

Distribution and phenology of natural forests dominated by *Picea abies* and *Abies alba* in Bulgaria

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Abstract

This study aimed to compare the geographical distribution, ecological characteristics and phenological behaviour of forests dominated by *Picea abies* (L.) H.Karst. and *Abies alba* Mill. in Bulgaria, combining data from the National Forest Inventory and remote sensing. Ecological variables such as altitude, latitude, longitude, aspect, and slope were analysed to characterise species-specific habitat preferences. Phenological events, including the start of the vegetation period (SVP), the end of the vegetation period (EVP), and the length of the vegetation period (LVP), were also compared. The results indicated that in Bulgarian forests, *P. abies* dominates significantly more stands than *A. alba*. Both species are mainly found in the middle mountain zone, but the average altitude of spruce forests is 1507.6 ± 170.8 m, while that of fir forests is notably lower at 1371.1 ± 164.7 m. Both species favour sloping terrain, with fir tolerating steeper slopes ($17.8^\circ \pm 7.2^\circ$), whereas spruce is more common on moderate slopes ($14.8^\circ \pm 6.2^\circ$). They prefer shady exposures, though spruce shows greater tolerance to sunny conditions (61.5 %/38.5 %), while fir is more restricted to shaded exposures (77.7 %/22.3 %). *P. abies* begins its active vegetation period (SVP) early (~ 10 April ± 13.7 days), whereas *A. alba* delays SVP by over a week (~ 18 April ± 9.9 days). EVP also occurs earlier in spruce forests (~ 24 September ± 12.5 days), while in fir forests it is delayed by more than a week (~ 3 October ± 10.8 days). As a result, in both spruce and fir forests, LVP lasts approximately 167.2 ± 20.3 days. These findings enhance our understanding of the ecological and phenological differences between the two conifers and can be utilised to improve the efficient, evidence-based management of forests dominated by these species in Bulgaria, which may be important for addressing the challenges posed by climate change.

Key words: end of vegetation period, European silver fir, length of vegetation period, Norway spruce, start of vegetation period.

Introduction

Climate change in Southeastern Europe is characterised by rising temperatures and shifts in intra-annual rainfall

patterns (Marinova and Bocheva 2023). The changes are most noticeable during summer (Marinova and Bocheva 2024) and strongly influence the active growth period in forests. Future climatic changes

could increase the mismatch between environmental conditions and the ecological requirements of forest tree species within their current ranges. Such changes may accumulate stress (Anev et al. 2016, Anev 2025c), affect competitiveness (Leuschner 2020, Anev and Marinova 2021), growth (Anderegg et al. 2020), and survival (Anev and Tzvetkova 2018), leading to shifts in species distributions (Klanderud and Birks 2003, Jump et al. 2009, Williams et al. 2013) and phenology (Piao et al. 2019; Gray and Ewers 2021; Inouye 2022; Anev 2023, 2025b; Skvareninova et al. 2024). In temperate forests, gymnosperms face greater risks (Niinemets and Valladares 2006) due to their primitive xylem structure (Jeřík et al. 2015, Panayotov et al. 2019, Zafirov et al. 2020) and slower renewal of photosynthetic organs (Solberg 2004, Petrik et al. 2022). The ranges of two of Europe's most economically and ecologically valuable coniferous tree species – *Picea abies* (L.) H.Karst. and *Abies alba* Mill. – often overlap. In Bulgaria, they are distributed mainly in the Rila-Rhodope massif, where they frequently occur in mixed coniferous forests. Despite extensive studies of these valuable forests, certain specific ecological features of the two species remain poorly understood. These features are likely to underpin differences in their ecological compatibility and phenological behaviour, and they affect their ability to dominate within stands.

P. abies is among the most widely distributed conifer species in Europe, dominating the boreal forests of Northern Europe and the subalpine regions of the Alps and Carpathian Mountains (San-Miguel-Ayanz et al. 2016). The species' distribution in Bulgaria is primarily in the western mountains of the country, where, in mixed forests at middle altitudes, it occurs with *Fagus sylvatica* L. and *A. alba*

under mesic conditions, and with *Pinus sylvestris* L. under drier conditions (Stefanov and Ganchev 1953). Although there are monodominant spruce forests on the northern slopes of Rila and Vitosha, the most compact range of the species is found in the Western Rhodopes (Executive Forests Agency 2023). According to Leuschner and Ellenberg (2017), *P. abies* is a secondary coloniser but can also be a pioneer and a climax species. It shows good yield and quality performance under very different site conditions. As a relatively shade-tolerant species, it can survive for decades under a closed canopy, but when the canopy opens, it grows rapidly after 5–10 years of age.

