FORESTRY IDEAS, 2023, vol. 29, No 2 (66): 245–257

Altitudinal and latitudinal variation in leaf phenology of European beech (*Fagus sylvatica* L.) in Western Bulgaria

Svetoslav Anev

Department of Dendrology, University of Forestry, 10 Kliment Ohridski Blvd., 1797 Sofia, Bulgaria. E-mail: svetoslav.anev@ltu.bg

Received: 20 August 2023 / Accepted: 4 October 2023 / Available online: 12 October 2023

Abstract

Forest phenology has gained increasing attention due to its role in understanding and monitoring the effects of climate change on ecosystems. This article compares the main phenological events of European beech (*Fagus sylvatica* L.) over six years in three mountains in Western Bulgaria – Western Stara Planina, Osogovo, and Belasitsa. The correlations between the start of the season (SOS) date, max of the season (MOS) date, end of the season (EOS) date, and length of the season (LOS), on one hand, and the altitude and latitude, on the other, was assessed. Results showed that all studied phenological events of European beech correlate significantly with the elevation – SOS and LOS positively, while MOS and EOS – negatively. The relations were more substantial in the north-sloped mountains and poorer in the Osogovo Mt., where stands cover northern, but also eastern and southern facing slopes. The latitude was a significant factor for MOS and EOS, which occur the later the further south the mountain is. The latest SOS in Osogovo, which leads to an alignment of LOS with that of Petrohan, decreases altitude's influence on these phenological events. Analysing spatial patterns of vegetation changes can help identify variations in phenological events across different areas.

Key words: end of season, forest phenology, length of season, max of season, remote sensing, start of season.

Introduction

Forest phenology studies the timing and seasonal patterns of various biological events within a forest ecosystem (Stearns and Lieth 1974). These events are often related to the life cycles and behaviours of plants, animals, and other organisms that inhabit the forest. Plant phenology focuses on timing critical events such as budburst, flowering, fruiting, leaf colour change, senescence, and leaf drop. In recent years, forest phenology has gained increasing attention due to its role in understanding and monitoring the effects of climate change on ecosystems (Richardson et al. 2013, Piao et al. 2019, Gray and Ewers 2021). Changes in phenology can indicate shifts in climate patterns and provide insights into how ecosystems respond to these changes (Jeong et al. 2011, Zhao et al. 2016). Studying forest phenology can help scientists and researchers better predict and manage potential impacts on forest ecosystems and their services, such as carbon sequestration, biodiversity support, and water regulation. Changes in phenology can have significant ecological implications, as they can impact the interactions between different species within the ecosystem. For example, if the timing of leaf unfolding and drop shifts due to changing climate conditions, it can affect the duration of photosynthetic activity and, as a result, carbon sequestration (Grossiord et al. 2022).

Phenology can change with increasing altitude and latitude due to variations in temperature, light, and other environmental factors. According to Hopkins' law (Hopkins 1918), in temperate latitudes, as the elevation or distance from the equator increase, temperatures tend to decrease, close to linear. Such variations can lead to a delay in the timing of phenological events. Spring phenological events like budburst, flowering, and leaf emergence may occur later at higher altitudes/latitudes than at lower altitudes/latitudes (Čufar et al. 2012, Dittmar and Elling 2005, Schieber et al. 2013). Conversely, autumn events occur earlier at higher altitudes/latitudes. As a result, the growing season at higher altitudes/latitudes is often shorter due to colder temperatures, affecting the duration and timing of various phenological events (Vitasse et al. 2009). In addition, Tzvetkova and Anev (2014) found that the spring phenophases in young beech individuals depend strongly on the autumn temperatures of the previous year. The shorter growing season may compress the time available for plants to complete their life cycles, potentially impacting their growth and reproduction.

Higher altitudes/latitudes are more likely to experience more extended periods of snow cover during the winter (Yue et al. 2022). Snow can act as an insulator, delaying the warming of the ground in spring. It can further delay the onset of spring phenological events. Changes in altitude/latitude can also influence the amount and quality of sunlight that reaches a location. Higher altitudes may receive more intense sunlight due to reduced atmospheric filtering. As a result, the timing of events like flowering and leaf development, which often depend on photoperiod (the duration of light exposure), can significantly impact. On the other hand, Ahrens and Henson (2015) show that on the same day and time, as the latitude increases, the zenith angle increases, which leads to more intensive refraction of light, primarily in the short-wave spectrum; direct solar radiation decreases, which reflects on the temperature regime and, therefore, on the phenology.

Altitudinal gradients can create diverse microclimates within relatively short distances than latitudinal gradients (Leuschner and Ellenberg 2017). These microclimates can lead to variations in phenological timing even within the same altitude range, as local factors such as slope, aspect, and topography can play a significant role. However, the correlation between altitude/latitude and phenology can be complex and vary depending on the specific geographic location, climate, and species present in the ecosystem. Researchers study these patterns to understand better how ecosystems respond to changing environmental conditions (Jeong et al. 2011), including shifts in temperature associated with increasing altitude. Schuster et al. (2014) conclude that cold-air pools considerably impact the vegetation period of deciduous trees.

Therefore, trees in the mid-hillside slopes gain advantages compared to lower elevations.

