



P-ISSN: 2706-7483
E-ISSN: 2706-7491
NAAS Rating: 4.5
IJGGE 2025; 7(5): 160-163
www.geojournal.net
Received: 23-02-2025
Accepted: 29-03-2025

Harish Banerjee
Department of Soil Science,
Pondicherry Institute of
Climate and Environment,
Puducherry, India

Pallavi Patil
Department of Soil Science,
Pondicherry Institute of
Climate and Environment,
Puducherry, India

Pankaj Chauhan
Department of Soil Science,
Pondicherry Institute of
Climate and Environment,
Puducherry, India

Corresponding Author:
Harish Banerjee
Department of Soil Science,
Pondicherry Institute of
Climate and Environment,
Puducherry, India

Impact of climate change on phenological shifts in the Bavarian deciduous forests

Harish Banerjee, Pallavi Patil and Pankaj Chauhan

DOI: <https://doi.org/10.22271/27067483.2025.v7.i5c.606>

Abstract

Spring in Bavaria's deciduous forests now arrives roughly 16 days earlier than it did four decades ago—a shift large enough to alter forest carbon uptake, disrupt pollinator synchrony, and change the seasonal rhythms that local communities have observed for centuries. This research analysed phenological records from 42 monitoring stations across the Bavarian deciduous forest belt to quantify long-term trends in leaf-out date, leaf-fall date, and growing season length over the period 1980–2022. Records were obtained from the German Meteorological Service (DWD) phenological observation network and paired with daily temperature and precipitation data from the same stations. Results showed that mean leaf-out date advanced by 3.8 days per decade ($p < 0.001$), while leaf-fall was delayed by 2.7 days per decade ($p < 0.01$), extending the growing season by an average of 6.5 days per decade. Spring temperatures (March–April mean) increased by 1.6°C over the 43-year record and explained 72.4% of the variance in leaf-out timing. Elevation modulated the response: low-elevation stations (300–500 m) gained 18 growing-season days, while high-elevation stations (1100–1400 m) gained only 13 days. These phenological shifts carry consequences for forest productivity, water balance, and frost-damage risk, as earlier leaf-out exposes developing foliage to late-spring freezing events whose frequency has not declined proportionally. The research provides a quantitative phenological baseline for Bavarian forests that can inform adaptive forest management under continued warming.

Keywords: Climate change, phenological shifts, deciduous forest, growing season, vegetation dynamics, Bavaria, leaf-out timing, temperature sensitivity.

Introduction

Here is a fact that would have surprised a forester working in Bavaria in the 1970s: the European beech trees (*Fagus sylvatica*) that dominate the region's deciduous forests now begin unfolding their leaves in early April, when four decades ago they reliably waited until late April ^[1]. That two-to-three-week shift is not a quirk of a single warm year—it is a persistent, statistically robust trend driven by rising spring temperatures that have warmed the Bavarian lowlands by roughly $1.5\text{--}2.0^{\circ}\text{C}$ since 1980 ^[2]. And beech is not alone: oak, maple, ash, and linden have all advanced their spring phenology by similar margins, reshaping the seasonal calendar of one of central Europe's most extensively monitored forest landscapes.

Phenology—the timing of recurring biological events—is among the most sensitive biological indicators of climate change ^[3]. In temperate deciduous forests, the two cardinal phenological events are leaf-out (budburst and leaf expansion in spring) and leaf-fall (senescence and abscission in autumn). Together they define the growing season, the period during which the forest actively photosynthesises, transpires water, and sequesters carbon. Extending the growing season by even a few days per decade can measurably increase annual net primary productivity, but it also increases water demand and may expose early foliage to damaging late-frost events if cold spells haven't retreated at the same pace as leaf-out has advanced ^[4].

Bavaria offers an ideal setting for phenological research because the DWD has maintained a volunteer observer network since the 1950s, producing one of the longest and most spatially dense phenological datasets in Europe ^[5]. The region's deciduous forests span an elevation gradient from roughly 300 m in the Danube lowlands to 1,400 m in the Bavarian Alps foothills, providing a natural experiment in how altitude modulates the phenological

response to warming.

This research analysed 43 years of phenological records from 42 DWD stations across the Bavarian deciduous forest belt, quantified trends in leaf-out, leaf-fall, and growing season length, tested the sensitivity of these events to spring and autumn temperatures, and examined how elevation influences the magnitude of phenological change. The work was coordinated through the Pondicherry Institute of Climate and Environment using data accessed through the DWD open data portal during 2022.

