

Leaf phenology and vegetation period of European beech (*Fagus sylvatica* L.) forests in Bulgaria

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Abstract

This study investigates variations of two main phenological events of European beech (*Fagus sylvatica* L.) across geographical gradients in its range in Bulgaria between 2017 and 2023. We found that altitude is the primary driver of leaf unfolding date, which is delayed by approximately 2.52 days per 100 m of elevation gain. In contrast, leaf colouring date is less influenced by altitude and more strongly driven by latitude, with a delay of about 2.12 days per degree northward. Leaf colouring date appeared more abrupt and latitude-dependent, likely due to regional climate differences in separate mountains. A modest influence of longitude on phenology was also detected, possibly linked to changes in continental climatic conditions in the west-east direction. These findings contribute to understanding how complex of geographic gradients shape the timing of phenological events and duration of vegetation period in European beech under the current climate in Bulgaria. They could be used as a basis for impact forecasting of future climate scenarios in the south-eastern part of the distribution of European beech forests.

Key words: leaf colouring date, leaf unfolding date, length of vegetation period, plant phenology index.

Introduction

European beech (*Fagus sylvatica* L.) is one of the most widespread tree species in European forests (Durrant et al. 2016). During the last glacial period, the European beech was wiped out of the central part of the continent and survived mainly in relatively small refugial areas in the Submediterranean and Mediterranean zones, also in the Balkans. From there, it began its secondary colonisation of Cen-

tral and later Western and Northern Europe. (Comps et al. 2001, Magri 2008). According to Leuschner (2020) and Leuschner and Ellenberg (2017), European beech is a temperate late-successional tree species, which can achieve high dominance under favourable growing conditions due to its ability to form an extensive shade crown and tolerate very low light intensities in both juvenile and adult life stage. European beech is typical dominant tree species in the natural vegeta-

tion of the lower mountainous ranges in Central Europe, gradually ascending into the mountains as the latitude decreases (Stefanov and Ganchev 1953). Beech is drought- and heat-sensitive. In Central Europe, it has a precipitation threshold of 500 to 550 mm per year, below which it gradually loses its dominance over oak and other tree species (Bolte et al. 2007). 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.

In Bulgaria, European beech is widely distributed, predominantly in the middle mountain zone (Stefanov and Ganchev 1953), where it forms part of forests across a significant range of latitudes and altitudes. The southernmost forests dominated by European beech are located near the Greek border around Veykata Peak in the Rhodope Mountains. At the same time, in the north, the species reaches as far as the Bozhuritza Reservoir above the village of Sinagovtsi in Vidin region, which is also its lowest-altitude site in Bulgaria (140 m a.s.l.) (Anev 2025). In the mountains, European beech often forms the upper forest boundary. In the easternmost parts of the Balkan Mountains and throughout southeastern Bulgaria, the European beech is often replaced by the Oriental beech (*Fagus orientalis* Lipsky) (Stefanov and Ganchev 1953). This broad range in latitude, longitude, and elevation corresponds to a considerable diversity of climatic conditions. The wide distribution of the European beech in Bulgaria shows that the species can successfully tolerate the climate of mountains under the influence of the temperate-continental region (e.g., the Balkan Mountains), as well as those under the transitional-continental (e.g., Osogovo) and the continen-

tal-Mediterranean climatic regions (e.g., the Rhodopes) (Anev 2025, Stefanov and Ganchev 1953), probably due to the higher precipitation rate in the elevated mountainous areas.

