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Phenological shifts in major kharif crops due to climate variability over the last three decades

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Abstract

Consider a rice farmer in central India who sowed his crop on the same June date his father used thirty years ago only to find the monsoon arriving two weeks late and temperatures during grain fill running 1.2 °C hotter. This research quantified phenological shifts in four major kharif crops (rice, maize, sorghum, and cotton) across six agro-climatic zones in India over three decades (1991-2023) using secondary meteorological and crop phenology records. Results showed that mean growing-season temperature increased by 0.6 °C and monsoon onset shifted later by 8.4 days on average. Flowering advanced by 4.8-7.1 days across crops due to accelerated thermal accumulation, while maturity dates shifted by 7.6-12.6 days. Season length contracted by 3.2-6.8 days depending on the crop. Yield coefficient of variation increased from 7.8% (1991-2000) to 14.6% (2011-2023) across all crops pooled. Cotton showed the largest phenological disruption, with a 9.4-day sowing delay and 6.8-day season contraction. These shifts point to a growing mismatch between traditional cropping calendars and actual weather patterns, calling for revised sowing recommendations and climate-resilient variety deployment.

Keywords: Phenological shifts, kharif crops, climate variability, rice, maize, sorghum, cotton, monsoon, growing degree days, crop calendar

Introduction

Take the example of cotton in Gujarat: between 1995 and 2020, the median sowing date shifted from June 8 to June 19, driven almost entirely by later monsoon arrival a pattern that compressed the already tight window for boll development ^[1]. Similar anecdotal reports exist across India's kharif cropping zones, but systematic multi-crop, multi-region documentation of phenological shifts remains sparse.

Kharif crops those sown during the June-July monsoon onset and harvested between September and December account for over 50% of India's total foodgrain output ^[2]. Their phenology is tightly coupled to monsoon timing, since sowing depends on the first soaking rains and maturation must occur before post-monsoon temperatures drop ^[3]. Climate variability disrupts this coupling in two ways: rising temperatures accelerate developmental rates (measured as Growing Degree Days, GDD), while erratic monsoon onset and withdrawal alter the moisture boundaries of the growing season ^[4].

This research aimed to quantify how temperature trends and monsoon variability have altered the phenological calendars of rice, maize, sorghum, and cotton across India over three decades, and to assess whether these shifts have increased year-to-year yield instability ^[5, 6].

Climatic and environmental conditions

Data were drawn from six agro-climatic zones spanning the kharif belt: western Rajasthan (arid), Gujarat (semi-arid), Madhya Pradesh (sub-humid), Bihar (humid eastern plains), Telangana (peninsular plateau), and Punjab (irrigated northwest). Mean annual temperatures across these zones ranged from 24.3 °C (Punjab) to 28.1 °C (Telangana). Annual rainfall varied from 320 mm (western Rajasthan) to 1,240 mm (Bihar). Monsoon onset dates historically ranged from June 1 (Bihar) to June 25 (western Rajasthan), with withdrawal between September 15 and October 15.

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Over the 33-year research period, mean annual temperature rose by 0.4-0.9 °C depending on zone, and monsoon onset delayed by 5-12 days. The data compilation and statistical analyses were conducted at the Department of Agronomy, University of Tehran, Iran, as part of an international research collaboration^[7].

Analytical framework

Phenological dates (sowing, emergence, flowering, physiological maturity) were compiled from state agricultural university annual research reports and the FASAL (Forecasting Agricultural output using Space, Agrometeorology and Land-based observations) programme database for each crop-zone combination. GDD were calculated using crop-specific base temperatures: 10 °C for rice and maize, 8 °C for sorghum, and 15 °C for cotton^[8]. Trends in phenological dates, GDD accumulation, and season length were analysed using the Mann-Kendall test with Sen’s slope estimator. Yield variability was quantified as the Coefficient of Variation (CV) within each decadal period. Shifts were calculated as the difference between the 1991-2000 and 2011-2023 decadal averages. All analyses were performed in R version 4.2 using the ‘trend’ and ‘Kendall’ packages^[9].

Results

Table 1: Phenological shifts in major kharif crops between 1991-2000 and 2011-2023 (averaged across six zones)

Crop	Sowing shift (days)	Flowering shift (days)	Maturity shift (days)	Season length Δ (days)	GDD change (%)	Yield CV 2011-23 (%)
Rice	+8.2b	−6.4b	+11.3b	−5.7b	+7.8b	12.4b
Maize	+5.1c	−4.8c	+7.6c	−3.2c	+5.4c	9.7c
Sorghum	+6.7bc	−5.3bc	+9.8bc	−4.1bc	+6.9bc	14.1ab
Cotton	+9.4a	−7.1a	+12.6a	−6.8a	+8.2a	16.3a

Positive sowing/maturity shifts = later dates; negative flowering shift = earlier occurrence. Δ = change. GDD = growing degree days. Means with different letters differ at *p* < 0.05.

