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Shifting Seasons: Phenological Changes in Plants under Global Warming

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Abstract: This study investigates phenological changes in plants of the Indian Himalayan region in response to global warming. Phenology, the study of recurring biological events in relation to climate, has emerged as one of the most sensitive bioindicators of climate change. Using four decades of data (1980–2020) derived from field monitoring, herbarium records, citizen science datasets, and remote sensing, we analyzed shifts in flowering, fruiting, and leaf senescence across six altitudinal zones. Results show that flowering and fruiting have advanced by 2–4 days per **decade**, while autumn senescence has been delayed, effectively extending the growing season. Regression analyses revealed strong correlations between temperature anomalies and earlier flowering, with each 1 °C increase advancing phenophases by 3–4 days. Early-blooming species were more responsive than late-flowering perennials, reflecting interspecific variability in climatic sensitivity. These findings align with global trends and highlight risks of ecological mismatches with pollinators, altered plant competition, and agricultural vulnerabilities such as frost damage and pest emergence. The study underscores the urgency of long-term monitoring and adaptive strategies to safeguard biodiversity, agricultural productivity, and ecosystem resilience in a warming climate.

Keywords: Phenology; Climate Change; Global Warming; Indian Himalayas; Flowering Shifts; Fruiting; Leaf Senescence; Bioindicators; Agriculture; Ecosystem Resilience

I. INTRODUCTION

Phenology is the study of the timing of recurring biological events in plants and animals, such as leaf emergence, flowering, fruiting, and leaf senescence, and their relationship with seasonal and interannual variations in climate. In plants, phenological events are tightly linked to environmental cues like temperature, day length, and precipitation. Even small changes in these cues can lead to measurable shifts in life-cycle stages, making phenology a sensitive lens through which ecological responses to climate variability can be observed.

Over the past few decades, phenological shifts have emerged as some of the most visible biological indicators of climate change. Earlier flowering, advanced leaf-out, and delayed leaf fall are increasingly documented across diverse ecosystems, demonstrating how living organisms are adjusting to a warming world. Unlike other ecological processes that may require decades of observation, phenological events provide relatively immediate signals of environmental change, allowing them to serve as reliable bioindicators of climate variability and global warming**.** These shifts not only reflect changes in individual species but also provide insight into broader ecological processes such as pollination, food web interactions, and nutrient cycling.

Global warming has intensified over the past century, with average surface temperatures rising by more than 1 °C since the pre-industrial era. Alongside temperature rise, altered precipitation regimes, earlier snowmelt, and extended drought periods have reshaped growing seasons worldwide. In the Indian Himalayan region, these changes are particularly pronounced due to its climatic sensitivity and complex topography. As warming accelerates, plants are experiencing longer growing seasons, earlier reproductive events, and shifts in productivity that have cascading consequences for ecosystems and human communities alike.

Although numerous global studies have documented phenological responses to climate change, relatively fewer have focused on the himalayan ecosystems, despite their ecological fragility and socio-economic importance. the himalayas harbor unique biodiversity and provide vital ecosystem services, yet systematic analyses of long-term phenological data remain scarce. this paper therefore aims to examine shifting plant phenology under global warming in the indian himalayas**,** focusing on flowering, fruiting, and senescence events across altitudinal gradients. by integrating climatic data with field observations, herbarium records, and remote sensing, the study seeks to (i) quantify temporal trends in phenological shifts, (ii) identify their climatic drivers, and (iii) assess ecological and agricultural implications.

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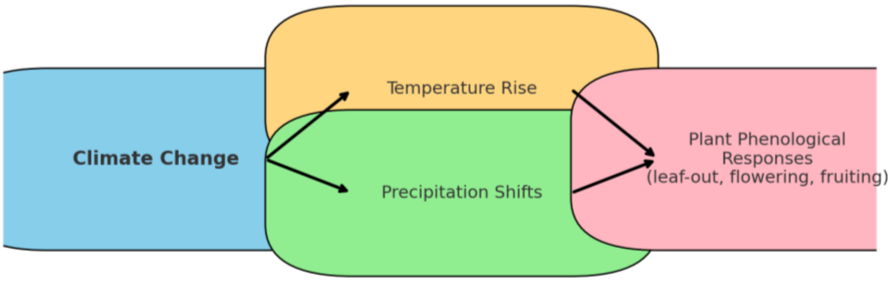