A. alba is an evergreen coniferous tree, mainly distributed in the montane areas of Central, Southern, and Eastern Europe (San-Miguel-Ayanz et al. 2016). According to Stefanov and Ganchev (1953), human activity significantly affected the extent of fir forests in the Bulgarian mountains. Within its current distribution in Europe, *A. alba* is most commonly associated with relatively moist environments, where the average annual precipitation ranges from 700 to 1800 mm (Tinner et al. 2013). The main limiting factors are a lack of summer heat and adequate moisture during the vegetation period, while new seedlings are extremely sensitive to frost damage (San-Miguel-Ayanz et al. 2016). *A. alba* is mostly found mixed with *P. abies* or *P. sylvestris* at higher altitudes, and with *F. sylvatica* at middle altitudes (Stefanov and Ganchev 1953, Leuschner and Ellenberg 2017), with which it competes successfully, thanks to its strong shade tolerance and relatively rapid natural regeneration.

The distribution and ecological performance of forest tree species in temperate Europe are closely linked to climatic conditions and the length of the vegetation

period, which determine the timing and duration of physiological activity in forest ecosystems. Long-term observations indicate that the timing of spring phenophases in many tree species has advanced during recent decades, reflecting the sensitivity of forest ecosystems to climatic variability (Leuschner and Ellenberg 2017). Key phenological indicators used to describe vegetation dynamics include the start and end of the vegetation period and its duration, which reflect the response of forest ecosystems to climatic variability (Vitasse et al. 2009, Piao et al. 2019). These phenological indicators provide a useful framework for assessing species-specific responses to environmental conditions and for comparing seasonal activity patterns among forest tree species.

The timing of phenological events in coniferous forests offers valuable insights into how well the ecological needs of tree species align with changing environmental conditions. They can be detected before visible signs of stress appear and are relatively easy to monitor (Gray and Ewers 2021), particularly with remote sensing technologies that can cover large areas and automate observations (Ciocîrlan et al. 2022, Anev 2025b). Numerous studies (Kramer et al. 2000; Vitasse et al. 2009, 2011; Flynn and Wolkovich 2018; Peaucelle et al. 2019; Piao et al. 2019; Skvareninova et al. 2024; Anev 2025b) suggest that forest phenology varies with altitude and latitude primarily due to differences in temperature, precipitation, and photoperiod. In addition to comparing convergence with environmental factors, phenological rhythms can be used to directly compare the competitive potential of two or more tree species (Anev 2025a) or provenances (Petkova et al. 2017) under similar conditions, thereby enhancing understanding of ecological differenc-

es among them. Local factors, such as slope, aspect, and topography, generate additional microclimatic variation, causing phenological events to differ even within the same altitude and latitude range depending on individual species preferences (Anev 2025a). Previous studies have analysed the phenological behaviour of dominant conifer species in European mountain forests. According to Pástorová et al. (2014), the onset of spring phenological phases in *P. abies* is strongly influenced by temperature conditions and varies among provenances originating from different elevations. Bud burst in Norway spruce has also been shown to respond closely to spring temperature variability (Schleip et al. 2008). In *A. alba*, long-term observations indicate that the timing of bud development, leafing, and leaf senescence varies substantially between years and is closely linked to climatic conditions (Jean et al. 2023). A particularly strong limiting factor for the species' spring phenology is drought (Csilléry et al. 2020), which, according to Mauri et al. (2016), limits its distribution in the southern part of its range.