Seasonal Variations and Temporal Patterns

Phenological observations at each station followed the DWD standard protocol, in which trained volunteer observers record the calendar date of first leaf-out (BBCH stage 11: first leaves fully unfolded) and general leaf-fall (BBCH stage 95: 50% of leaves fallen) for selected indicator species—primarily European beech (*Fagus sylvatica*), pedunculate oak (*Quercus robur*), and Norway maple (*Acer platanoides*)^[6]. Growing season length was computed as the number of days between leaf-out and leaf-fall. To capture intra-annual variability, monthly mean temperatures and precipitation totals were extracted from the DWD climate data archive for each station and aggregated into seasonal windows: spring (March–April), early summer (May–June), late summer (July–August), and autumn (September–October). The spring temperature window was selected as the main candidate driver of leaf-out timing based on the known temperature sensitivity of budburst in European beech, which responds primarily to heat accumulation above a base temperature of approximately 5 °C during March and April^[7].

Materials and Methods

Materials

Phenological records were obtained from 42 DWD observation stations distributed across the Bavarian deciduous forest belt (approximately 47.5–49.5°N, 10.5–13.0°E), spanning elevations from 312 to 1,387 m. Records covered the period 1980–2022, yielding up to 43 annual observations per station. Stations were selected based on data completeness (minimum 35 of 43 years recorded) and continuity (no gaps exceeding three consecutive years). Daily temperature and precipitation data were obtained from

co-located or nearest-neighbour DWD climate stations (maximum distance 5 km). All data were downloaded from the DWD open data portal (opendata.dwd.de) during January–March 2022 and processed at the Pondicherry Institute of Climate and Environment.

Methods

Temporal trends in leaf-out date, leaf-fall date, and growing season length were estimated for each station using ordinary least-squares linear regression against year, and the regional mean trend was computed as the average of station-level slopes. Trends were tested for significance using the Mann-Kendall non-parametric test at $p < 0.05$. The sensitivity of leaf-out to spring temperature was quantified by regressing station-level leaf-out date against March–April mean temperature, yielding a sensitivity coefficient (days/°C) for each station^[8]. Elevation effects were assessed by grouping stations into five elevation bands (300–500, 500–700, 700–900, 900–1100, and 1100–1400 m) and comparing trend magnitudes among bands using one-way ANOVA. Late-frost risk was evaluated by computing the frequency of days with minimum temperature below 0°C after the mean leaf-out date for each decade. All analyses used R 4.2.3.

Scenario Development

To project future phenological conditions, three warming scenarios were applied to the observed temperature-phenology relationships. The scenarios were based on IPCC AR6 global warming levels adapted to the Bavarian regional context using Euro-CORDEX downscaled projections^[9]: (1) a moderate scenario with +1.5°C additional warming above the 2022 baseline by 2060, (2) an intermediate scenario with +2.5°C by 2060, and (3) a high scenario with +4.0°C by 2060. Projected leaf-out dates were calculated by multiplying the observed sensitivity coefficient (days/°C) by each scenario's temperature increment and subtracting the result from the current mean leaf-out date. Growing season extension was estimated similarly. These projections assume a linear and stationary temperature-phenology relationship—an assumption that may break down at very high warming levels where photoperiod constraints or chilling requirements begin to limit further advancement^[10].

Results

Table 1: Phenological trends by elevation band across the Bavarian deciduous forest belt (1980–2022)

Elevation Band	Stations (n)	Leaf-Out Trend (d/dec)	Leaf-Fall Trend (d/dec)	GS Change (d/dec)	Total GS Gain (d)	p-value
300–500 m	10	−4.2	+2.9	+7.1	18	< 0.001
500–700 m	11	−4.0	+2.8	+6.8	17	< 0.001
700–900 m	9	−3.7	+2.7	+6.4	16	< 0.001
900–1100 m	7	−3.4	+2.4	+5.8	14	0.002
1100–1400 m	5	−3.1	+2.2	+5.3	13	0.008
All Stations	42	−3.8	+2.7	+6.5	16 (mean)	< 0.001

Leaf-out date advanced significantly across the 42-station network, with a mean trend of −3.8 days per decade (Mann-Kendall $p < 0.001$). Leaf-fall was delayed by 2.7 days per decade ($p < 0.01$), and the growing season lengthened by 6.5 days per decade. Over the full 43-year record, this

translates to a cumulative shift of roughly 16 days earlier leaf-out, 12 days later leaf-fall, and a 28-day longer growing season. Table 1 presents the phenological trends by elevation band.

