Forecasting Phenological Shifts in Forest Tree Species using Herbarium Records from the Kumaun Himalaya, India

Zoya Shah[1*], Dhani Arya[2]

[1,2] Department of Botany, Soban Singh Jeena University, Almora, Uttarakhand, India-263601

Abstract

Climate change is shifting phenological timing, i.e., flowering, in forest ecosystems. The research here investigates phenological change in flowering in eight ecologically different tree species of the forest in the Kumaun Himalaya, i.e., *Acacia dealbata*, *Pyrus pashia*, *Quercus floribunda*, *Quercus leucotrichophora*, *Rhododendron arboreum*, *Cedrus deodara*, *Pinus roxburghii*, and *Pinus wallichiana*. Following Generalized Additive Models (GAMs), herbarium records (1985–2020) and recent field observations (2015–2021) were used to estimate phenological change. Advanced shift in the date of flowering onset, from 13 to 42 days earlier, owing mainly to rising temperatures, is revealed by the findings. The phenological changes have ecological and socio-economic implications, e.g., reduced fruit productivity in *P. pashia*, which can result in enhanced wildlife crop-raiding. The findings underscore the value of the integration of historical herbarium observations with recent observations in monitoring phenological responses to climate change, and the necessity of longer-term, region-specific monitoring protocols.

Keywords: Phenological shifts, Climate change impacts, Herbarium records, Flowering period shifts, Kumaun Himalaya.

Introduction

Phenological events such as flowering and fruiting are well established as sensitive indicators of ecosystem response and climate change (Parmesan & Yohe, 2003; Cleland et al., 2007). Flowering date, in general, is crucial to plant reproductive success, species interactions, and ecosystem process (Forrest & Miller-Rushing, 2010). The timing of these events has been strongly linked to the recent warming with numerous studies showing earlier progress in spring phenology particularly in mountain ecosystems that are vulnerable to climate change like the Himalayas (Keenan et al., 2014; Singh et al., 2019; Kumar et al., 2016). Although temperature precipitation humidity and photoperiod are some of the environmental cues that control phenology species-specific and regional responses cause notable variability in the patterns that are observed (Menzel et al., 2006; Vitasse et al., 2018; Sharma & Rana, 2020).

The Intergovernmental Panel on Climate Change (IPCC, 2021) recognizes recurring advance of spring events in the world along with rising temperatures and heightened frequency of extreme weather. An extended growing season may appear favorable on the surface, but it typically implies greater frost exposure, extended pest and disease seasons, and disruption of symbiotic relationships such as plant-pollinator relationships (Schwartz et al., 2013; Wolkovich et al., 2012). In the Indian Himalayan Region (IHR), such comparable changes in phenology may have cascading impacts on forest regeneration, conservation of biodiversity, and agriculture-based livelihoods and forest-based livelihoods (Singh et al., 2019; Rawal et al., 2021; Mishra et al., 2024).

Although various studies have documented phenological trends in temperate and the Himalayas (Kumar et al., 2016; Sharma & Rana, 2020), fewer have focused on the central Kumaun Himalaya, particularly from herbarium records and recent field observation. Herbarium collections provide temporally dated, verifiable records of plant phenophases and have proved to be useful resources for monitoring long-term phenological trends in the absence of continuous field observations (Willis et al., 2017; Davis et al., 2015; Primack et al., 2004). Integrating these earlier records with current data offers a singular opportunity to investigate phenological responses on multi-decadal timescales (Lavoie & Lachance, 2006; Joshi et al., 2022).

