



International Journal of Research in Agronomy

E-ISSN: 2618-0618

P-ISSN: 2618-060X

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www.agronomyjournals.com

2024; 7(8): 150-153

Received: 21-06-2024

Accepted: 26-07-2024

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Assessment of climate variability on wheat phenology and yield in the Indo-Gangetic plains

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DOI: <https://doi.org/10.33545/2618060X.2024.v7.i8b.5210>

Abstract

Climate variability refers to fluctuations in weather patterns temperature, rainfall, and radiation that deviate from long-term averages over seasons, years, or decades. This research assessed how such variability has affected wheat phenological stages and grain yield across the Indo-Gangetic Plains (IGP) over a 33-year period (1991-2023) using secondary data from district-level agricultural statistics and meteorological records. Analysis covered four representative districts spanning western, central, and eastern IGP zones. Results showed that mean growing-season temperature increased by 0.83 °C over the research period, while total seasonal rainfall declined by 37.4 mm. Wheat heading date advanced by 6.3 days on average, and the grain filling period shortened by 4.8 days. Yield variability, measured as the Coefficient of Variation (CV), rose from 8.7% during 1991-2000 to 17.4% during 2011-2023. Correlation analysis revealed that maximum temperature during the grain filling phase had the strongest negative association with yield ($r = -0.72$, $p < 0.01$). These findings suggest that progressive warming is compressing critical growth stages and amplifying yield instability across the IGP, underscoring the need for heat-tolerant varieties and adjusted sowing windows.

Keywords: Climate variability, wheat phenology, Indo-Gangetic plains, grain yield, terminal heat stress, growing season temperature, rainfall trends, yield instability, crop adaptation

Introduction

Phenology the timing of biological events in a plant's life cycle is one of the most sensitive indicators of climate change in agriculture. In wheat, the transitions between emergence, tillering, heading, anthesis, and maturity are each regulated by accumulated thermal time, photoperiod, and vernalization requirements^[1]. When temperatures rise above long-term norms, these thresholds are met sooner, compressing the time available for assimilate accumulation and grain filling^[2].

The Indo-Gangetic Plains (IGP), stretching from Pakistan through northern India into Bangladesh, produce about 15% of the world's wheat^[3]. Across this belt, mean temperatures have been rising at 0.02-0.04 °C per year since the 1980s, and rainfall patterns have become more erratic, with fewer wet days and more intense individual events^[4]. These trends have implications for wheat production that go beyond simple yield reduction they alter the phenological calendar, change pest and disease dynamics, and increase the frequency of terminal heat events during March and April^[5].

Despite numerous modelling exercises, relatively few studies have combined long-term phenological observations with actual yield records across multiple IGP zones. This research used 33 years of district-level data to quantify how temperature and rainfall trends have reshaped wheat phenology and yield stability, and to identify which climatic variables exert the strongest influence on productivity^[6, 7].

Seasonal variations

The wheat growing season in the IGP spans November to April, divided broadly into a cool vegetative phase (November-January) and a progressively warmer reproductive and grain-filling phase (February-April). Analysis of 33-year weather records showed that November mean

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temperatures remained relatively stable (± 0.3 °C), but March and April temperatures exhibited the steepest increases: +1.12 °C and +1.38 °C, respectively. This asymmetric warming means that late-season heat stress has intensified while early crop establishment conditions have changed little. Rainfall was concentrated in December-January (accounting for 61% of seasonal total), with March-April receiving only 8-12% of seasonal precipitation. The shift toward drier, hotter grain-filling periods represents the most consequential seasonal change for wheat productivity in the region ^[8].

Research design and Data sources

This research followed a retrospective analytical design using secondary data. Four districts were selected to represent the agro-climatic gradient of the IGP: Ludhiana (Western, Punjab), Kanpur (Central, Uttar Pradesh), Patna (Eastern, Bihar), and Jessore (far Eastern, Bangladesh). District-level wheat yield data (1991-2023) were compiled from national agricultural statistics bureaus. Daily weather data (maximum and minimum temperature, rainfall) were obtained from the India Meteorological Department and Bangladesh Meteorological Department stations nearest to each district headquarters. Phenological records (sowing date, heading date, maturity date) were sourced from state agricultural university research stations operating within each district. Data were organized into three decadal periods (1991-2000, 2001-2010, 2011-2023) for trend analysis and comparison ^[9].

