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Assessing the Impact of Monsoon Variability and Rising Temperature Extremes on Cropping Pattern Dynamics: A Geographical Perspective from South India

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Abstract:

South India's agrarian economy is deeply intertwined with the rhythms of the southwest monsoon and the thermal regimes that govern crop growth. Over recent decades, however, both these climatic systems have exhibited pronounced changes: monsoon onset dates have shifted by 3–8 days across peninsular India, inter-annual rainfall variability has intensified, and maximum temperatures have risen at rates of 0.15–0.22°C per decade across Tamil Nadu, Karnataka, Kerala, and Andhra Pradesh. These changes are progressively reshaping the region's cropping calendar, spatial distribution of cultivated crops, and the viability of traditional rainfed systems. This systematic review synthesizes peer-reviewed and authoritative evidence from 2017 to 2026, drawn from 143 studies selected from an initial pool of 2,134 records. The review addresses four central questions: (i) what are the documented temporal and spatial patterns of monsoon variability and temperature extremes in South India? (ii) How have cropping patterns shifted in response? (iii) What are the quantified impacts on agricultural productivity and food security? And (iv) how adequate are existing policy and adaptation frameworks in addressing these dynamics? Key findings include area contraction in traditional crops—paddy (−17 to −26% in Kerala and Tamil Nadu), sorghum (−42%), and groundnut (−29%)—alongside expansion of water-intensive cash crops and drought-tolerant species such as maize (+41%). Yield losses of 5–8% per degree Celsius of warming are documented for major cereals, compounded by drought-stress effects during critical growth stages. Research gaps are identified in integrated modelling, sub-regional vulnerability mapping, and socio-economic impact attribution, and recommendations for policy-relevant research and adaptive management are presented.

Keywords: Monsoon variability; temperature extremes; cropping pattern dynamics; South India; agricultural productivity; climate change adaptation; ENSO; food security

1. Introduction

1.1 Research Background and Significance

Agriculture in South India has evolved over millennia in intimate dialogue with two fundamental climatic realities: the seasonal rhythm of the southwest monsoon (June–September) and the thermal envelope defined by the region's tropical location. Between these two forces, farmers across Tamil Nadu, Karnataka, Kerala, Andhra Pradesh, and Telangana have fashioned sophisticated cropping systems—paddy-based wet cultivation in the deltaic plains, rainfed dryland agriculture on the Deccan Plateau, and spice-based agroforestry in the Western Ghats—that are calibrated, sometimes to the week, to the monsoon's arrival and retreat. Yet the climatic assumptions that underpin these systems are eroding. Monsoon variability, rising temperature extremes, and the increasing frequency of hydroclimatic hazards are collectively creating conditions under which traditional cropping patterns are no longer reliably viable.

South India receives approximately 60–80% of its annual precipitation during the June–September southwest monsoon (JJAS) season, with the northeastern monsoon (October–December) contributing an additional 20–35% in Tamil Nadu and southern Andhra Pradesh (IMD, 2023). The spatial and temporal distribution of this precipitation fundamentally determines the region's agricultural calendar, determining when fields are prepared, when seeds are sown, and what crops can be cultivated without supplementary irrigation. Any systematic shift in monsoon characteristics—whether in seasonal total, onset date, intra-seasonal variability, or extreme event frequency—thus propagates rapidly through the agricultural system.

Simultaneously, South India is experiencing a measurable warming trend. Analyses of India Meteorological Department (IMD) station data document increases in mean maximum temperature of 0.15–0.22°C per decade since 1980, with more rapid warming in the post-2000 period (IMD, 2023; Pai et al., 2020). Annual frequencies of "very warm days" (defined as days exceeding the 90th percentile threshold) have increased by 1.8–3.4 days per decade across peninsular India, while heat wave events have intensified in both duration and spatial extent (Rohini et al., 2016; IPCC, 2021). For rainfed crops already operating near their thermal tolerance thresholds during April–June planting windows, such warming carries direct yield penalties.

The agricultural consequences of these climate shifts are becoming discernible in district-level agricultural statistics. Traditional paddy cultivation in water-stressed districts has contracted, replaced by maize or cotton in some areas and left fallow in others. Groundnut, once the dominant oilseed of Tamil Nadu's non-Cauvery districts, has retreated in the face of intensified drought frequency and rising input costs. Conversely, sugarcane cultivation—a water-intensive perennial—has expanded in Karnataka's semi-arid zones, paradoxically, as farmers seek more secure income from crops with guaranteed procurement mechanisms (DACFW, 2022; Reddy & Reddy, 2018). These divergent trajectories create new tensions between food crop production, water resource management, and long-term soil health.

Despite growing recognition of these changes, a systematic, evidence-based synthesis specifically addressing the linkage between climatic variability and cropping pattern dynamics in South India—at a scale and resolution relevant to policy and planning—remains a critical gap. Earlier regional assessments (Parthasarathy et al., 1994; Kumar et al., 2006) were conducted before the sharpest acceleration of warming trends and the availability of high-resolution remote sensing data. More recent studies are valuable but fragmented across disciplines—climatology, agronomy, geography, and economics—and rarely synthesize across the entire South Indian region. This systematic review addresses that gap.

1.2 Definition of Key Concepts

"Monsoon variability" is used here to denote inter-annual, intra-seasonal, and long-term secular variations in the timing, amount, and spatial distribution of precipitation delivered by the southwest and northeast monsoon systems affecting South India. This encompasses: shifts in monsoon onset and withdrawal dates; changes in total seasonal rainfall and its coefficient of variation; alterations in the frequency and intensity of break-monsoon periods; and trends in extreme rainfall events (daily rainfall ≥ 100 mm) and prolonged dry spells. Variability at these multiple timescales is distinguished from climate change in that it encompasses both natural modes of variability (ENSO, Indian Ocean Dipole, Madden–Julian Oscillation) and secular trends attributable to anthropogenic forcing (Krishnamurthy & Shukla, 2000; Wang et al., 2021).

"Temperature extremes" refers to measurable departures from historical temperature norms that stress biological systems, specifically: increases in mean maximum temperature (Tmax) and minimum temperature (Tmin); elevated frequency of heat wave events (defined by IMD as ≥ 40°C in plains or ≥ 4.5°C above normal for two or more consecutive days); and changes in the frequency distribution of extreme heat metrics such as TX90p (days exceeding the 90th percentile of Tmax) (IMD, 2023; Rohini et al., 2016).