According to local warming trends there is compelling evidence from recent phenology studies of Himalayan herbaria that flowering dates vary among species (Kumar et al., 2016; Sharma & Rana, 2020). Additionally, phenological event changes and their potential ecological ramifications have been accurately predicted by modeling techniques that combine field and herbarium records (Zhou et al. 2023 Hassan et al. 2022). There are currently few comparative long-term studies on gymnosperms and angiosperms in the area using standard models. By combining current field observations with herbarium records this study seeks to predict flowering phenological shifts in the main forest tree species of the Kumaun Himalaya. Tested hypotheses include: (1) flowering dates have changed dramatically over the past few decades due to rising temperatures (2) the degree of phenological change varies with elevation and plant life form (angiosperms vs. Gymnosperms) and (3) Herbarium records are useful for evaluating the impact of climate change because they accurately reflect such changes as current observation data. Predicting ecological and socioeconomic effects in the delicate Himalayan Mountain ecosystem requires a thorough understanding of these changes (Mishra et al., 2024; Rana et al., 2024)

Material and Methods

Herbarium collections from the Botanical Survey of India (BSI), Dehradun; the Forest Research Institute (FRI), Dehradun; and the National Botanical Research Institute (NBRI), Lucknow were consulted. Species were selected for their ecological significance (e.g., co-dominant or dominant canopy trees), frequency of occurrence in herbaria, and broad elevational range in the Kumaun Himalaya. Specimen metadata were recorded for each sample, including specimen number, locality of collection, date of collection, elevation, and collector's name. Flowering dates were estimated as day of year (DOY) from dates of collection and visible reproductive phenophases. When dates of collection were imprecise (e.g., month/year only), the 15th of the month was taken as date of collection. Records with temporal uncertainty of more than two weeks were excluded from analysis.

Phenological data for target species were also obtained from the Global Biodiversity Information Facility (GBIF; https://www.gbif.org), based on corresponding data fields (location, date, elevation, etc.). Climatological data for the study period (January 1985–December 2020) were retrieved from the Indian Meteorological Department (IMD), Dehradun. Missing values in the IMD data set were filled by the NASA Langley Research Center (LaRC) POWER project (https://power.larc.nasa.gov). Herbarium and recent field-based flowering phenology were evaluated together in order to examine trends in flowering phenology. Biological collections, both in herbaria and in botanical gardens, have increasingly been shown to be valuable in climate-driven phenological change monitoring when uninterrupted long-term field data are unavailable (Robbirt et al., 2011).

Eight species were used in the analysis (Table 1). Different numbers of herbarium and observation records were available for each species, with *Pyrus pashia* and *Quercus floribunda* being more represented. The difference in sample size was accounted for while interpreting phenological trends among taxa.

Results

Eight dominant and co-dominant tree species of the Kumaun Himalayan Forest showed considerable changes in flowering phenology. Advance in flowering dates varied between 13 and 42 days, which indicated clear responses to climatic change. The changes were more pronounced in herbarium-based records, though recent field observations also showed the same trend. *Acacia dealbata* showed the highest shift, flowering 42 days earlier in herbarium records and 5 days earlier in observational records based on field records. *Pyrus pashia* showed 28 days of shift in herbarium records and 7 days in recent observations.

Quercus floribunda flowered 28 days in advance in herbarium observations and 4 days in advance in field observations. *Quercus leucotrichophora* brought forward its flowering by 30 days (herbarium) and 6 days (observed), with unusually early flowering events reported between early December and early January in 2021. *Rhododendron arboreum* exhibited flowering advances of 30–33 days in herbarium observations and 6–7 days in observations.

In *Cedrus deodara*, flowering was 20 days earlier in herbarium records and 4 days earlier in field records, in *Pinus roxburghii* it changed by 17 days (herbarium) and 3 days (field), and in *Pinus wallichiana* flowering was 13 days earlier in herbarium records and 2 days earlier in field records. For each species studied the mean annual temperature and the flowering day-of-year (DOY) showed statistically significant correlations according to the Generalized Additive Model (GAM) analysis. The model performed well in capturing nonlinear trends and species-specific variance. $R^2 = 0.62$, $p< 0.$

001 for Pyrus pashia, Quercus floribunda: p< 0. 01 R^2= 0. 59, Rhododendron arboreum: p <0. 001, R^2= 0. 66, Cedrus deodara: p = 0. 02, R^2= 0. 53 and Pinus wallichiana: p = 0. 03, R^2= 0. 38.

