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Research Article

Monitoring European beech phenology in two long-term ecological research sites by remote sensing

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Abstract

The impact of latitude and altitude on phenological rhythms was studied from 2017 to 2023 at two European beech forest sites in western Bulgaria, Petrohan and Belasitsa. These sites are part of the European Long-Term Ecological Research network. We used products from the Copernicus program's High-Resolution Vegetation Plant Productivity to extract the main phenological events: start-of-season date, max-of-season date, end-of-season date, and season length. Our findings indicate that the spring phenology of European beech is closely linked to altitude, while autumn events are more significantly affected by latitude. Spring phenological events were delayed by 2.9 days per 100 m at Petrohan and 2.3 days per 100 m at Belasitsa. This relationship weakens in summer and almost disappears in autumn when latitude becomes a leading factor. The average difference in the end-of-season date between Belasitsa and Petrohan is 10.8 days, which means 5.4 days per degree of latitude. Although the end of the season has been occurring later each year, the relationship is still insignificant. The dynamics of individual phenological events in different years, at various altitudes and latitudes, show that European beech has good potential for acclimating to present climate conditions in the western Bulgarian mountains. Further research is needed on the influence of longitude, considering the uneven transition between Mediterranean and temperate-continental climates in the southeastern part of the species' range.

Key words: Belasitsa, LTER forest site, Petrohan, plant phenology index

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1. Introduction

European beech is one of the most widespread broadleaved tree species in Europe. Its natural range extends from southern Scandinavia in the north to Sicily in the south, and from the Cantabrian Mountains in the west to the Carpathians and Balkan Mountains in the east (Durrant et al. 2016). While the species is typical of the plains in Western and Central Europe, it climbs to 2000 m a.s.l. in Southern and Southeastern Europe. According to Kramer et al. (2010), climate change may impact its future distribution, particularly at the extremes of its range, where it is likely to become less competitive in the south and east due to drought.

Assessing forest ecosystems involves comprehensively understanding how environmental factors impact their processes and functions (Leuschner and Ellenberg 2017). Environmental factors, including solar radiation, air temperature, relative humidity, precipitation amount and chemical composition, contribute to forest productivity, species diversity, and sustainability. Their influence varies from the daily dynamics of primary physiological processes to the annual dynamics of phenological manifestations, biomass accumulation, and even to longer-term successional changes, biodiversity, and soil characteristics (Lambers and Oliveira 2019). According to Urban et al. (2015), phenological and ecophysiological observations can complement each other, providing information with different resolutions. Keenan et al. (2014) suggested that accelerated warming over northern latitudes, based on satellite-observed phenological events, appears to have significantly increased plant carbon uptake. Lian et al. (2020) assume that earlier spring greening of northern vegetation may exacerbate summer soil drying, reducing productivity.

The Long-Term Ecological Research (LTER) network is a global community of scientists and researchers studying ecological processes over extended periods. Established by the US National Science Foundation in 1980, the network aims to understand and predict the causes and consequences of environmental change (Callahan 1984; Robertson et al. 2012). The LTER network includes multiple research sites across various ecosystems, such as forests, grasslands, aquatic systems, wetlands, deserts, and urban areas. Researchers within the network collect data on ecological patterns and processes, including phenological vegetation dynamics, nutrient cycling, species interactions, and ecosystem productivity, to understand how these systems function and respond to environmental stressors (Mirtl et al. 2018).

Phenology is one of the most straightforward processes to track changes in forest ecology in response to climate change (Rosenzweig et al. 2007) because it is a crucial component of forest ecosystem dynamics, as it is directly linked to critical processes in the carbon, water, and energy cycles. Spring and autumn phenological events, such as leaf unfolding, leaf colour change, and leaf fall, are susceptible to climate and local weather changes and, simultaneously, are easy to observe (Inouye 2022). The altered timing of these spring events has been reported for many species and locations in temperate forest zones (Sparks et al. 2000; Menzel 2003), which makes it a vital area of focus for understanding the climate response of ecosystems annually (Norton et al. 2023).

Phenology can change with increasing altitude and latitude due to variations in temperature, light, and other environmental factors. According to Hopkins' law (Hopkins 1918), temperatures in temperate latitudes tend to decrease linearly with increasing elevation or distance from the equator, leading to delays in the timing of phenological events. For example, spring events like budburst, flowering, and leaf emergence may occur later at higher altitudes and latitudes than at lower ones (Dittmar and Elling 2005; Čufar et al. 2012; Schieber et al. 2013). Conversely, autumn events tend to occur earlier at higher altitudes and latitudes. Consequently, the growing season at higher altitudes and latitudes is often shorter due to colder temperatures, which affects the duration and timing of various phenological events (Vitasse et al. 2009b). Such a shorter growing season may compress the time available for plants to complete their life cycles, potentially impacting their growth and reproduction. Higher altitudes and latitudes are more likely to experience extended periods of snow cover during winter (Yue et al. 2022). Snow acts as an insulator, delaying ground warming in spring and further postponing the onset of spring phenological events.

