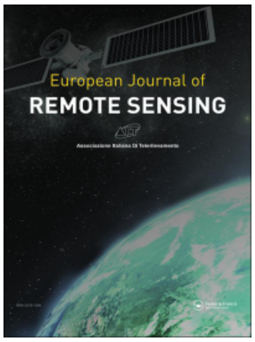

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Phenological trends of European beech stands along the Carpathian arc: a 20-year MOD13Q1/MYD13Q1 based analysis

Marian Švik[a,b], Olga Brovkina[a], Tatjana Veljanovski[c] and Matjaž Čater[d,e]

[a]Department of Remote Sensing, Global Change Research Institute of the Czech Academy of Sciences, Brno, Czech Republic; [b]Faculty of Science, Department of Geography, Laboratory on Geoinformatics and Cartography, Masaryk University, Brno, Czech Republic; [c]Institute of Anthropological and Spatial Studies, Research Centre of the Slovenian Academy of Sciences and Arts, Ljubljana, Slovenia; [d]Department of Yield and Silviculture, Slovenian Forestry Institute, Ljubljana, Slovenia; [e]Department of Silviculture, Faculty of Forestry and Wood Technology, Mendel University, Brno, Czech Republic

ABSTRACT

European forests are severely threatened by rapid global climate change. Predicting the effects of climate change on the future performance of tree species can be enhanced by using geographical gradients as space-time proxies. This study focuses on analysing seasonal and inter-annual phenological trends for eight sites of European beech (*Fagus sylvatica* L.) in the Carpathians along such geographical gradient. Using time series of the Enhanced Vegetation Index (EVI) from 2003 to 2022, derived from 16-day MODIS Terra and Aqua vegetation products, combined with meteorological parameters (temperature and precipitation) interpolated for a grid and Land Surface Temperature (LST) data from Landsat, we compared annual forest development at the study sites and extracted key phenological metrics (start, length, and end of the growing season) using the phenofit software package for R. Our results show varied responses of the studied forest sites to climate change. The end of season extended significantly at Soveja (slope = 0.50, $p = 0.023$). Spring temperatures had negative correlations with the start of season ($r = -0.37$) and autumn temperatures positive correlation with the end of season ($r = 0.43$). Understanding these patterns is crucial for developing adaptive forest management strategies in Carpathians.

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Carpathians; European beech; MODIS; land surface phenology; time series; vegetation index

Introduction

Phenological analysis, the study of periodic events in biological life cycles and their relationship to climate is becoming increasingly important in the context of global environmental change (Berra & Gaulton, 2021; Piao et al., 2019). Forest phenological analysis provides valuable insights into the temporal patterns of tree events and their recent responses to environmental conditions (Gray & Ewers, 2021). The Carpathian forests form an extensive range stretching from Central to South-Eastern Europe. They provide essential ecological, economic, and social benefits, including water regulation (Kholiavchuk et al., 2023), soil fertility (Klimek et al., 2020), biodiversity conservation (Mirek & Piekos-Mirkowa, 1992), carbon sequestration (Kruhlov et al., 2018), and wood production. The production is vital for sustaining economic stability and social balance in rural areas along the Carpathian arc, as well as serving as a crucial renewable resource for forest-based sectors. Understanding the phenological dynamics of Carpathian forests is essential for the management and prediction of the ecosystem services under changing environmental conditions.

To observe and describe the phenological phase of forests at the species individual tree scale, systematic personal visual observations are required (Donnelly et al., 2017; Templ et al., 2018). To analyse phenological events at the local scale, a network of phenological ground stations is usually used (Czernecki et al., 2018; Seyednasrollah et al., 2019). Larger and diverse forest ground observations along the Carpathian Mountains, could be very difficult or at least time, cost and labour-intensive and would rarely provide long-term data (Misra et al., 2016; Reyes-González et al., 2021). Satellite remote sensing (RS) is a valuable tool that enables the development of methods to characterise the long-term phenological response of forests at local and regional scales (Gray & Ewers, 2021). In the context of RS a Land Surface Phenology (LSP) refers to the spatio-temporal development of the vegetated land surface as revealed by satellite sensors (De Beurs & Henebry, 2005; De Beurs et al., 2009).

Recently, several phenological studies have been published on the forests of the Carpathians. A satellite-based approach to phenological events was presented for Slovakian beech forests in the Western

CONTACT Marian Švik svik.m@czechglobe.cz Department of Remote Sensing, Global Change Research Institute of the Czech Academy of Sciences, Belidla 986/4a, Brno 603 00, Czech Republic
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Carpathians, using MODIS satellite products (Bucha & Koren, 2017; Bucha et al., 2022). The results showed that leaf unfolding shifted to a later date by 0.8 days per decade, and leaf fall by 1.9 days per decade. The trends were not statistically significant ($p > 0.34$), but the intra-annual variabilities of both phenophase dates were statistically significant, associated with altitude ($p < 0.01$). Schieber et al. (2017) and Popescu and Șofletea (2020) reported that the increase in mean air temperature extended the growing season in beech forest of the Western Carpathians in Slovakia and Romania by up to two weeks between 1995 and 2015. Earlier bud burst was also observed in the Western Carpathians and the Pannonian Basin, based on NDVI derived from MODIS products (Barka et al., 2019). Griffiths et al. (2014) analysed changes in forest types, forest disturbance, and forest recovery from Landsat satellite data (1985–2010) for the Carpathian ecoregion. After 2000, extensive forest disturbances occurred in the Polish, Slovakian, Czech and Romanian Carpathians such as windthrows, droughts and bark beetle outbreaks (Kholiavchuk et al., 2023), which can have immediate and long-term effects on forest phenology. Changes in soil composition, nutrient cycling, and microclimate can influence the timing of biological events (Löw & Koukal, 2020).

Both air and soil temperatures have the greatest influence on the start and duration of the growing season (Hatfield & Prueger, 2015; Qin et al., 2023). For beech trees, leaf unfolding typically starts when mean daily temperatures consistently remain above 10°C (Dantec et al., 2014; Škrk Dolar et al., 2020), indicating that cambial activity has already commenced slightly before this point. Other factors influencing beech leaf unfolding are the photoperiod and the chilling period (Heide, 1993). Forest canopy temperature is closely linked to air temperature and follows similar seasonal trends (Guo et al., 2023). Landsat satellite thermal RS can therefore provide an additional tool to complement current forest phenological analysis with observational data and provide reliable information on land surface temperature trends in the forest canopy (Smigaj et al., 2024).

All the above studies were based on relatively small forest areas in the Carpathians and emphasised that further phenological studies of larger areas are needed to better explain the spatial variations of phenological events, especially in the eastern, south-eastern Romanian, Ukrainian, and Serbian Carpathians, which have not been studied as intensively (Kholiavchuk et al., 2023).

When predicting the impact of climate change on the future performance of tree species in the Carpathians, a geographical gradient may serve as a useful space -time proxy (Čater & Levanič, 2019). The influence of climate on beech and fir along the entire Carpathian arc was investigated by Adamič et al. (2023), who confirmed different radial growth of beech and fir since the 1950s and their response to climatic conditions along the Carpathians, while Darenova et al. (2024) demonstrated spatial variability of soil respiration in relation to soil water content, soil carbon and nitrogen content without influence on canopy gaps. The study by Čater et al. (2024) established a relationship between assimilation efficiency and light intensity in young beech and fir trees and confirmed different responses between the Dinaric and the Carpathian Mountains.

The present study follows the results of Adamič et al. (2023); Čater et al. (2024) and Darenova et al. (2024) on the phenological aspect along the Carpathian Mountains, using a remote sensing approach with MODIS satellite time-series. This study aimed to: 1) extract LSP metrics (start, length and end of the growing season) for selected forest sites dominated by European beech (*Fagus sylvatica* L.) in the period from 2003 to 2022; 2) analyse the seasonal and inter-annual change trend along these sites; and 3) investigate the relationship between LSP metrics, precipitation, air temperature and Land Surface Temperature (LST) of study sites. By addressing these objectives, this study seeks to enhance our understanding of the phenological responses of European beech forests to climate change across a broader geographical scope within the Carpathian region.