Discussion

This study records significant advances in flowering phenology of eight widespread forest tree species of the Kumaun Himalaya, with flowering advancing by 13 to 42 days. The findings agree with local and global trends of temperature-driven phenological change (Parmesan, 2006; Cleland et al., 2007). One of the most notable observations is the greater magnitude of flowering advance in herbarium records in comparison with field observations. For instance, *Acacia dealbata* exhibited a 42-day advance in herbarium records, whereas field observations recorded only a 5-day change. For a number of reasons this disparity is likely to happen. Field observations only cover 2015–2021 reflecting recent variability while herbarium records cover a longer time period (1985–2020) including decadal warming trends. Additionally, herbarium specimens are likely to fall during periods of peak flowering which could lead to phenological sampling bias and overestimate the observed phenophase changes (Primack et al. 2004). Furthermore, whereas observational records offer a higher temporal resolution herbarium data are probably sparse in both space and time. To identify climate-mediated changes in phenology these disparities highlight the complementary strengths of each data set and the importance of combining several lines of evidence (Gallinat et al. in 2015).

The results are consistent with a number of earlier Himalayan studies, (Khan et al. 2023) reported flowering 15–21 days earlier in Olea ferruginea in the Western Himalaya, based on both herbarium and field data, with GAM models returning $R^2 = 0.59$ ($p < 0.01$). Gaira et al. (2011) reported shifts of selon 17–25 days in the medicinal plant Aconitum heterophyllum, based on herbarium observations over centuries. The shifts reported here (13–42 days) are within or just above these estimates, indicating that forest tree species in the Kumaun region could be responding at similar or even faster rates.

Extensive phenological advancement has also been reported for Rhododendron arboreum. Bhatt et al. (2015) reported up to 97 days of change between 1893 and 2011 in the Uttarakhand Himalaya, attributing this to extreme post-monsoon warming. Compared to this, the current findings of 30–33 days of advancement are still significant and in accordance with these long-term trends. Other regions outside of the Indian subcontinent have seen comparable albeit less drastic changes. Cleland et al. (2007) observed that temperate species in North America and Europe experienced phenological advancements of 2. 5 to 5. 0 days every decade. The more drastic changes seen in this study might be a result of the Himalayan montane ecosystems increased sensitivity to climate change where phenological responses are amplified by localized warming and steep elevational gradients (Inouye 2008 Yu et al. (2010). The robust modeling of temperature-flowering day-of-year (DOY) non-linear trends has been made possible by the use of Generalized Additive Models (GAM). As previously shown in earlier Himalayan studies temporal variation and species-specificity are made possible (Gaira et al. (2011) Khan and associates. in 2023). The studys GAM findings support statistically significant trends in all species of concern and reaffirm that temperature is the primary driver of phenological change (Vitasse et al., 2011; Chen et al., 2020).

Although the evidence is strong, some limitations are worth mentioning:

•Herbarium observations can disproportionately record peak flowering phases and thereby overestimate phenological progress (Primack et al., 2004).

•Inadequate metadata (e.g., missing elevation, ambiguities in date) excluded some specimens.

•The brief observational span (2015–2021) sets a limit on discovering long-term, non-linear patterns or lag effects.

•Microclimatic heterogeneity and site-level variability can provide extra noise not accounted for by regional climate means employed in the models.

However, this research gives one of the earliest overall evaluations of phenological changes in forest tree species of the Kumaun Himalaya based on herbarium and field data combined with statistical modeling. The results confirm earlier reports from the central and western Himalayas and underscore the increasing need for regionally specific multi-year long-term monitoring programs. Since phenological changes can disrupt ecological interactions like pollination and seed dispersal they may have broader effects on forest biodiversity and community dynamics(Forrest & Miller-Rushing, 2010; Renner & Zohner, 2018). Changes in flowering phenology may also affect the availability of non-timber forest products which in turn may affect the livelihoods of people in rural Himalaya (Rawal et al. (2021). Rich ecological insights into climate change responses can be gained through integrative methods that combine digitalized historical data with current observations supported by reliable statistical frameworks. For the purpose of developing adaptive forest management plans directing conservation agendas and preserving ecosystem resilience in biodiversity hotspots such as the Indian Himalayas these studies are crucial.