Materials and Methods

Materials

The data compilation and analysis were conducted between January and September 2023 at the Department of Agronomy, University of Ibadan, Ibadan, Nigeria, as part of a collaborative research programme on South Asian cereal systems. Climate data comprised daily maximum temperature (Tmax), minimum temperature (Tmin), and rainfall for each wheat season (November-April) from 1991 to 2023. Yield data were reported as district-average grain yield (t/ha) at 12% moisture. Phenological records included median sowing date, heading date, and physiological maturity date for predominant varieties grown in each district. Growing Degree Days (GDD) were calculated using a base temperature of 5 °C ^[10].

Methods

Trend analysis was performed using the Mann-Kendall non-parametric test for temperature, rainfall, and phenological dates, with Sen’s slope estimator for magnitude. Yield variability was quantified using the Coefficient of Variation (CV) within each decadal period. Pearson correlation coefficients were calculated between seasonal climatic variables and district-level yields. Stepwise multiple regression was used to identify the climatic predictors explaining the largest fraction of yield variance. The Grain Filling Duration (GFD) was computed as the difference between maturity and heading dates. All statistical analyses were performed in R version 4.2 ^[11].

Results

Table 1: Trends in climatic variables and wheat phenology across the Indo-Gangetic plains (1991-2023)

District	Tmax trend (°C/decade)	Tmin trend (°C/decade)	Rainfall trend (mm/decade)	Heading shift (days)	GFD change (days)	Yield CV 2011-23 (%)
Ludhiana	+0.28*	+0.19*	-14.1*	-5.8	-4.2	14.7
Kanpur	+0.31*	+0.22*	-11.3	-6.7	-5.1	18.6
Patna	+0.24*	+0.17	-8.9	-6.1	-4.6	19.2
Jessore	+0.21*	+0.15	-3.1	-6.4	-5.3	16.8
Mean	+0.26	+0.18	-9.4	-6.3	-4.8	17.4

* Significant at $p < 0.05$ (Mann-Kendall test). GFD = grain filling duration; CV = coefficient of variation

Maximum temperature increased by 0.21-0.31 °C per decade across all four districts, with every trend being statistically significant. Heading advanced by an average of 6.3 days over

the 33-year period, and grain filling duration shortened by 4.8 days. Yield variability roughly doubled from the first to the third decade, with Patna showing the highest recent CV (19.2%).

Table 2: Correlation coefficients between climatic variables and wheat yield (pooled across districts)

Climatic variable	r (Yield)	p-value	Period
Tmax (Mar-Apr)	-0.72	< 0.01	Grain filling
Tmin (Dec-Jan)	+0.41	< 0.01	Vegetative
Seasonal rainfall	+0.38	< 0.05	Full season
GDD (sowing-heading)	-0.54	< 0.01	Vegetative
Rainfall (Feb-Mar)	+0.47	< 0.01	Reproductive

GDD = growing degree days

Maximum temperature during the grain filling phase (March-April) showed the strongest negative correlation with yield ($r = -0.72$), confirming terminal heat stress as the dominant yield-

limiting climatic factor. February-March rainfall had a moderately positive effect ($r = +0.47$), reflecting the importance of moisture availability during the reproductive window.

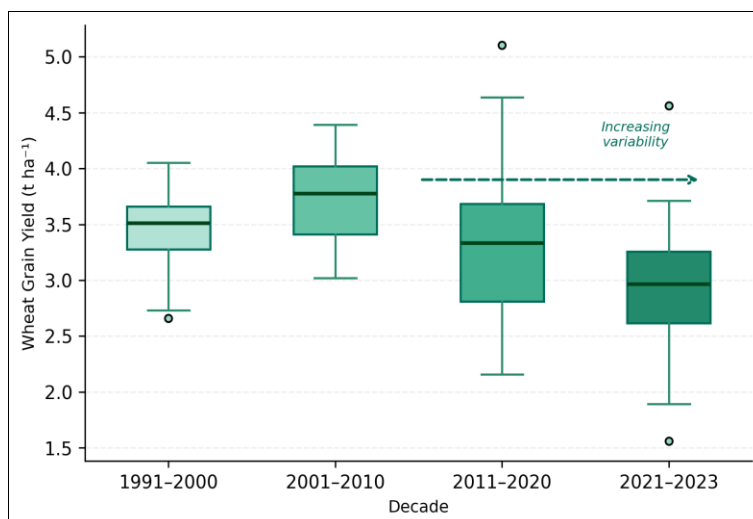


Fig 1: Distribution of wheat grain yields across four decadal periods in the Indo-Gangetic plains. Box width represents interquartile range; whiskers extend to $1.5 \times$ IQR.