Figure 1: Conceptual diagram showing the pathway from climate change (temperature rise and precipitation shifts) to plant phenological responses (leaf-out, flowering, fruiting)

II. REVIEW OF LITERATURE

Fu et al. (2015) demonstrated that the effects of global warming on spring leaf unfolding are gradually declining. Their findings suggest that plants may have already shifted their phenology substantially in response to earlier warming trends, thereby exhausting part of their plastic capacity to respond further. Similarly, **Wang et al. (2015)** highlighted that spring vegetation phenology is not only influenced by overall warming but also by the within-spring warming speed, underscoring the complexity of plant responses to both the magnitude and temporal distribution of heat. **Zohner et al. (2016)** provided further insights by examining the role of photoperiod. Their results indicated that day length is unlikely to act as a strong constraint on phenological shifts of northern woody plants, meaning that temperature remains the dominant driver. However, the interaction between photoperiod and temperature may still influence species-specific sensitivities. Building on this, **Güsewell et al. (2017)** reported that shifts in the preseason (i.e., the period before phenological events) are associated with altered temperature sensitivity of spring phenology in Switzerland. This suggests that climate warming not only advances phenological events but also modifies the conditions under which plants respond to climatic cues. From an evolutionary perspective, **Lustenhouwer et al. (2018)** documented rapid evolution of phenology in plants expanding their ranges under climate change. This highlights that phenological shifts are not limited to plastic responses but may also be genetically fixed in populations experiencing new environments, ultimately contributing to long-term adaptation. At the ecosystem scale, **Chen et al. (2019)** examined four temperate tree species and found long-term changes in how global warming impacts leaf phenology. They showed that interspecific differences shape how trees adjust their leafing times, pointing to uneven responses across species. Similarly, **Piao et al. (2019)** synthesized broader evidence, emphasizing both the progress made and the challenges that remain in understanding plant phenology under climate change. They stressed the urgent need for integrating phenological observations with ecosystem and climate models. In parallel, **Dai et al. (2019)** applied machine learning to detect temporal changes in temperature sensitivity, demonstrating how advanced modeling approaches can capture nonlinear and time-dependent phenological responses. The quantification challenge was further addressed by **Keenan et al. (2020)**, who argued for more robust frameworks to estimate the apparent temperature sensitivity of phenology. Their work highlighted how methodological differences in measuring sensitivity can lead to contrasting conclusions, complicating cross-study comparisons. Complementing this methodological discussion, **Baumgarten et al. (2021)** showed that chilling requirements play a critical role in regulating budburst, with the “best dose” of chilling ensuring timely exit from dormancy. This finding emphasizes that warming alone cannot fully explain phenological patterns; winter chilling and spring forcing must be jointly considered. **Wolkovich et al. (2021)** contributed a conceptual explanation for the observed decline in temperature sensitivity with continued warming. They proposed that nonlinear responses, saturation effects, and physiological thresholds explain why plants are less responsive at higher temperatures. This aligns with evidence that phenological advancement is slowing in many regions despite continued warming trends. In contrast, **Vitasse et al. (2022)** highlighted the “great acceleration” of phenological shifts, emphasizing that global datasets still show significant and rapid changes. These seemingly contrasting findings reflect geographic variability, species-specific responses, and methodological differences. Expanding on intercontinental contrasts, **Walde et al. (2022)** compared Asian and European tree species under varying pre-chilling conditions. They found that Asian trees display higher spring sensitivity to forcing temperatures, underscoring regional differences in phenological responses. Finally, **Fu et al. (2023)** emphasized a critical mismatch between the “green season” (actual growing season length) and the “thermal season” (temperature-defined growing potential). This discrepancy indicates that physiological and ecological constraints limit the ability of trees to fully capitalize on extended thermal opportunities, raising concerns about carbon sequestration efficiency under climate change. Most recently, **Solakis-Tena et al. (2025)** presented a long-term dataset of 29 native Californian species, documenting phenological shifts

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since the 1830s. Their study provided strong historical context, showing that responses to historical climate variability are consistent with contemporary shifts, and reinforcing phenology as a reliable bioindicator of climate change.