Observations of phenology using remote sensing devices, such as satellite imagery and Unmanned Aerial Vehicles (UAVs), along with machine learning, are promising techniques (Ciocîrlan et al. 2022). Remote sensing can detect abrupt changes in vegetation cover, indicating the occurrence of phenological events (Morain 1974). For instance, a sudden increase in greenness may indicate the onset of leaf emergence, while a decrease in greenness could signify leaf senescence. Remote sensing can provide information at various spatial scales, from individual pixels to extensive landscapes (Asner and Martin 2008, Pettorelli 2013). Analysing spatial patterns of vegetation changes can help identify variations in phenological timing across different areas. Remote sensing methods can be used to determine phenological events by monitoring changes in vegetation characteristics from a distance, often using satellites or airborne sensors (Kimball et al. 2004). These methods are based on the fact that different phenological stages can result in distinct changes in the reflectance of light from vegetation, which can be detected and analysed using remote sensing spectral indices (Treitz and Howarth 1999). Remote sensing sensors capture data over time, allowing for the creation of time series datasets. Researchers can identify shifts in phenological events by analysing the changes in spectral indices or other vegetation-related parameters over time (Garonna et al. 2014). Algorithms and statistical techniques can be applied to detect the timing of specific events based on these changes. Remote sensing data can be used to develop models that relate phenological events to environmental variables (Waggoner and Parlange 1974). For example, temperature, precipitation, and photoperiod can influence a phenological event's timing.

Spectral indices are mathematical combinations of different bands of light reflected from the Earth's surface. Examples include the most used index – Normalized Difference Vegetation Index (NDVI) (Pettorelli 2013) and the Enhanced Vegetation Index (EVI) (Jiang et al. 2008, Zhang et al. 2014). These indices are sensitive to changes in greenness and water content in vegetation. They can be used to track the onset of the growing season (budburst), the peak of photosynthetic activity (full canopy), and the senescence of vegetation (leaf colour change). The Plant Phenology Index (PPI) is a relatively new physically based spectral index that quantifies the timing of various phenological events in plants, such as leaf emergence and leaf senescence, and which improved monitoring of plant phenology because strongly related to the leaf area index (Jin and Eklundh 2014). Seasonal trajectories of the PPI (ST-PPI), 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 NDVI. ST-PPI is used for the calculation of phenological events such as start of season (SOS) date, max of season (MOS) date, end of season (EOS) date, and length of season (LOS) in days. The biophysical parameters available in the Copernicus land monitoring platform at ten-day intervals monitor the vegetation phenology and the productivity of ecosystem habitats. 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.

The study aimed to assess the correlation between the main phenological events of European beech and altitude and latitude. SOS, MOS, EOS, and LOS of beech stands in three mountains in Western Bulgaria – Stara Planina, Osogovo, and Belasitsa, were compared.

Materials and Methods

Objects

Three typical for European beech (*Fagus sylvatica* L.) mountains in Western Bulgaria (Western Stara Planina, Osogovo, and Belasitsa) were chosen to assess the relation of phenology with altitude and latitude because of the wide variation in elevation and the position in the north-south direction of these mountains. The experimental-and-training forest range 'Petrohan' in Western Stara Planina Mountain, the hunting enterprise 'Osogovo' in Osogovo Mountain, and the forest enterprise 'Petrich' in Belasitsa Mountain were chosen because of compact European beech stands and their similar longitude. Petrohan and Petrich enterprises are situated on the north slope of the Western Stara Planina and Belasitsa Mountains, while Osogovo enterprise covers northern but also eastern and southern facing slopes (Fig. 1).

Three forest enterprises' management plans (IAG 2023) were used to describe the experimental objects. Only stands of natural origin, within the studied mountains and with the domination of European beech in the canopy, are evaluated (Table 1).

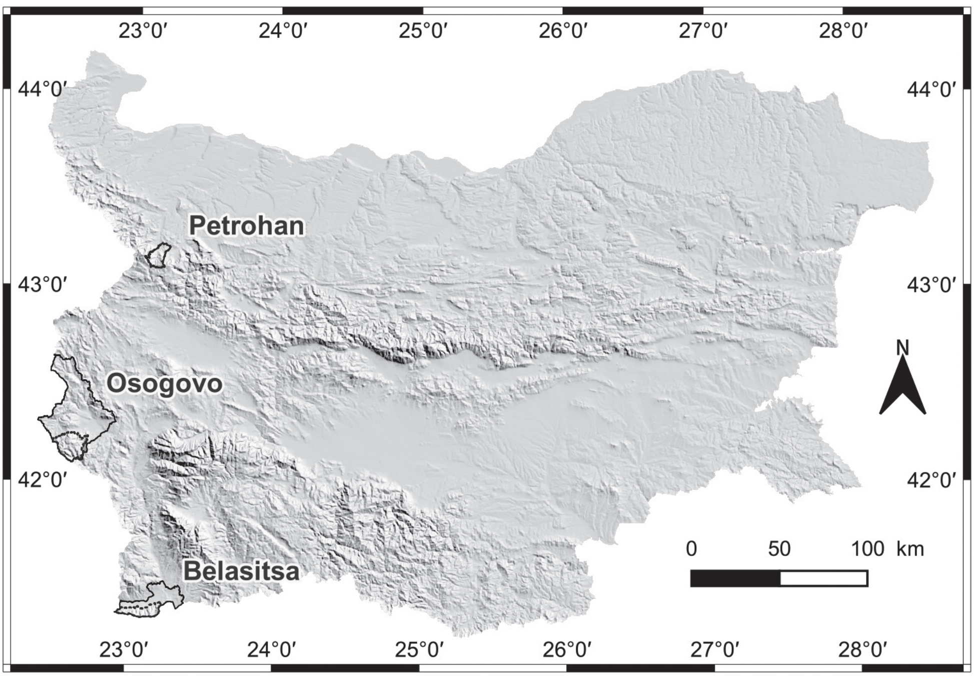

Fig. 1. Experimental objects on a Bulgaria relief map.