Altitudinal gradients can create a wide range of microclimates within a relatively short distance compared to latitudinal gradients. Local factors such as slope, aspect, and topography can significantly influence the microclimate. As a result, variations in phenological timing can occur even within the same altitude range. Schuster et al. (2014) concluded that cold-air pools significantly impact the vegetation period of deciduous trees, with trees on mid-hillside slopes gaining advantages compared to those at lower elevations.

The role of chilling temperatures and the photoperiod in determining the budburst date for some late-leafing species, including European beech, has been widely studied. In European beech, the budburst thermal time requirement and chilling duration are linearly related (Vitasse et al. 2009a). In another study, Vitasse and Basler (2013) caution that this relationship should be interpreted carefully because photoperiod may confound the relationship between warming temperatures (forcing) and chilling requirements. However, Vilhar et al. (2018) demonstrate that first leaf unfolding dates in beech can be satisfactorily predicted based on tree phenological phases observed at national phenological stations and recommend combining ICP Forests and national methodologies to improve the phenological networks.

Phenology observations using remote sensing devices, such as satellite imagery and unmanned aerial vehicles, are promising techniques (Ciocîrlan et al. 2022). Remote sensing methods can determine phenological events by monitoring changes in vegetation greenness from a distance, often using satellites or airborne sensors (Kimball et al. 2004). These methods are based on changes in vegetation's light reflectance during different phenological stages, which can be detected and analysed using remote sensing spectral indices. According to Bucha and Koren (2017), researchers can identify shifts in phenological events by analysing the spatial and temporal changes in these spectral indices. Algorithms and statistical techniques can be applied to detect the timing of specific events.

The main phenological events determined by the seasonal course of the vegetation indices include the dates and values for the start and end of the season, the length of the growing season, the peak of the season, the season amplitude, and the slope of greening and browning periods (Smets et al. 2025). However, most vegetation indices do not have a biophysical character and are especially unsuitable for phenological observations in forests with a deep canopy. Delbart et al. (2005) showed that the correlation between spectral band information and spring phenology is weak due to the snow and heterogeneous conditions of forest stands. According to Gao et al. (2023), for the commonly used normalized difference vegetation index (NDVI), the chlorophyll-absorbing red band quickly becomes insensitive with increasing vegetation canopy closure, while the near-infrared (NIR) band continuously increases due to multiple scattering effects. Another frequently used vegetation index, the enhanced vegetation index (EVI), reacts more sensitively to phenological changes but is much more influenced by the moment of capture, as well as by atmospheric gas composition, such as fine dust particles and water vapour (Tariq et al. 2021).

According to Jin and Eklundh (2014), the plant phenology index (PPI) is a biophysical vegetation index optimised for efficiently monitoring phenology. PPI is derived from a radiative transfer equation and is computed from red and near-infrared reflectance. It has a nearly linear relationship with canopy green leaf area index (LAI), enabling it to depict canopy foliage density well. A comparison of satellite-derived PPI with ground observations of plant phenology and gross primary productivity (GPP) shows substantial similarity in temporal patterns (Jin and Eklundh 2014).

Sentinel-2 satellite images are invaluable for forest monitoring due to their high spatial resolution, multispectral capabilities, frequent revisit times, and free and open data policy, which enables tracking of seasonal changes in forest phenology. Time series analysis of Sentinel-2 imagery can reveal vegetation growth patterns and phenological events. Ciocîrlan et al. (2022) point out that the biophysical parameters based on Sentinel satellites, available on the Copernicus land monitoring platform, showed satisfactory accuracy in predicting an average site value of the percentage of leaf cover. Seasonal trajectories of the PPI (ST_{PPI}), constructed according to Jönsson et al. (2018), use a model regression sum over double logistic functions (Fischer 1994), adapted by Beck et al. (2006) for NDVI. ST_{PPI} products are provided yearly after the end of the vegetation growing season. They are derived as a regular time series every ten days by fitting a smoothing and gap-filling function to the raw Plant Phenology Index (Smets et al. 2025). ST_{PPI} is used to calculate phenological events such as the start-of-season date (SOSD), max-of-season date (MOSD), end-of-season date (EOSD), and length of season in days (LOSD).

This study examined the phenological events in two LTER forest sites in Bulgaria, which are mono-dominated by European beech. We tested the influence of latitude and altitude on these objects' main phenological events over seven years (2017–2023). We aimed to understand whether and why phenological events vary over the years and between sites.

2. Materials and methods

2.1. Sites

The Petrohan and Belasitsa sites were chosen for the present study for several reasons. Both forest LTER sites have a predominant presence of European beech in their forest composition. Additionally, their territories are mountainous and located on the northern macro slopes of two mountains in western Bulgaria, Stara Planina and Belasitsa (Fig. 1).

Site Petrohan is part of the University of Forestry's educational forest territory, covering 7190.5 ha in the West Stara Planina Mts. The region's relief is mountainous and steep, with deeply cut river valleys and secondary watersheds. Due to the long-term systematic storage of biometric, chemical, and physiological data, Petrohan is a representative forest site in the national network for long-term research and the European ecological network LTER. Protected forests account for 74% of the total area, differentiated as zones for water resources, including drinking water. The soil is brown acid (District/Eutric cambisols) developed on granite, with a mean depth exceeding 80 cm (Malinova and Petrova 2019). The total growing stock in European beech stands is more than 1.35 million m^3, covering 5097.6 ha.