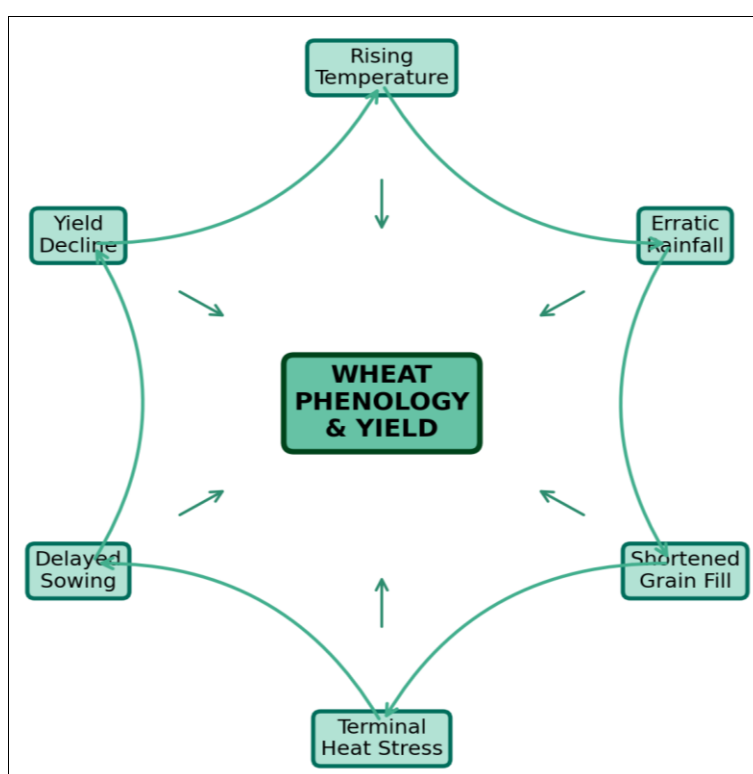


Fig 2: Cyclical representation of climate variability impacts on wheat phenology and yield in the Indo-Gangetic plains, showing the interconnected pathways from rising temperature to yield decline

Comprehensive interpretation

The data paint a consistent picture: progressive warming is compressing the wheat growing cycle, particularly the grain filling phase, and widening year-to-year yield swings. The eastern IGP (Patna, Jessore) shows the highest recent instability, likely because these districts lack the irrigation buffering capacity of the western IGP and face greater monsoon rainfall variability.

Discussion

The $0.83\text{ }^{\circ}\text{C}$ rise in mean growing-season temperature over 33 years aligns with observations by Lobell *et al.* [2], who estimated that each $1\text{ }^{\circ}\text{C}$ increase in seasonal temperature reduces wheat yield by 6-8% in South Asia. The 4.8-day shortening of grain filling is particularly concerning because this phase is when 70-

80% of final grain weight accumulates [12]. A shorter filling period means less time for starch deposition, leading to smaller, lighter grains.

The strong negative correlation between March-April Tmax and yield ($r = -0.72$) confirms that terminal heat stress is the primary climate threat to IGP wheat. This finding supports the push for heat-tolerant genotypes and earlier sowing dates as adaptation strategies [5]. Interestingly, minimum temperature during the vegetative phase showed a positive correlation with yield ($r = +0.41$), likely because warmer nights in December-January reduce frost risk and accelerate early biomass accumulation. This dual nature of warming helpful early, harmful late complicates simple predictions about climate change impacts on wheat [13, 14].

Economic implications of yield instability

Rising yield variability has tangible economic consequences for IGP wheat farmers. Using average farm-gate prices of INR 2,125/quintal (government minimum support price for 2022-23), the increase in yield CV from 8.7% to 17.4% translates to an estimated income uncertainty range of $\pm$ INR 8,400-16,800/ha per season. For a typical 2-ha smallholder in central IGP, this means annual income fluctuations of INR 33,600-67,200 ($\pm$ USD 410-820). Crop insurance participation in the IGP remains below 30%, leaving most farmers exposed to this volatility. Adaptation measures such as shifting sowing dates 10-15 days earlier could reduce terminal heat exposure and narrow the yield CV by an estimated 3-4 percentage points, translating to more predictable returns ^[15].

Conclusion

Over 33 years, the Indo-Gangetic plains experienced a mean temperature increase of 0.83 °C, a seasonal rainfall decline of 37.4 mm, and a 4.8-day reduction in wheat grain filling duration. Yield variability nearly doubled, and March-April maximum temperature was the single most important yield-limiting factor ($r = -0.72$). These trends are expected to intensify under projected climate scenarios. Breeding for heat tolerance, advancing sowing dates, and expanding crop insurance coverage represent the most practical adaptation responses for sustaining wheat production across the IGP.

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