Note: Solid lines present the territory of experimental enterprises, while the dot-lines are enclosed their cross-section with studied mountains.

Table 1. Geographic coverage of European beech stands in the experimental objects.

Object	Petrohan	Osogovo	Belasitsa
Latitude range	43°06’28”–43°12’47”	42°06’01”–42°21’07”	41°18’54”–41°22’56”
Longitude range	23°04’20”–23°13’46”	22°22’04”–22°45’13”	22°56’16”–23°13’47”
Altitude range* of stands, m a.s.l.	1241 [394–1635]	1061 [680–1741]	1430 [378–1808]
Main soil type	Cambisols	Cambisols	Cambisols
Average age of stands, years ±SE	115.6 ±1.7	99.5 ±0.9	109.8 ±1.2
Number of stands	922	2400	1124
Average height of stands, m ±SE	21.87 ±0.22	18.52 ±0.13	20.66 ±0.20
Average DBH, cm ±SE	31.15 ±0.43	29.17 ±0.38	30.48 ±0.42

Note: * Altitude range is present as Δ altitude [Min–Max].

The wide range of altitudinal variation of three objects allows for examining the influence of elevation on phenology. At the same time, the significant difference in latitude entitles the effect of geographical position to be outlined. Petrohan enterprise is open on the northeast to the vast Moesia Plain and protected on the southwest from the main Stara Planina Mountain ridge. The Struma River valley and the local influence of the western transfer of air masses along the Strumeshnica River valley influence the Belasitsa climate. Osogovo is surrounded by the high fields of Western Bulgaria, characterized by a harsher climate – cold winters and hot and dry summers. Altitude and latitude variations provoke significant differences in climatic conditions, especially in air temperature and precipitation (Fig. 2).

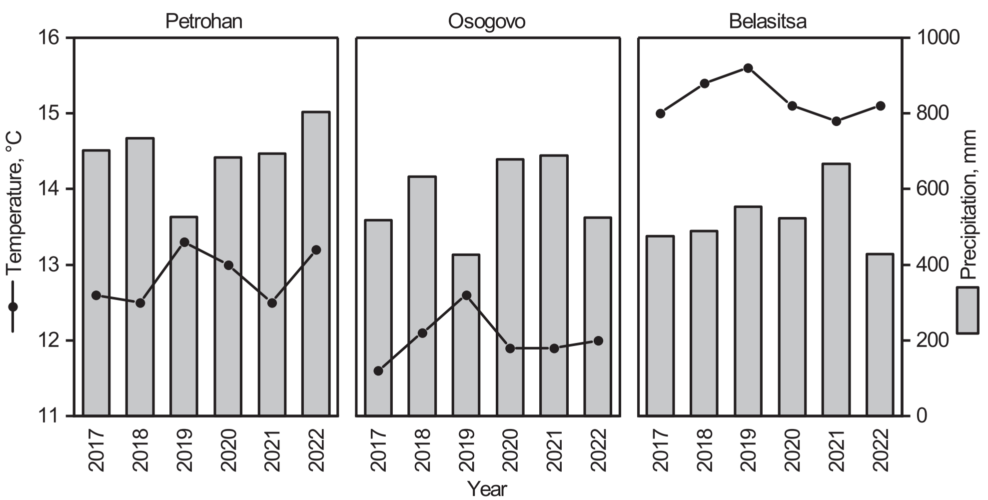

Fig. 2. Annual average air temperature and total precipitation trends for the study period.

Note: The annual temperature and precipitation are presented at the foot of the mountains – town of Berkovitsa (405 m a.s.l.) for Perohan, town of Kyustendil (518 m a.s.l.) for Osogovo, and town of Petrich (227 m a.s.l.) for Belasitsa.

Methods

SOS, MOS, EOS, and LOS of each stand were determined based on satellite images by the 'Copernicus Land Monitoring Service' by 'High-Resolution Vegetation Phenology and Productivity' product. Satellite images for western Bulgaria were downloaded from the servers of Copernicus WEkEO (Copernicus 2023) for the related phenological indicators. The values of assessed events were calculated from the seasonal trajectory (Zhang et al. 2014) of the plant phenological index (*PPI*) (eq. 1) (Jin and Eklundh 2014):

$$PPI = -K \cdot \ln\left(\frac{DVI_{\max} - DVI}{DVI_{\max} - DVI_{soil}}\right), \qquad (1)$$

where: *DVI* is the difference of near-infrared and red reflectance; DVI_{max} is the temporal maximum of *DVI*; DVI_{soil} is the soil *DVI*; *K* is a gain factor given by the canopy light extinction efficiency, which depends on leaf inclination angle ≈ 0.5, according Jin and Eklundh (2014), solar angle and the diffuse fraction of solar radiation. The seasonal trajectory ($STPPI_{DOY}$) was constructed with a non-linear double logistic function (Fischer 1994), adapted by Beck et al. (2006) for NDVI, and described for *PPI* by Smets et al. (2022) (eq. 2):

$$STPPI_{DOY} = MINV + (MAXV - MINV) \cdot \left(\frac{1}{1 + e^{-L_{SLOPE} \cdot (DOY - SOS)}} + \frac{1}{1 + e^{-R_{SLOPE} \cdot (DOY - EOS)}} - 1\right), \qquad (2)$$

where: *MINV* is average $DVI_{\min}$ before SOS and after EOS; *MAXV* is a maximum *DVI* in growing period; L_{SLOPE} and R_{SLOPE} are slope of greening up and senescent period, respectively; *DOY* is a day of the year. $STPPI_{DOY}$ is used to derive the assessed phenological events, calculated after the end of each growing season.