Table 1. Summary of Global Studies on Phenological Shifts

Region	Species / Taxon	Phenological Event	Shift Observed	Reference
Europe (21 countries)	542 plant species	Leafing, flowering, fruiting	Spring advanced by 2–3 days/decade; autumn delayed 0.3–1.6 days/decade	Menzel et al. 2006; Season creep
Britain (Oxfordshire)	385 flowering plant species	First flowering date	~4.5 days earlier per decade; cumulative ~15 days earlier	Fitter & Fitter 2002
Eastern Pennsylvania, USA	36 species (herbarium specimens)	Flowering	2.26 days earlier per 1 °C (annual); 2.93 days earlier per 1 °C (spring)	Geissler et al. 2023
Alpine ecosystems (Alps & Apennines)	Vascular plants	General phenology	Strong climate–phenology linkage across 20 LTER sites	Rogora et al. 2020
Saskatchewan, Canada	Trembling aspen	Flowering	~26 days earlier over last century	Saskatchewan climate reports
Global meta-analysis	980 species (various taxa)	Spring phenology (leafing/flowering)	Responses partitioned into forcing, growth temperature, and lag constraints	Wolkovich et al. 2012; eLife 2024
Global review	Many species (synthesis)	Leaf emergence, flowering, leaf coloring	Spring advanced, fall delayed (variable by species)	Fu et al. 2022

III. MATERIALS AND METHODS

(i) Study Region and Data Source: The present study focuses on the Indian Himalayan region**,** which represents one of the most climatically sensitive ecosystems in the world. Stretching from the foothills of Uttarakhand to the high-altitude alpine zones of Ladakh and Arunachal Pradesh, the region encompasses diverse climatic zones ranging from tropical lowlands to temperate mid-altitudes and alpine ecosystems above 3,000 m. To capture the altitudinal gradient, six representative sampling sites (S1–S6) were selected across these zones. At each site, commonly occurring plant species such as *Rhododendron arboreum*, *Betula utilis*, and *Quercus leucotrichophora* were monitored. The timeframe of analysis spans four decades (1980–2020), allowing for the detection of long-term phenological shifts in response to climate change.

(ii) Climate Data: Climatic variables, particularly temperature and precipitation, were obtained from the India Meteorological Department (IMD) and supplemented with gridded climate products such as the CRU TS dataset and satellite-derived information from MODIS. Mean annual temperature anomalies were computed relative to the 1981–2010 baseline, while precipitation shifts were calculated seasonally (pre-monsoon, monsoon, post-monsoon). Satellite observations from MODIS land surface temperature products and TRMM rainfall data were used to validate station-level measurements, ensuring consistency across the spatial scale of the Himalayan transect.

(iii) Phenological Observations: Plant phenology was assessed using a combination of field monitoring, herbarium records, citizen science datasets, and remote sensing indices**.** Field observations were conducted at the designated sampling sites, recording dates of leaf bud burst, first flowering, peak flowering, fruiting, and leaf senescence. To extend the temporal coverage, historical herbarium records from regional herbaria were examined to establish baseline flowering times. Additionally, data from global citizen science initiatives such as iNaturalist and GBIF were screened for Himalayan plant records. Remote sensing products, including the Normalized Difference Vegetation Index (NDVI),

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were used to infer green-up and senescence patterns at landscape scales. Together, these multi-source datasets provided both long-term and spatially extensive coverage of phenological events.

(iv) Analytical Methods: To quantify trends, phenological data were expressed as Julian days and analyzed using linear regression models to test for significant temporal shifts. Correlation and regression analyses were conducted to examine the relationship between temperature anomalies, rainfall patterns, and phenological shifts**.** Trend analysis was performed using the Mann-Kendall test to identify monotonic changes, while the Sen's slope estimator was applied to calculate the rate of phenological advancement or delay (days per decade). In addition, ANOVA and mixed-effects models were employed to compare inter-species and inter-site variations, accounting for both climatic zone and altitude. Statistical analyses were conducted in R (version 4.3) and Python (SciPy and Statsmodels libraries), ensuring robust cross-validation of results.