Conclusion

Important new information about the phenological variations of the dominant forest tree species in the Indian Himalayas under various climate conditions is provided by this study. When current observation data is compared with herbarium records there is evidence of an early flowering that is primarily caused by rising temperatures. Significant ecological and socioeconomic repercussions result from these phenological changes including changes in species interactions and effects on local livelihoods. For example, increased wildlife foraging in crops and subsequent crop damage have been linked to *Pyrus pashia* as early flowering which has a negative impact on local communities social and economic well-being. The results highlight the need to add phenological records of other species and Himalayan regions in order to fill in the current knowledge gaps. Adaptive management techniques and phenological monitoring are essential to reducing the unintended consequences of these changes especially for societies that depend on forests. Phenological observations will help create more effective conservation and resource management plans and increase the accuracy of predictions. Enhancing our knowledge of how climate change affects Himalayan ecosystems and the human components associated with them requires constant research and observation.

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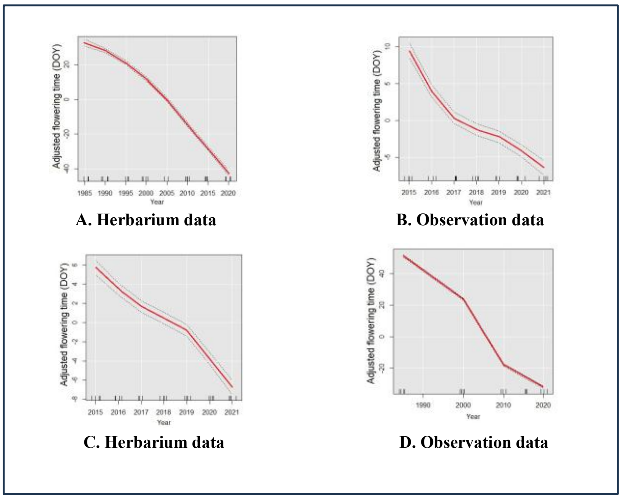

Figure 1. GAM-predicted early flowering over the years of *Acacia dealbata* a. using the herbarium data and questionnaire data and b. using the observation data and of *Pyrus pasia* c. using the herbarium data and questionnaire data and d. using the observation data

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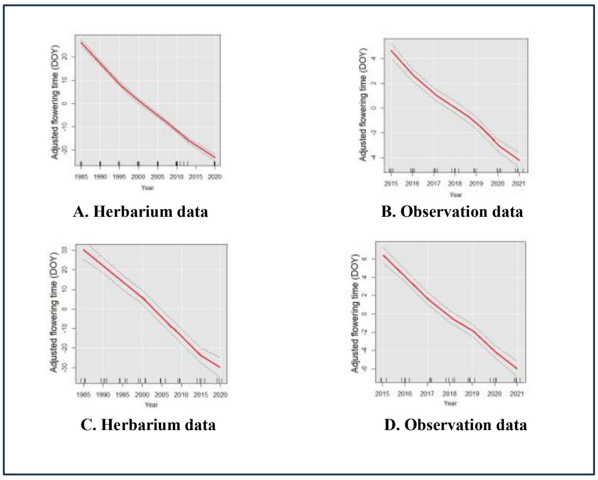

Figure 2. GAM-predicted early flowering over the years of *Quercus floribunda*(a) using the herbarium data and questionnaire data and (b) using the observation data and of *Quercus leucotrichophora*(c) using the herbarium data and questionnaire data and d. using the observation data

