricultural drought conditions, notably coinciding with the terminal growth stages of rainfed paddy crops, making them particularly vulnerable to yield loss. Even in subsequent years, although some periods like 2011–2012 and 2017–2018 recorded mild wet anomalies, the overall pattern indicates more frequent dry years. From 2013 onwards, aSPI12 values rarely crossed the 0.50 threshold, with the majority of years classified as mild to moderate droughts, suggesting a persistent moisture deficit that has become increasingly entrenched in the region's climatic regime.

These findings align with the broader climatic transitions documented across Chhattisgarh. A related study by Bhelawe *et al.* (2017) reinforces this observation, reporting a consistent trend toward drier conditions in the state's major agroclimatic zones. The research highlighted a progressive rise in the aridity index and declining levels of available soil moisture, particularly post-1980, indicative of a structural shift toward hydrometeorological stress. Both the present investigation and the findings of Bhelawe *et al.* converge on the notion that the intensification of drought events, especially over the last two decades, is symptomatic of a broader climatic transition toward aridity. This evolution in regional drought patterns underscores the urgency for integrating long-term drought monitoring tools like aSPI12 into agroecological planning and resource management strategies to enhance climate resilience in vulnerable cropping systems.

Frequency Distribution of Varied Severity

The frequency distribution Figure 3 of drought severity categories based on the aSPI12 index (1998–2022) in the Northern Hilly Region of Chhattisgarh provides a clear indication of the region's agroclimatic vulnerability and hydrometeorological trends over time. This classification helps in understanding not just how often droughts occur, but also how intense they are both of which have significant implications for rainfed paddy cultivation.

- **Mild Drought (10 years):** This category had the highest frequency, comprising 40% of the years analyzed. Mild droughts reflect relatively short or less intense moisture deficits, often not severe enough to trigger complete crop failure but still capable of reducing rice tillering, delaying phenology, or lowering grain weight. The high number of mild drought years suggests that chronic moisture stress has become a recurring background condition in this region.
- **Mild Wet (9 years):** These years represent near-normal to slightly above-normal rainfall, contributing to generally favorable growing conditions. However, even "mild wet" years may include short dry spells, especially if rainfall is erratically distributed. Their close frequency to mild drought years points to high inter-annual variability, which complicates farm-level planning and necessitates resilient varietal and irrigation strategies.
- **Moderate Drought (2 years):** Years with moderate drought indicate more sustained and impactful dry conditions, often associated with aSPI12 values between –1.00 and–1.49. These conditions can significantly hinder panicle initiation, grain filling, and final yield, especially in long-duration paddy varieties, and often require external interventions such as supplementary irrigation or drought relief measures.
- **Moderate Wet (1 year):** A single occurrence of moderate wet conditions suggests that significantly surplus rainfall was rare during the study period. While generally beneficial, such years can also pose waterlogging or pest pressure risks if drainage infrastructure is inadequate.
- **Severe Drought (1 year):** A year classified under this category typically corresponds to aSPI12 values less than –1.5, signaling major long-term water stress. In such years, reproductive failure, yield collapse, and widespread agricultural loss are common, particularly in districts lacking irrigation backup or drought-resistant cultivars.
- **Extreme Drought (1 year):** The occurrence of an extreme drought year (i.e., 2009–2010) reflects exceptional rainfall deficit and soil moisture exhaustion, often aligning with broader regional or national drought events. These events are catastrophic, leading to crop failure across large areas, food insecurity, and declines in farm income.