Materials and methods

Carpathian region and sites description

The Carpathians extend over a 1500 km long arc, the width of which varies between 170 km in the eastern and western parts and to less than 80 km in the southern part. The western climate type with its anticyclonic weather pattern dominates over most of the arc. The eastern slopes of the Eastern Carpathians are characterised by a continental climate. The average air temperature in July is 19°C in the Western Carpathians and 22°C in the Southern Carpathians. In the south-western part, the air temperature drops by 0.8°C per 100 metres difference in altitude and by 0.5°C in the south-eastern part of the Carpathians. Annual precipitation ranges from around 500 mm in the southern Carpathians to over 2000 mm on the peaks of the Tatra Mountains in the north. Flysch predominates in the eastern and outer Western Carpathians, crystalline and volcanic rocks in the inner band, and metamorphic rocks in the Southern Carpathians (Golonka et al., 2018; Rădulescu & Săndulescu, 1973).

Eight sites were selected in the Carpathian Mountains, at elevations between approximately 800 and 1200 metres above sea level, each with mature fir and beech forest stands (Figure 1 and Table 1). The sites were strategically distributed along the Carpathian arc

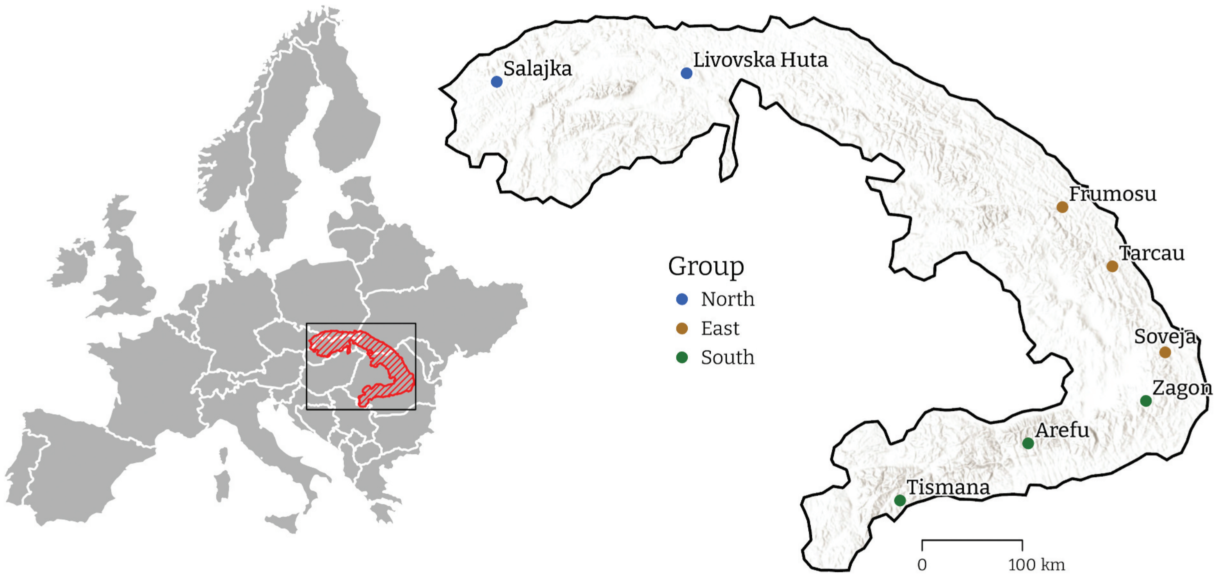

Figure 1. Map of Carpathian arc with selected study sites.

Table 1. Elevation, slope orientation and meteorological characteristics of study sites.

Plot	Elevation [m]	Mean annual temperature [°C]	Mean temperature Apr-Sep [°C]	Mean precipitation [mm/month]	Mean precipitation Apr-Sep [mm/month]	Slope orientation
Tismana	1018	5.57	11.71	91.04	116.70	NW
Arefu	1183	8.25	14.90	69.31	88.56	W
Zagon	1217	7.71	14.58	62.58	79.83	W
Soveja	844	9.22	16.56	50.00	66.05	NW
Tarcau	914	6.64	13.81	58.99	77.01	S
Frumosu	1011	7.69	14.79	57.15	77.40	W
Livovska Huta	876	8.00	14.62	64.88	84.07	NE
Salajka	779	7.94	14.30	83.57	99.32	W

to allow for meaningful space -time substitution. The focus was on sites primarily characterised by the presence of natural beech and fir regeneration, as described in Adamič et al. (2023) and Čater et al. (2024). Finally, the sites were deliberately selected based on their historical stability, which indicates minimal human intervention over extended periods of time.

The beech (*Fagus sylvatica* L.) is a dominant forest tree species in Europe (Ellenberg, 1988), with a large distribution area between Scandinavia and the Mediterranean region (Aunon et al., 2011). Despite its functional adaptability and high ecological plasticity, it is affected by drought, as confirmed by studies on its response in southern Europe (Jump et al., 2006). It thrives in pure and mixed stands with conifers, especially firs (*Abies* spp.). In predicting the consequences of climate change for tree species, studying the response of species on a geographical gradient can highlight the key parameters that are important for tree growth on a larger scale and help predict future responses. The Carpathian Mountains exhibit sufficient latitudinal and longitudinal gradients, associated with significant temperature and precipitation differences, as well as differences in seasonal patterns (Micu et al., 2014).

Satellite data and products

MODIS vegetation indices

Data from the MODIS satellite-based sensor on board the Terra and Aqua satellites was used for remote sensing. Specifically, the Terra Vegetation Indices (MOD13Q1) Version 6.1 (Didan, 2021b) and Aqua Vegetation Indices (MYD13Q1) version 6.1 (Didan, 2021a) products were used. The data was accessed via the Google Earth Engine data catalogue (Gorelick et al., 2017). Both products are created every 16 days with a spatial resolution of 250 metres and provide two primary vegetation layers. For this study, we used the second layer – the Enhanced Vegetation Index (EVI), which has a higher sensitivity in regions with high biomass compared to the Normalised Difference Vegetation Index (NDVI; which is also part of this MODIS product) (Huete et al., 2002). The MOD/MYD13Q1 product maps the best available pixel value from all images of the 16-day period. Low cloud cover, low viewing angle and the highest EVI value are used as criteria. Pixel reliability (also known as MODLAND QA bits) layer was used in further processing to set the weights in the phenofit package (more on that in the section 2.4).

Landsat land surface temperature

The land surface temperature (LST) values were produced using the statistical mono-window algorithm, which was originally developed for climate data records from Meteosat satellites (Duguay-Tetzlaff et al., 2015; Li et al., 2013; Sun et al., 2004). The approach was based on an empirical relationship between the top-of-atmosphere brightness temperatures in a single thermal infrared channel and LST and utilized simple linear regression. The process was implemented in Google Earth Engine online platform using Landsat 5, 7, 8 and 9 satellite data, following the code repository published in Ermida et al. (2020). The LST values were derived in the range of MODIS pixels (250 m × 250 m). The number of available LST values for each forest site varied between months and between years because of different site locations, layout of acquired satellite data and cloudiness. The code of Ermida et al. (2020) was enhanced with the ee.Reducer.count procedure (Pikl et al., 2024) to count the number of valid pixels (i.e. without clouds and shadows) for each site and date for the period 2003 – 2022. The LST values were then sorted by site and date, and only those with more than 75% valid pixels were used. In total, we had 467 dates for Tismana, 516 for Arefu, 426 for Zagon, 472 for Soveja, 302 for Tarcau, 497 for Frumosu, 246 for Livovska Huta, and 375 for Salajka (Figure 2). The forest site with the highest number of missing LST dates was Livovska Huta. It had the most missing LST dates primarily in December, March, and October. The most significant gaps in LST data across all sites tended to occur in January, March, and December. A trend was then created for each site between 2003 and 2022. We analysed the land surface temperature throughout the year, assuming that winter months can help identify shifts in temperature, which are critical for understanding the long-term effects of climate change on forest ecosystems.