The altitude of each stand is calculated based on Copernicus' digital elevation map of Europe – EU-DEM, v.1.1 (Copernicus 2016). All satellite images were processed with an object-oriented Python framework for the popular open-source geographic information system QGIS, v.3.28.10 – Firenze. Python code (Gandhi 2021) automates image processing with built-in raster extraction and zonal statistics tools. The resulting attribute tables were exported as CSV comma-delimited files for processing in the open-source statistical software RStudio (v.2023.06.2+561) and MS Excel (Office 365).

Pearson correlation coefficients were calculated between phenological events and the latitude of each stand in three objects, year by year, for the 2017–2022 period. One-way ANOVA tests and Tukey post hoc analysis were performed to determine the difference between the average dates of occurrence of SOS, MOS and EOS, and LOS in days of the whole period for Petrohan, Osogovo and Belasitsa.

Results and Discussion

SOS correlates strongly positively with the elevation of stands in all three mountains, although significant variations can be observed in separate years (Fig. 3).

The highest correlation coefficients (above 0.75) in all years, except 2018, were observed in Petrohan. Such a strong correlation can be explained by the highest latitude among the studied objects, suggesting the latest warming in the spring. The correlation is significantly poorer in Osogovo, where, due to the hollow nature of the foot of the mountain, late spring colds are more frequent. A part

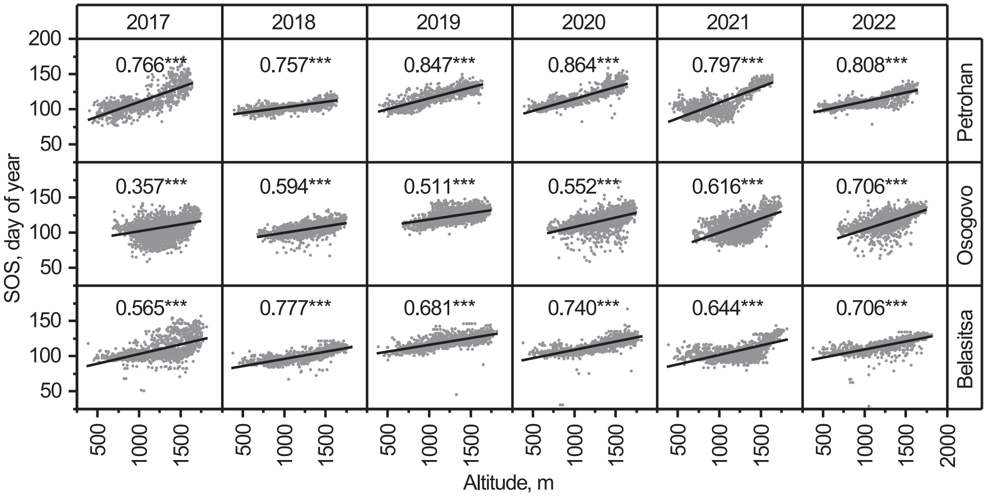

Fig. 3. Start of season (SOS) date in relation to altitude during studied period (2017–2022).

Note: Dots present SOS of each stand. The black lines show a correlation between altitude and SOS. Values above the line are Pearson correlation coefficients (*** – *p*-value < 0.001).

of the stands in Osogovo grows on the mountain's southern slope, which may be an additional factor that weakens the correlation between SOS and altitude. Average slopes (±SE) of linear regressions show that SOS delay on every 100 meters elevation gain is 2.33 ±0.04 days in Belasitsa, 2.67 ±0.04 days in Osogovo, and 3.16 ±0.04 days in Petrohan. Our results are comparable to those of other authors investigating the correlation between unfolding in European beech and altitude. Dittmar and Elling (2005) established around two days every 100-meter delay at the start of vegetation in Southern Germany. Similar results were reported by Čufar et al. (2012) for Slovenia, where the leaf unfolding shift is 2.6 days for every 100 meters. Schieber et al. (2013) showed a 2.83–3.00 days shift in the onset of spring phenophases per 100 m of an increase in altitude in the Inner Western Carpathians, Slovakia.

The tendency is similar for the relation between altitude and MOS. Except for 2018, in which April was extremely dry, Petrohan's MOS depends strongly positively on altitude. In more southern Belasitsa and especially in Osogovo, where there are stands at a south slope, this correlation weakens significantly, especially in 2017 and 2019, which can be explained by a potentially better adaptation of European beech populations in these mountains to the small amount of precipitation (Fig. 4).

The linear regressions' mean slopes (±SE) show that the MOS delay per 100 meters of altitude is 2.74 ±0.04 days in Belasica, 2.45 ±0.04 in Osogovo, and 2.89 ±0.05 in Petrohan.

The correlations between altitude and EOS are negative, significantly weak than with SOS and MOS, and are even lost in individual years (Fig. 5).