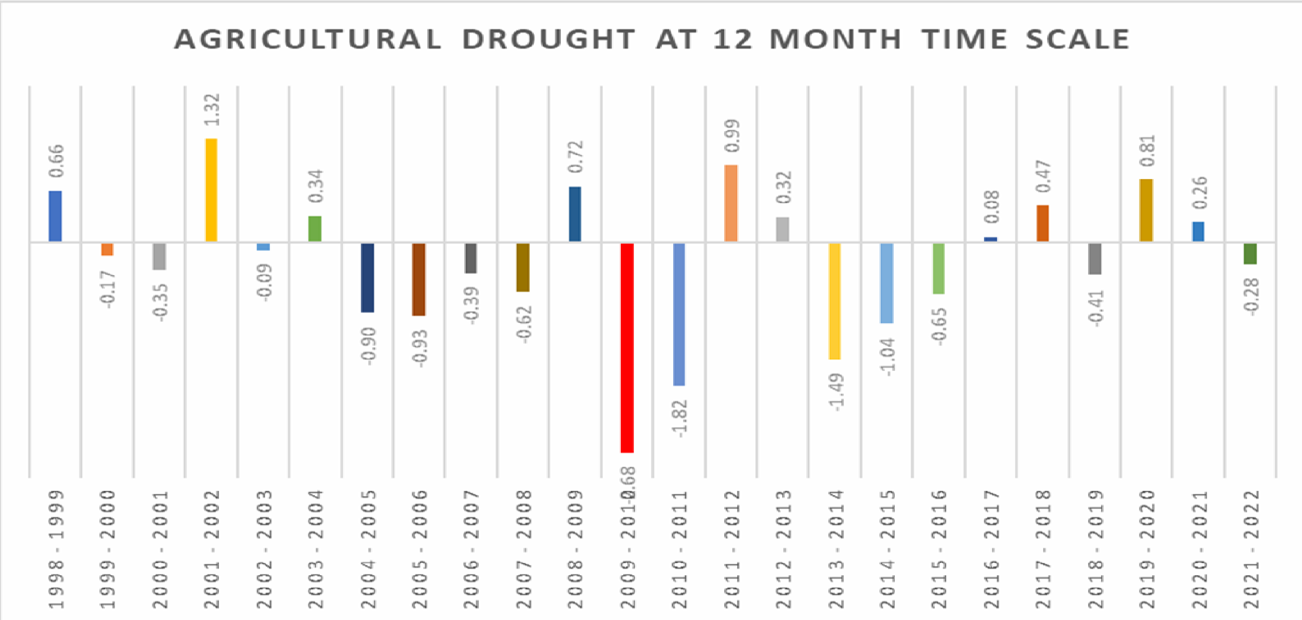

Fig. 2 : Monitoring of Agricultural Droughts (aSPI) at a 12-Month Timestep

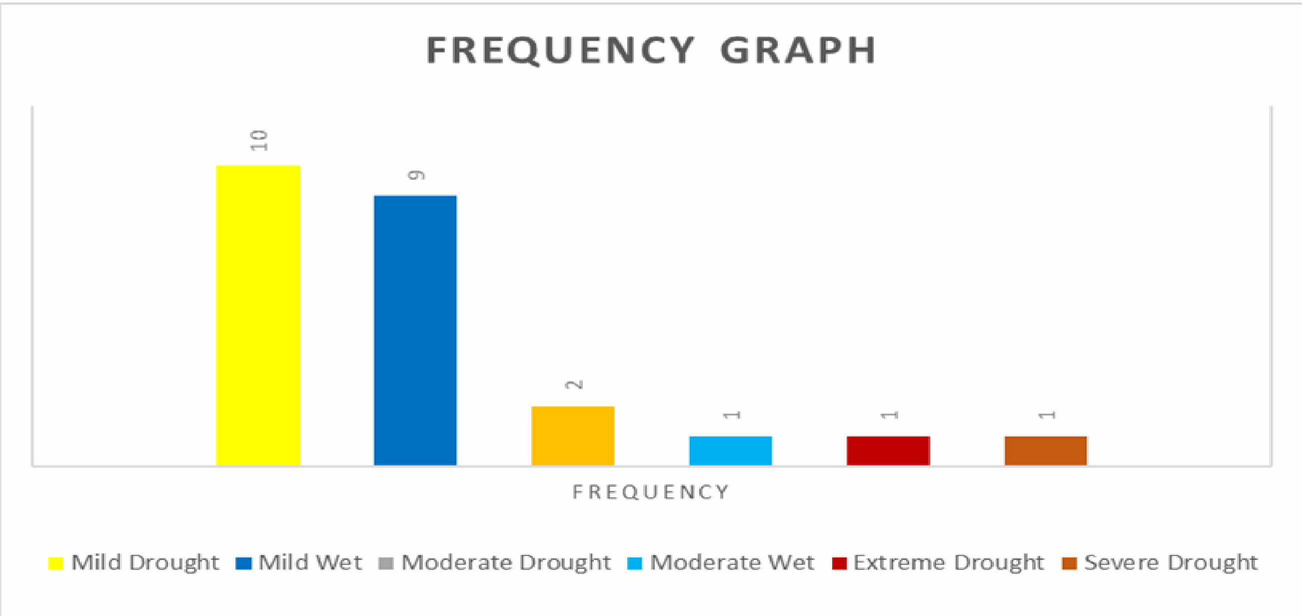

Fig. 3 : Frequency Graph of Different Severity Levels

Annual comparison of agricultural drought severity (aSPI12) and standardized paddy yield anomalies in the Northern Hilly Region of Chhattisgarh (1998–2022)

To assess the suitability of rice yield data for parametric statistical analysis, a normality test was conducted using the Shapiro–Wilk method. The test yielded a p-value less than the designated significance threshold ($\alpha = 0.05$), indicating that the data significantly deviated from a normal distribution. Consequently, the null hypothesis (H_0: data are normally distributed) was rejected in favour of the alternative hypothesis (H_1: data are not normally distributed). Given this violation of the normality assumption, a Box–Cox transformation was subsequently applied to stabilize variance and approximate a Gaussian distribution, thereby enabling the use of further parametric procedures.

Following transformation, the analysis proceeded to quantify the influence of agricultural drought on rice yield across the study region. Results revealed that drought intensity exhibited a statistically significant effect on rice production, with clear spatial variability in yield response patterns. Each district within the

Northern Hilly Region of Chhattisgarh demonstrated distinct magnitudes of yield reduction corresponding to different levels of aSPI12-classified drought severity, underscoring the heterogeneous impact of drought stress on crop performance across localized agro-ecological zones. The temporal relationship between agricultural drought intensity and paddy yield in the Northern Hilly