The absence of the European beech in the plains, despite the more continental climate compared to Italy and Spain, is attributed by some authors to the high summer temperatures and dry periods (Fang and Lechowicz 2006). At the north-eastern distribution range, it seems to be more a late frost limit (Bolte et al. 2007, Leuschner and Ellenberg 2017). According to Magri (2008), the European beech requires at least 140 favourable days per year for vegetation, which explains why it does not survive far north in Scandinavia. The European beech enters deep dormancy and withstands low winter temperatures well, but it is susceptible to late spring frosts (Stefanov and Ganchev 1953). Well-developed leaf buds allow it to delay leafing (Anev 2025), and in Bulgaria, leaf emergence occurs from the first week of April at the lower range boundary, to early May at the upper range boundary (Kuzmanova 2021; Tzvetkova and Anev 2014; Anev 2023, 2025). However, late spring frosts have a strongly adverse effect, especially on young individuals that have not yet developed resistance mechanisms and leaf out significantly earlier than mature trees. Slavov and Kazandjiev (2005) established a strong relationship between the individual phenological events in European beech, but not between unfolding and autumn colouration. Petkova et al. (2017) note that Bulgarian provenances of European beech have a longer growing season than German ones, but their early development makes them more sensitive to low spring temperatures.

Phenology can change with increasing altitude and latitude due to variations in

temperature, light, and other environmental factors (Čufar et al. 2012; Schieber et al. 2013; Gressler et al. 2015; Vilhar et al. 2018; Lukasová et al. 2020; Anev 2023, 2025; Skvareninova et al. 2024). According to Hopkins' law (Hopkins 1918), temperatures in temperate latitudes tend to decrease linearly with increasing elevation or distance from the equator. This can lead 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-unfolding species, including European beech, has been widely studied (Falusi and Calamassi 1990; Vitasse and Basler 2013; Kuzmanova 2015, 2021; Roberts et al. 2015; Flynn and Wolkovich 2018; Wang et al. 2022). 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 NPN methodologies to improve the national phenological network.

Studied wild species spring phenology over decades, which mainly focused on temperate woody species, shows 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). Roberts et al. (2015) also found that European beech was less sensitive to spring forcing than other European tree species and pointed out the role of dormancy induction 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.

Phenology observations using remote sensing devices, such as satellite imagery and Unmanned Aerial Vehicles (UAVs), 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 the fact that different phenological stages cause distinct changes in the reflectance of light from vegetation, 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.

This study aimed to evaluate the influence of altitude, latitude and longitude on leaf unfolding, autumn leaf colouration, and the duration of the growing season of European beech dominated forests in Bulgaria.

Object and Methods

The study was conducted in forests dominated by European beech throughout Bulgaria. The data and polygons were taken from the national forest inventory, which is available at <https://maps.iag.bg/>. Within the boundaries of the studied forests, symmetrical sample points ($n = 294,665$)

were generated in QGIS (v. 3.42.1), which were 100 m apart using the 'qgis:regular-point' tool (Fig. 1).

The average age of the studied forests is 104.7 (± 37.8 years standard deviation), ranging from 1 to 250 years. Despite this wide variation, 50 % of forests are between 80 and 130 years old, and 90 % are between 40 and 160 years old (Fig. 2A).

The 'native:rastersampling' tool was used to extract the altitude of points from the EuroDEM raster layer downloaded from EuroGeographics (2025). Based on the EuroDEM raster image, the 'grass:r.slope.aspect' tool (Grass GIS, v. 8.4.1) was used to calculate the slope and aspect of the terrain, on which the points are located. European beech forests are normally distributed by altitude with average elevation 1060.0 (± 249.1 m standard deviation) and 50 % of them fall between 888 and 1228 m, and 90 % are between 649 and 1482 m (Fig. 2B). Although European beech forests are distributed throughout the country in terms of latitude, fifty per cent of them are concentrated in the range $42.14^\circ - 42.87^\circ$ with an average of 42.53° ($\pm 0.57^\circ$ standard deviation), and 90 % are between 41.44° and 43.25° (Fig. 2C). Despite being more evenly distributed in longitude, studied forests are mainly in Western and Central Bulgaria. Fifty per cent of them are in the range $23.3^\circ - 24.9^\circ$, with an average value of 24.14° ($\pm 1.06^\circ$ standard deviation), and 90 % are between 22.6° and 26.0° (Fig. 2D). The phenological events in the studied forests were identified using data from the Copernicus Land Monitoring Service (WEKEO 2025). Analysis was based on the Seasonal Trajectory series of the Plant Phenology Index (PPI), as described by Jin and Eklundh (2014), Smets et al. (2022), and referenced in Anev (2023). The leaf unfolding dates (LUD) and autumn leaf colouration