The poor correlations are possible because the transition between summer and winter is shorter with climate changes. This is consistent with other authors' findings that phenological phases at the

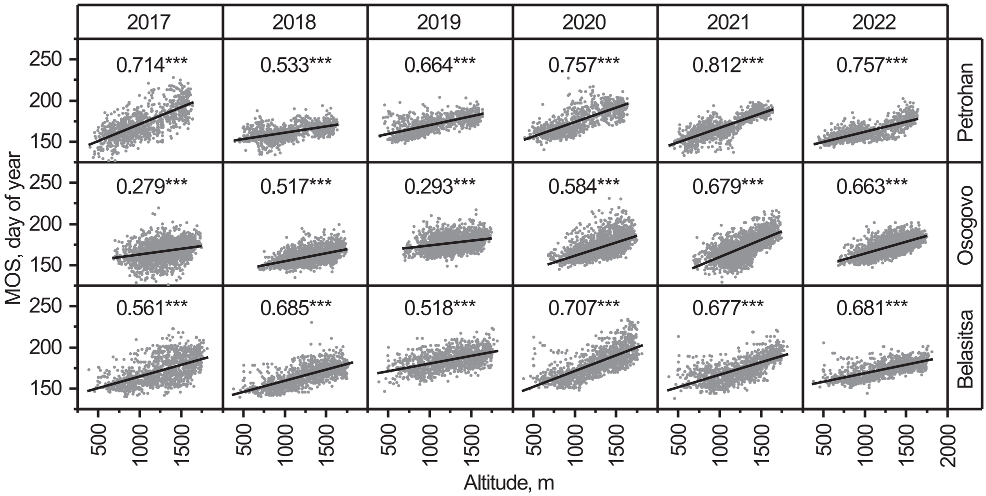

Fig. 4. Max of season (MOS) date in relation to altitude during studied period (2017–2022).
Note: Dots present MOS of each stand. The black lines show a correlation between altitude and MOS. Values above the line are Pearson correlation coefficients (*** – *p*-value < 0.001).

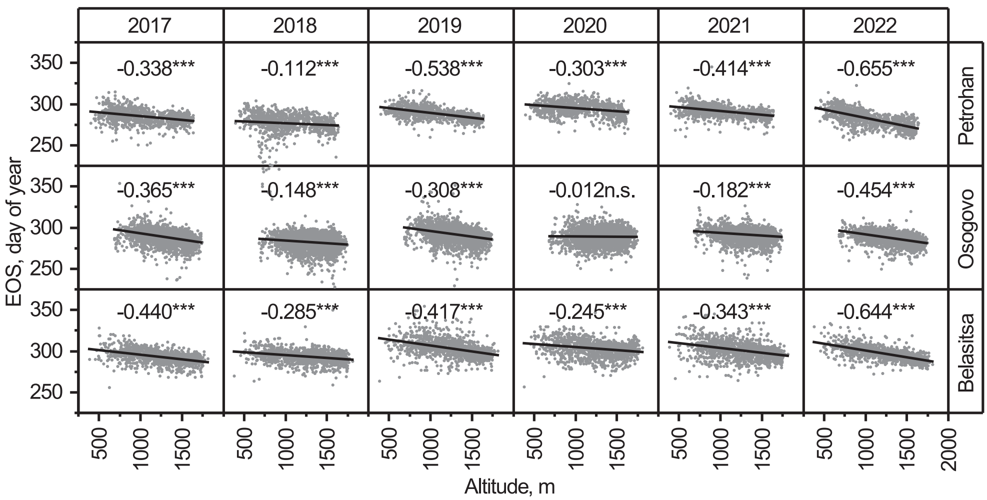

Fig. 5. End of season (EOS) date in relation to altitude during studied period (2017–2022).
Note: Dots present EOS of each stand. The black lines show a correlation between altitude and EOS. Values above the line are Pearson correlation coefficients (*** – *p*-value < 0.001; n.s. – non-significant).

end of the growing season are poorly related to altitude (Chmielewski and Rötzer 2001). Still, they may also be due to the greater sensitivity of European beech to late spring frosts than to autumn chills (Stefanov and Ganchev 1953), which recent studies (Wang et al. 2022) suggest may be on the wane. There is no clear tendency to strengthen or weaken the correlation among years or sites of the study.

Given that the correlation is lost in individual years, a more substantial factor than altitude can be assumed to determine autumn leaf colouration in European beech. For every 100-meter increase in altitude, EOS occurs earlier by 1.14 ±0.04 days in Belasica, 0.94 ±0.03 days in Osogovo, and 1.05 ±0.04 days in Perohan. While, for Slovenia, Čufar et al. (2012) established a slightly higher value of regression slope (1.89 ±0.02) between altitude and leaf colouring, but in Southern Germany, leaf discolouration showed no altitudinal dependence due to cold-air tailback (Dittmar and Elling 2005).

The length of the season, as a function of SOS and EOS, lengthened substantially after the 1980s (Garonna et al. 2014), mostly due to the later onset of EOS (Jeong et al. 2011, Zhao et al. 2016). However, the negative correlation with altitude remains strong, especially on northern slopes (Fig. 6).

Vegetation season is getting shorter with an increase of altitude by 100-metre, with 3.34 ±0.05 days in Belasica, 3.53 ±0.05 days in Osogovo, and even 4.21 ±0.05 days in Petrohan. The correlations were poorer in Petrohan and Osogovo in 2018, when spring was arid and intensified at all three sites in the warmer 2019 and 2022. The poorer correlations in Osogovo are probably due to the variety of exposures. Still, they may also be because of the later SOS (Fig. 7) due to the valley character of the climate. Such local influences in southern Germany have a more substantial impact on the end than on the beginning of the growing season (Dittmar and Elling 2005). Schieber et al. (2013) establish that the duration of the growing season shortened by about 4.4 days per each altitudinal 100 m in the vertical gradient in Inner Western Carpathians, Slovak Republic.