Meteorological data

The climate data were obtained from the Climatic Research Unit Timeseries version 4.01 (CRU TS 4.01; Harris et al., 2020), accessed through the Royal Netherlands Meteorological Institute's Climate Explorer platform (https://climexp.knmi.nl/). This dataset provides monthly mean near-surface temperature and monthly total precipitation values on a 0.5° × 0.5° latitude-longitude grid. The CRU TS product employs angular distance weighting (ADW) spatial interpolation to create these global grids, incorporating station data from over 4000 meteorological stations worldwide. In this dataset, monthly values are derived from station observations collected and updated routinely through international collaborations (e.g. via the World Meteorological Organisation, National Climatic Data Center, and the Met Office Hadley Centre) as written in more detail in Harris et al. (2014).

Land surface phenology extraction

Körner et al. (2023) describe four distinct ways of defining a growing season, primarily based on ground-level observations of phenological events (e.g. leaf flushing and autumnal leaf coloration). In this study, we adapt their definition to the context of LSP derived from RS data. Specifically, we define the growing season as the period between the start and end of detectable vegetation activity, as captured by spectral indices such as EVI. The start of the growing season corresponds to the onset of greenness increase (e.g. spring green-up), while the end corresponds to the decline in greenness (e.g. autumn senescence). These LSP-based events serve as proxies for the ground-level phenological events described by Körner et al. (2023).

The LSP extraction from the satellite-based EVI data was carried out in the following steps: Splitting the time series into shorter sequences (each representing one growing season), curve fitting (also known as VI time series reconstruction) and extraction of LSP metrics. For this processing chain, we

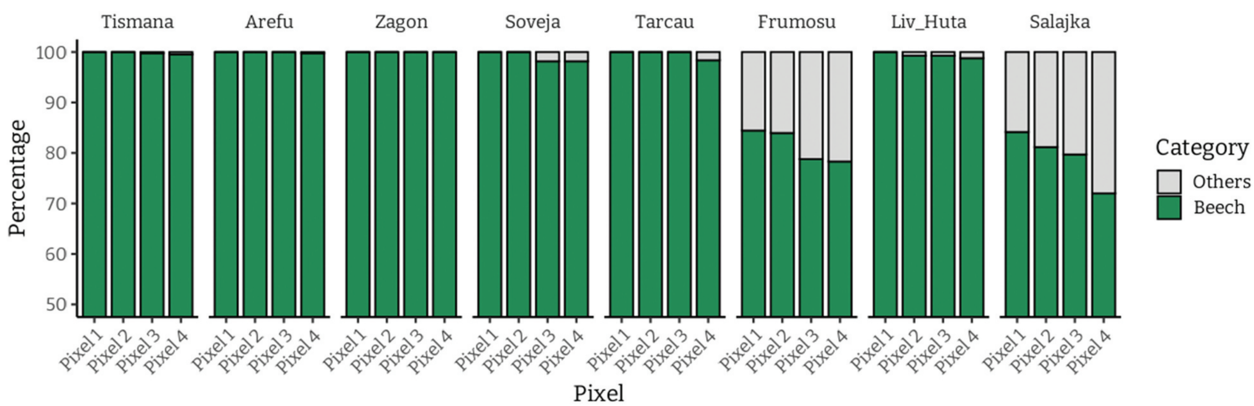

Figure 2. Scatter plots for each forest site, showing the dates of LST Landsat acquisitions.

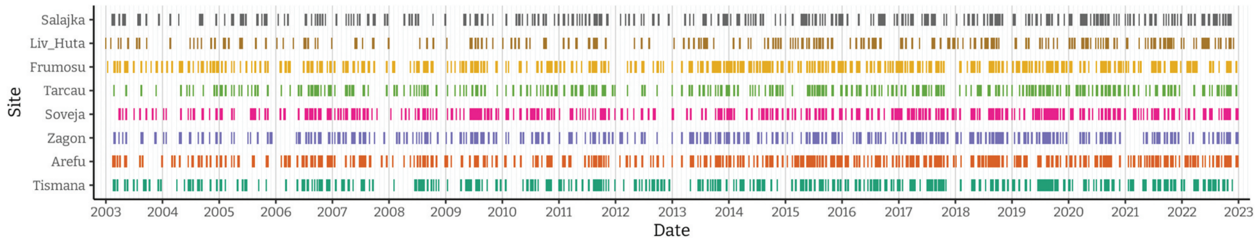

Figure 3. Beech percentage occurrence of chosen pixels.

used the R library phenofit (Kong et al., 2022). In the first step, observations were categorised into three categories based on the MODLAND QA layer – good, marginal and poor (Didan & Munoz, 2019) and corresponding weights were assigned to those observations. In our case, the value 1 was assigned to good, 0.5 to marginal and 0 for poor, ensuring that even the minor observations that were not categorised as "good" could provide valuable information and contribute to the further steps. Poor (e.g. cloudy and snowy) pixels were assigned a value of 0 and excluded from further analysis. The weights were selected after careful consideration and comparative evaluation of the various weight configurations. "Spikes" i.e. values that deviate significantly from the moving average in their vicinity were removed from these time series. A curve was fitted to the data to capture the seasonal signals of the vegetation. In the context of phenofit, this process is referred to as "rough fitting" and was carried out iteratively, with the weighting of the individual points being adjusted after each run. For overestimated points that were below the fitted curve and more likely to be contaminated, the weighting was decreased, and for underestimated points that were above the fitted curve and more likely to be clear, the weighting was increased to approximate the upper envelope of the EVI time series. The performance metrics of the coarse fit were extracted in the form of the coefficient of determination (R^2) to observe performance at different study sites. While the coarse fit was used for the entire time series, a more robust fine fit was applied for each individual growing season to capture the rapid changes in EVI. Of the five methods of curve fine fitting, Beck logistic (Beck et al., 2006) was used after a thorough comparison of all methods. The final and most crucial step is the extraction of the LSP metrics themselves – start of season (SOS), end of season (EOS) and length of season (LOS, calculated as EOS – SOS). For this purpose, the phenofit package offers four different methods – threshold, derivative, inflexion and Gu method. For the purposes of this study, we used the widely employed first-order derivative method (although the results were very comparable to a threshold method with a threshold of 0.5).

LSP evaluation using dominant beech canopy pixels

Since the pixels corresponding with the coordinates of each study site contained different proportions of beech, fir, and in some cases, also spruce trees, we decided to find the pixels with the highest proportion of beech in a 5 × 5 km area around the study sites. We used 10 m forest classification dataset (European Environment Agency, 2020), which we aggregated to the MODIS pixel for information about species percentages. For each site, we found four such pixels (Figure 3) and used their average values for the LSP evaluation.

To evaluate the significance and magnitude of trends of LSP, we applied the Mann-Kendall trend test and the Theil-Sen slope estimator. The Mann-Kendall test is a non-parametric method used to assess the presence of monotonic trends in time series data. It tests the null hypothesis that there is no trend against the alternative hypothesis that there is a monotonic increasing or decreasing trend. The test statistic (S) is calculated based on the ranks of the data, and the significance of the trend is determined using the p-value derived from the standardized test statistic (Z). The Theil-Sen slope estimator was used to quantify the magnitude of the trend. This method calculates the median of all possible slopes between pairs of points in the time series, making it robust against outliers and non-normal data distributions. The slope represents the rate of change in the variable over time.

To assess the relationship between LSP indicators and climatic variables (temperature and precipitation), we used Spearman's rank correlation coefficient. This non-parametric method was chosen due to its robustness to non-normal data distributions and its ability to capture monotonic relationships. First, we pooled data from all sites to evaluate overarching trends and identify the months with the strongest correlations. Based on these results, we then performed site-specific correlation analyses only for the months that showed the highest correlations in the pooled analysis. This two-step approach allowed us to first identify globally significant patterns across all sites and then investigate localized relationships at individual sites.