Remote sensing techniques, e.g. satellite imagery, serve as effective tools for monitoring phenology. Large-scale satellite analyses have shown that variations in the start and end of the vegetation period strongly influence its length across European ecosystems (Garonna et al. 2014). Numerous studies have shown that changes in how vegetation absorbs red and infrared light, as measured with multispectral cameras, reveal different stages of plant phenology (Bucha and Koren 2017, Lukasová et al. 2019, Gray and Ewers 2021, Soudani et al. 2021, Ciocîrlan et al. 2022, Grabska-Szwagrzyk and Tymieńska-Czabańska 2024). The main phenological metrics derived from

seasonal variation in vegetation indices include the dates and values of the season start and end, the season length, the season peak, the season amplitude, and the slopes of the leaf greening and browning periods (Delbart et al. 2005, Tariq et al. 2021, Smets et al. 2022, Gao et al. 2023). The Plant Phenology Index (PPI), introduced by Jin and Eklundh (2014), is a biophysical vegetation index optimised for effective phenological monitoring, designed to minimise the errors of other indices, such as NDVI and EVI (Karkauskaite et al. 2017), when examining the forest canopy.

This study aimed to compare the geographical distribution, ecological characteristics and phenological behaviour of forests dominated by *P. abies* and *A. alba* in Bulgaria, using a novel approach that integrates data from the National Forest Inventory and satellite observations. The findings are expected to contribute to the methodological framework for studying conifer phenological dynamics, enhance understanding of the ecology of the studied species and support evidence-based forest management strategies, which are crucial for conifer forests' adaptation to climate change challenges.

Object and Methods

This study focuses on monodominated forests of two conifer species: *P. abies* and *A. alba*, located in the southeastern part of their distribution in Bulgaria. According to the German Forestry and Agriculture Biomass Model (FABio-Forest model) (Böttcher et al. 2018, Welle et al. 2022), we defined a forest stand as dominated by one species if at least 80 % of the main tree layer consisted of that species. In the FABio-Forest model, it is accept-

ed that with a participation of over 80 %, the dominant tree species determines the main structural, productive, and ecological characteristics of the stand. Therefore, it can be considered and managed as a single-species stand.

Tree species composition and stand polygons were obtained from the National Forest Inventory database (Executive Forests Agency 2023), current as of 2022, and available at <https://iag.bg/> (Fig. 1). The polygons for the stands conformed to the boundaries outlined during the forest inventory. Before the analysis, a validity check algorithm was applied to the vector layer geometries, and no errors were detected.

Table 1 shows that *P. abies* dominates substantially more forest stands and occupies a considerably larger area than *A. alba* in Bulgaria.

The National Forest Inventory database (Executive Forests Agency 2023) and satellite raster imagery were processed using QGIS (v. 3.40.9). Mean stand coordinates (latitude and longitude) were calculated using the 'native:meancoordinates' tool. The EuroDEM raster layer (EuroGeographics 2025) was used to derive altitude, slope, and exposure. The raster was reprojected to EPSG:32635 using the 'gdal:warp' tool (GDAL v. 3.10.2). Slope and aspect rasters were subsequently generated using the 'r.slope.aspect' tool (GRASS GIS v. 2.12.99). Because the exposure raster represents circular data ($0^\circ = 360^\circ = \text{north}$), direct averaging would produce incorrect values. This limitation was addressed using the trigonometric method described in Anev (2025a).

Phenological events were derived from the Copernicus Land Monitoring Service, using satellite imagery from the High-Resolution Phenology and Productivity se-