The studied period was too short to establish significant SOS, MOS, EOS, and LOS change trends in individual years. For this reason, the average dates of occurrence of the main phenological events (SOS, MOS, and EOS) and the average length of the growing season (LOS) were

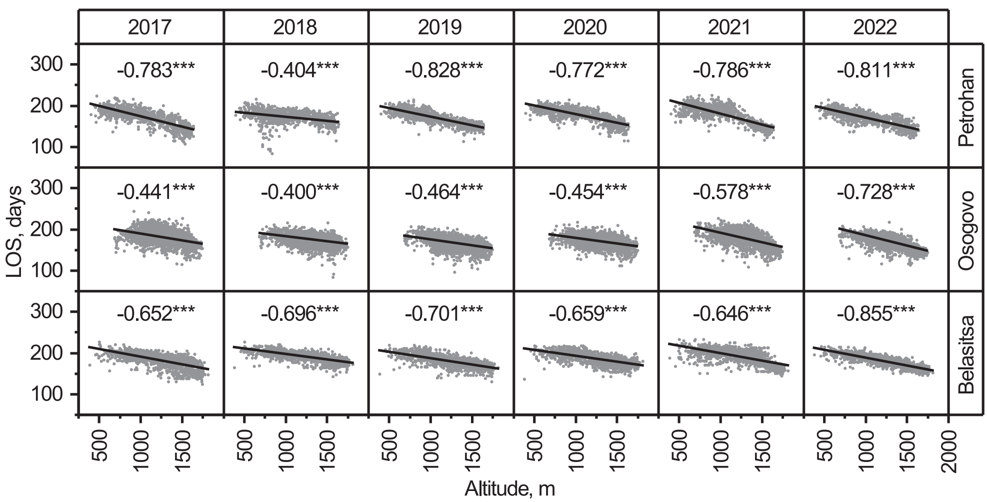

Fig. 6. Length of season (LOS) in relation to altitude during studied period (2017–2022).

Note: Dots present LOS of each stand. The black lines show a correlation between altitude and LOS. Values above the line are Pearson correlation coefficients (*** – *p*-value < 0.001).

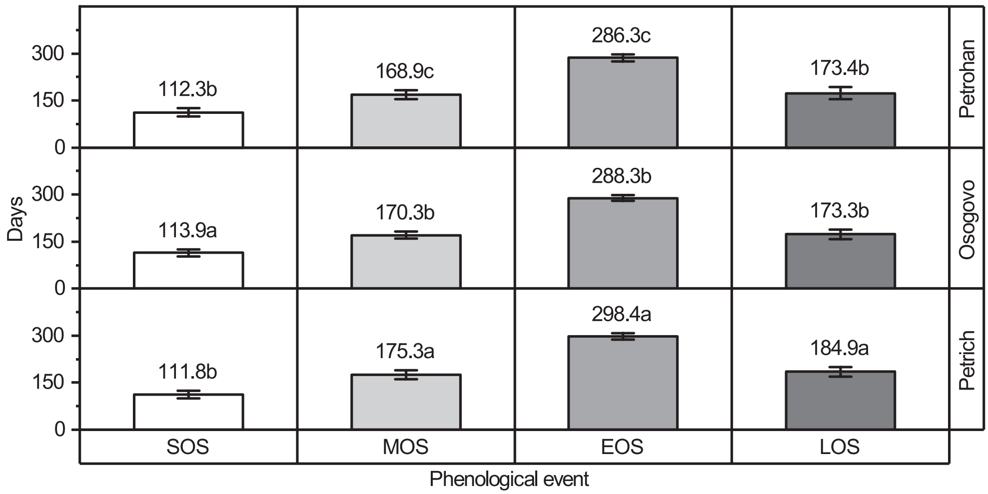

Fig. 7. Average dates (in days of the year) of occurrence of SOS, MOS and EOS and average LOS (in days) for the studied period (2017–2022).

Note: The column and values above are the average phenological events of each object. The whiskers represent the standard deviation. The different letter denotes statistically significant difference averages among objects (one-way ANOVA using Tukey post hoc tests with α = 0.05).

calculated (Fig. 7).

The vegetation season of European beech starts on 21 April (23 March – 20 May) in Belasitsa, 23 April (31 March – 18 May) in Osogovo and 22 April (26 March – 18 May) in Petrohan, which is around a week early than leaf unfolding for the same region, observed in our previous study (Tzvetkova and Anev 2014) and in Southern Germany (Dittmar and Elling 2005) but is closer to leaf unfolding in Slovenia (Čufar et al. 2012). In contrast to SOS, which reliably occurs at the latest in Osogovo, MOS and EOS occur the later, the smaller the geographical latitude of the object. MOS occurs on 24 June (23 May – 26 July) in Belasitsa, 19 June (27 May – 13 July) in Osogovo, and 18 June (19 May – 17 July) in Petrohan.

As Gressler et al. (2015) and Kuzmanova (2021) point out, autumn phenophases can be significantly longer than spring due to the considerable distance in the time of leaf fall along the vertical profile of the assemblage in the forest. However, our results show a shorter period of autumn phenophases compared to spring ones. EOS occurs on 25 October (06 October – 12 November) in Belasitsa, 15 October (29 September – 31 October) in Osogovo, and on 13 October (24 September – 02 November) in Petrohan, versus 18 October from our previous survey (Tzvetkova and Anev 2014). This is probably due to the homogeneous nature of the stands in terms of composition and age, which resulted from the widely applied short-term cutting system in the past. As a result, LOS increases only in Belasitsa – 184 (151–219), while in Osogovo – 173 (144–203), the season lasts as long as in Petrohan – 173 (134–214), regardless of the difference in latitude. However, the growing season of European beech in Western Bulgaria turns out to be considerably longer than in Southern Germany

– 161 and Northern Germany – 154 days (Dittmar and Elling 2005) and significantly closer to that in Slovakia – 128–181 days (Schieber et al. 2013).