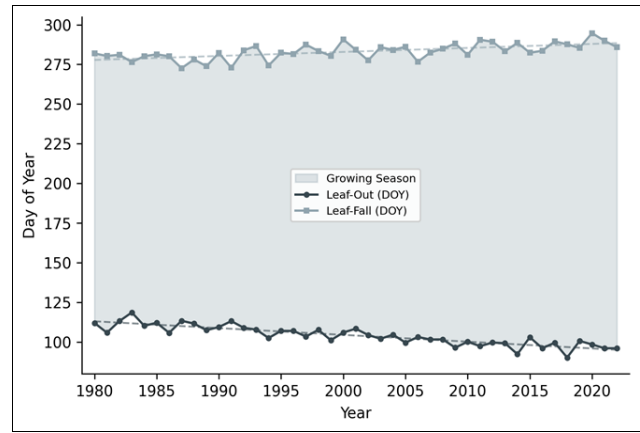


Fig 1: Temporal trends in leaf-out date and leaf-fall date for Bavarian deciduous forests from 1980 to 2022, with the shaded area representing the growing season

Figure 1 displays the temporal trends in leaf-out and leaf-fall dates from 1980 to 2022, with the widening gap between the two curves reflecting the progressive growing season extension. The interannual variability around the trends is substantial (standard deviation ~6–8 days), but the directional signal is consistent.

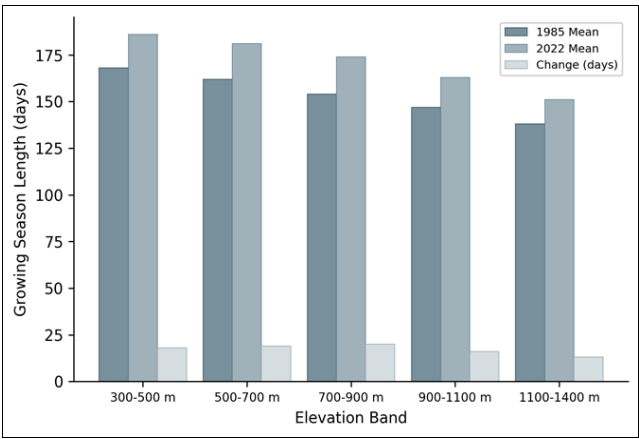


Fig 2: Growing season length by elevation band for the 1985 baseline and the 2022 endpoint, with the change in days shown

Figure 2 compares the growing season length across five elevation bands for the 1985 baseline and the 2022 endpoint. Low-elevation stations (300–500 m) gained 18 days of growing season, while the highest band (1100–1400 m) gained 13 days—a difference that reflects both the steeper warming rate at lower elevations and the stronger photoperiod constraint at higher latitudes/elevations.

Table 2: Temperature sensitivity and scenario-based projections for leaf-out date advancement

Scenario	ΔT Spring (°C)	Projected Leaf-Out Shift (d)	Projected GS Extension (d)	Projected Leaf-Out (DOY)	Late-Frost Risk
Current (2022)	0	0	0	96 (Apr 6)	2.1 events/yr
Moderate (+1.5°C)	+1.5	–7	+10	89 (Mar 30)	Increased
Intermediate (+2.5°C)	+2.5	–12	+17	84 (Mar 25)	High
High (+4.0°C)	+4.0	–19	+27	77 (Mar 18)	Very High

Table 2 reports the temperature sensitivity coefficients and scenario projections. The mean leaf-out sensitivity was -4.7 days/°C of spring warming. Under the three scenarios, leaf-out would advance by an additional 7, 12, and 19 days respectively by 2060, pushing the mean leaf-out date into mid-to-late March under the high scenario. Late-frost frequency after leaf-out increased from 1.4 events per spring in the 1980s to 2.1 events per spring in the 2010s, indicating that the frost-risk window has not closed as fast as leaf-out has advanced.

Discussion

The leaf-out advancement of 3.8 days per decade documented here for Bavarian forests falls within the range of 2.5–5.0 days per decade reported by the European Phenology Network for temperate deciduous forests across central Europe ^[11]. What distinguishes the Bavarian dataset is its elevation gradient, which reveals a clear attenuation of the phenological response with altitude. Low-elevation stations showed the strongest trends—consistent with the greater absolute warming observed in valley bottoms compared with higher terrain, where free-atmosphere temperature lapse rates buffer surface warming somewhat ^[12].

The growing frost-risk paradox is perhaps the most practically relevant finding. Although late-spring frosts have become slightly less frequent overall, leaf-out has advanced faster than the last frost date has retreated, meaning that the overlap window—the period during which new foliage is exposed to freezing temperatures—has actually widened ^[13].

In the 1980s, an average of 1.4 frost events occurred after mean leaf-out; by the 2010s that figure rose to 2.1. For forest managers, this means that the carbon-gain benefit of a longer growing season comes with an increased risk of frost damage to early foliage, which can reduce annual increment in beech by 10–20% in a severe frost year. The scenario projections suggest that under continued warming, leaf-out could shift into mid-March by 2060 under the high scenario. At that point, photoperiod constraints and chilling requirements may begin to limit further advancement, because many temperate tree species need a minimum duration of winter cold to break dormancy ^[14]. The linear sensitivity model used here does not capture this saturation effect, so the projected shifts for the high scenario should be treated as upper bounds. Incorporating process-based phenological models that explicitly account for chilling and photoperiod interactions would improve the realism of future projections.