The LSP extraction procedure described in the previous section (2.4.) was applied to the 5 × 5 km area (20 × 20 MODIS pixels) around each site. For each pixel with more than 50% beech canopy, a trend between the years 2003 and 2022 was created and visualised in the form of a map. This visualization serves as an illustration of how our method looks when mapped spatially, however all further results are based on the information obtained from the four pixels as written in the first paragraph.

Results

LSP trends in the last two decades

The spatio-temporal course of the LSP indicators showed different patterns both between and within various study sites (Figure 4, Supplementary Table S1). The earliest mean start of season (SOS) was observed at the north-western most site Salajka (DOY 105), followed by Soveja (DOY 109) at the easternmost surveyed point of the Carpathians, which also had the highest mean air temperature (9.22°C). The two locations with the highest mean SOS DOY values were Livovska Huta and Zagon – both 119, with Zagon being the location with highest elevation. Zagon had the largest range of values (106–142) and Tismana the smallest (105–126). However, none of the observed trends were statistically significant (alpha level 0.05).

The time of the end of the season (EOS DOY) varied between the analysed sites, similar to SOS, with some different patterns. Salajka, with the earliest SOS, showed a medium EOS among the sites analysed (273), in contrast to Zagon, with one of the latest starts and also one of the latest EOS (276), while Soveja (270), notable for its high average temperature, closely matched Tismana. The EOS trends mirror the SOS trends, but with notable differences. Statistically significant trend on Soveja with a positive slope of 0.50 (p-value = 0.023), indicates that the end of the growing season is extended by about half a day each year. The range of EOS at the different sites emphasises the diversity of phenological responses. Tismana and Frumosu showed a wider range in EOS DOY (258–290 and 264–292, respectively).

The length of the season (LOS) was longest in Salajka (168 days) with considerable annual fluctuations and shortest in Livovska Huta (152 days) with the smallest range of 26.8 days. Zagon (157 days) had the largest range of all locations at 36.5 days. The Mann-Kendall trend and Theil-Sen slope analysis confirmed different trends in LOS in the individual sites; however, none of the trends were statistically significant (alpha level of 0.05).

LSP trends (Figure 5) were mostly stable in Tismana, Zagon and Livovska Huta and variable even within the small area around the study site Tarcau; moreover, some homogeneous spatial patterns were observed. A heterogeneity of species around Frumosu and Salajka was observed (see also Figure 2). Apart from Arefu and the eastern part of Soveja, the LOS is increasing at most of the surveyed sites.

SOS, LOS and EOS vs. Precipitation and temperature

The interaction between LSP indicators, precipitation and temperature is shown in Figure 6. All correlations were evaluated at an alpha level of 0.05. April precipitation correlated positively with SOS ($r = 0.37$, $p < 0.001$) and negatively with LOS ($r = -0.35$, $p < 0.001$); more precipitation in April could be related to a shorter growing season. September precipitation correlated negatively with the EOS ($r = -0.33$, $p < 0.001$).

The effects of temperature were more pronounced and consistent in April, May and September. April temperatures correlated negatively

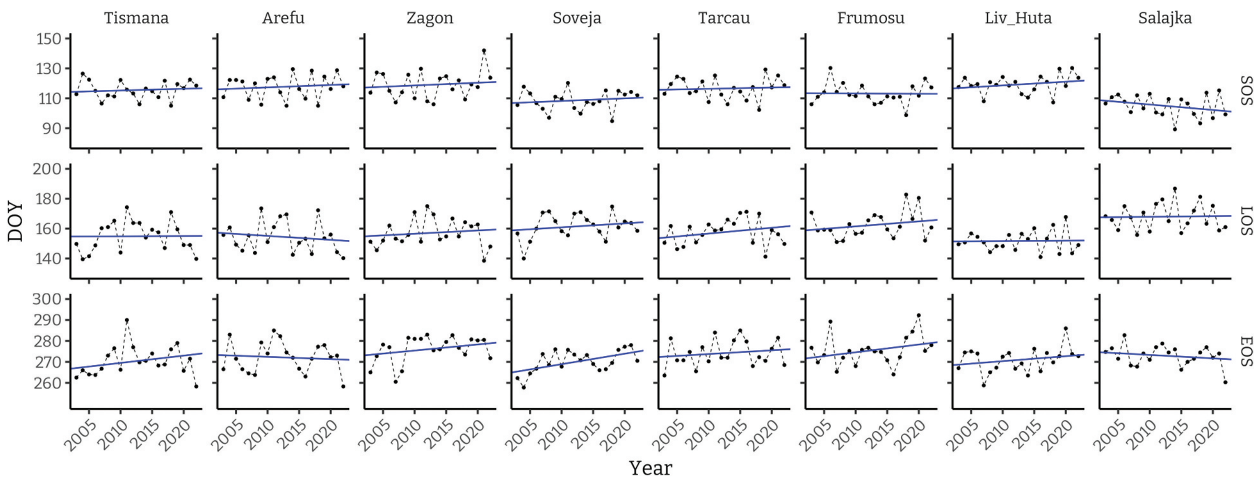

Figure 4. Day of year of start, length and end of season on eight research sites between the years 2003 and 2022 with Theil-Sen's slope (blue line).

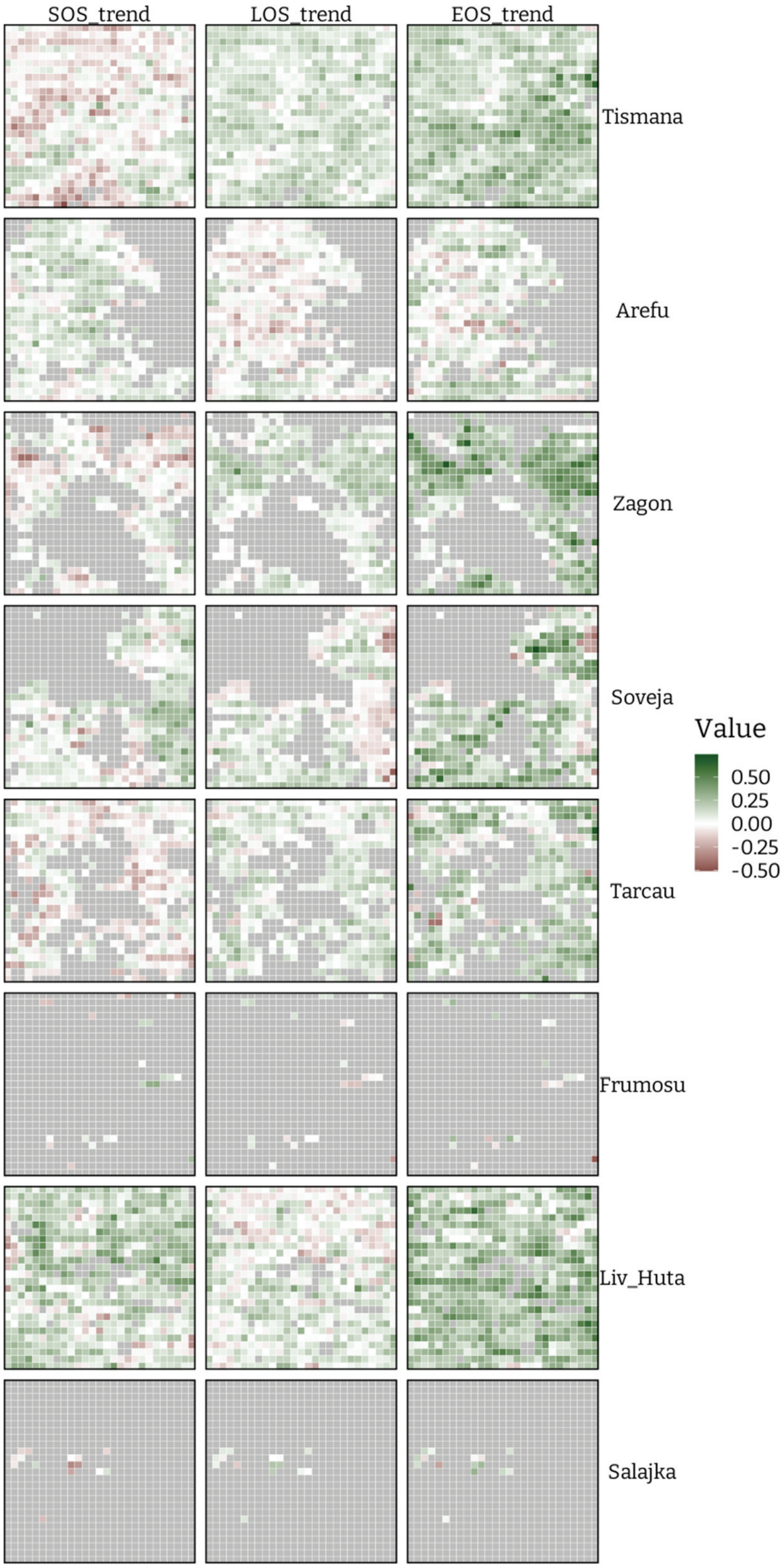

Figure 5. Map of land surface phenology trends between 2003 and 2022 period in the vicinity of each study site (green for shift to later DOY, red for shift towards earlier DOY). Pixels with less than 50% beech canopy cover are masked. Values show Theil–Sen's slope.