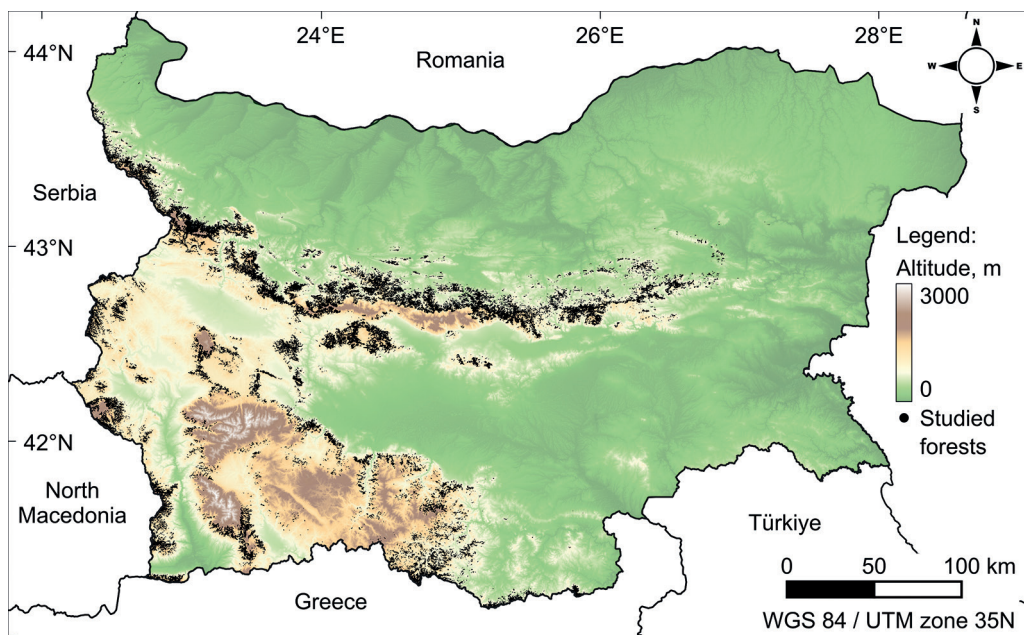


Fig. 1. Geographical distribution of European beech dominated forests in Bulgaria on a digital elevation map background.

Note: studied forests ($n = 294,665$), used for analysis, are shown with black solid dots.

dates (LCD), as well as the length of the vegetation period (LVP), were extracted with the 'native:rastersampling' tool from the raster images from the SOSD, EOSD and LOSD series, season 1, covering the territory of the studied beech forests. The collected information in the vector layer for the studied indicators was exported in csv-format with the 'gdal:gdal2xyz' tool (GDAL v. 3.10.2). In MS Excel (Office365, Microsoft), the data were statistically processed using the built-in functions and VBA-scripts (VBA v.7.1, Microsoft). One-way ANOVA with the Tukey test was used to compare phenological events in different years. Pearson's correlation coefficients were calculated between altitude, latitude, and longitude on the one hand, and LUD, LCD, and LVP, on the other. Multiple linear regressions were applied to calculate estimated indicator values of the

vegetation period according to changes in the complex geographical characteristics of sample points.

Results

Significant variation in the LUD were observed over the seven years studied. European beech opens the leaf buds and forms leaves from the end of March to the end of May. On average, during the study period, this event occurred on 26 April (± 11.4 days standard deviation), and in the 95th percentile, it varied from 03 April to 19 May (Fig. 3A).