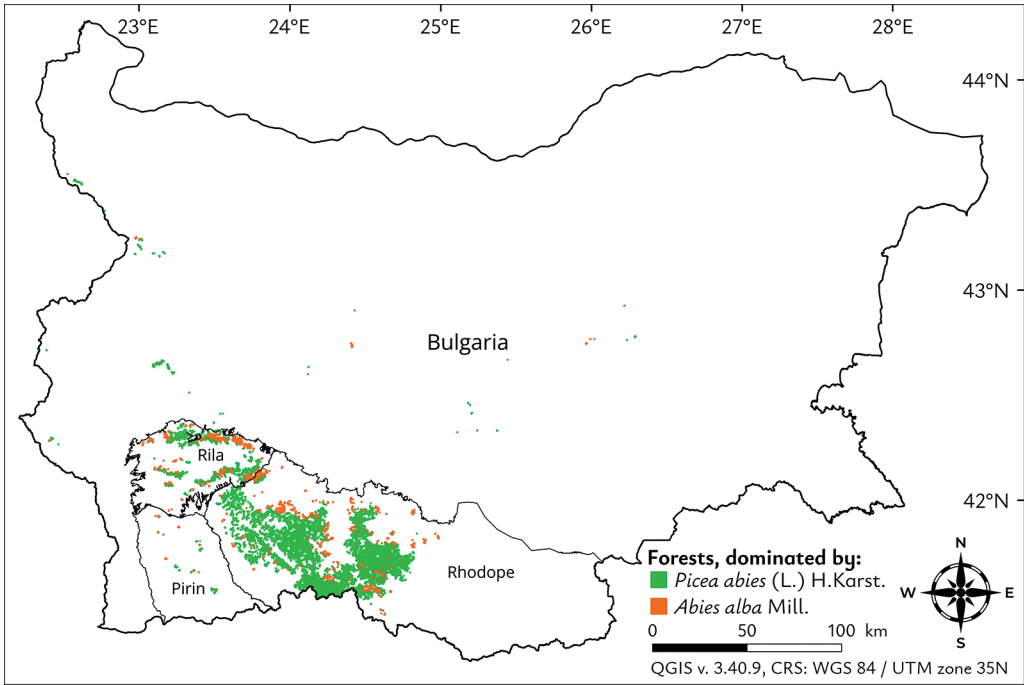


Fig. 1. Geographical distribution of forests dominated by *P. abies* and *A. alba* and the boundaries of the major mountain ranges in which they are distributed in Bulgaria.

Table 1. Area and age of studied forests.

Variants	Number of stands	Area		Stand age, years (mean $\pm$ SD)
		ha	%	
PA-dominated forests	7852	169,690	0.83	86.7 $\pm$ 33.1 b
AA-dominated forests	772	31,808	0.10	95.2 $\pm$ 34.6 a

Note: Percentages refer to the total forested area of Bulgaria. Stand age is expressed as mean $\pm$ SD. Means followed by different letters differ significantly between forest types according to a two-sample *t*-test ($p < 0.05$).

ries (CLMS 2026a) of the Copernicus programme (CLMS 2026b). The analysis used the Seasonal Trajectory of the Plant Phenology Index (ST-PPI) (Jin and Eklundh 2014), particularly the start of the season (SOSD), end of the season (EOSD), and length of season (LOSD) rasters for season one from the years 2017 to 2023. According to Smets et al. (2022), for each stand, the SOSD, defined as the spring day when the ST-PPI reaches 25 % of its

maximum annual value, was used to estimate the average start date of the vegetation period (SVP); EOSD, defined as the autumn day when the ST-PPI drops to 15 %, was used to estimate the average end date of the vegetation period (EVP); and LOSD, defined as the difference between EOSD and SOSD, was used to estimate the average length of the vegetation period (LVP) in days. Twenty-two raster images were analysed for each

phenological event during the 2017–2023 study period ($N = 462$).

Images were reprojected using 'gdal:warp' and mosaicked with 'gdal:build-virtualraster' (GDAL v. 3.10.2). Zonal statistics ('native:zonalstatisticsfb') were then employed to calculate mean values of phenological events for each stand polygon. The final dataset, combining geographic and phenological attributes, was exported with the 'gdal:gdal2xyz' tool and imported into MS Excel (Office 365, Microsoft) for visualisation and statistical analysis. Statistical processing was performed using built-in functions and VBA scripts (VBA v. 7.1, Microsoft). Because the data failed of the normality test (Kolmogorov-Smirnov) and unequal sample sizes, a Mann-Whitney U -test (p -value < 0.05) was used to compare geographical and phenological variables between the two conifer-dominated forest types.

Results

Distribution

Species-specific variation in distribution by latitude and longitude was observed when comparing forests dominated by *P. abies* and *A. alba*. Both species have a broad distribution across the Bulgarian mountains, but monodominant stands are confined to the south-western part of the country. Despite the substantial overlap in their ranges, *A. alba* is more prevalent in the Rila mountain, while *P. abies* occupies a wider area within the Rodope Mountains. This leads to significant differences in the average latitude and longitude of their distributions (Fig. 2A, B).