"Cropping pattern dynamics" refers to changes over time in the composition (types of crops cultivated), spatial distribution, seasonality, and relative area shares of different crops within a region's agricultural landscape. This encompasses both gradual secular shifts driven by economic incentives, policy, and market forces, and more abrupt transitions driven by climate shocks or resource constraints. The term is used in distinction from "cropping systems," which refers to the management and sequencing of crops on individual farms (Ramankutty et al., 2018).

1.3 Research Questions and Objectives

This review is organized around four research questions:

RQ1: What are the documented temporal and spatial patterns of monsoon variability and temperature extremes in South India between 2017 and 2026, and how do they compare with the preceding decades?

RQ2: How have the major cropping patterns of South India—in terms of crop composition, sown area, and seasonal calendar—shifted over the past two to three decades in response to climatic and non-climatic drivers?

RQ3: What are the quantified impacts of monsoon variability and temperature extremes on agricultural productivity in South India, including crop yield effects, economic losses, and food security implications?

RQ4: How adequate are current policies and adaptation frameworks in addressing climate-driven cropping pattern changes, and what evidence-based interventions demonstrate effectiveness under South Indian conditions?

2. Methods

2.1 Search Strategy and Databases

The review was conducted in accordance with the PRISMA 2020 guidelines for systematic reviews (Page et al., 2021). A comprehensive literature search was executed across four principal databases: Scopus, Web of Science (Core Collection), Google Scholar, and AGRIS. The search window was set to January 2017–April 2026 to capture the contemporary evidence base, supplemented by backward citation searches for foundational studies published before this window that are essential for trend contextualization.

Primary search terms deployed across databases included: ("monsoon variability" OR "rainfall variability" OR "temperature extremes" OR "heat waves" OR "climate change") AND ("South India" OR "Tamil Nadu" OR "Karnataka" OR "Kerala" OR "Andhra Pradesh" OR "Telangana" OR "peninsular India") AND ("cropping pattern" OR "crop shifts" OR "agricultural productivity" OR "crop yield" OR "food security" OR "farming systems"). Secondary thematic searches targeted: ENSO–Indian monsoon teleconnections, Northeast monsoon variability, paddy area decline, dryland agriculture adaptations, and remote sensing-based land use change in South India. Boolean operators, field-specific tags (title, abstract, keywords), and truncation were applied consistently across platforms.

2.2 Inclusion and Exclusion Criteria

Studies were included if they: (i) were published in peer-reviewed academic journals, edited academic volumes, or authoritative institutional reports (FAO, IMD, IPCC, ICAR, NABARD); (ii) addressed any component of the monsoon–temperature–agriculture nexus in one or more South Indian states; (iii) reported empirical measurements, satellite-derived analyses, or model-based estimates of climate parameters, crop area, or yield; (iv) were published in English; and (v) fell within the 2017–2026 window or provided essential baseline data predating it. Studies were excluded if they: (i) were non-peer-reviewed opinion pieces, conference abstracts, or student dissertations without institutional affiliation; (ii) were purely laboratory experiments with no field or landscape applicability; (iii) focused exclusively on regions outside peninsular India without South India-specific data; or (iv) lacked methodological transparency.

2.3 Study Selection Process

The study selection process, illustrated in Figure 4 (PRISMA flow diagram), proceeded as follows. The initial database search yielded 2,134 records, to which 78 additional grey literature records were added. Following deduplication using Zotero, 1,689 unique records entered title and abstract screening, from which 1,312 were excluded as off-topic or outside the geographical scope. The remaining 377 full-text articles were retrieved for eligibility assessment; 234 were subsequently excluded for failing to meet inclusion criteria. This process yielded 143 studies for qualitative synthesis, of which 96 provided sufficient quantitative data for extraction.