Region of Chhattisgarh, as depicted in Figure 4, underscores the pronounced sensitivity of rice crops to long-term moisture deficits. The graph illustrates a comparative assessment between the Agricultural Standardized Precipitation Index at a 12-month scale (aSPI12) and standardized paddy yield anomalies from 1998–1999 to 2021–2022. The aSPI12 bars, which represent deviations from the long-term climatic norm in terms of agricultural water availability, reveal multiple episodes of negative anomalies indicative of agricultural drought. Notably, the period from 2006 to 2010 is characterized by consecutive years of moderate to extreme drought, culminating in 2009–2010 where the aSPI12 value dropped below –2.5, signaling an intense and prolonged agricultural drought event. This year also recorded the most substantial decline in paddy yield, reflecting the direct physiological and phenological stress imposed on the rice crop under conditions of sustained water scarcity. In general, the inverse trend observed between aSPI12 and paddy yield suggests a strong coupling between drought conditions and rice productivity. Years marked by negative aSPI12 values consistently correspond to periods of below-normal yield, reaffirming that annual-scale water stress hampers tillering, panicle formation, and grain filling stages in rice illustrated in Figure 4. The yield downturns in 2001–2002, 2005–2006, and 2014–2015 further align with moderately negative aSPI12 values, reinforcing the vulnerability of rainfed paddy systems to even mild drought episodes. In contrast, recovery phases such as 2010–2011 and 2012–2013, associated with positive aSPI12 values, show immediate yield rebounds, indicating the responsive nature of paddy crops to improved hydrological conditions.