Half of the forests dominated by *P. abies* were confined to a latitude range between 41.6° and 41.8° and a longitude range between 24.1° and 24.6° . Simulta-

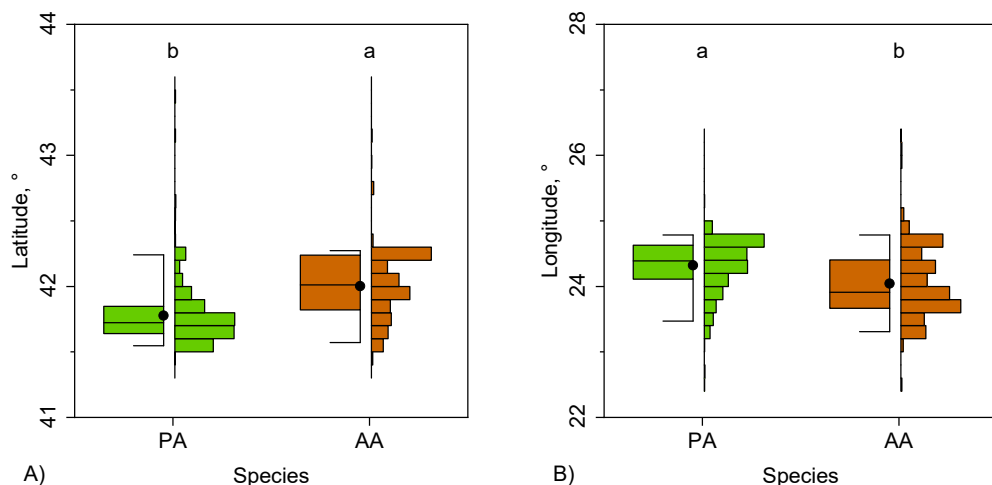


Fig. 2. Distribution extent of *P. abies* (PA) and *A. alba* (AA) dominated forests by: A) latitude, B) longitude.

Note: Mean values are indicated by a solid dot, the median by a line, the box represents the 25th–75th percentiles, and the whiskers indicate the 5th–95th percentiles. Histograms show the distributions with a bin size of 0.5° . Different letters indicate significant differences between *P. abies* and *A. alba* (Mann-Whitney U -test, $p < 0.05$).

neously, the ranges for *A. alba* were considerably broader. Half of the forests dominated by this species occupy the range between 41.8° and 42.2° latitude and between 23.7° and 24.4° longitude.

Significant differences in the altitude and slope of typical habitats complement variations in mountain preferences. *P. abies* inhabits the more rounded ridges of the Rhodopes, while *A. alba* descends to the steeper slopes in both mountains (Fig. 3A, B).

Half of the *P. abies*-dominated forests were located between 1396 and 1618 m a.s.l., while those of *A. alba* occur between 1265 and 1496 m a.s.l. At the same time, *P. abies*-dominated forests are generally found on gentler slopes, with half of these forests occurring on slopes between 10.3° and 19.0°, compared to 12.8° and 23.0° in *A. alba*-dominated forests.

The distribution of forests dominated by *P. abies* and *A. alba* also varied

with terrain exposure. Both species were more frequently found on shady exposures, although fir occurred more often in shaded areas (77.7 % of the dominated stands), whereas a greater proportion of spruce-dominated stands (38.5 %) occurred on sunnier exposures (Fig. 4A, B).

However, most fir-dominated forests occurring in sunny habitats were located on western slopes (11.7 %), whereas relatively few were found on south-facing slopes. Spruce-dominated forests were also most frequently associated with western exposures among sunny habitats, but occurred more often on south-facing slopes than fir.

Phenology

P. abies begins its active vegetation period (SVP) early, around 10 April (± 13.7 days), while *A. alba* delays SVP by over a week, around 18 April (± 9.9 days). In forests