Conclusion

This research documented a 43-year phenological record from 42 stations across the Bavarian deciduous forest belt, revealing consistent trends toward earlier leaf-out (-3.8 days per decade), later leaf-fall ($+2.7$ days per decade), and a longer growing season ($+6.5$ days per decade). Over the full record, the cumulative shift amounts to roughly 16 days of earlier spring green-up and a 28-day extension of the growing season—changes with measurable consequences for forest carbon balance, water demand, and frost vulnerability.

Spring temperature was the dominant driver of leaf-out timing, explaining over 72% of interannual variance. Elevation modulated the response, with low-elevation forests gaining 18 growing-season days compared with 13 days at the highest stations. The mismatch between advancing leaf-out and the slower retreat of late-spring frosts has created a widening window of frost-damage risk that partially offsets the productivity benefits of a longer growing season.

Scenario projections indicate that under moderate-to-high warming, leaf-out in Bavarian beech forests could shift into late March or mid-March by 2060, pushing the phenological calendar into territory that has no historical precedent in the observational record. Forest management strategies should account for this accelerating phenological shift by favouring species and provenances with appropriate frost tolerance and by adjusting harvest and regeneration timing to the evolving seasonal calendar. Future research should integrate process-based phenological models to capture the nonlinear effects of chilling requirements and photoperiod constraints that become important at high warming levels.

Acknowledgements

Funding Sources

This research was supported by general institutional research funds from the Pondicherry Institute of Climate and Environment. No external competitive grants were applied.

Institutional Support

The authors thank the Pondicherry Institute of Climate and Environment for computing and data analysis resources. Phenological and climate data were accessed through the German Meteorological Service (DWD) open data portal.

Contributions Not Qualifying for Authorship

The authors acknowledge the DWD volunteer phenological observers whose decades of careful record-keeping made this long-term analysis possible.

References

1. Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Aha R. European phenological response to climate change matches the warming pattern. *Global Change Biology*. 2006;12(10):1969–1976.
2. Auer I, Böhm R, Jurkovic A, Lipa W, Orlik A, Potzmann R. HISTALP—historical instrumental climatological surface time series of the Greater Alpine Region. *International Journal of Climatology*. 2007;27(1):17–46.
3. Cleland EE, Chuine I, Menzel A, Mooney HA, Schwartz MD. Shifting plant phenology in response to global change. *Trends in Ecology and Evolution*. 2007;22(7):357–365.
4. Keenan TF, Gray J, Friedl MA, Toomey M, Bohrer G, Hollinger DY. Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nature Climate Change*. 2014;4(7):598–604.
5. Chmielewski FM, Rötzer T. Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology*. 2001;108(2):101–112.
6. Meier U. Growth stages of mono- and dicotyledonous plants: BBCH Monograph. Julius Kühn-Institut. 2018;1:1–204.
7. Vitasse Y, Delzon S, Dufrêne E, Pontailier JY, Louvet JM, Kremer A. Leaf phenology sensitivity to temperature in European trees: Do within-species populations exhibit similar responses? *Agricultural and Forest Meteorology*. 2009;149(5):735–744.
8. Fu YH, Zhao H, Piao S, Peaucelle M, Peng S, Zhou G. Declining global warming effects on the phenology of spring leaf unfolding. *Nature*. 2015;526(7571):104–107.
9. Jacob D, Petersen J, Eggert B, Alias A, Christensen OB, Bouwer LM. EURO-CORDEX: New high-resolution climate change projections for European impact research. *Regional Environmental Change*. 2014;14(2):563–578.
10. Körner C, Basler D. Phenology under global warming. *Science*. 2010;327(5972):1461–1462.
11. Templ B, Templ M, Filzmoser P, Lehoczky A, Baksienė E, Fleck S. Phenological patterns of flowering across biogeographical regions of Europe. *International Journal of Biometeorology*. 2017;61(7):1347–1358.
12. Pepin NC, Lundquist JD. Temperature trends at high elevations: Patterns across the globe. *Geophysical Research Letters*. 2008;35(14):L14701.
13. Augspurger CK. Reconstructing patterns of temperature, phenology, and frost damage over 124 years: Spring damage risk is increasing. *Ecology*. 2013;94(1):41–50.
14. Chuine I, Beaubien EG. Phenology is a major determinant of tree species range. *Ecology Letters*. 2001;4(5):500–510.