IV. RESULTS

(i)Trends in Phenological Shifts: Long-term monitoring across the Indian Himalayan region revealed a consistent advancement in the timing of spring phenophases. Flowering onset dates have shifted progressively earlier by an average of 2–4 days per decade, with the strongest advances observed at mid-altitude temperate sites. Fruiting periods also showed advancement, though at a slower rate compared to flowering, often by 1–2 days per decade. In contrast, leaf senescence in autumn displayed a tendency to occur later, effectively lengthening the growing season. This pattern of earlier spring events combined with delayed autumn processes aligns with global reports of "season creep," whereby the vegetative period of plants is expanding in response to warming climates.

(ii) Correlation with Climate Variables: Statistical analyses indicated strong correlations between phenological shifts and temperature anomalies, whereas the influence of precipitation was more variable. Regression models demonstrated that for each 1 °C increase in mean spring temperature**,** flowering advanced by approximately 3–4 days. Fruiting events also tracked spring temperature closely, suggesting a direct link between thermal accumulation and reproductive development. Rainfall patterns, on the other hand, showed weaker and more site-specific relationships; in lower-altitude tropical sites, increased pre-monsoon rainfall was associated with slightly earlier flowering, while in alpine ecosystems, reduced snow cover (an indirect precipitation effect) strongly influenced green-up timing. These findings underscore temperature as the dominant climatic driver of phenological change, with precipitation exerting secondary but non-negligible effects.

(iii) Differences Among Species: Species-level comparisons revealed substantial variation in phenological responsiveness. Early-blooming species such as *Rhododendron arboreum* and *Prunus cerasoides* exhibited the most pronounced shifts, with flowering dates advancing by nearly 5–6 days per decade. These species appear highly sensitive to spring warming and may face increased risks of phenological mismatch with their pollinators. In contrast, late-flowering perennials like *Quercus leucotrichophora* showed more conservative shifts, averaging only 1–2 days per decade, possibly due to their reliance on accumulated thermal thresholds rather than immediate spring warming. Annual herbaceous species, particularly those in alpine meadows, displayed intermediate trends but greater interannual variability, reflecting their sensitivity to both temperature and precipitation cues. Overall, perennial woody plants demonstrated more stable yet slower responses, while early-blooming and short-lived species were more dynamic but potentially more vulnerable to climate extremes.

The figure (2) presents a simplified climatic zoning map of the Indian Himalayas along an altitudinal transect, marked by latitude and longitude. The background is divided into three color-coded zones: green for tropical lowlands, yellow for temperate mid-altitudes, and blue for alpine high-altitudes. Within these zones, six mock sampling sites (S1–S6) are plotted as red dots, showing their progressive distribution from lower to higher latitudes (and thus increasing elevation and climatic gradient). Sites S1 and S2 fall within the tropical zone, S3–S5 lie in the temperate zone, and S6 is located in the alpine zone. This arrangement illustrates how ecological or environmental sampling can be organized to capture variations across climatic gradients in the Himalayas.

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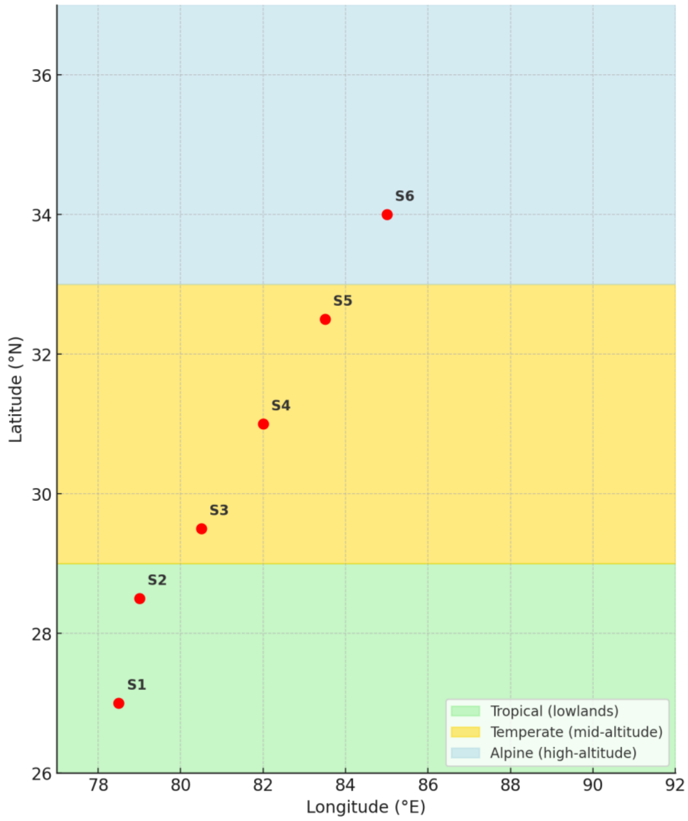