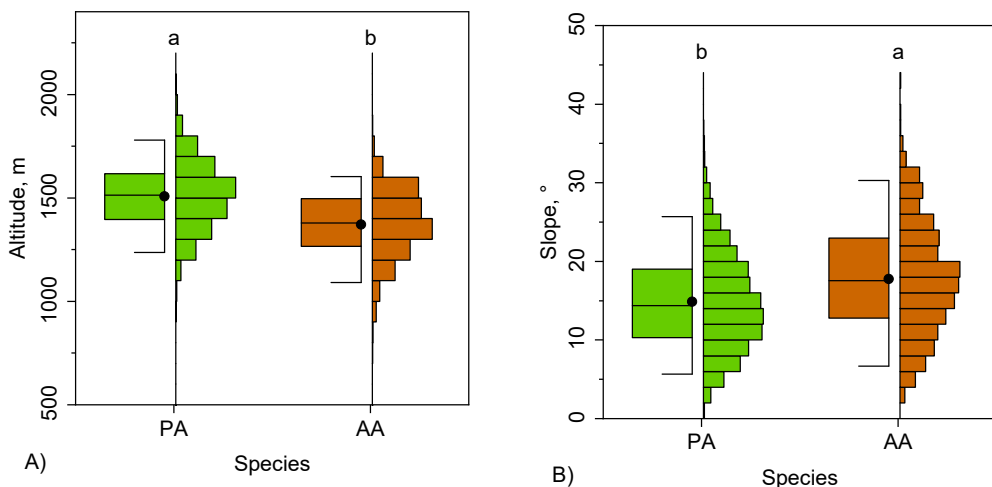


Fig. 3. Distribution of forests dominated by *P. abies* (PA) and *A. alba* (AA) according to: A) altitude; B) slope.

Note: Mean values are indicated by a solid dot, the median by a line, the box represents the 25th–75th percentiles, and the whiskers indicate the 5th–95th percentiles. Histograms show the distributions with a bin width of 100 m for altitude and 1° for slope. Different letters indicate significant differences between *P. abies* and *A. alba* (Mann-Whitney U-test, $p < 0.05$).

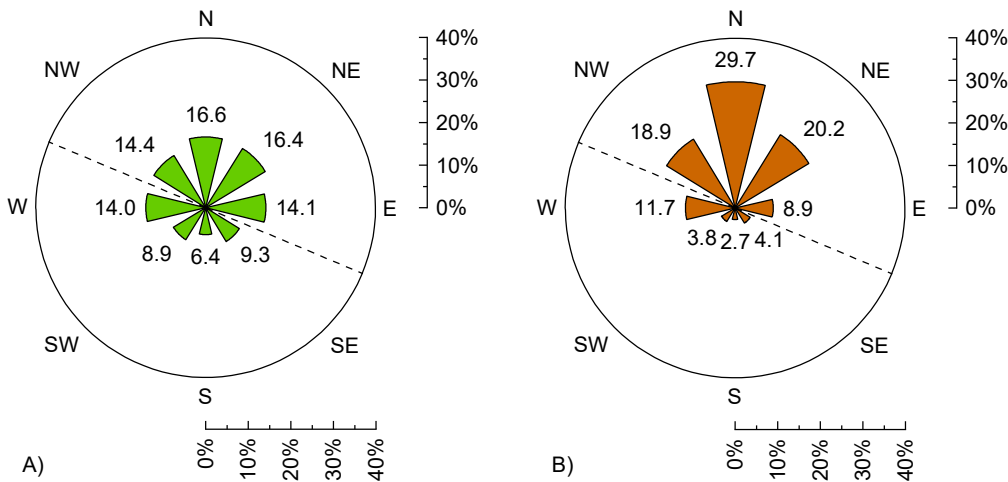


Fig. 4. Distribution of terrain exposures in forests dominated by: A) *P. abies* and B) *A. alba*.

dominated by *A. alba*, this process occurs more spontaneously, with half of these forests reaching SVP between 11 and 25 April. Conversely, in spruce forests, the SVP is spread over a longer time interval and typically occurs from 31 March to 20 April in half of these forests (Fig. 5A).

A similar tendency was observed for the autumn event EVP, where statistically significant differences were also detected. EVP tends to happen earlier in spruce forests, around 24 September (± 12.5 days), whereas in fir forests, it is delayed by over a week and occurs around 3 October

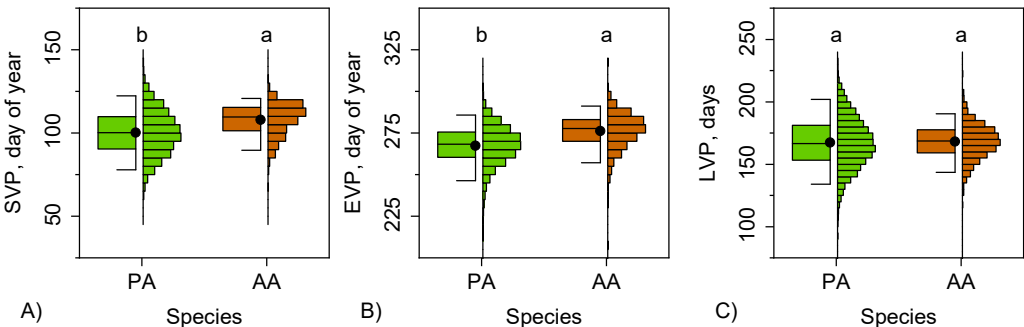


Fig. 5. Phenological events: A) start of vegetation period (SVP), B) end of vegetation period (EVP), and C) length of vegetation period (LVP) in forests dominated by *P. abies* (PA) and *A. alba* (AA).