Conclusions

A significant correlation was established between the start of season date, max of season date, end of season date, and length of season on the one hand and the altitude and latitude on the other. The established correlations are more significant in the north-sloped mountains and poorer in the Osogovo, where the stands cover the northern, eastern and southern slopes, but also due to the valley character of the climate at the foot of this mountain. Latitude was essential for max of season date and end of season date occurring later the further south the mountain. The latest start of season date at Osogovo, which results in a length of season equalised to that of Petrohan, reduces the influence of altitude on these phenological events. Analysing the spatial patterns of vegetation changes can help identify variations in phenological events in different areas. The information provided by phenological observations will be increasingly valuable in large-scale approaches to forest management and remote methods for establishing phenological events would greatly facilitate their tracking in time and space.

Acknowledgements

The study was funded by the project 'The National Roadmap for Research Infrastructure (2020–2027)', Ministry of Education and Science of Republic of Bulgaria, through agreements No DO1-405/18.12.2020 and DO1-163/28.07.2022.

We thank the two peer reviewers whose remarks and recommendations helped to improve the initial manuscript.

References

Ahrens C.D., Henson R. 2015. Meteorology Today. Cengage Learning. 656 p.

Asner G.P., Martin R.E. 2008. Spectral and chemical analysis of tropical forests: Scaling from leaf to canopy levels. Remote Sensing of Environment 112(10): 3958–3970. https://doi.org/10.1016/j.rse.2008.07.003

Beck P.S.A., Atzberger C., Høgda K.A., Johansen B., Skidmore A.K. 2006. Improved monitoring of vegetation dynamics at very high latitudes: A new method using MODIS NDVI. Remote Sensing of Environment 100(3): 321–334. https://doi.org/10.1016/j.rse.2005.10.021

Chmielewski F.-M., Rötzer T. 2001. Response of tree phenology to climate change across Europe. Agricultural and Forest Meteorology 108(2): 101–112. https://doi.org/10.1016/S0168-1923(01)00233-7

Ciocîrlan M. I., Curtu A. L., Radu G. R. 2022. Predicting Leaf Phenology in Forest Tree Species Using UAVs and Satellite Images: A Case Study for European Beech (*Fagus sylvatica* L.). Remote Sensing 14(24), 6198. https://doi.org/10.3390/rs14246198

Copernicus 2016. European Digital Elevation Model (EU-DEM), version 1.1. European Environment Agency (Producer). https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1 (Accessed on 10 August 2023).

Copernicus 2023. High Resolution Vegetation Phenology and Productivity (HR-VPP) service. WEkEO (Producer). https://www.wekeo.eu (Accessed on 10 August 2023).

Čufar K., De Luis M., Saz M.A., Črepinšek Z., Kajfež-Bogataj L. 2012. Temporal shifts in leaf phenology of beech (*Fagus sylvatica)* depend on elevation. Trees 26(4): 1091–

1100. https://doi.org/10.1007/s00468-012-0686-7

Dittmar C., Elling W. 2005. Phenological phases of common beech (*Fagus sylvatica* L.) and their dependence on region and altitude in Southern Germany. European Journal of Forest Research 125(2): 181–188. https://doi.org/10.1007/s10342-005-0099-x

Fischer A. 1994. A model for the seasonal variations of vegetation indices in coarse resolution data and its inversion to extract crop parameters. Remote Sensing of Environment 48(2): 220–230. https://doi.org/10.1016/0034-4257(94)90143-0

Gandhi U. 2021. Running Processing Algorithms via Python (QGIS3). QGIS Tutorials and Tips (Producer). https://www.qgistutorials.com/en/docs/3/processing_algorithms_pyqgis.html (Accessed on 12 August 2023).

Garonna I., de Jong R., de Wit A.J.W., Mücher C.A., Schmid B., Schaepman M.E. 2014. Strong contribution of autumn phenology to changes in satellite-derived growing season length estimates across Europe (1982–2011). Global Change Biology 20(11): 3457–3470. https://doi.org/10.1111/gcb.12625

Gray R.E.J., Ewers R.M. 2021. Monitoring Forest Phenology in a Changing World. Forests 12(3), 297. https://doi.org/10.3390/f12030297

Gressler E., Jochner S., Capdevielle-Vargas R.M., Morellato L.P.C., Menzel A. 2015. Vertical variation in autumn leaf phenology of Fagus sylvatica L. in southern Germany. Agricultural and Forest Meteorology 201: 176–186. https://doi.org/10.1016/j.agrformet.2014.10.013

Grossiord C., Bachofen C., Gisler J., Mas E., Vitasse Y., Didion-Gency M. 2022. Warming may extend tree growing seasons and compensate for reduced carbon uptake during dry periods. Journal of Ecology 110(7): 1575–1589. https://doi.org/10.1111/1365-2745.13892

Hopkins A.D. 1918. Periodical Events and Natural Law as Guides to Agricultural Research and Practice. U.S. Government Printing Office. 42 p.

IAG 2023. Forestry plans. Executive Forests Agency (Producer). http://www.procurement.iag.bg (Accessed on 02 August 2023).