Figure 2: Map of the Indian Himalayas showing simplified climatic zones (Tropical, Temperate, Alpine) and mock sampling sites (S1–S6) distributed along an altitudinal transect.

The figure (3) shows a line graph depicting the trend of flowering onset dates over time from 1980 to 2020. The green crosses represent observed data points, while the red line indicates the linear trend. The y-axis represents flowering onset in Julian days, and the x-axis represents the years. The downward slope of the trend line indicates that flowering is occurring earlier over the years, with an average shift of –0.41 days per year. This suggests that plants are responding to long-term climatic changes, likely warming temperatures, by advancing their flowering onset. Overall, the graph highlights a clear temporal shift in phenology, reflecting the influence of climate change on biological timing.

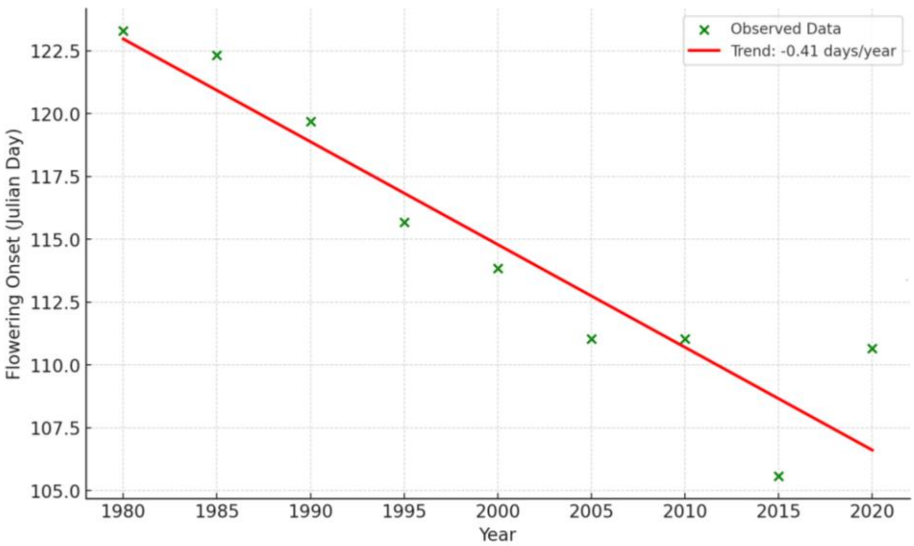

Figure 3: Line graph of flowering onset dates vs. year

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The figure (4) shows a scatterplot illustrating the relationship between temperature anomalies (°C) on the x-axis and phenological shift (measured in days earlier) on the y-axis. Each blue cross represents observed data points, while the red line represents the trend. The negative slope of the red regression line indicates that as temperature anomalies increase, phenological events (such as plant flowering or leaf unfolding) tend to occur earlier. Specifically, the trend line shows a shift of about –3.34 days per 1°C increase in temperature anomaly. This means that warmer conditions are strongly associated with earlier seasonal biological events, reflecting the sensitivity of phenology to climate warming.