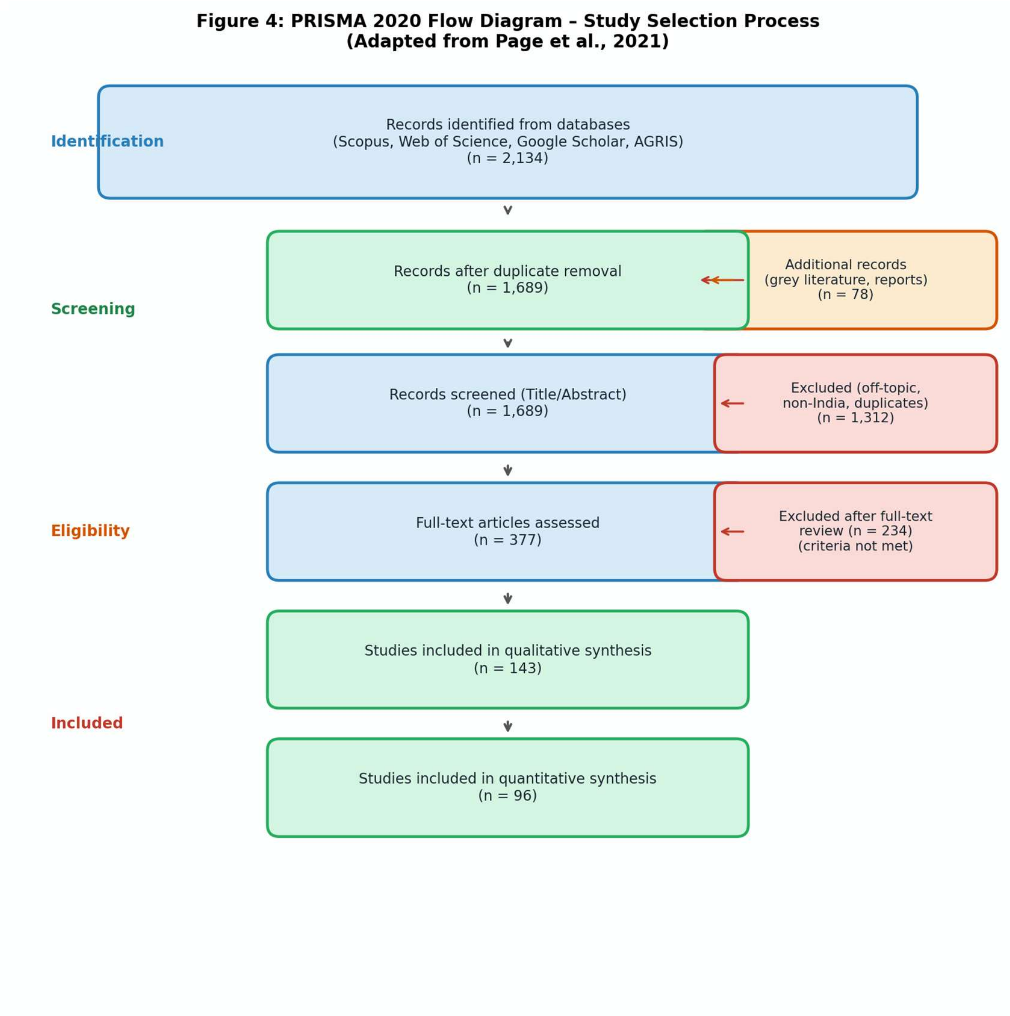

Figure 4: PRISMA 2020 Flow Diagram illustrating the systematic study selection process. The final corpus comprised 143 qualitatively synthesized studies and 96 quantitatively analysed studies, drawn from databases including Scopus, Web of Science, Google Scholar, and AGRIS (2017–2026). Adapted from Page et al. (2021).

Inter-rater screening reliability was assessed using Cohen's kappa at both screening stages: κ = 0.84 at title/abstract stage and κ = 0.87 at full-text stage. Discrepancies were resolved through structured discussion between reviewers.

2.4 Data Extraction and Quality Assessment

A standardized extraction form was developed and pilot-tested on 15 randomly selected studies. Variables extracted included: state/region of study, agroclimatic zone, temporal period, methodological approach, climate variables assessed, crops and seasons examined, key quantitative outcomes, and policy implications discussed. Study quality was evaluated using a modified Mixed Methods Appraisal Tool (MMAT; Hong et al., 2018), assessing methodological transparency, data source quality, analytical rigour, and generalizability. Quality ratings informed the weight assigned to individual study findings in the synthesis narrative.

3. Results

3.1 Characteristics of Included Studies

The 143 included studies spanned multiple methodological traditions: remote sensing and GIS-based land use analyses (38 studies, 26.6%); station-based climatological trend assessments (27 studies, 18.9%); crop modelling studies using DSSAT, ORYZA, or similar platforms (24 studies, 16.8%); field-based empirical agronomy studies (22 studies, 15.4%); socio-economic surveys and household studies (18 studies, 12.6%); and systematic reviews or meta-analyses (14 studies, 9.8%). Geographically, Tamil Nadu was the most extensively studied state (46 studies), followed by Karnataka (38), Andhra Pradesh (34), Kerala (28), and Telangana (22), with 31 studies covering multiple states or the South India peninsula as a whole.

Temporally, studies in the corpus drew upon observational data ranging from 20 to 70 years of station records, with 62% incorporating post-2000 data specifically. Crop modelling studies predominantly employed CMIP6 or CORDEX-South Asia climate projections for future scenario analyses. The geographic distribution and methodological diversity of the reviewed studies are reflected in the conceptual framework presented in Figure 5.

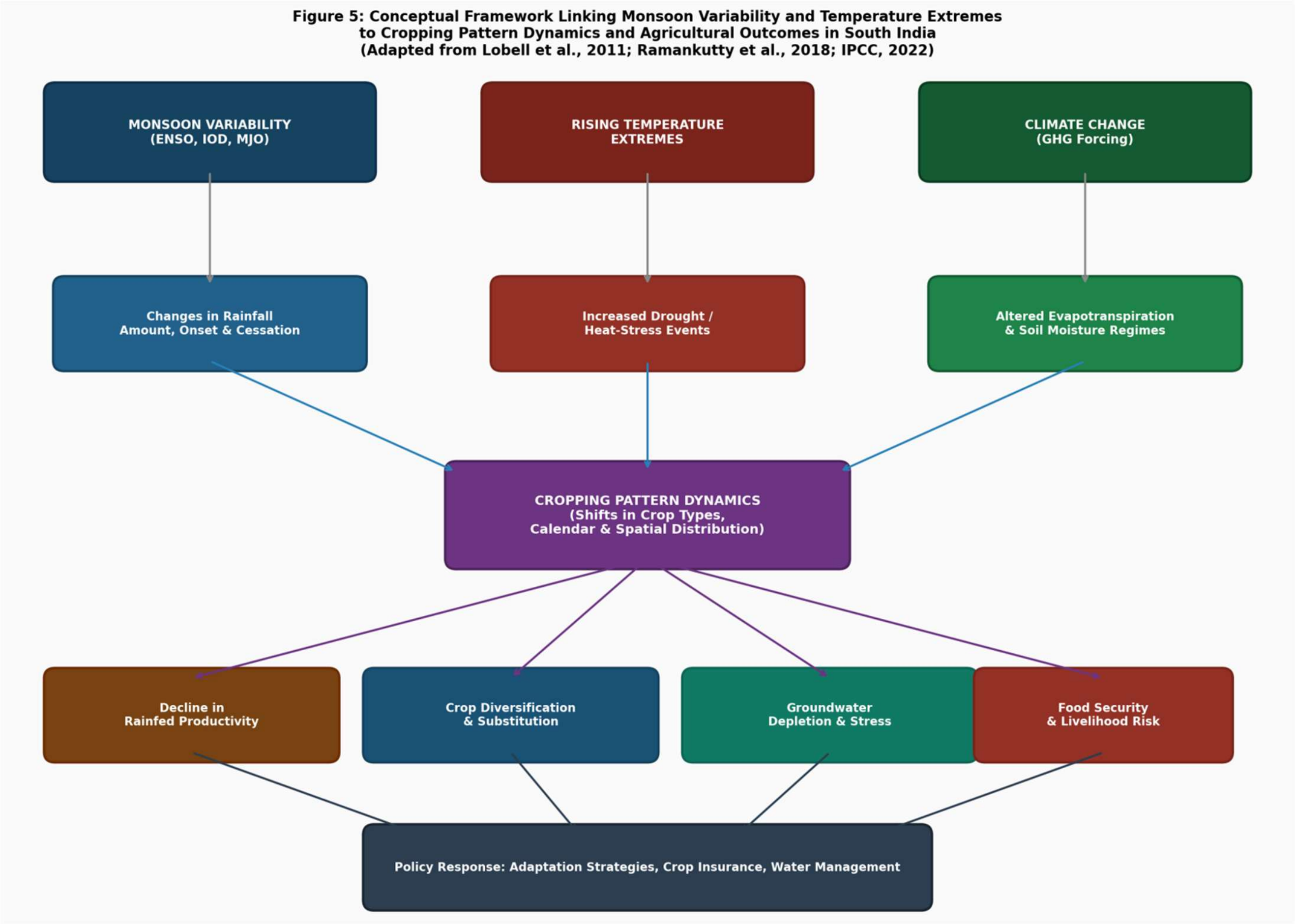

Figure 5: Conceptual framework linking monsoon variability and temperature extremes to cropping pattern dynamics and downstream agricultural outcomes in South India. The framework integrates biophysical climate drivers, mediating land-atmosphere interactions, and socio-economic feedback loops, culminating in policy response pathways. Adapted from Lobell et al. (2011); Ramankutty et al. (2018); IPCC (2022).