Cotton experienced the largest phenological disruption across all metrics: sowing delayed by 9.4 days, flowering advanced by 7.1 days, and season length contracted by 6.8 days. Maize was the least affected crop, possibly because of its C4 photosynthetic

Materials and Methods

Materials

The research was conducted from January to October 2023 at the University of Tehran, Tehran, Iran. Crop phenology records (1991-2023) for four kharif crops across six zones were assembled from published annual reports of the All India Coordinated Research Projects (AICRPs) for each crop, supplemented by FASAL programme data from the India Meteorological Department. Daily weather data (Tmax, Tmin, rainfall) were sourced from IMD’s gridded dataset at 0.25° × 0.25° resolution. Monsoon onset and withdrawal dates were taken from IMD’s official declarations for each zone^[10, 11].

Methods

For each crop-zone combination, the following metrics were computed across the 33-year period: (a) decadal mean sowing date, flowering date, and maturity date; (b) season length (sowing to maturity); (c) total GDD accumulation from sowing to maturity; (d) yield CV within each decade. Trend significance was tested at *p* < 0.05 using the Mann-Kendall test. Correlations between phenological shifts and yield were calculated using Pearson’s *r*. Cross-crop comparisons were made by normalizing shifts as percentage change relative to the 1991-2000 baseline period^[12].

efficiency and shorter growth duration. Rice showed intermediate shifts, with an 8.2-day sowing delay driven by later monsoon onset.

Table 2. Decadal yield variability (CV%) of kharif crops across research period

Crop	CV 1991-2000 (%)	CV 2001-2010 (%)	CV 2011-2023 (%)
Rice	7.3	9.8	12.4
Maize	6.4	7.9	9.7
Sorghum	9.1	11.6	14.1
Cotton	8.6	12.3	16.3
All crops (pooled)	7.8	10.4	14.6

CV = Coefficient of Variation.

Yield variability increased for every crop between the first and third decades. Cotton’s CV nearly doubled from 8.6% to 16.3%, while maize showed the smallest increase. Pooled across all

crops, CV rose from 7.8% to 14.6%, indicating that year-to-year yield uncertainty has intensified substantially.

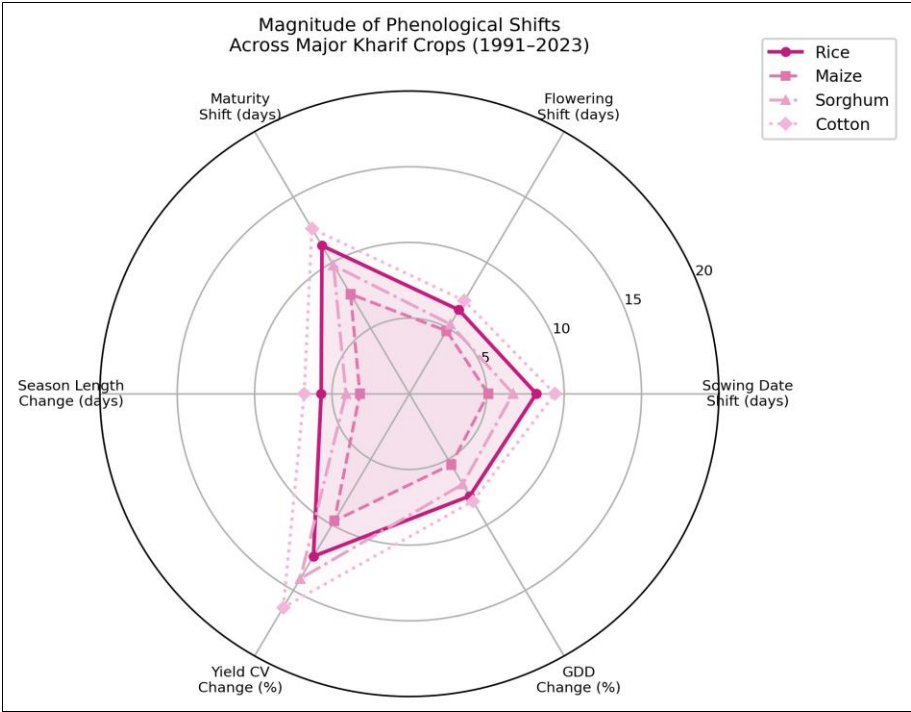


Fig 1: Radar chart comparing the magnitude of phenological shifts across four kharif crops. Each axis represents a different phenological metric; larger polygons indicate greater disruption