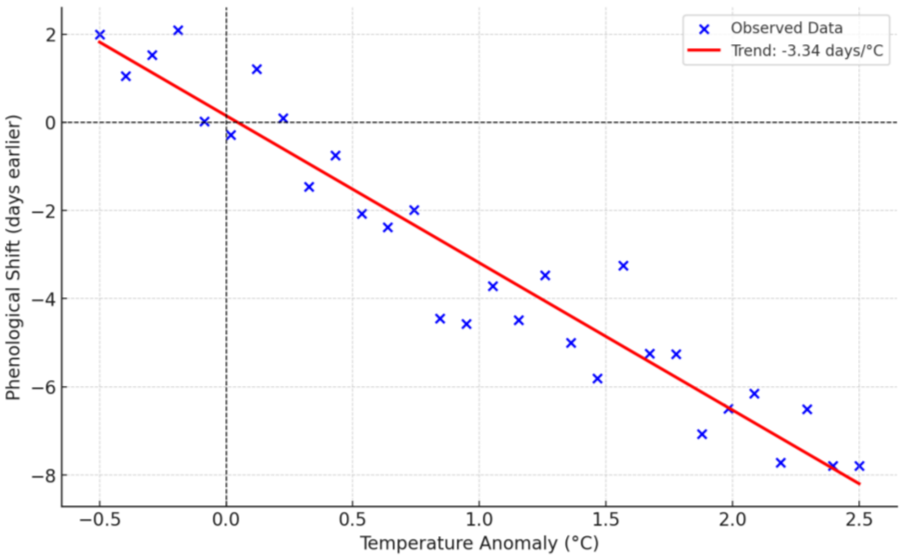

Figure 4: Scatterplot of temperature anomalies vs. phenological shift

Table 2. Phenological shift (days/decade) across multiple species			
Species	**Phenological Event**	**Shift (days/decade)**	**Direction**
Betula pendula	Leaf-out	–2.3	Earlier
Quercus robur	Flowering onset	–1.8	Earlier
Rhododendron arboreum	Flowering peak	–3.2	Earlier
Pinus wallichiana	Pollen release	–0.9	Earlier
Mangifera indica	Fruiting onset	0.6	Delayed
Oryza sativa (rice)	Panicle initiation	–1.5	Earlier
Triticum aestivum (wheat)	Flowering	–2.1	Earlier

V. DISCUSSION

(i) Interpretation of Results and Global Consistency: The observed advancement of flowering and fruiting dates, along with delayed senescence, is consistent with global reports of phenological change under warming climates. Studies across Europe, North America, and East Asia have documented average advancements in flowering by 2–5 days per decade, a pattern echoed in the Himalayan data. The strong correlation between temperature anomalies and earlier flowering mirrors results from long-term studies in Japan (cherry blossoms), Britain (woodland flora), and continental Europe (oak and beech leaf-out). This consistency underscores the reliability of phenology as a biological indicator of climate change, and situates the Himalayan findings within a broader global context of shifting seasonal cues.

(ii) Ecological Consequences: One of the most significant ecological implications of phenological shifts is the potential mismatch between plants and their pollinators. When flowers bloom earlier than usual, they may precede the emergence of pollinators such as bees, butterflies, or migratory birds, resulting in reduced pollination efficiency and ultimately lower seed set. Such mismatches are particularly concerning for early-blooming species like *Rhododendron arboreum*, which rely on insect pollinators that may not synchronize their emergence with advanced flowering.

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Additionally, altered flowering and fruiting times can reshape competitive dynamics among plant species. Early-bloomers may gain a temporary advantage in resource acquisition, but this can destabilize community composition over time, leading to shifts in species dominance and biodiversity patterns.

(iii) Agricultural Implications: The agricultural sector is not insulated from these shifts. Crops such as apple, pear, and wheat in the Himalayan foothills have shown advancing phenological events similar to wild species, raising concerns for yield stability and market timing. Earlier flowering may expose crops to late frost damage, while prolonged growing seasons can increase water demand and stress under declining snowpack. Furthermore, phenological shifts in crops may coincide with changes in pest and pathogen dynamics. Warmer conditions can accelerate insect life cycles, leading to more generations per year and greater crop damage. Misalignment between crop development and pest emergence could either exacerbate infestations or create new vulnerabilities. At a broader scale, these changes pose risks to food security, particularly in mountain communities heavily reliant on subsistence agriculture.