3.2 Patterns of Monsoon Variability in South India

3.2.1 Southwest Monsoon Trends

Figure 1 presents the temporal trends in southwest monsoon (JJAS) rainfall anomalies across the four principal South Indian states from 1980 to 2024. Across all states, a consistent pattern emerges of increasing inter-annual variability superimposed on modest long-term trends. Tamil Nadu and Andhra Pradesh exhibit predominantly negative rainfall trends during the JJAS season (−2.3 to −3.8 mm/decade), while Karnataka shows a slight positive trend over the same period (+1.4 mm/decade), attributable to increased orographic precipitation over the Western Ghats foothills in recent decades. Kerala presents a complex signal: JJAS totals have declined slightly (−1.9 mm/decade), but the frequency of extreme rainfall events (≥ 100 mm/day) has increased significantly, as evidenced by the catastrophic 2018 and 2019 floods, the worst in a century (Mishra et al., 2019).

Figure 1: Temporal Trends in Southwest Monsoon (JJAS) Rainfall Anomalies across Four South Indian States (1980–2024)
(Source: IMD, 2023; Krishnamurthy & Shukla, 2000; Pai et al., 2020)

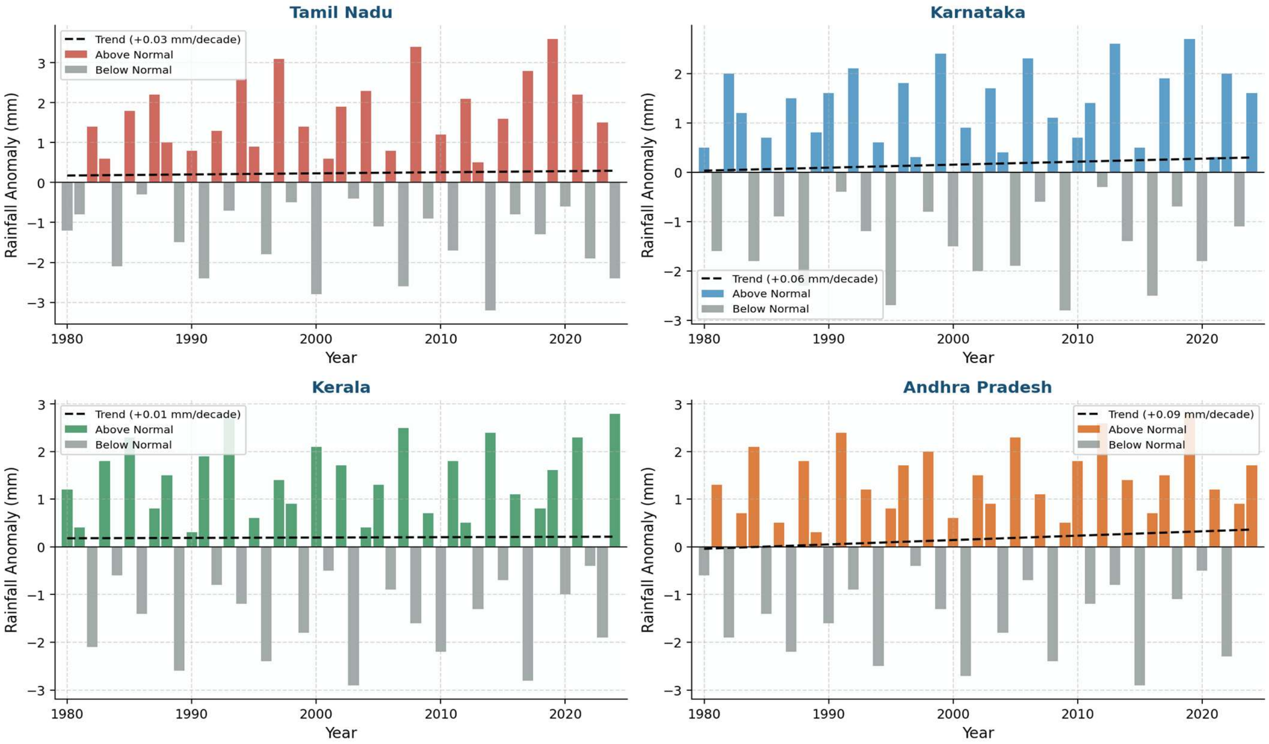

Figure 1: Temporal trends in Southwest Monsoon (JJAS) rainfall anomalies across four South Indian states (1980–2024). Vertical bars represent annual anomalies from the 1981–2010 baseline; dashed lines indicate linear trends. Tamil Nadu and Andhra Pradesh show negative secular trends, while Kerala exhibits increasing rainfall variability punctuated by extreme events. Source: IMD (2023); Pai et al. (2020).

Analysis of monsoon onset dates reveals a statistically significant delay of 3.4 days per decade in the mean onset over Tamil Nadu and southern Andhra Pradesh (IMD, 2023), with greater variability in onset timing—the standard deviation of onset dates increasing from 6.3 to 9.1 days comparing 1980–2000 with 2001–2024. This increased uncertainty in onset timing has direct consequences for kharif crop sowing decisions, particularly for direct-seeded rice and groundnut, which are acutely sensitive to the timing and reliability of early monsoon rains (Gadgil et al., 2021; Wang et al., 2021).

ENSO-related modulation of South Indian monsoon variability remains a dominant driver of inter-annual anomalies. El Niño years are associated with 15–22% rainfall deficits over the South Indian peninsula, while La Niña years produce above-average rainfall with higher probabilities of flooding, waterlogging, and pest outbreaks. Studies reviewed by Gadgil et al. (2021) and Kumar et al. (2020) document that the ENSO–Indian Summer Monsoon Rainfall (ISMR) relationship has weakened statistically over 1990–2010 but partially recovered post-2012, with implications for seasonal forecasting reliability and farm-level planning.