LCD lasts from mid-September to mid-November. On average, during the study period, this event occurred on 19 October (± 15.7 days standard deviation), and in the 95th percentile, it varied from

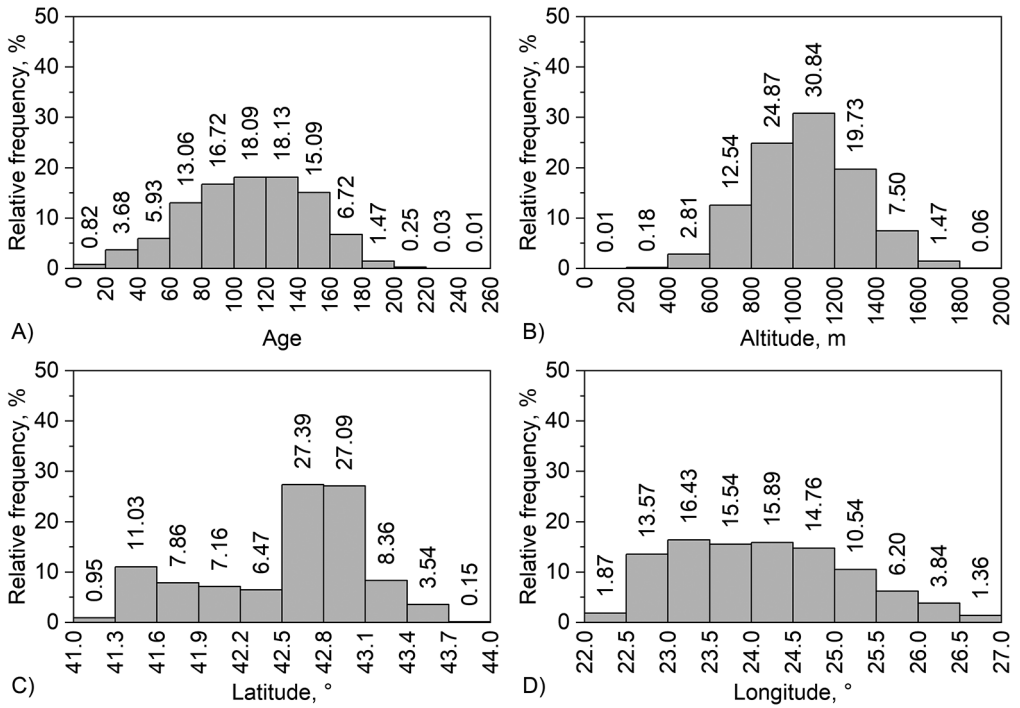


Fig. 2. Structure of studied European beech forests.

Note: the histogram's bins show the relative frequency (%) of European beech forests in each: A) age class (20 years), B) altitude (200 m), C) latitude (0.3°), and D) longitude (0.5°).

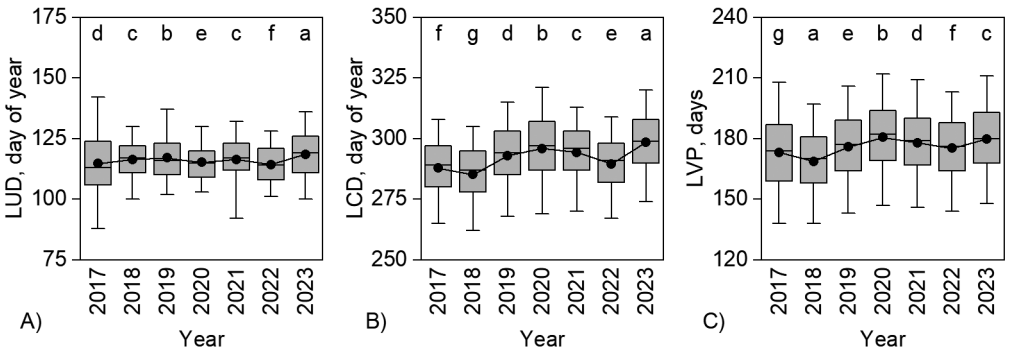


Fig. 3. Phenological events: A) Leaf unfolding date, B) Leaf colouring date, C) Length of vegetation period.