Site Belasitsa is a Bulgarian Nature Park located in the eponymous mountain, in the southwestern part of Bulgaria, at the border with Greece and North Macedonia. Belasitsa Mountain serves as a climatic and floristic boundary between the Mediterranean and the Transitional-Continental regions. The cli-

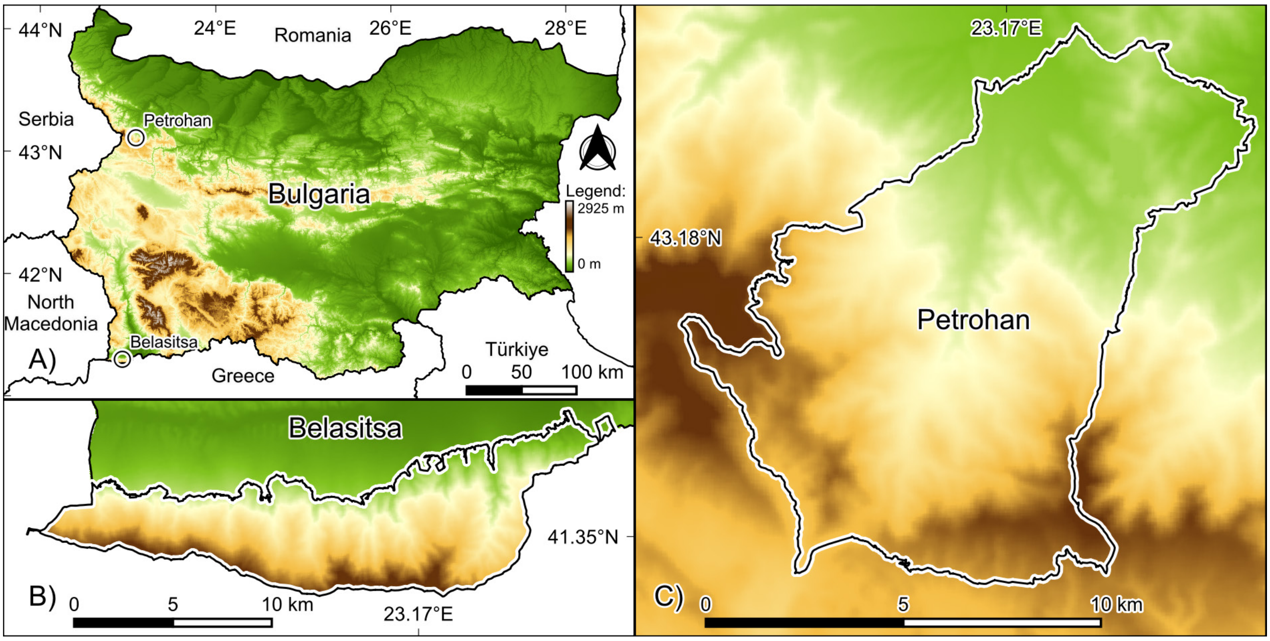

Figure 1. Location of the study sites. **A** general view on a relief map of Bulgaria **B** Site Belasitsa **C** Site Petrohan.

mate is characterized by rainy winters and hot, dry summers. This Nature Park was established to protect centuries-old forests composed mainly of European beech (*Fagus sylvatica* L.) and common chestnut (*Castanea sativa* Mill.), as well as natural habitats of the Oriental plane (*Platanus orientalis* L.). The total area of the park is 11732.4 ha along the northern macro slope of the mountain, which stretches in a west-east direction. The total growing stock in European beech stands is about 0.85 million m^3, covering 4924.8 ha.