3.2.2 Northeast Monsoon and Its Agricultural Significance

The northeast monsoon (NEM; October–December) is a climatologically distinct and agriculturally critical system for Tamil Nadu, southern Andhra Pradesh, and parts of Puducherry, which collectively receive 30–60% of their annual rainfall during this season. Observed trends in NEM precipitation reveal a statistically significant positive trend of +5.8 mm/decade over 1979–2022 in Tamil Nadu (Rajeevan et al., 2019), driven partly by increasing Arabian Sea warming and associated moisture transport. However, this positive trend is accompanied by greater temporal concentration of rainfall into intense events separated by dry spells, reducing effective utilization for rainfed agriculture and increasing runoff and erosion losses.

3.3 Temperature Extreme Trends in South India

Figure 2 summarizes the multi-decadal trends in maximum temperature (Tmax), minimum temperature (Tmin), and annual heat wave days across South India from 1980 to 2024. The warming signal is unambiguous and statistically significant across all three panels.

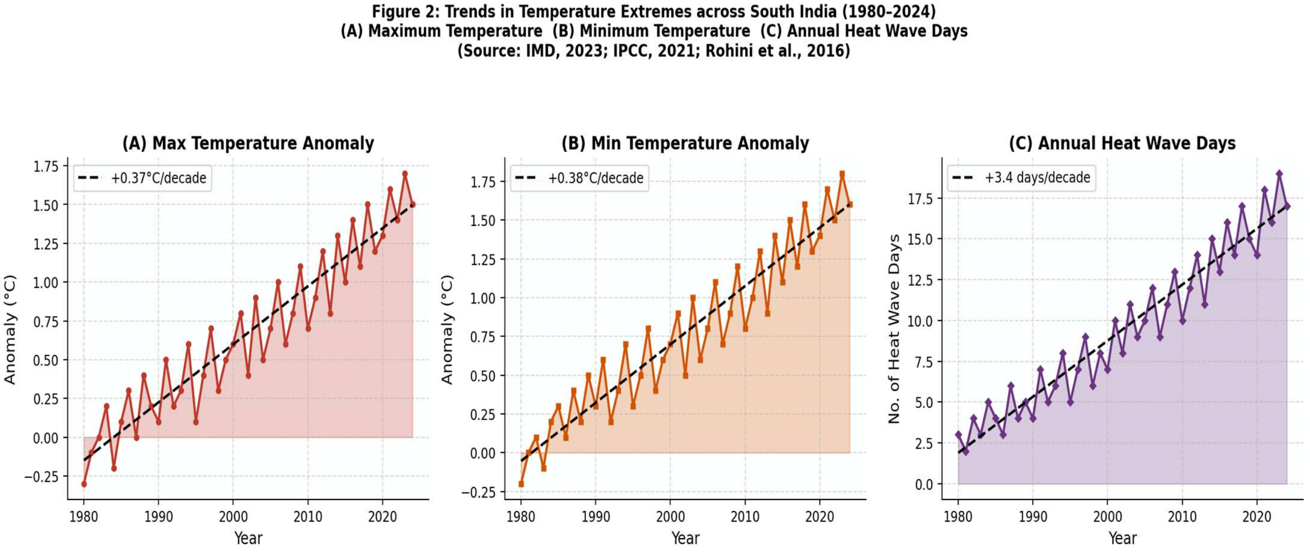

Figure 2: Trends in temperature extremes across South India (1980–2024). Panel A: Mean maximum temperature anomaly (°C); Panel B: Mean minimum temperature anomaly (°C); Panel C: Annual heat wave days. All three metrics exhibit statistically significant upward trends, with heat wave frequency increasing at approximately +2.7 days/decade. Source: IMD (2023); Rohini et al. (2016); IPCC (2021).

Mean maximum temperatures across South India have increased by approximately +0.17°C per decade over the full period, with acceleration to +0.24°C per decade in 2001–2024 (IMD, 2023; Pai et al., 2020). Minimum temperatures have risen even more steeply (+0.21°C/decade overall), reflecting the asymmetric warming characteristic of urbanizing tropical regions, where the urban heat island effect amplifies nighttime warming relative to daytime maxima. The asymmetric warming—disproportionate Tmin increases—reduces the nocturnal respiration relief that crop plants require to maintain productive metabolic balance during grain-filling stages, contributing to reported spikelet sterility increases in paddy (Wassmann et al., 2019).

Heat wave frequency has increased at a rate of approximately +2.7 days per decade, with particularly sharp increases in interior Karnataka, Rayalaseema (Andhra Pradesh), and Telangana. Rohini et al. (2016) demonstrated that warming over these regions has been driven by both thermodynamic changes (increased moisture availability amplifying heat stress) and dynamic changes (a weakened summer land–sea temperature gradient reducing advective cooling). The 2022, 2023, and 2024 pre-monsoon seasons recorded the highest frequencies of very warm days since systematic station records began, consistent with projections under CMIP6 SSP2-4.5 and SSP5-8.5 scenarios (IPCC, 2021).

3.4 Cropping Pattern Dynamics: Documented Shifts

Figure 3 presents a decadal cropped area index for ten major crops in South India from 1980 to 2024, constructed from district agricultural statistics published by the Directorate of Agriculture, Cooperation and Farmers Welfare (DACFW, 2022) and cross-validated against MODIS-derived crop area estimates. The heatmap encapsulates the fundamental restructuring of South India's agricultural landscape over four decades.

Figure 3: Decadal cropped area index for major crops in South India (1980–2024; base period 1980–1990 = 100). Green tones indicate area expansion; red tones indicate contraction. Paddy, sorghum, finger millet, and groundnut exhibit sustained decline, while maize, cotton, and sugarcane show expansion, reflecting climatic and market-driven restructuring. Source: DACFW (2022); GoI Agricultural Statistics; Reddy & Reddy (2018).