Note: Mean values are indicated by a solid dot, the median by a line, the box represents the interquartile range (25th–75th percentiles), and the whiskers extend from the 5th to the 95th percentile. Histograms show the distributions with a bin width of five days. Different letters indicate statistically significant differences between species according to a Mann-Whitney *U*-test (p -value < 0.05).

(± 10.8 days). The occurrence of this phenological event spans approximately 15 days in half of the spruce forests (from 18 September to 3 October) and 13 days in half of the fir forests (from 27 September to 10 October).

Because of the temporal shift between SVP and EVP, a comparable LVP was seen in forests dominated by *P. abies* and *A. alba*. In both forest types, the LVP averages about 167.2 days (± 20.3 days). Primarily due to greater variation in SVP, spruce-dominated forests also show a broader range in LVP, which, for half of these forests, varies from 153 to 181 days. Meanwhile, in fir-dominated forests, this variation ranges from 159 to 178 days.

Discussion

This study demonstrates a clear differentiation in the spatial distribution of forests dominated by *P. abies* and *A. alba* in Bulgaria, reflecting differences in the present-day distribution of the two species. Within the analysed stands, *P. abies* typically occurs at higher elevations and on more gently sloping terrain, whereas *A. alba* is more frequently found at lower elevations and on steeper slopes. This vertical differentiation is characteristic of European mountain forests, where altitudinal temperature gradients strongly influence species distribution and competitive dynamics (Lebourgeois et al. 2010, Hilmers et al. 2019). The more restricted distribution of fir supports its narrower ecological niche, as described by Leuschner and Ellenberg (2017). However, the observed distribution patterns may also partly reflect the long history of forest management and land-use change in Bulgarian mountain forests, in addition to the ecological differences between the two species.

Topographic factors such as slope and aspect further highlight the ecological divergence between the two species. *P. abies* shows broader tolerance of aspect and is more commonly associated with moderately inclined terrain, whereas *A. alba* is more frequently found on steeper slopes and in shaded exposures. Similar patterns have been observed in other European mountain systems, where *A. alba* is commonly associated with protected, humid environments, whereas *P. abies* occurs across a broader range of site conditions (Hilmers et al. 2019, Paluch and Jastrzębski 2023). The stronger association of *A. alba* with shaded aspects is consistent with its high shade tolerance and its ability to sustain growth under reduced radiation and more stable microclimatic conditions (Bledý et al. 2024). This pattern may be related to differences in root system architecture between the species, including the shallower roots in *P. abies*. Spruce also prefers western exposure in sunny habitats and tolerates the southern slope better than fir, likely due to its higher-altitude forests.

The frequent occurrence of *A. alba* on steep terrain may also reflect differences in root system architecture. Compared with *P. abies*, *A. alba* develops a deeper, more stable root system, enhancing anchorage and facilitating access to deeper soil moisture. This trait likely favours its establishment on steep, potentially unstable slopes, where both mechanical stability and water availability are critical (Bożena et al. 2018, Paluch and Jastrzębski 2023). In contrast, the typically shallower root system of *P. abies* may increase susceptibility to windthrow and limit stability on steep slopes (Leuschner and Ellenberg 2017).

The most pronounced interspecific differences were observed in phenological

rhythms. In *P. abies*-dominated forests, the active vegetation period begins earlier than in those dominated by *A. alba*. However, these estimates may partly reflect local site effects within Bulgaria, including altitudinal differences and the distribution of natural versus planted stands of *P. abies*. According to Vitasse et al. (2009, 2011) and Flynn and Wolkovich (2018), the timing of SVP is primarily controlled by late-winter and early-spring temperatures, heat accumulation, and interactions between temperature and photoperiod. Comparable temperature-driven variability in spring phenology has been reported for Norway spruce throughout Central Europe, with bud burst and early shoot development closely linked to spring temperatures (Schleip et al. 2008, Pástorová et al. 2014). The delayed onset of vegetation in *A. alba* may reflect a more conservative phenological strategy, in which growth initiation is postponed until more stable thermal conditions are established, thereby reducing the risk of frost damage to newly formed tissues during late-spring cold events (Song et al. 2021). In addition, the later onset may be reinforced by the ecological characteristics of the analysed stands, as *A. alba* forests are more frequently associated with shaded, steeper sites where spring warming is generally slower (Bledý et al. 2024).