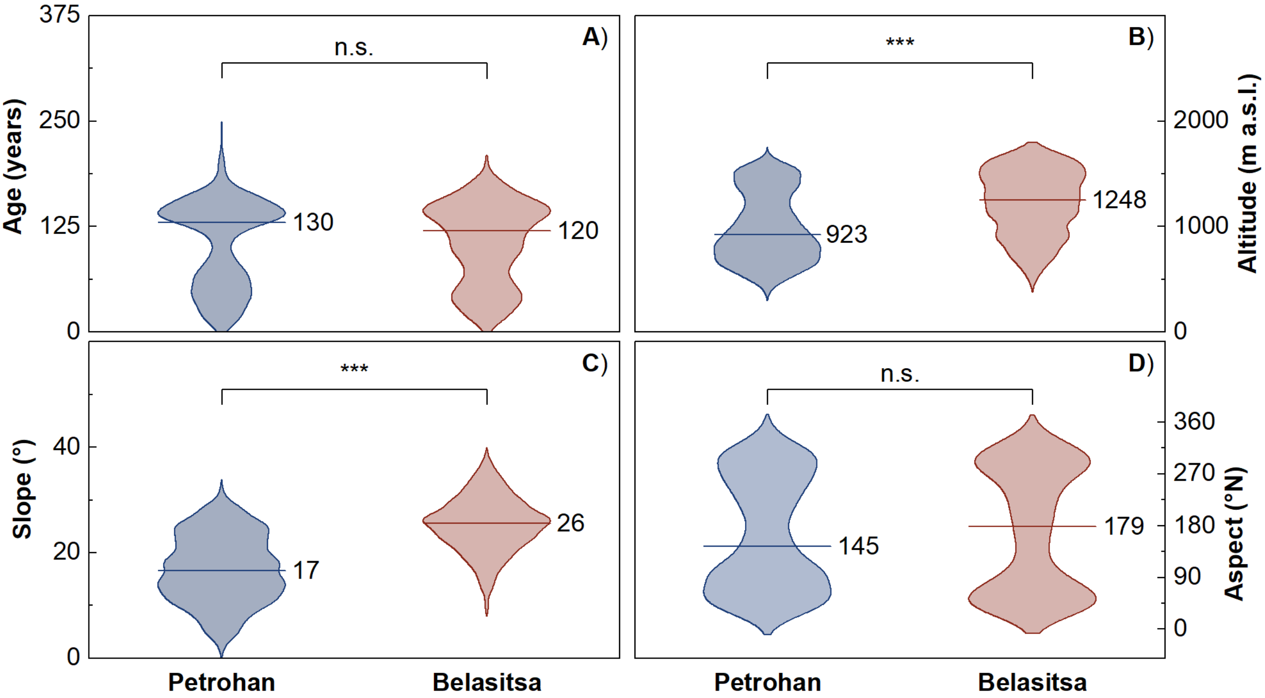

Figure 2. Site description. **A** age **B** altitude **C** slope **D** aspect of European beech forests in Petrohan and Belasitsa sites.

A vector layer, including the boundaries of stands with a dominant European beech presence for both sites, was taken from the Bulgarian National Forest database (EFA 2025). Both sites have similar longitude (Fig. 1) and do not differ significantly in the average age of beech forests (Fig. 2A).

The average altitude of the European beech forests in Belasitsa is 1222±70 m (ranging from 492 to 1772 m), and in Petrohan, it is 990±55 m (ranging from 377 to 1634 m) (Fig. 2B). The slopes of Belasitsa are slightly steeper (25.3±11.1°) than those of Petrohan (16.9±6.7°) (Fig. 2C). In Petrohan, northeast exposures slightly predominate, while in Belasitsa, both northeast and northwest slopes are equally present, but the difference is not significant (Fig. 2D).

2.2. Phenology

According to the Standard Observation Protocol of the LTER network, the High-Resolution Vegetation Phenology and Productivity (HR-VPP) Database from the Copernicus Land Monitoring Service (2025) was used for the determination of the phenological events in the experimental sites, using descriptions in Jin and Eklundh (2014) plant phenology index (PPI) (Anev 2023). Seasonal trajectories of plant phenology index (ST_{PPI}), which show the status of the vegetation at a regular time interval of ten days, with gaps filled in the observations due to clouds or other disturbances, were used in the entire temporal range (36 images per year for all seven years). Each ST_{PPI} is constructed according to Jönsson et al. (2018), in which the model regression is a sum over double logistic functions (Fischer 1994), adapted by Beck et al. (2006) for vegetation indices (Cai et al. 2023). ST_{PPI} is used to derive the assessed phenological events, calculated after the end of each growing season. The HR-VPP has been produced on the Copernicus Data and Access Information Service (DIAS) platform WEkEO. The TIMESAT 4 procedure was applied to Sentinel-2 data to extract 13 phenological parameters for each growing season (Cai et al. 2023). The start-of-season date (SOSD) was defined as the spring day when the ST-PPI increases to 25% of the seasonal amplitude. The end-of-season date (EOSD) was defined as the autumn day when the ST-PPI decreases to 15% of the seasonal amplitude. The peak of the double logistic function (indicating the day with the highest PPI) was used as the max-of-season date (MOSD). The length of season (LOSD) was calculated as the difference between EOSD and SOSD.

Two tile images (T34TFN and T34TFL) cover the study area. SOSD, EOSD, MOSD, and LOSD rasters for season 1 from 2017 to 2023 were downloaded from the WEkEO servers. The zonal statistics tool in QGIS (‘native:zonalstatisticsfb’) was employed to calculate mean values of phenological events, and the join attributes by field value tool (‘native:joinattributestable’) was used to combine the estimated data for each year and for each of the studied stands. The mean altitude of each stand was calculated based on Copernicus’ digital elevation map of Europe (EU-DEM, v.1.1) (Copernicus Land Monitoring Service 2016). The final dataset, combining the altitudes and phenological attributes, was exported into MS Excel (Office 365, Microsoft) for visualisation and statistical analysis. Linear regression slopes were calculated between altitude (as an independent variable) and SOSD, MOSD, EOSD, and LOSD (as dependent variables). Student’s t-tests were performed to determine the difference between the average dates of phenological events and between slopes of linear regressions of each year in the whole period for Petrohan and Belasitsa.