Note: Box plots present the distribution of phenological events. Mean values are shown with a solid dot, median with a line, box range presents 25–75 % quartiles, and whiskers present 5–95 % range. Means that do not share a letter differ significantly (one-way ANOVA with Tukey test, p -value < 0.05).

17 September to 16 November (Fig. 3B). Variations in LUD and LCD lead to variations in LVP. On average, during the study period, LVP lasts 176 days (± 15.8 days standard deviation). The shortest LVP was 169 days in 2018, while the longest was 181 days in 2020 (Fig. 3C).

The results of the correlation analysis between the geographical factors, altitude, latitude, and longitude, on the one hand, and the investigated phenological events, on the other, show a weak, albeit statistically significant relationship. The most substantial positive correlation was observed between LUD and altitude ($R = 0.519$, p -value < 0.001), while LCD correlates considerably less with altitude ($R = -0.061$, p -value < 0.001). The later start of the growing period with increasing elevation results in a negative correlation between LVP and altitude ($R = -0.339$, p -value < 0.001). The growing season is much less related to latitude. The correlation coefficients between latitude and LUD, LCD, and LVP are $R = -0.031$, $R = -0.057$, and $R = -0.026$, all with p -value < 0.001 . Similar and no longer so categorically negative is the correlation between

longitude and the studied indicators of the vegetation period – LUD ($P = -0.091$), LSD ($P = 0.017$) and LVP ($P = 0.064$), all with p -value < 0.001 .

The results of the multivariate linear regression show that leaf unfolding is the variable most strongly dependent on the geographical factors studied. Multiple regression coefficients for each factor show that unfolding of European beech is delayed by 2.519 (± 0.004 SE) days for every 100 m increase in altitude, by 2.197 (± 0.016 SE) days for every degree of northward shift, and by 1.581 (± 0.009 SE) days for every degree of eastward shift (Fig. 4A).

While altitude plays the strongest role in leaf unfolding, latitude is the leading factor in autumn leaf colouration. With a one-degree change to the north, the LCD happens earlier by 2.115 (± 0.038 SE) days, while with a 100-meter elevation increase it advances only by 0.073 (± 0.009 SE) days, and with a one-degree shift to the east it advances by 0.415 (± 0.022 SE) days (Fig. 4B). Thus, the growing period is shortened by 4.312 (± 0.045 SE) days for every degree of northward shift, by

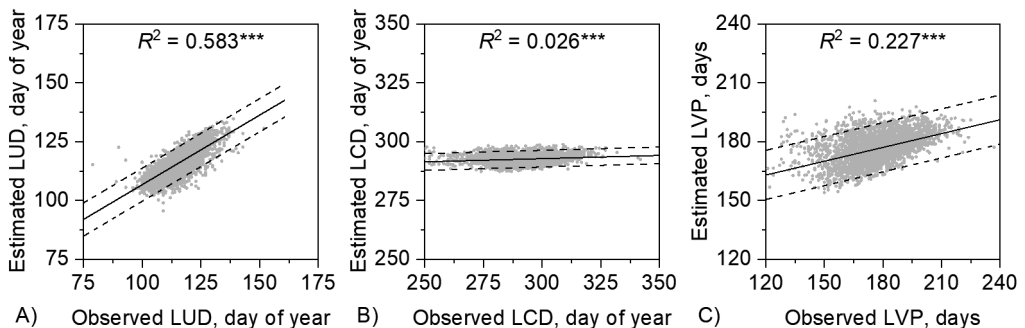


Fig. 4. Estimated vs. observed: A) leaf unfolding date, B) leaf colouring date, C) length of vegetation period.