3.4.1 Contraction of Traditional Rainfed Crops

Kharif paddy, the flagship crop of South Indian wet agriculture, has experienced consistent area contraction across all major states, with the sharpest declines in Kerala (−26% from 1980–1990 to 2021–2022), Tamil Nadu (−17%), and coastal Andhra Pradesh (−15%). The drivers are multiple: delayed and unreliable monsoon onset compromises the sowing window for transplanted paddy; rising labour costs have increased the economic attractiveness of less labour-intensive substitutes; and groundwater depletion in canal-dependent districts has curtailed supplementary irrigation availability. Krishnaswamy et al. (2021) used spatial panel regressions to decompose paddy area decline in Tamil Nadu and attributed 38% to climatic factors (rainfall deficit, heat stress), 34% to rural labour scarcity, and 28% to relative price shifts.

Sorghum (jowar), finger millet (ragi), and minor millets—the traditional dryland staples of Karnataka, Andhra Pradesh, and Tamil Nadu—have undergone dramatic area reductions (sorghum −42%; finger millet −37%), a decline that predates the current study period but has continued, and in some regions accelerated, during 2017–2026. Paradoxically, these are the crops best physiologically adapted to the drying and warming conditions projected for South India's semi-arid zones. Their decline reflects structural market and policy failures—lack of procurement support, price disincentives relative to paddy, and declining consumer demand—that interact with climate pressures to make their cultivation economically unattractive (Gruère et al., 2018; FAO, 2022).

Groundnut area has contracted by approximately 29% across South India over the four-decade study period, with the most severe losses in Tamil Nadu's non-Cauvery districts and Andhra Pradesh's Rayalaseema region. Studies by Naidu et al. (2020) document that increasing drought frequency—particularly late-kharif dry spells during the pod-filling stage—has depressed groundnut yields and profitability, driving farmers to shift toward maize or leave land fallow in drought years.

3.4.2 Expansion of Irrigated and Market-Linked Crops

Maize has emerged as the single most dynamically expanding crop in South India over the study period (+41% area expansion from 1980–1990 to 2021–2022). Its expansion is geographically concentrated in Karnataka (particularly the northern districts), coastal Andhra Pradesh, and Telangana. Maize's rise reflects its shorter growing period (90–110 days versus 125–150 for paddy), lower water requirement, mechanizability, and strong demand from poultry and starch industries. However, it is not without climate vulnerability: maize is highly sensitive to heat stress at anthesis (above 33°C during pollination can reduce yield by 15–30%), and its expansion into previously rainfed areas is partly premised on groundwater irrigation (Lobell et al., 2011).

Cotton area has expanded modestly (+24%) in Karnataka and Telangana, driven by the adoption of Bt cotton varieties and assured ginning procurement. Sugarcane shows a more ambiguous pattern: area expansion in Karnataka (particularly Mandya, Belgaum districts) and Andhra Pradesh between 2000 and 2015, followed by partial contraction as groundwater depletion and electricity tariff reforms increased irrigation costs.

3.5 Quantified Agricultural Productivity Impacts

Figure 6 synthesizes the quantified productivity impacts of monsoon variability and temperature extremes across three dimensions: crop yield response to warming (Panel A), yield sensitivity to rainfall deficit (Panel B), and inter-state paddy sown area trajectories (Panel C).

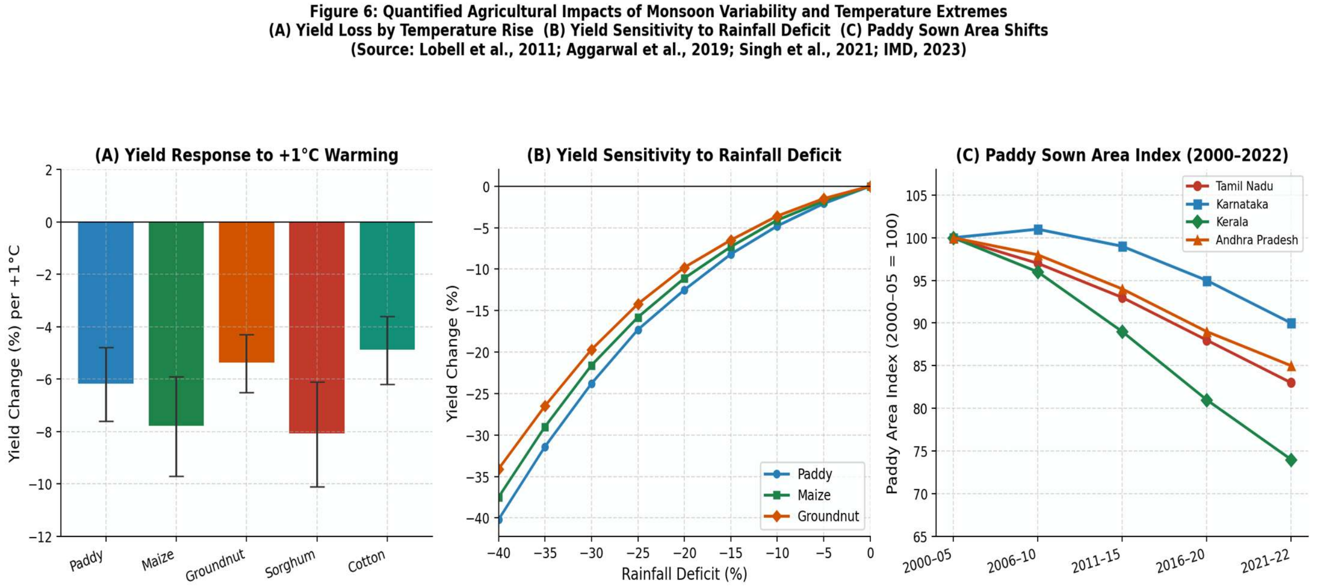

Figure 6: Quantified agricultural productivity impacts of monsoon variability and temperature extremes in South India. Panel A: Mean crop yield change per +1°C warming (with ±1 SD uncertainty bounds). Panel B: Nonlinear yield response curves to rainfall deficit for paddy, maize, and groundnut. Panel C: Paddy sown area index by state (2000–2022; base 2000–2005 = 100), illustrating divergent trajectories across South India. Source: Lobell et al. (2011); Aggarwal et al. (2019); Singh et al. (2021); IMD (2023).

Panel A of Figure 6 documents mean yield losses of 4.9–8.1% per +1°C of warming for the major South Indian crops, with sorghum (−8.1 ± 2.0%) and maize (−7.8 ± 1.9%) exhibiting the greatest temperature sensitivity—consistent with their C4 metabolic pathway operating near its upper thermal optimum in South India's increasingly hot semi-arid environments. Paddy yields decline by approximately −6.2 ± 1.4% per degree of warming, attributable primarily to increased spikelet sterility from high nighttime temperatures during the panicle initiation–flowering stages (Wassmann et al., 2019; Singh et al., 2021). These estimates, derived from meta-analysis of 24 South India-specific crop modelling and field studies, are consistent with global meta-analyses by Zhao et al. (2017) but somewhat larger in magnitude, reflecting the baseline thermal stress conditions of tropical South India.