3. Results

The seasonal trajectories of the PPI in experimental objects have specific interannual dynamics. For both objects, the maximum summer values of PPI were reached in 2019 and 2021, while relatively lower summer values of PPI were observed in 2017, 2020 and 2022 (Fig. 3).

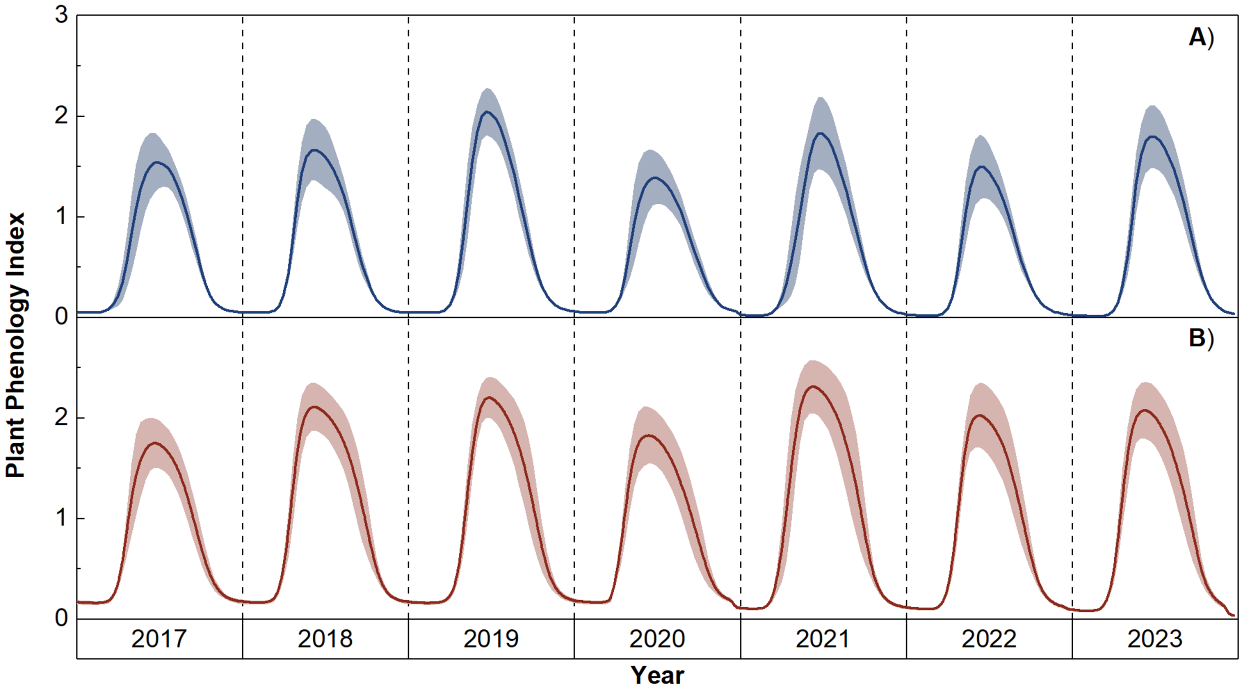

Figure 3. Seasonal trajectory of the Plant phenology index. **A** site Petrohan **B** Belasitsa.

According to Marinova and Bocheva (2023), both 2019 and 2021 were characterized by warmer and drier summers (June–August) than 2017 and 2020. Still, essential differences between 2019/2021 and the other years in the period are the precipitation sums and temperature averages in the preceding dormancy period (November–April). In 2019 and 2021, there were moderate temperatures and rainfall, while in the other years, there was more significant variation around the averages. The dormancy period was relatively colder before 2017 and 2022, to a lesser extent before 2018, and significantly warmer before 2020 and 2023.

These variations affect the cardinal points of the ST_{PPI}. While the spring phenology differed less and in fewer years in Petrohan and Belasica, the two sites had different autumn phenology. On average, SOSD is on April 21 (±12.6 days) and April 22 (±11.5 days) for Petrohan and Belasitsa, respectively, which is similar to the dates for the Western Carpathians observed by Bucha and Koren (2017) and by Skvareninova et al. (2024). Although the most probable average unfolding date in Petrohan is April 26 (2019, 2020 and 2023), there are years when the unfolding date occurs significantly earlier, e.g., in the year 2018 with a hot and wet dormancy period, when the average SOSD was April 13 (±6.3 days). This is also one of the years in which the two sites' SOSDs did not significantly differ. In Belasitsa, the vegetation in 2018 began on April 12, but there are years when it happens much later, e.g., in 2019, when SOSD was as late as May 1 (±8.0 days) (Fig. 4A).