with SOS ($r = -0.37$, $p < 0.001$) and positively with LOS ($r = 0.41$, $p < 0.001$), indicating an earlier start and a longer growing season. May temperatures also correlated negatively with SOS ($r = -0.51$, $p < 0.001$). The effects of temperature on EOS varied, with a positive correlation in September ($r = 0.43$, $p < 0.001$).

Both precipitation and temperature showed no significant correlation with the months September – December of the preceding year. Both precipitation

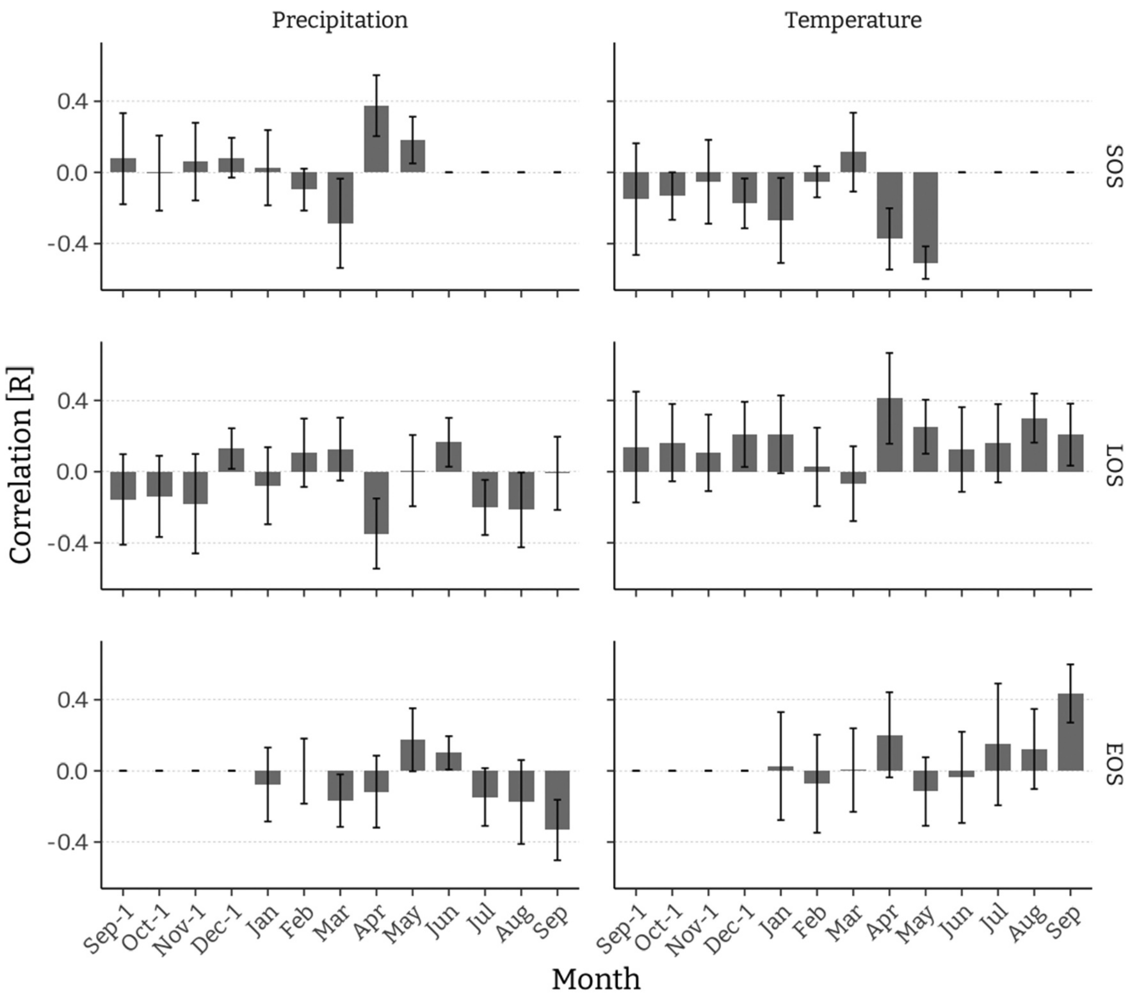

Figure 6. Spearman correlation between each LSP indicator and precipitation/temperature (mean of all sites) with error bars showing standard deviation.

and temperature play a significant role in timings of the studied phenological parameters, but in different ways depending on the season. The spring months, especially April and May, are of vital importance, with precipitation and temperature showing opposite effects on the SOS. Similarly, the late summer and early autumn months (September) show the effect of temperature, which extends the growing season and potentially offsets any precipitation-related advances in EOS.

Site-specific relations between LSP and Meteorological parameters in April, May and September

Following the broader analysis of the relations between LSP indicators and climatic variables across months, an examination at the site level for April, May, and September (months identified for their significant correlations) revealed how precipitation and temperature uniquely affect vegetation dynamics at different locations (Figure 7). All correlations were evaluated at an alpha level of 0.05.

The correlation of both April and May temperature with SOS show an earlier start to the season with warmer conditions, which was most pronounced at Tismana ($r_{May} = -0.65$, $p = 0.005$; $r_{April} = -0.62$, $p = 0.02$) and Arefu ($r_{May} = -0.57$, $p = 0.004$; $r_{April} = -0.51$, $p = 0.02$) and was also consistent at other sites. The correlation with LOS was also negative, with September temperature being the decisive factor. September temperature in Zagon showed the highest positive EOS correlation ($r = 0.74$, $p < 0.001$) of all sites and months, and the same pattern was confirmed in Tismana, Tarcau and Soveja.

April precipitation in Arefu ($r = 0.62$, $p = 0.006$), Tismana ($r = 0.55$, $p = 0.01$) and Livovska Huta ($r = 0.54$, $p = 0.03$) showed a strong positive correlation with the SOS. The influence of September precipitation, especially on EOS, was notable in Zagon ($r = -0.55$, $p = 0.04$) and Arefu ($r = -0.45$, $p = 0.04$), where increased precipitation correlated with an earlier end of the growing season.