Note: Grey dots represent estimated vs. observed LUD, LCD, and LVP values for all sample points ($n = 294,665$) and all seven years in the studied period ($N = 7 \cdot n = 2,062,655$). The solid line represents a multiple linear regression (MLR) trend; the dashed lines are the 95% prediction band. MLR's coefficients of determination (R^2) are shown above lines ($^{***} p$ -value < 0.001).

3.254 (± 0.011 SE) days for every 100 m higher altitude, and by 2.000 (± 0.026 SE) days for every degree of eastward shift (Fig.4C).

Discussion

We found that altitude is the leading factor in European beech's spring phenology, while latitude is the leading factor in its autumn phenology. Studied wild species spring phenology over decades, which mainly focused on temperate woody species, shows 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). Bulgaria's 13-hour daylight duration occurs between 7 and 9 April and varies slightly due to the slight variation in latitude across the country. While the photoperiod is relatively independent of the geographical characteristics studied and has a well-pronounced seasonality, winter and spring temperatures are strongly influenced, especially by altitude. According to Marinova and Bocheva (2024), in the mountains temperature decreases with altitude by 0.3–0.4 °C per 100 m in January, by 0.6–0.7 °C per 100 m in April, by about 0.7 °C per 100 m in July, and by 0.5 °C per 100 m in October. Such a significant decrease in temperatures with increasing elevation, especially in spring, may explain the strong relationship between unfolding and altitude.

We predict that the LUD delay is 2.519 days per 100 m, or more than 49 days per the whole altitudinal diapason (1950 m) of European beech forests in Bulgaria. Our results are comparable to those of other authors who established the correlation between leaf unfolding of Euro-

pean 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 days shift in the onset of spring phenology per 100 m of an increase in altitude in the Inner Western Carpathians, Slovakia ($\sim 49^\circ$ 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. 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. Vitasse et al. (2010) found a linear relationship between spring phenology of European beech saplings and air temperature, with leaf unfolding occurring 5 days earlier for each degree higher mean annual temperature. At the same time, the relationship between autumn phenology and mean yearly temperature is hyperbolic, with leaf senescence occurring at the latest at temperatures of 8–9 °C (Vitasse et al. 2010).

The influence of altitude on autumn leaf colouration was significantly less. If spring phenological events occur slowly at different altitudes, autumn phenological events occur more expressively and spontaneously. We predict that the LCD delay is only by 0.073 days per 100 m, or less than 1.5 days per the whole altitudinal diapason (1950 m) of European beech forests in Bulgaria. 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 phenology. The expected influence of latitude on autumn leaf colouration is significantly greater, 2.115 days per one degree of northward shift. 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. As a major climatic factor, the latitude determines the levels of heat balance and, thence, the affiliation of the country to the regions with warmer climates in Europe (Marinova and Bocheva 2024). The European beech responds positively to climate warming in the eastern part of its range (Peters 1997, Fang and Lechowicz 2006, Bolte et al. 2007), 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. However, we predict a delay of 1.581 days in the LUD and a two-day shortening of the LVP for each degree of eastward shift, which may be due to decreased precipitation and increased temperatures from west to east in Bulgaria (Marinova and Bocheva 2024).

Conclusions

The phenology of European beech forests in Bulgaria is closely related to the factors of latitude, altitude, and longitude. 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 lat-

itude or longitude. In the autumn, the geographical latitude stands out as a limiting factor. Thus, latitude and altitude simultaneously impact the length of the growing season and even reinforce each other's influence. The dynamics of individual phenological events in different years, at various altitudes and different geographical latitudes and longitudes, show preserved potential for European beech acclimation to the current climate changes in the Bulgarian mountains. These findings contribute to understanding how complex of geographic gradients shape the timing of phenological events and duration of vegetation period in European beech under the current climate in Bulgaria. They could be used as a basis for impact forecasting of future climate scenarios in the south-eastern part of the distribution of European beech forests.

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