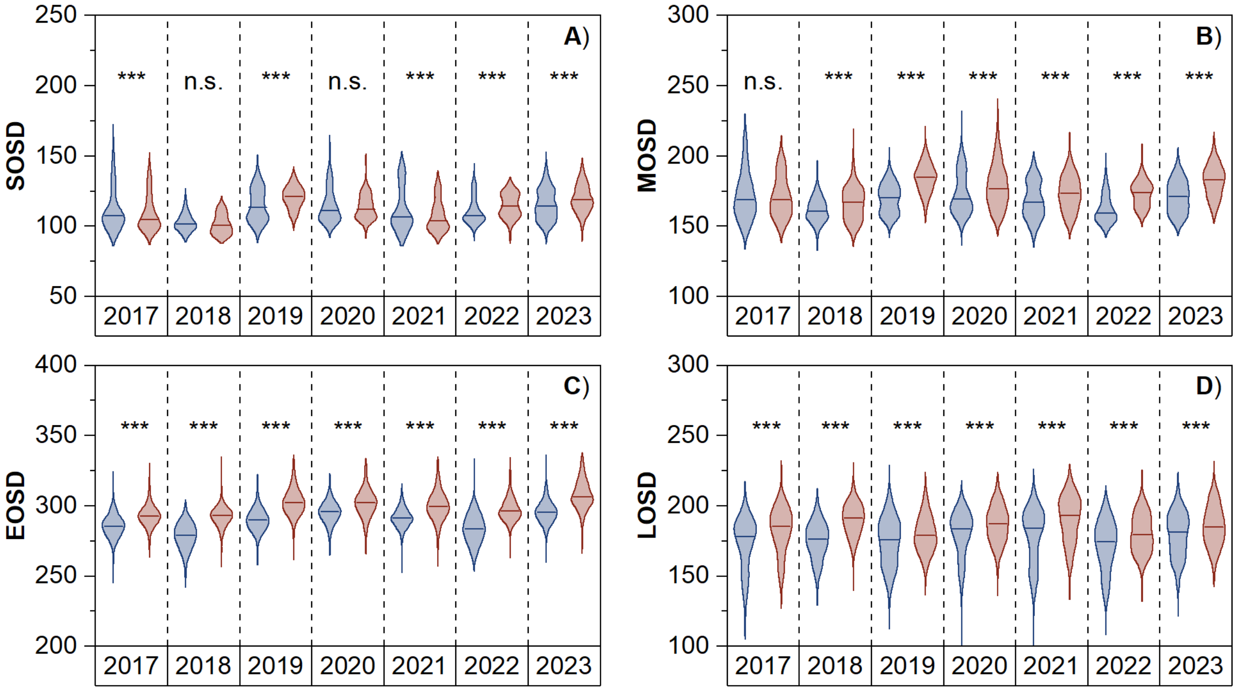

Figure 4. Phenological events. **A** Start-of-season day (SOSD) **B** max-of-season day (MOSD) **C** end-of-season day (EOSD) **D** length of season in days (LOSD) in Petrohan (blue) and Belasitsa (red) sites. The violin plots illustrate the distribution of phenological events among the European beech stands in the sites, with a median as a line. Asterisks (***) above violins indicate significant (P-value < 0.001) differences between the mean of sites (Student's two-sample t-test).

Petrohan's average MOSD was June 17 (±13.3 days), while Belasitsa's was a whole week later—June 24 (±13.8 days). In Petrohan, MOSD varied from June 11, 2018 (±8.7 days), to June 23, 2020 (±14.8 days); in Belasitsa, the variations in this indicator were even greater—from June 16, 2018 (±11.9 days) to July 4, 2019 (±10.4 days) (Fig. 4B). The end of vegetation occurs significantly later in Belasitsa than in Petrohan. In Petrohan, on average, this happens on October 15 (±10.3 days), while in Belasitsa, it occurs as much as 11 days later—on October 26 (±10.4 days). Furthermore, in Belasitsa, EOSD was later in each studied year, with the lag varying from 6 days in 2021 to 14 days in 2018 and 2022 (Fig 4C). The later end of the growing season in Belasitsa also means a longer growing season there compared to that in Petrohan. In Petrohan, LOSD is, on average, 176.1 (±17.3) days, and in Belasitsa, 185.2 (±14.7) days. The difference varied from 5 days in 2019 to 15 days in 2018 (Fig. 4D).

SOSD lags by an average of 2.9 days per 100 m elevation (from 1.4 in 2018 to 3.7 in 2021). On the slope of Belasitsa, this ascent is significantly faster (2.3 days per 100 m elevation) in most years except for 2018 and 2022. Moreover, this indicator varied less than in Petrohan—from 2.0 days per 100 m in 2019 to 2.7 days per 100 m in 2023 (Fig. 5A).