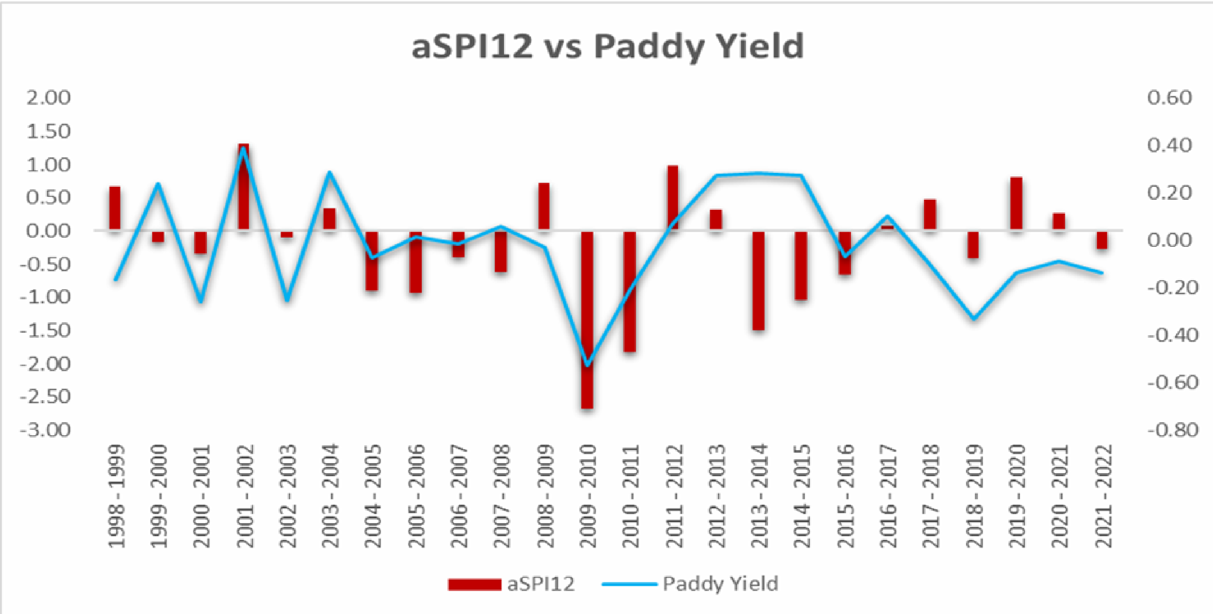

Fig. 4 : Annual comparison of (aSPI12) and paddy yield

However, the persistence of moderate drought in subsequent years (e.g., 2016–2018) despite modest yield stabilization suggests the influence of adaptive agronomic practices or residual soil moisture buffering. This long-term comparison highlights the utility of the aSPI12 index in quantifying agricultural drought impacts at a plant-relevant timescale. The consistency of the drought–yield interaction provides a robust framework for integrating aSPI12 into early warning systems and agro-advisory protocols tailored to upland rice-growing regions. Given the climatic volatility and topographic constraints of the Northern Hilly Zone, such drought-yield assessments are critical for informing climate-resilient agricultural planning and ensuring the sustainability of paddy cultivation in vulnerable agroecological zones.

Drought risk mapping

The present study focuses on analyzing the spatiotemporal behavior of agricultural drought by generating frequency distribution maps derived from aSPI12 (Agricultural Standardized Precipitation Index) data spanning the period 1998 to 2022. The analytical methodology involves converting continuous drought index values into binary categorical representations, enabling the classification of drought events into distinct severity levels—namely mild, moderate, severe, and extreme. By systematically tracking the recurrence of drought episodes at each spatial unit, the study produces a detailed, location-specific understanding of agricultural drought frequency and intensity. The resulting frequency maps (refer to Figure 5) serve as a valuable diagnostic tool for identifying areas of persistent agricultural drought exposure within the Northern Hilly Region of Chhattisgarh. This spatially explicit approach facilitates a nuanced evaluation of both the temporal persistence and geographical concentration of drought risk. In doing so, it supports a more informed interpretation of regional drought vulnerability patterns, providing critical input for adaptive planning, drought preparedness, and policy formulation aimed at safeguarding rainfed agriculture in this climatically sensitive zone.