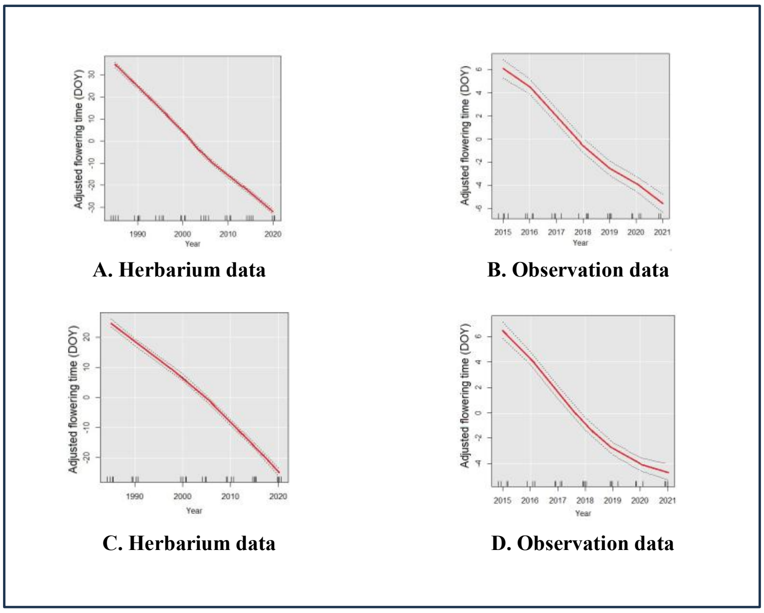

Figure 3. GAM-predicted early flowering over the years of *Rhododendron arboreum* a. using the herbarium data and questionnaire data and b. using the observation data and of *Cedrus deodara* c. using the herbarium data and questionnaire data and d. using the observation data

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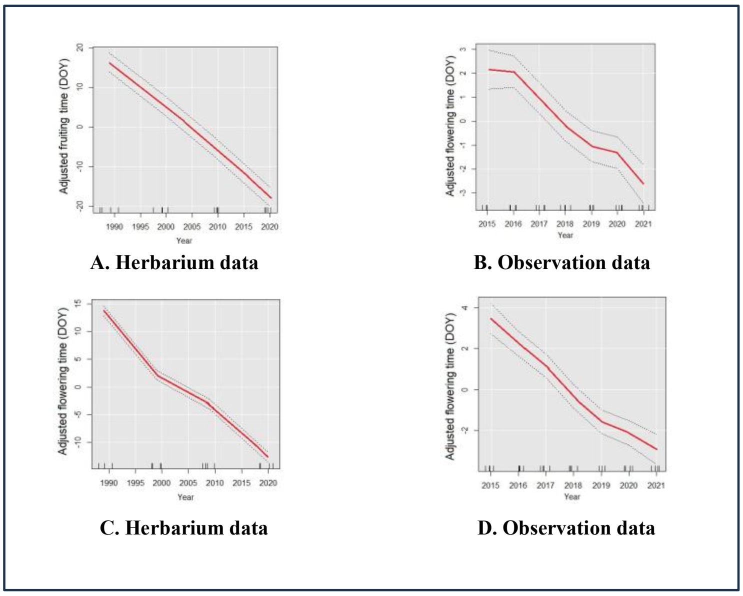

Figure 4. GAM-predicted early flowering over the years of *Pinus roxburghii* a. using the herbarium data and questionnairedata and b. using the observation data and of *Pinus wallichiana* c. using the herbarium data and questionnaire data and d. using the observation data