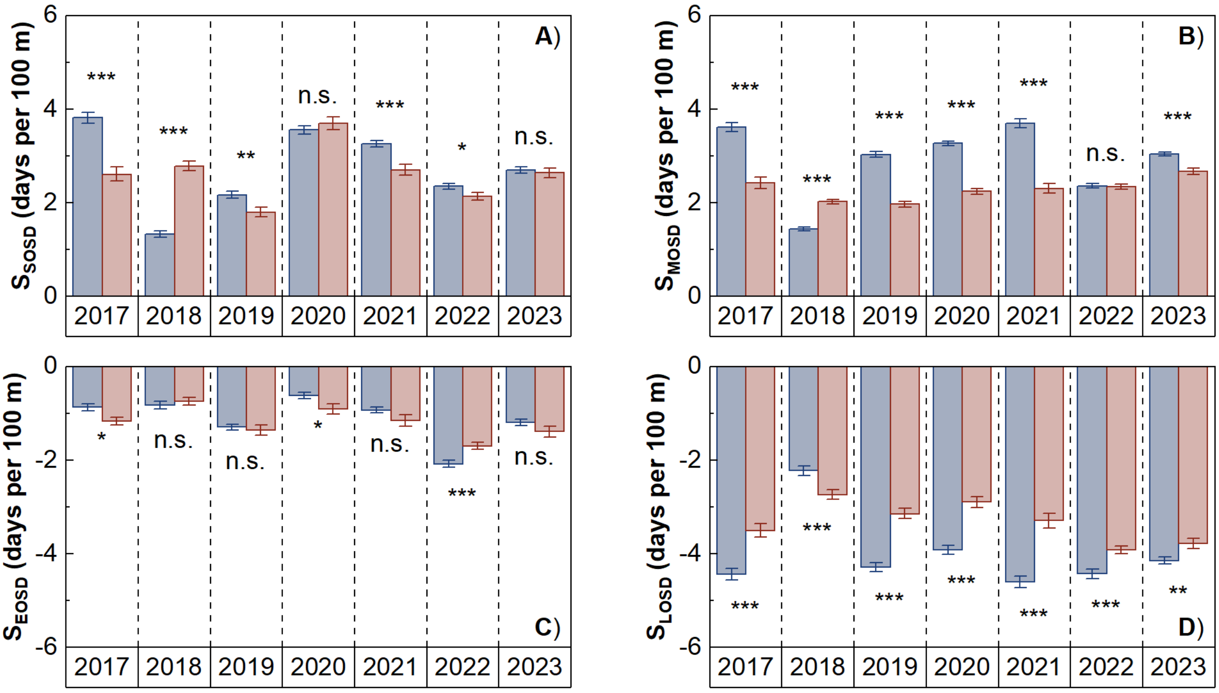

Figure 5. Slopes (S) of linear regression between altitude and phenological events. **A** slope of start-of-season day (S_{SOSD}) **B** slope of max-of-season day (S_{MOSD}) **C** slope of end-of-season day (S_{EOSD}) **D** slope of length of season in days (S_{LOSD}) in Petrohan (blue) and Belasitsa (red) sites. Bars represent slopes, and whiskers represent a standard error calculated by linear regressions. Symbols above bars indicate differences (n.s. P-value > 0.05; * P-value < 0.05; ** P-value < 0.01; *** P-value < 0.001) between slopes of two objects (Student's t-test).

In Petrohan MOSD occurred, on average, 2.7 days later for every 100 m elevation and varied between 1.3 days in 2018 and 3.8 days in 2017. In Belasitsa, the average lag of this indicator is similar, 2.6 days per 100 m elevation and varied from 1.8 days in 2019 to 3.7 days in 2020 (Fig. 5B). In autumn, leaves lose their photosynthetic pigments significantly faster at different altitudes. In both Petrohan and Belasitsa, EOSD occurred with 1.1 days for every 100 m of elevation, and in most of the studied years the differences between the two sites in this indicator were insignificant (Fig. 5C). For this reason, the differences in the length of the growing season at different altitudes is probably because of the slower leaf emergence in spring and not because of the autumn phenological events, which occurred more simultaneously in steep slopes. For every 100 m elevation, LOSD was shorter by 4.0 days in Petrohan (from 2.2 in 2018 to 4.6 in 2021) and by 3.3 days in Belasitsa (from 2.7 days in 2018 to 3.9 days in 2022) (Fig. 5D).

4. Discussion

In two forest LTER sites in western Bulgaria, the influence of latitude, altitude, and related specific temperature-humidity regimes on phenological rhythms was investigated. We found that even a relatively small difference in latitude (<2°) can lead to substantial differences in phenological rhythms, although these differences are not always unidirectional. Despite a similar trend in the seasonal trajectories at the two sites, the maximum levels of the plant phenological index are reached at different optimal temperatures that differ as much as the mean temperatures in the two regions. Such a distinction indicates the European beech's acclimation to temperature variations in Bulgaria's distribution range.