Jeong S.-J., Ho C.-H., Gim H.-J., Brown M.E. 2011. Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982–2008. Global Change Biology 17(7): 2385–2399. https://doi.org/10.1111/j.1365-2486.2011.02397.x

Jiang Z., Huete A.R., Didan K., Miura T. 2008. Development of a two-band enhanced vegetation index without a blue band. Remote Sensing of Environment 112(10): 3833–3845. https://doi.org/10.1016/j.rse.2008.06.006

Jin H., Eklundh L. 2014. A physically based vegetation index for improved monitoring of plant phenology. Remote Sensing of Environment 152: 512–525. https://doi.org/10.1016/j.rse.2014.07.010

Jönsson P., Cai Z., Melaas E., Friedl M.A., Eklundh L. 2018. A Method for Robust Estimation of Vegetation Seasonality from Landsat and Sentinel-2 Time Series Data. Remote Sensing 10(4), 635. https://doi.org/10.3390/rs10040635

Kimball J.S., McDonald K.C., Running S.W., Frolking S.E. 2004. Satellite radar remote sensing of seasonal growing seasons for boreal and subalpine evergreen forests. Remote Sensing of Environment 90(2): 243–258. https://doi.org/10.1016/j.rse.2004.01.002

Kuzmanova R. 2021. Phenological studies of common beech. Snezhani. Sofia. 152 p. ISBN: 978-619-91033-2-6

Leuschner C., Ellenberg H. 2017. Ecology of Central European Forests: Vegetation Ecology of Central Europe. Springer. 971 p.

Morain S.A. 1974. Phenology and Remote Sensing. In: Lieth H. (Ed.), Phenology and Seasonality Modeling. Springer, Berlin, Heidelberg: 55–75.

Pettorelli N. 2013. The Normalized Difference Vegetation Index. Oxford University Press. 194 p.

Piao S., Liu Q., Chen A., Janssens I.A., Fu

Y., Dai J., Liu L., Lian X., Shen M., Zhu X. 2019. Plant phenology and global climate change: Current progresses and challenges. Global Change Biology 25(6): 1922–1940. https://doi.org/10.1111/gcb.14619

Richardson A.D., Keenan T.F., Migliavacca M., Ryu Y., Sonnentag O., Toomey M. 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. Agricultural and Forest Meteorology 169: 156–173. https://doi.org/10.1016/j.agrformet.2012.09.012

Schieber B., Janik R., Snopkova Z. 2013. Phenology of common beech (*Fagus sylvatica* L.) along the altitudinal gradient in Slovakia (Inner Western Carpathians). Journal of Forest Science 59(4): 176–184. https://doi.org/10.17221/82/2012-JFS

Schuster C., Kirchner M., Jakobi G., Menzel A. 2014. Frequency of inversions affects senescence phenology of Acer pseudoplatanus and Fagus sylvatica. International Journal of Biometeorology 58(4): 485–498. https://doi.org/10.1007/s00484-013-0709-0

Smets B., Cai Z., Eklundh L., Tian F., Bonte K., Hoost R.V., Roo B.D., Jacobs T., Camacho F., Sánchez-Zapero J., Martinez-Sánchez E., Swinnen E., Scheifinger H., Hufkens K., Jönsson P. 2022. HR-VPP Product User Manual Seasonal Trajectories and VPP parameters. European Environment Agency (Producer). https://land.copernicus.eu/ (Accessed on 10 August 2023).

Stearns F., Lieth H. 1974. Introduction. In: Lieth H. (Ed.), Phenology and Seasonality Modeling. Springer, Berlin, Heidelberg: 23–24.

Stefanov B., Ganchev A. 1953. Dendrology. 2 ed. Zemizdat (in Bulgarian), Sofia. 651 p.

Treitz P.M., Howarth P.J. 1999. Hyperspectral remote sensing for estimating biophysical parameters of forest ecosystems. Progress in Physical Geography: Earth and Environment 23(3): 359–390. https://doi.org/10.1177/030913339902300303

Tzvetkova N., Anev S. 2014. Phenological observations of young common beech stands from a representative site in Bulgaria. In: Efe R., Ozturk M. (Eds), Environment and Ecology in the Mediterranean Region II. Cambridge Scholars Publishing, Newcastle: 373–382.

Vitasse Y., Delzon S., Dufrêne E., Pontailler J.-Y., Louvet J.-M., Kremer A., Michalet R. 2009. Leaf phenology sensitivity to temperature in European trees: Do within-species populations exhibit similar responses? Agricultural and Forest Meteorology 149(5): 735–744. https://doi.org/10.1016/j.agrformet.2008.10.019

Waggoner P.E., Parlange J.-Y. 1974. Modeling Seasonality. In: Lieth H. (Ed.), Phenology and Seasonality Modeling. Springer, Berlin, Heidelberg: 301–327.

Wang H., Lin S., Dai J., Ge Q. 2022. Modeling the effect of adaptation to future climate change on spring phenological trend of European beech (*Fagus sylvatica* L.). Science of The Total Environment 846, 157540. https://doi.org/10.1016/j.scitotenv.2022.157540

Yue S., Che T., Dai L., Xiao L., Deng J. 2022. Characteristics of Snow Depth and Snow Phenology in the High Latitudes and High Altitudes of the Northern Hemisphere from 1988 to 2018. Remote Sensing 14(19), 5057. https://doi.org/10.3390/rs14195057

Zhang X., Tan B., Yu Y. 2014. Interannual variations and trends in global land surface phenology derived from enhanced vegetation index during 1982–2010. International Journal of Biometeorology 58(4): 547–564. https://doi.org/10.1007/s00484-014-0802-z

Zhao J., Wang Y., Zhang Z., Zhang H., Guo X., Yu S., Du W., Huang F. 2016. The Variations of Land Surface Phenology in Northeast China and Its Responses to Climate Change from 1982 to 2013. Remote Sensing 8(5), 400. https://doi.org/10.3390/rs8050400