The sites were divided into three groups according to the geomorphological division of the

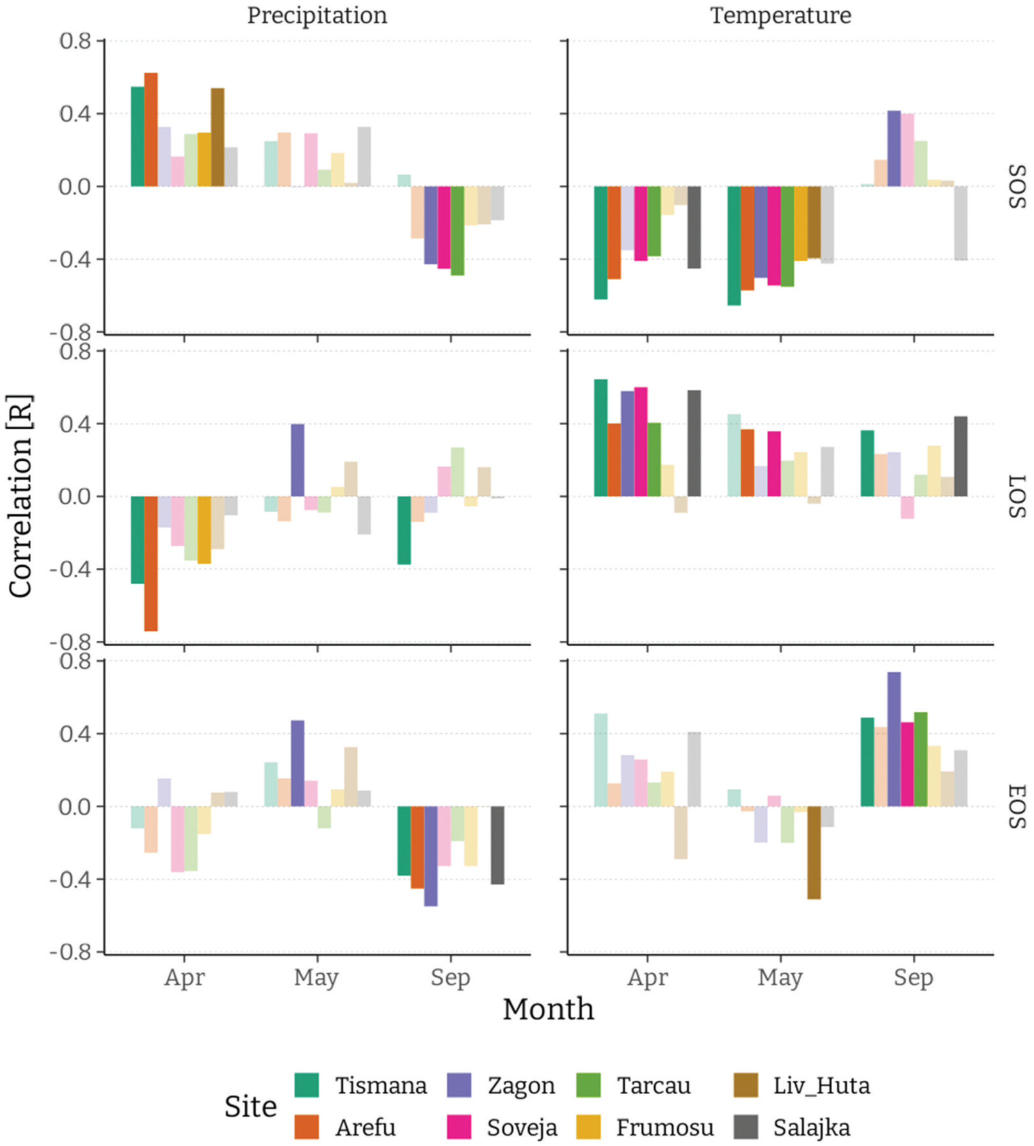

Figure 7. Spearman correlation between each LSP indicator and precipitation/temperature for individual sites for April, May and September. Darker colour indicates significant correlation ($p < 0.05$).

Carpathians: south (Tismana, Arefu, Zagon), east (Soveja, Tarcau, Frumosu) and north (Livovska Huta, Salajka) (Supplementary Figure S1). The correlation between spring temperature and both SOS and LOS were strongest in the southern Carpathian sites, with the eastern sites following. Likewise, the correlation between September temperature and EOS was also strongest in the southern Carpathian sites, followed by the eastern sites. A similar pattern was observed for precipitation: the correlation between April precipitation and LOS, as well as September precipitation and EOS, was strongest in the southern Carpathian sites, with the eastern sites again coming second. However, the correlation between April precipitation and SOS was an exception; it was stronger in the northern sites than in the eastern sites (though it remained strongest in the southern sites).

Analysis of LST over the last two decades

Mean annual LST from the Landsat time series (2003–2022) revealed the years with the maximum and minimum land surface temperatures for each study site (Table 2).

Analysis of the LST trend (Figure 8) revealed an increasing trend for Zagon, and a decreasing trend for Soveja; both values were statistically significant ($p < 0.1$). A non-significant increasing trend was found for Arefu, while no trends could be confirmed for the other sites. Over the last 20 years, the land surface temperature has increased by 3°C in Zagon and decreased by 2°C in Soveja. The warmest land surface temperatures were recorded at Livovska Huta, Arefu, and Zagon, with mean LSTs for the entire 20-year period being 13.5°C, 11.3°C, and 11.2°C, respectively. The coldest was at Frumosu, with a mean LST for the same period of 7.6°C.

Table 2. Mean annual LST for study sites. Bold values are maximum and minimum mean annual LST.

Year	Tismana	Arefu	Zagon	Soveja	Tarcau	Frumosu	Livovska Huta	Salajka
2003	**4.1**	7.2	**3.4**	7.5	8.9	3.6	**4.8**	11.9
2004	9.7	11.6	13.3	15.0	12.7	6.6	11.8	13.0
2005	4.2	**6.2**	1.4	8.9	11.3	5.8	12.3	**3.2**
2006	8.0	9.7	9.8	11.9	7.2	5.3	15.3	9.4
2007	11.4	15.0	11.5	11.7	9.5	12.5	15.7	10.9
2008	**12.8**	**15.3**	14.9	14.9	16.3	**13.8**	12.3	12.2
2009	11.0	13.4	12.1	13.3	10.2	9.1	16.0	11.9
2010	9.7	8.6	10.0	12.3	6.2	**2.3**	11.2	11.2
2011	6.1	12.9	11.5	7.9	7.4	9.1	14.9	12.0
2012	12.1	13.3	9.7	11.5	16.3	12.1	12.8	10.1
2013	9.5	15.7	13.5	4.1	9.4	9.2	11.3	13.4
2014	9.7	10.8	7.9	4.0	**4.8**	8.4	9.9	6.2
2015	9.8	11.8	**16.1**	13.5	**16.5**	8.1	**16.1**	10.3
2016	5.6	10.0	12.5	**3.1**	9.9	4.4	13.7	10.7
2017	7.8	12.6	16.0	7.4	13.2	6.8	7.9	9.9
2018	9.2	11.4	13.3	13.7	7.8	8.4	15.8	**13.5**
2019	8.1	11.5	12.8	**15.1**	8.9	8.3	11.8	12.1
2020	9.2	13.9	15.3	10.4	4.6	9.5	12.5	9.9
2021	8.6	13.0	12.2	4.7	6.8	6.5	11.6	3.7
2022	7.7	7.1	5.5	10.2	5.1	4.9	6.6	10.3