A similar interspecific difference is evident in autumn phenology. *A. alba* exhibited a later termination of active vegetation, approximately one week after *P. abies*. In temperate forests, the end of the vegetation period is governed by interactions among photoperiod, temperature, and internal physiological controls associated with dormancy induction (Flynn and Wolkovich 2018, Piao et al. 2019). The delayed cessation of activity in *A. alba* may reflect both species-specific physiological traits

and the more sheltered, humid conditions of its habitats, where reduced thermal and moisture stress can prolong physiological activity (Bledý et al. 2024). Long-term observations also show that the timing of seasonal transitions in *A. alba*, including bud development and leaf senescence, varies considerably between years and is closely linked to environmental variability (Jean et al. 2023), highlighting the sensitivity of fir phenology to climate change.

Despite clear differences in the timing of vegetation activity, the overall LVP remains similar between forests dominated by *P. abies* and *A. alba*. These patterns indicate a compensatory relationship between spring and autumn phenology: the later onset in *A. alba* is offset by its later termination. Such compensation across phenological phases has been documented in temperate tree species and is often attributed to the coordination of photoperiod, temperature regimes, and internal physiological constraints (Vitasse et al. 2011, Flynn and Wolkovich 2018, Piao et al. 2019). Large-scale satellite analyses of European vegetation dynamics further demonstrate that both the timing of spring events and autumn senescence contribute to variations in LVP (Garonna et al. 2014). Consequently, the comparable length of the vegetation period reflects distinct yet functionally equivalent strategies. *P. abies* benefits from earlier utilisation of spring resources, whereas *A. alba* reduces frost risk and sustains activity longer under sheltered conditions. These contrasting strategies ultimately support their coexistence in mountain forest ecosystems.

Nevertheless, several limitations should be considered when interpreting the results of the present study. The analysis was restricted to Bulgaria, which represents the south-eastern part of the European distribution range of both spe-

cies. Consequently, the range of climatic and ecological conditions covered is more limited than studies encompassing the entire European distribution range of the two species. The phenological analysis was based on satellite observations from 2017 to 2023, representing a relatively short time period compared with long-term phenological studies, but corresponding to the period for which data from the selected satellite product are available. In addition, the National Forest Inventory does not include national parks and strict nature reserves, where natural stands of both species also occur, and these areas were therefore not represented in the present analysis. Despite these limitations, the results provide a robust basis for the comparative assessment of the ecological characteristics and phenological behaviour of the two species under Bulgarian conditions.

Conclusions

The present study demonstrates clear ecological differentiation between forests dominated by *P. abies* and *A. alba* in Bulgaria. *P. abies* is associated with higher elevations and a broader range of environmental conditions, whereas *A. alba* is concentrated in lower, steeper, and more shaded habitats. The two species also differ in their phenological strategies, with fir showing a delayed onset of the vegetation period and maintaining vegetation activity later into autumn. In contrast, spruce initiates the vegetation period earlier and exhibits an earlier cessation of growth. These differences have important implications for forest management under ongoing climate change. The later onset of the vegetation period in *A. alba* may reduce the risk of damage from late-spring frosts.

Conversely, the broader ecological amplitude of *P. abies* may enhance its ability to persist across a wider range of mountain habitats. At the same time, the strong association of fir with shaded and humid environments suggests greater sensitivity to increasing drought frequency and climate warming, particularly at the southern edge of its European distribution. The observed ecological and phenological contrasts indicate that the two species may respond differently to future climatic changes, potentially altering their competitive relationships, regeneration dynamics, and spatial distribution in Bulgarian mountain forests. Consequently, species-specific ecological requirements and phenological behaviour should be considered when developing adaptive forest management strategies to maintain the stability and resilience of mountain conifer ecosystems. The findings of this study provide a scientific basis for developing adaptive forest management strategies aimed at increasing the resilience of Bulgarian mountain conifer forests under future climate change.

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