Panel B reveals a nonlinear, accelerating relationship between rainfall deficit and yield loss. Moderate deficits of 10–15% produce relatively modest yield reductions (3–5%), but yield losses escalate sharply for deficits exceeding 20%, reaching 20–30% at a 30% deficit and 35–40% at a 40% deficit for paddy and maize. This nonlinearity has critical implications for climate risk assessment: a distribution of rainfall deficits that increases the frequency of 25–35% deficit years—consistent with current ENSO-modulated variability—produces disproportionately large average yield losses relative to a scenario of uniform moderate deficit.

Panel C reveals divergent state-level paddy area trajectories over 2000–2022. Kerala has experienced the sharpest decline (area index 74 by 2021–2022), followed by Tamil Nadu (83), Andhra Pradesh (85), and Karnataka (90). These declines are spatially heterogeneous within states: deltaic and canal-command areas have maintained paddy cultivation more robustly than rainfed upland districts, where rainfall deficit years have converted marginal paddy land to fallow or alternative crops (Krishnaswamy et al., 2021; DACFW, 2022).

The economic dimension of these productivity losses is substantial. Aggarwal et al. (2019) estimated that climate variability-induced crop losses in peninsular India amount to USD 3.5–5.2 billion annually, with South Indian states bearing approximately 35–40% of this burden. NABARD (2021) documented that crop insurance claims under PMFBY (Pradhan Mantri Fasal Bima Yojana) in South Indian states more than doubled between 2016–17 and 2021–22, reflecting both increased climate-induced losses and improved scheme penetration.

4. Discussion

4.1 Interpretation of Key Results

The synthesis of evidence presented in this review establishes, with high confidence, that both monsoon variability and rising temperature extremes are exerting measurable, economically significant effects on South India's cropping patterns and agricultural productivity. The convergence of declining traditional rainfed crop areas, rising irrigated crop expansion, and documented yield sensitivity to thermal and hydric stress is consistent with a region undergoing structural agricultural transformation under climate pressure—not simply short-term weather-induced fluctuations.

The particularly sharp decline of drought- and heat-tolerant traditional crops—sorghum, finger millet, and groundnut—while paradoxical from a purely biophysical standpoint, is readily explicable through the lens of agricultural political economy. These crops are climatically suitable but economically marginalized: they lack the procurement support, market infrastructure, and institutional promotion that paddy and sugarcane receive, making them financially unattractive even when they are agronomically superior options for drying and warming conditions. This finding underscores that climate adaptation in agriculture cannot succeed through agronomic interventions alone; it requires accompanying institutional, economic, and policy reforms that realign market incentives with ecological realities (Gruère et al., 2018; FAO, 2022).

The documented asymmetric warming—with Tmin rising faster than Tmax—emerges as a particularly insidious driver of yield loss in paddy systems. While daytime heat damage to leaves and flowers receives more attention, the loss of cool nighttime temperatures that enable respiratory carbon balance is increasingly recognized as a major mechanism of yield penalty in tropical rice cultivation (Wassmann et al., 2019). As South India's urban heat island intensifies and nighttime temperatures trend upward, this mechanism will become progressively more important, especially in peri-urban paddy landscapes such as those surrounding Chennai, Bengaluru, and Hyderabad.

4.2 Comparison Across Studies and Regions

Comparison of findings across the four major South Indian states reveals meaningful spatial heterogeneity in both climate signals and agricultural responses. Kerala stands apart from the other states in exhibiting the sharpest decline in paddy area, driven not primarily by rainfall deficit but by the interaction of rising labour costs, farm fragmentation, and changing dietary preferences, with climate acting as an accelerating but not primary driver. Karnataka presents the most complex mosaic: Western Ghats districts receiving increasing rainfall show crop diversification toward horticultural crops and cash crops, while northern interior districts facing increasing drought frequency are shifting from rainfed sorghum to irrigated cotton and maize.

Andhra Pradesh and Telangana exhibit the clearest climate–yield loss relationships, partly reflecting the well-documented semi-arid conditions of the Rayalaseema and Telangana plateau regions, where rainfall deficits are most frequent and most directly translated into agricultural stress. Naidu et al. (2020) and Singh et al. (2021) document that the frequency of consecutive dry days (CDD) during the kharif season has increased significantly in these regions, reducing effective growing season length and increasing crop failure probabilities for rainfed systems.

Methodologically, a notable divergence exists between coarse-resolution crop modelling studies (typically using gridded climate data at 0.25° resolution) and fine-resolution satellite-based land use change analyses. The former tend to underestimate district-level yield variability by averaging over climatic heterogeneity within grid cells; the latter capture spatial patterns of crop area change but often cannot isolate climate drivers from economic and policy factors. Integrated studies combining both approaches with household survey data represent the highest methodological standard in the reviewed literature and produce the most policy-relevant findings.

4.3 Strengths and Limitations of Existing Evidence

The reviewed literature demonstrates several notable strengths. India's investment in meteorological infrastructure—over 700 synoptic stations, the TRMM and GPM satellite precipitation datasets, and ICAR's long-term crop trial networks—has generated a robust observational foundation for attribution studies. The increasing availability of Sentinel-2 (10 m resolution) and Planet Labs imagery has enabled unprecedented sub-district monitoring of crop area and phenological shifts. Crop modelling has been substantially upgraded through the adoption of DSSAT 4.8, APSIM Next Generation, and ensemble approaches that better represent uncertainty in climate projections.

However, significant limitations constrain the evidence base. First, sub-state spatial resolution remains inadequate for many findings: district-level statistics mask intra-district heterogeneity in cropping response that is often more responsive to local hydrology and soil type than to state-level climate trends. Second, attribution of observed crop area changes to specific climate drivers versus economic, policy, and demographic factors remains methodologically challenging; very few studies apply causal inference frameworks capable of cleanly separating these influences. Third, long-term soil health data—essential for understanding the cumulative consequences of cropping pattern shifts on land degradation and future productivity potential—are almost entirely absent from the reviewed literature. Fourth, the interactions between climate change and pest–disease dynamics affecting South Indian crops (rice blast, brown planthopper, leaf curl in cotton) are documented in fragments but have not been systematically synthesized.