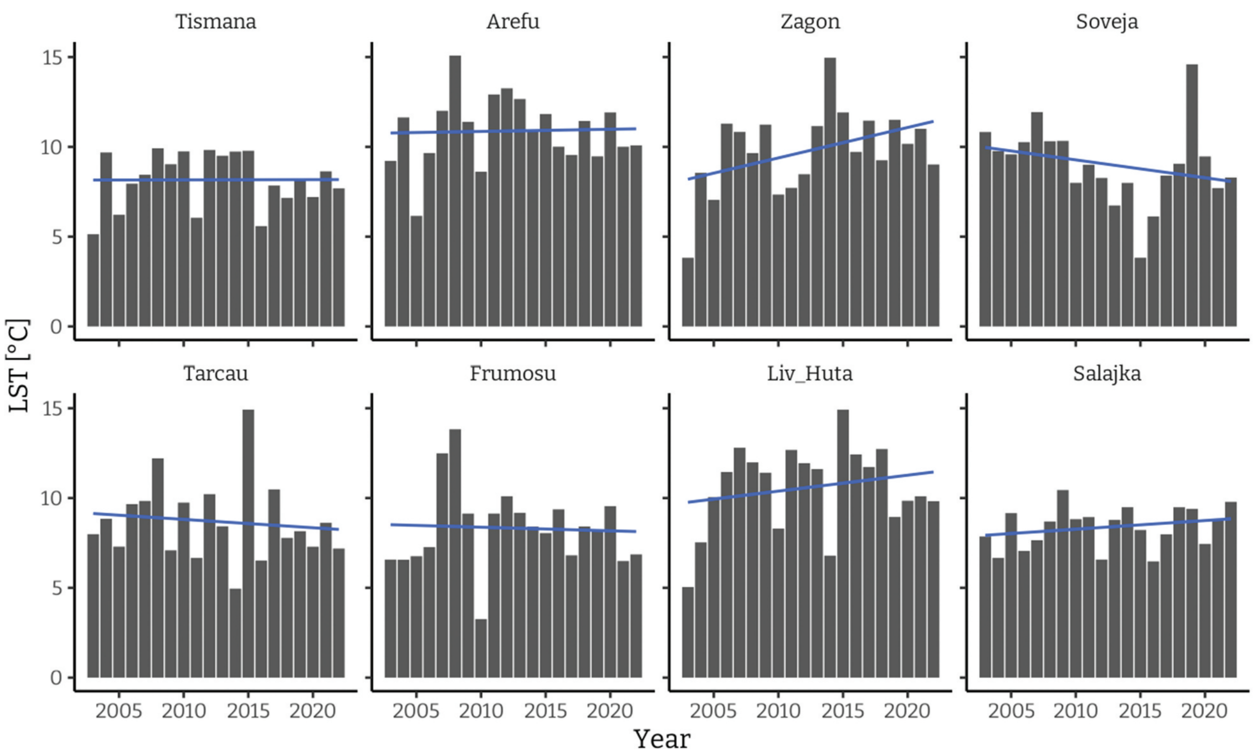

Figure 8. Land surface temperature (LST) trends. Yearly LST means.

In the Carpathian Mountains, April and May typically mark the period of budburst, leaf-out, and early leaf development. September often corresponds to the onset of autumn senescence, where leaves start to change colour and drop. It marks the end of the growing season and is significant for understanding the duration of the growing period and the timing of senescence. Highlighting monthly means LST of these months can provide insights into the timing and progression of phenological events across different years (Figure 9).

The comparative analysis of eight sites reveals a picture of LST trends in April, May, and September during study period. While some sites show clear LST patterns and peaks in specific years, others exhibit high variability and data gaps. In April, most regions exhibit significant LST fluctuations. Arefu, Frumosu, and Salajka show pronounced peaks indicating possible regional climatic variations. Arefu, Salajka, and Livovska Huta have peaks in 2003, Tarcau, Zagon and Soveja – in 2004. Zagon and Tismana display more consistent trends compared to other sites in April. In May, LST showed a generally increasing trend in many regions, such as Arefu and Soveja, suggesting a potential rise in temperatures or related metrics over time. Tismana in 2001 and Livovska Huta

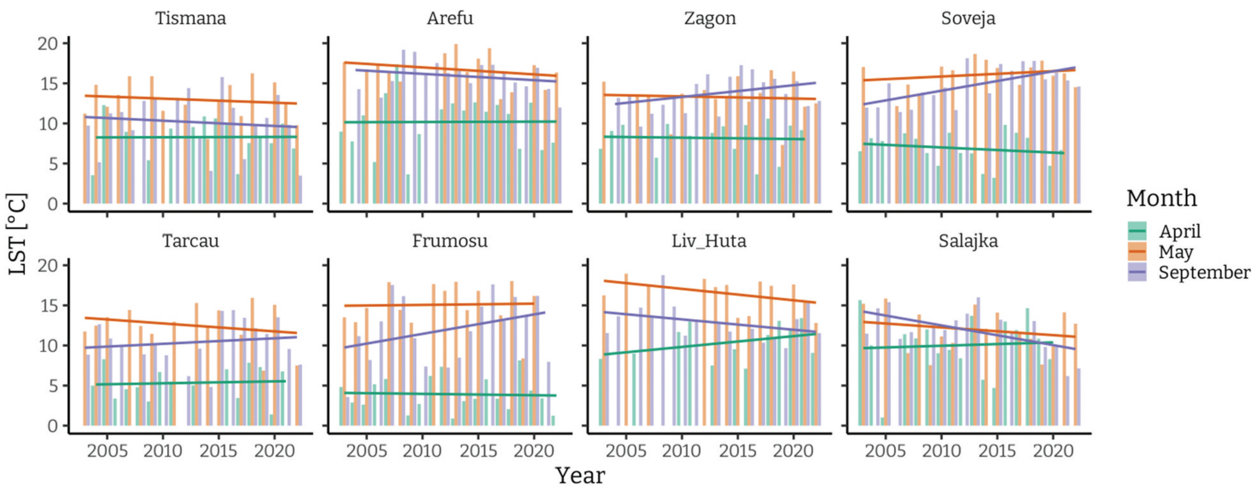

Figure 9. Land surface temperature (LST) trends. Monthly LST means in April, May, and September.

in multiple years have missing values in May, which complicates the analysis. In September, LST showed the highest variability across all sites, especially Arefu, Frumosu, and Salajka have significant variations. Positive trend has Soveja, Zagon, Frumosu, and Tarcau, particularly towards the later years of LST dataset. Generally, Zagon, Tismana, and Soveja demonstrated the most stability across the analysed LST. Their data shows minor fluctuations and consistent trends, suggesting stable environmental conditions compared to other sites.

Discussion

Understanding inconsistencies in LSP trends

The lack of statistical significance of the trends for SOS at the observed sites indicates a high variability in the ecological conditions affecting the studied sites and highlights the complexity of predicting phenological responses based on climatic variables alone, considering the complex interactions between climate, topography, and local environmental conditions.

Zagon's high elevation appears to influence both the beginning and end of its growing season, possibly due to its cooler climate and shorter growing season. The distinct climatic conditions at high elevations could be affecting phenological phases differently compared to lower elevations, reflecting how microclimatic variations influence vegetation dynamics. The greater variability in the timing of season's end at Tismana and Frumosu, as reflected in the range of EOS DOY, could be attributed to environmental heterogeneity or variability in climatic conditions across years. These sites might be experiencing different microclimatic impacts or variations in other ecological factors that affect the end of the growing season. The extended LOS observed at Salajka could be beneficial for certain plant species, allowing for longer growing seasons and potentially higher biomass production (Blundo et al., 2018). This trend might indicate a positive ecological response to current climate conditions at this site, offering a potential advantage in terms of productivity and carbon sequestration.

The observation that shifts in LOS due to factors such as climate change are either gradual or obscured by year-to-year variability suggests a complex interaction between climatic drivers and vegetation responses. This complexity underlines the need for long-term studies to discern clear trends and develop predictive models that accurately reflect the ecological dynamics of forest ecosystems under changing climatic conditions.

Overall, the lack of statistical significance could be due to several factors, including small sample sizes, high variability in SOS from year to year, or the possibility that other variables not included in this analysis might better explain changes in SOS. It is also possible that beech trees do not significantly respond to temperature changes regarding the onset of phenological events, as other studies have also shown no statistically significant trends in SOS, LOS, and EOS for beech stands (Bucha et al., 2023). Schieber et al. (2017) also describe beech as a conservative tree in terms of its phenological response. Future research could explore longer time spans, include more sites, or consider additional variables that might affect the start of the growing season.

Temperature and precipitation influence on forest LSP

In general, the results of our study are consistent with recent findings that changes in forest phenology are primarily related to temperature fluctuations, and only secondarily to precipitation, especially in mid- and high-elevation forest ecosystems (Caparros-Santiago et al., 2021). This observation is despite the beech being considered a conservative tree in terms of its phenological response (Schieber et al., 2017). The correlation between April precipitation and SOS, where increased spring precipitation could delay the onset of vegetation growth, emphasises the sensitivity of vegetation phenophases to fluctuations in spring precipitation (Arnič et al., 2021; Skvareninova et al., 2024). This delay in the onset of vegetation growth could be due to the cooling effects of increased cloud cover or the direct effects of soil moisture on plant physiological processes (Cui et al., 2022). The role of temperature, especially in April and September, shows its decisive influence on phenological events. Warmer temperatures in April favour an earlier start to vegetation and longer growing season, reflecting the need for warmth for bud burst and leaf development. Conversely, warmer temperatures in late summer or early autumn appear to delay senescence and thus extend the growing season. This extension of the active growing season not only supports continued photosynthetic activity but may also promote overall plant growth and biomass accumulation (Piao et al., 2013), which are critical to the ecological capacity and carbon sequestration of forests.