According to Larcher (2003), the optimal temperature in Central Europe for European beech photosynthesis is 20°C and varies with the altitudinal and latitudinal temperature gradients. Studied on wild species spring phenology in the course of decades, which mainly focused on temperate woody species show that three major cues underlie budburst and leaf unfolding: warm spring forcing temperatures, increasing photoperiod, and length and intensity of winter chilling temperature (Flynn and Wolkovich 2018). Variations in temperature sums for many phenological phases, especially temperate forests, have repeatedly explained interannual phenological dynamics (Roberts et al. 2015; Flynn and Wolkovich 2018; Melaas et al. 2018). The interannual specificity we found in the seasonal trajectories of the plant phenological index is probably due to specific conditions in the preceding vegetation and the dormant period rather than in the spring forcing, which may be related to the European beech's specific strategy to invest considerable resources and time in winter bud formation. Roberts et al. (2015) also found that European beech was less sensitive to spring forcing than other European tree species and pointed out dormancy induction's role in spring phenology. Badeck et al. (2004) showed that interannual variation in the timing of phenological events can reach up to one month. On the other hand, Vitasse and Basler (2013) establish that the bud burst date of European beech shows fewer temporal and spatial variations than most of the other deciduous tree species in Europe, which this species' late leaf unfolding could explain. Similarly, this is likely the reason for the more minor differences between the two sites, which we found in SOSD compared to MOSD and even more so compared to EOSD. We found no significant differences in SOSD between the two sites after a dry and warm rest period (November–April), while the highest differences in this indicator were found after a wetter and cooler dormancy period, which delays leaf unfolding in the more southerly site. The most considerable differences in MOSD between the two sites were found after a drier spring (March–June), explaining the earlier depletion of the potential of PPI to increase in Petrohan. The forests in Belasitsa are probably better adapted to less rainfall and are less sensitive to this stress factor. EOSD is the phenological indicator with the most significant differences between the two sites. Vegetation in Belasitsa ends 1–2 weeks later than in Petrohan, probably due to the higher temperature and less precipitation in autumn. The early EOSD in 2018 and 2022 at both sites occurred against a background of very dry Octobers, and the late EOSD was observed during the relatively warmer and wetter autumns of 2019 and 2023. In contrast to the prediction of Roberts et al. (2015) and established by Skvareninova et al. (2024), we did not observe a significant time shift in SOSD or other phenological events, probably due to the short study period.

Contrary to the trend for higher differences in autumn phenological events occurring at the two sites (Anev 2023), the rate at which these events occur with an elevation change is more prominent in spring. In Petrohan, it takes more than 38 days for the leaf unfolding of the European beech to overcome 1300 m altitude; in Belasitsa, it takes ten days less for almost the same elevation range.

Our results are comparable to those of other authors who established the correlation between leaf unfolding of European beech and altitude. Similar results were reported by Čufar et al. (2012) for Slovenia, where the leaf unfolding shift is 2.6 days for every 100 m. Schieber et al. (2013) showed a 2.83–3.00-day shift in the onset of spring phenology per 100 m of an increase in altitude in the Inner Western Carpathians, Slovakia (~ 49° N), while Skvareninova et al. (2024) showed a 2.2 days shift for the same region. Even more, Dittmar and Elling (2005) established a shift of two whole days per 100 m faster at the start of vegetation in South Bavaria with the Northern Alps and Bavarian Forest, compared to the northern regions of Bavaria, which they explain as unfavourable warmth and radiation conditions in the north.

The differences are more minor for MOSD, and for EOSD, even in most years, they become insignificant. If spring phenological events occur slowly at different altitudes, obviously later phenological events are significantly less related to this factor, and the role of latitude also decreases. Similar are the results of Skvareninova et al. (2024), who found a significantly higher variation of the autumn phenology (1.1–2.9 days per 100 m) than the spring ones. Lukasová et al. (2020) showed that on mid-altitude stands in the eastern part of Slovakia, the autumn phenology of European beech has a very significant positive effect on increasing temperature and heat waves. This effect is lost at lower and higher altitudes in the central and western parts of the country. The European beech responds positively to climate warming in the eastern part of the range, probably because colder air masses from the northeast invade, strengthening the climate's continental character, which suggests strengthening the longitude factor at the expense of the altitude and latitude factors. The only year with a more significant influence of altitude for the autumn event (2.1 days per 100 m on Petrohan and 1.7 days per 100 m on Belasitsa) was 2022. This was also the year with the shortest growing season during the study period. Despite small variations in individual years, the growing season tends to be shorter at higher altitudes, and this is much more pronounced in Petrohan than in Belasitsa. Urban et al. (2015) showed that leaf colour change starts late at higher temperatures, but leaf unfolding is more insensitive to elevated temperatures.

5. Conclusions

Phenology in European beech is closely related to the factors of latitude and altitude. It is the visible manifestation of the environmental factors' influence on primary physiological processes, especially in transitional seasons. Spring phenological events show a stronger relationship with altitude than with latitude. In the summer, this relationship weakens, and in the autumn, the geographical latitude stands out as a limiting factor. Although the end of the season occurs later with each passing year, the relationship is still insignificant, possibly due to the short period of the study. The dynamics of individual phenological events in different years, at various altitudes and different geographical latitudes show good potential for European beech acclimation to the current climate conditions in Western Bulgarian mountains. Further research on the influence of longitude is also needed, given the uneven transition between Mediterranean and temperate-continental climates within the southeastern part of the species' range.

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Additional information

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No conflict of interest was declared.

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No ethical statement was reported.

Use of AI

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Author contributions

Conceptualization: SD, SMA. Data curation: SMA. Formal analysis: SMA. Funding acquisition: SD. Investigation: SMA. Methodology: SMA. Project administration: SD. Resources: SMA. Software: SMA. Supervision: SMA. Validation: SMA. Visualization: SMA. Writing - original draft: SMA. Writing - review and editing: SMA.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.