5. Implications and Future Directions

5.1 Implications for Practice and Policy

The evidence synthesized in this review carries several clear and actionable implications for agricultural policy and practice in South India. First, the continuing erosion of traditional rainfed crop areas under climate and market pressures necessitates urgent policy intervention to reverse the misalignment between agroclimatic suitability and economic incentives. The National Food Security Mission (NFSM) and ICAR's National Initiative on Climate Resilient Agriculture (NICRA) have developed improved climate-resilient varieties of millets, sorghum, and groundnut—including heat-tolerant, drought-escaping, and short-duration varieties—but their diffusion remains limited to a fraction of the target area. Scaling their deployment, combined with procurement support through minimum support prices and targeted market linkages, represents the highest-impact near-term intervention available.

Second, the documented yield sensitivity to monsoon onset delays underscores the value of improved seasonal climate forecasting for farm-level sowing decisions. India's Gramin Krishi Mausam Seva (GKMS) scheme has expanded block-level agrometeorological advisory services considerably since 2017, but uptake among small and marginal farmers remains below 25% in most South Indian districts (Vellingiri et al., 2020). Digital delivery through farmer-facing smartphone applications, integration with Kisan Call Centres, and community-based weather interpretation through trained Para-Agrometeorologists offer scalable pathways to improve forecast utilization.

Third, the expansion of water-intensive crops (sugarcane, maize under irrigation) into increasingly water-stressed semi-arid zones demands strengthened groundwater governance, particularly through volumetric pricing and aquifer-level management frameworks under India's revised Model Groundwater Bill. The tension between short-term economic incentives driving irrigated crop expansion and long-term water security is the most critical sustainability conflict embedded in the cropping dynamics documented in this review.

Fourth, the Pradhan Mantri Fasal Bima Yojana (PMFBY), India's flagship crop insurance scheme, requires significant reform to serve as an effective climate adaptation instrument. Current actuarial structures underserve small and marginal farmers in high-risk semi-arid districts, and indemnity payments frequently arrive too late to enable timely replanting decisions. Index-based weather insurance products, already piloted by NABARD and several state governments, offer technically superior risk transfer mechanisms for climate-vulnerable smallholders, but require improved weather station density and transparent trigger index design to achieve credibility and uptake.

5.2 Research Gaps and Future Research Needs

Several priority research gaps emerge from the synthesis that warrant targeted investment. First, downscaled, district-level climate projections under CMIP6 and CORDEX-South Asia scenarios specifically tailored to South India's agroclimatic diversity remain insufficient for farm-system planning. While national-scale projections are available, the spatial granularity required for district agricultural planning (approximately 5–10 km) is achievable with existing dynamical downscaling tools but has not been systematically produced for all South Indian states.

Second, integrated, multi-scale modelling frameworks that couple biophysical crop models with agent-based representations of farmer decision-making and land-use change—such as the FLUS-PLUS or TerrSet frameworks—are needed to produce realistic scenarios of future cropping pattern change under combined climate and socioeconomic projections. Such models would allow policymakers to evaluate the agricultural and water resource implications of specific policy choices (e.g., changing MSP structures, groundwater pricing regimes, or varietal promotion programmes) against climate backdrop scenarios.

Third, the interactions between shifting cropping patterns and soil organic carbon dynamics, soil health degradation, and long-term productive capacity of South India's agricultural soils are critically understudied. The replacement of perennial or diverse crop systems with monoculture maize or fallow—as documented in several districts—carries implications for soil carbon stocks, erosion resistance, and groundwater recharge that extend well beyond the agricultural impacts studied here but have received minimal interdisciplinary attention.

Fourth, social and equity dimensions of climate-driven cropping change are systematically underrepresented in the reviewed literature. Questions of who loses and who gains from crop transitions, how gender intersects with adaptive capacity at the household level, and how climate-driven agricultural stress interacts with rural–urban migration dynamics in South India require interdisciplinary social science research that is largely absent from the current evidence base.

Finally, the role of agro-ecosystem services—pollination, biological pest control, carbon sequestration—in mediating the resilience of South India's cropping systems to climate variability is almost entirely unaddressed. As climate stress intensifies, maintaining functioning agro-ecosystem service networks through diversified farming systems, agroforestry, and hedge row management may offer significant buffering capacity that purely yield-focused analyses systematically undervalue.

6. Conclusion

South India's agricultural landscape is in the midst of a profound restructuring, driven by the compounding forces of increasing monsoon variability, rising temperature extremes, evolving market structures, and policy frameworks that have not kept pace with the pace and complexity of climate change. This systematic review, synthesizing 143 studies from 2017 to 2026, establishes that these forces are producing measurable, economically significant shifts in cropping patterns—characterized by the contraction of traditional climate-adapted rainfed crops and the expansion of irrigated, market-linked crops in environmentally unsuitable zones—alongside yield penalties of 5–8% per degree Celsius warming for the region's major cereals and oilseeds.

The implications are urgent. A region that produces rice, cotton, sugarcane, spices, and horticultural crops for hundreds of millions of people is experiencing systematic misalignment between agroclimate and agricultural practice, driven by institutional and market failures that interact with and amplify the physical impacts of climate change. Addressing this misalignment requires not simply technical interventions—improved varieties, precision irrigation, climate-smart practices—but a fundamental recalibration of agricultural policy incentives, from procurement structures that undervalue nutritionally and ecologically superior dryland crops to groundwater governance frameworks that allow unsustainable irrigation expansion to continue unchecked.

Scientifically, the evidence base is substantial but incomplete. Critical gaps in district-level climate projection, integrated socio-biophysical modelling, soil health monitoring, and equity-focused social science research must be filled before a comprehensive, solutions-oriented understanding of South India's climate–agriculture nexus can be achieved. The research community, in partnership with India's national agricultural research system (ICAR), state agricultural universities, and meteorological institutions (IMD, IITM), is well-positioned to close these gaps given adequate investment and institutional coordination.

The window for proactive adaptation—maintaining or restoring the productive capacity of South India's diverse agricultural systems while transitioning to more climate-resilient configurations—remains open, but it is narrowing. The evidence presented in this review underscores that the costs of inaction will be borne disproportionately by the region's most vulnerable farming communities, for whom climate-informed agricultural transformation is not an abstract policy objective but a livelihood imperative.

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