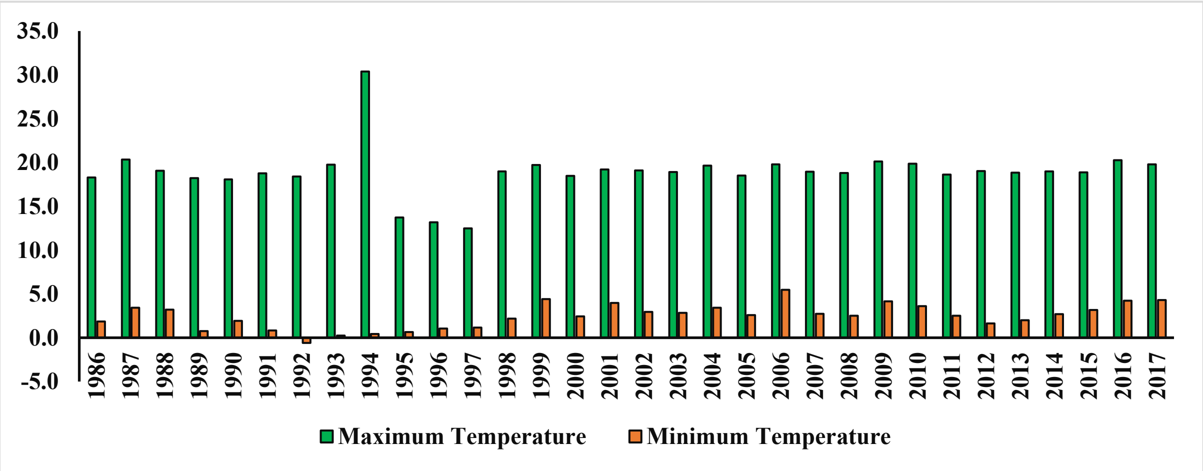

Figure 5. Annual maximum and minimum temperature variations in Ramgarh block

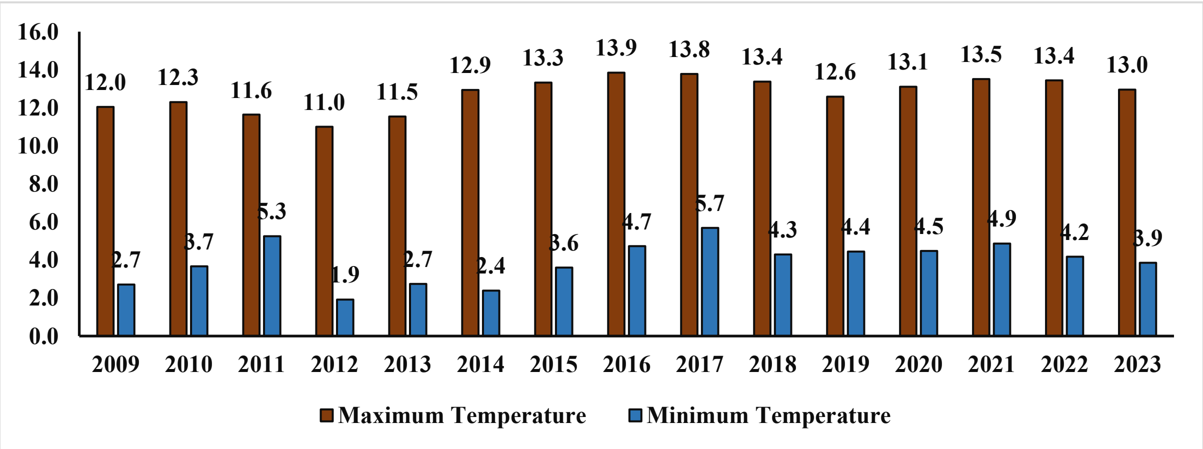

Figure 6. Annual maximum and minimum temperature variation in Joshimath block

Table 1. Phenological Shifts in Flowering Date according to Herbarium and Observational Records

No	Species	Herbarium Shift (Days Earlier)	Observational Shift (Days Earlier)
1	*Acacia dealbata*	42	5
2	*Pyrus pashia*	28	7
3	*Quercus floribunda*	28	4
4	*Quercus leucotrichophora*	30	6
5	*Rhododendron arboreum*	30–33	6–7
6	*Cedrus deodara*	20	4
7	*Pinus roxburghii*	17	3
8	*Pinus wallichiana*	13	2

Table 2: Flowering Advance Summary Table

Species	Herbarium Shift (Days Earlier)	Observed Shift (Days Earlier)	GAM R^2	p-value
Acacia dealbata	42	5	N/A	N/A
Pyrus pashia	28	7	0.61	< 0.001
Quercus floribunda	28	4	0.58	< 0.01
Quercus leucotrichophora	30	6	N/A	N/A
Rhododendron arboreum	30–33	6–7	0.65	< 0.001
Cedrus deodara	20	4	0.52	0.02
Pinus roxburghii	17	3	N/A	N/A
Pinus wallichiana	13	2	0.37	0.05

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