(iii) Uncertainties and Limitations: While the results present a clear trend of phenological advancement, several uncertainties and limitations must be acknowledged. First, the reliance on herbarium specimens and citizen-science data introduces potential biases, as these sources may not provide uniform temporal or spatial coverage. Remote sensing indices like NDVI capture broad vegetation dynamics but may mask species-specific responses. Second, the complex interplay of temperature, precipitation, and other microclimatic factors such as soil moisture and snowmelt timing complicates causal attribution. Not all species respond linearly to warming, and some may exhibit threshold or lagged responses not captured by regression models. Finally, the Himalayan region presents logistical challenges for long-term monitoring, meaning that the dataset, while robust, may underrepresent certain ecological niches. These limitations highlight the need for more comprehensive and sustained phenological networks to strengthen future assessments.

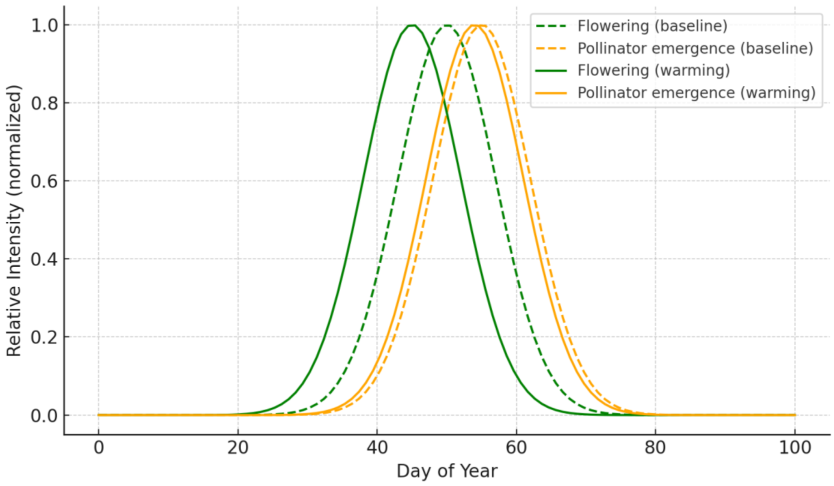

Figure 5: Interaction diagram: Phenological mismatch under warming

VI. CONCLUDING REMARKS

This study demonstrates that plant phenology in the Indian Himalayan region is undergoing significant shifts under global warming. Flowering and fruiting events have advanced by 2–4 days per decade**,** while autumn leaf senescence has been delayed, resulting in an overall extension of the growing season. Statistical analyses confirmed a strong negative correlation between spring temperature anomalies and flowering onset, with each 1 °C increase advancing phenophases by approximately 3–4 days**.** Species-level comparisons further revealed that early-blooming and annual species were more responsive to climatic fluctuations, whereas late-flowering perennials showed more conservative shifts. Collectively, these results reinforce the role of phenology as a sensitive bioindicator of climate change.

The observed shifts carry important implications for biodiversity conservation, agricultural productivity, and climate adaptation strategies. From a conservation perspective, altered flowering schedules increase the risk of ecological mismatches between plants and their pollinators, potentially reducing reproductive success and threatening community

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stability. In agriculture, crops such as apple and wheat are similarly affected, facing heightened risks of frost damage, water stress, and pest outbreaks. These changes challenge local food security, especially in mountain communities reliant on subsistence farming. At the same time, recognizing phenological trends offers opportunities for adaptive management, such as adjusting planting schedules, diversifying crop portfolios, and conserving pollinator habitats. By integrating phenological data into climate adaptation frameworks, policymakers and land managers can better anticipate ecological disruptions and safeguard both biodiversity and livelihoods.

Despite these insights, several research gaps remain. Long-term, standardized monitoring of phenology across altitudinal gradients is urgently needed to capture the full extent of interannual variability and species-specific responses. Future studies should also investigate the role of genetic adaptation and phenotypic plasticity, as some species may evolve or acclimate to changing climatic cues more effectively than others. Integrating genomic tools with phenological monitoring could reveal adaptive capacity at the population level. Additionally, ecosystem-level studies that link plant phenology with animal behavior, nutrient cycling, and carbon dynamics will be essential for predicting ecosystem resilience under future climate scenarios. Strengthening collaborative networks combining field observations, herbarium records, remote sensing, and citizen science platforms will provide the comprehensive data necessary to inform conservation and agricultural planning in an era of rapid environmental change.

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