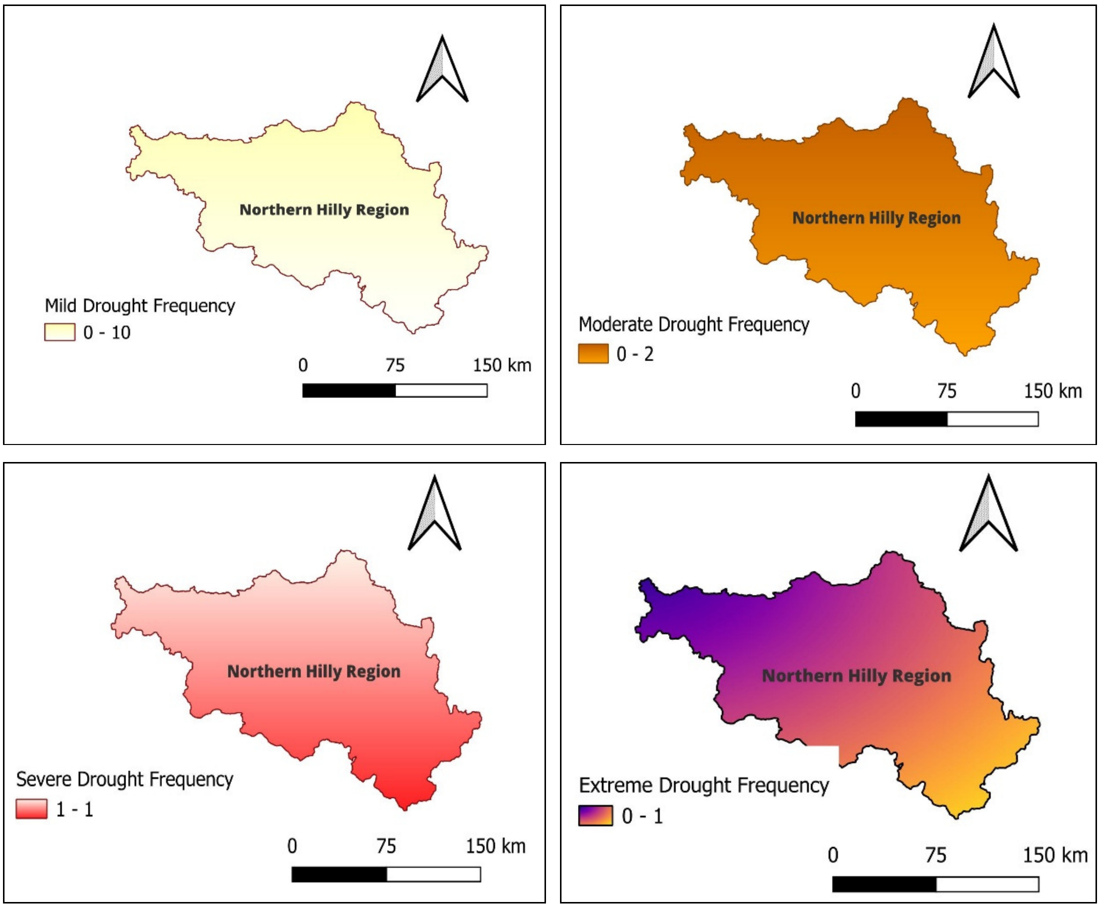

Fig. 5 : Drought risk mapping

Conclusion

The analysis of agricultural drought patterns in the Northern Hilly Region of Chhattisgarh, based on aSPI12 over the period 1998–2022, revealed a clear trend towards increasing frequency and intensity of drought events. The most severe impacts on paddy yield were associated with extreme and severe drought years, notably during 2009–2010 and 2010–2011. Mild droughts were the most frequent, underscoring the chronic nature of water stress in the region. The study confirmed that agricultural drought significantly influences rice yield variability, with each district exhibiting unique response patterns. By applying a standardized drought index (aSPI12) through DrinC software and integrating it with yield data, this study offers a comprehensive framework for drought monitoring and risk assessment. These findings support the implementation of targeted drought adaptation measures and policy interventions to safeguard rainfed agriculture in upland rice-growing zones.

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Conflict of Interest Statement: The authors declare that there is no conflict of interest regarding the publication of this paper.

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