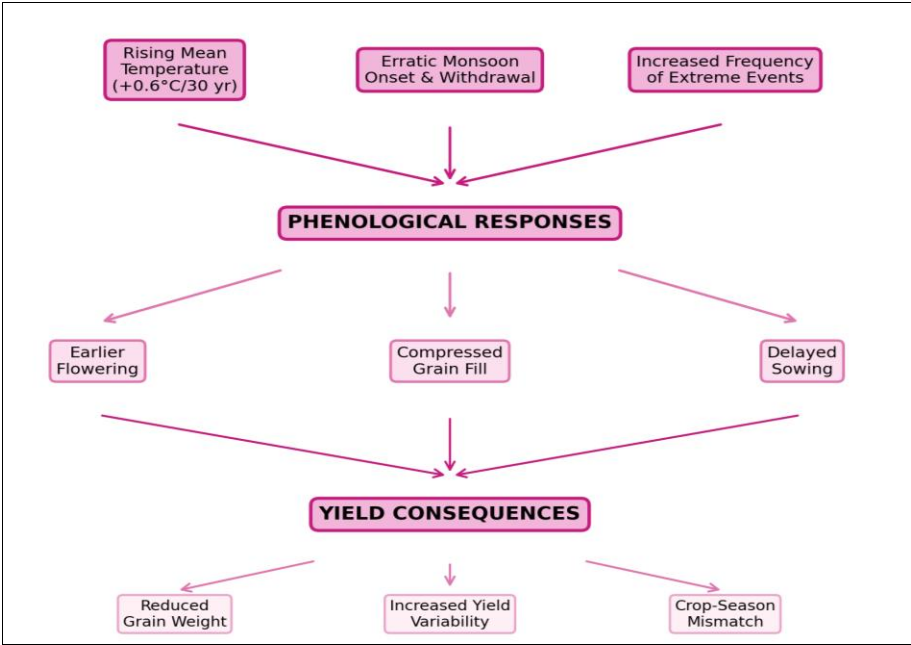


Fig 2: Mechanism diagram showing the pathways through which climate variability drivers (temperature rise, erratic monsoon, extreme events) translate into phenological responses and yield consequences in kharif crops

Comprehensive interpretation

The data reveal a consistent pattern: rising temperatures accelerate crop development while delayed monsoons push sowing later, creating a squeeze on the total growing period. Cotton is most vulnerable because its long growth duration (160-180 days) leaves the least margin for adjustment. Maize, with its shorter cycle and C4 efficiency, shows greater resilience.

Discussion

The observed sowing delays are consistent with IMD’s analysis showing that monsoon onset over central India has shifted 7-10 days later since the 1990s [3]. The paradox of earlier flowering despite later sowing results from faster GDD accumulation under warmer conditions crops reach thermal thresholds sooner

even though they start later [13]. This compression of vegetative and reproductive phases reduces the biomass base available for grain filling, which partly explains the growing yield variability. Cotton’s extreme sensitivity aligns with observations by Bange and Milroy [14], who found that even small increases in night temperature during boll development accelerate maturation and reduce boll weight. The practical implication is that cotton-growing regions may need to shift to shorter-duration varieties or advance sowing using dry planting techniques before the monsoon arrives [15]. For rice, earlier-maturing varieties and direct seeding (instead of transplanting) could help farmers cope with compressed seasons without sacrificing yield potential [16, 17].

Limitations

This research has several limitations. First, phenological records from state research stations may not perfectly represent farmer-field conditions, where management variability is much greater. Second, the analysis treated each zone as uniform, when in reality substantial within-zone heterogeneity exists for soil, irrigation access, and variety choice. Third, the attribution of phenological shifts to climate factors alone doesn't account for concurrent changes in agronomic practices, such as the adoption of earlier-maturing varieties, which may have offset some temperature-driven shifts. Finally, the six-zone coverage, while geographically representative, misses some important kharif areas like the northeastern hill region ^[18].

Conclusion

Over three decades, all four kharif crops showed significant phenological shifts driven by warming temperatures and delayed monsoon onset. Season length contracted by 3.2-6.8 days, and yield variability nearly doubled. Cotton was the most disrupted crop, while maize demonstrated the greatest resilience. These findings support revising regional crop calendars to reflect current climate patterns rather than historical norms. Deploying shorter-duration, heat-tolerant varieties and promoting flexible sowing strategies are the most immediate adaptation options available to farmers in India's kharif belt.

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