Adamič et al. (2023) confirmed that above-average precipitation in July and precipitation in June have a positive effect on the growth of beech trees at the same study sites, while above-average precipitation in September has a negative effect on the radial growth of mature beech trees. Above-average temperatures in June, July and August have a clearly negative effect on the radial growth of beech. The predicted loss of forest productivity is particularly pronounced at the southern limit of the beach's natural range, where the intensity of the drought is likely to increase (Martinez Del Castillo et al., 2022).

The physiological response of young beech trees to different light intensities was similar in the Carpathian and Dinaric Mountains; it increased with more precipitation and decreased with increasing temperatures, indicating different patterns in phenological triggers and assimilation performance (Čater et al., 2024). Fir, as a more drought-sensitive species, responded similarly to beech in Dinaric region and vice versa in the Carpathians, where annual rainfall average is half of that in the Dinarides.

The site-specific responses to warming in spring, as observed in the temperature correlations with the SOS in April and May, indicate a widespread response of vegetation to rising temperatures. This warming causes an earlier start to the growing season, particularly noticeable in Tismana and Arefu, the two southernmost study areas. In addition, the exceptionally strong positive correlation of September temperatures with the EOS in Zagon indicates that warmer early autumn temperatures can significantly delay and possibly extend the growing season. At higher elevations such as Zagon, temperature becomes an even more influential parameter when all other site conditions are in the optimal range. The correlation of April precipitation with SOS at several sites emphasises the role of moisture in controlling the phenological phases. Increased precipitation in spring appears to delay the onset of vegetation growth, probably by influencing soil moisture and temperature regimes. In contrast, the effects of the September precipitation on the EOS, which were observed particularly at the southernmost sites of Tismana, Arefu and Zagon, indicate that the late summer precipitation could accelerate the end of the growing season. Apart from the direct cooling effect of precipitation, this earlier end to the growing season could be due to a combination of factors, including the weakening of the temperature due to increasing cloud cover and the change in light availability, which is crucial for preparing trees for dormancy (Larcher, 2003).

Suitability of MODIS for LSP extraction

While the work of (Kong et al., 2022) points to the possibility of using phenofit with the higher spatial resolution images from the Landsat and Sentinel-2 missions, there are still problems with this approach. The main problem is that the phenofit only uses observations of the current season to estimate LSP indicators, which means that the seasonal vegetation curve cannot be correctly reconstructed in the case of sparse coverage of the mentioned satellites. The temporal resolution of MODIS is much higher, so that the observations of the EVI product are much better suited to reconstruct the seasonal vegetation curve. When using 16-day MODIS product (MOD13Q1 & MYD13Q1), one must be aware of the fact that those 16 days are represented only by the "best" pixel which can influence the phenological curve, especially near the SOS and EOS. This limitation could certainly lead to a minor shift of those indicators in certain cases, and the use of daily MODIS product might prove to be more accurate. In recent years, a new product combining Landsat and Sentinel-2 into a harmonised product (HLS product) has been developed (Claverie et al., 2018), which could prove useful for studies where finer spatial resolution is important. The spatial resolution of MODIS of 250 m might be too coarse for very heterogeneous sites as stated by study from Zhang et al. (2017) in which they compared LSP extracted from 500 m vs 30 m and found out that SOS can vary as much as 40 days in highly heterogenous pixels. In our case, when we tried to extract the LSP parameters from mixed pixels (usually pixels containing both broadleaf beech and coniferous fir), the information was much more obscured by the spectra of fir, where seasonality is much less pronounced. Another consideration is the historical aspect of a particular sensor – how long the time series has been available. This factor is particularly important to determine the long-term trends in the data. The trends in the changing LSP indicators in this study were not statistically significant in most cases. This limitation could be attributed to the unavailability of longer time series of observations, although even that might not ensure less variability as noted by the impact of the NAO on tree phenology (Cook et al., 2005; Scheifinger et al., 2002). Future research should focus on refining the integration techniques of different satellite data sources to optimise phenological monitoring. Advances in machine learning and data fusion could play a crucial role in this process by enabling the effective merging of datasets with different spatial and temporal resolutions to create a seamless phenological overview across different scales. As satellite technologies evolve, and new products become available, continued validation and calibration of phenological models against ground-based observations will continue to be essential. These efforts will ensure that remote sensing tools remain accurate and relevant for tracking the ecological impacts of climate change.

Forest LST trends

Analysing maximum and minimum mean LST for each study site (Table 2) can provide the information about potentially extreme years, such as 2003, 2008 and 2015. Tismana, Zagon and Livovska Huta had a minimum mean LST in 2003. Tismana, Arefu and Frumosu had a maximum mean LST in 2008. Zagon, Tarcau and Livovska Huta had a maximum mean LST in 2015. However, statistical analysis indicates that the detected temperature trends are not significant at the 95% confidence level. These results therefore indicate that interannual variability, rather than a sustained directional trend, drives the observed changes.

The increase in land surface temperature to 3°C on Zagon over a period of 20 years did not lead to an earlier start of the growing season as might be expected but may have contributed to the longer duration and late end of the growing season on Zagon's during the 20-year period studied. Schieber et al. (2017) reported that the growing season of European beech was extended by more than two weeks over the 20-year period within the increasing mean monthly air temperature.

Although the surface temperature of the forest in Soveja decreased by 2°C over a period of 20 years, this site had one of the highest surface temperatures, which is consistent with the highest air temperature among the study sites (Table 1). The decreasing trend in land surface temperature in Soveja can be attributed to the influence of colder winter months observed in the period from 2010 to 2015 (Figure 8). The lower LST in Soveja may also indicate cooling due to phenological shift. Park and Jeong (2023) demonstrated the sensitivity of LST to advanced SOS and delayed EOS over northern deciduous forests and explained the cooling effect of the phenological shift by the reduced aerodynamic resistance of trees. As was revealed in our study, Soveja had the second earliest mean start after Salajka, and the extended end of the growing season.

The LST in forest can be influenced by the intensity and duration of sunlight (Li et al., 2023), by affecting the balance between absorbed and reflected solar radiation as well as by affecting ecophysiological processes such as evapotranspiration and shading. This aspect was not considered in our study and is suggested as an additional factor to be investigated in future research on forest phenology in the Carpathians.

Conclusion

The analysis of LSP shifts and their relation to climate variables in the Carpathian region during the last two decades shows a complex interaction between environmental factors and vegetation dynamics. Site-specific analyses showed that the influence of temperature and precipitation on the phenological phases varies depending on the month and geographical location.

Although the trends in LSP indicators were not statistically significant during the study period, the site-specific nuances of vegetation responses to changing climatic conditions were detected. Analysing the temperature trends in the forest canopy provided further insights into canopy dynamics, although an additional factor such as intensity and duration of solar radiation was suggested for further investigation.

The study emphasises the need for further long-term research to better understand the complexity of phenological responses to climate change and to develop effective conservation and management strategies for forest ecosystems in the Carpathian region. Future research should focus on the further development of machine learning and data fusion methods to optimise phenological monitoring and validate the results with ground-based observations.

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Data availability statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.15308525.

References

Adamič, P. C., Levanič, T., Hanzu, M., & Čater, M. (2023). Growth response of European beech (Fagus sylvatica L.) and silver fir (Abies Alba Mill.) to climate factors along the Carpathian Massive. *Forests*, *14*(7), 1318. Article 7. https://doi.org/10.3390/f14071318

Arnič, D., Gričar, J., Jevšenak, J., Božič, G., von Arx, G., & Prislan, P. (2021). Different wood anatomical and growth responses in European beech (Fagus sylvatica L.) at three forest sites in Slovenia. *Frontiers in Plant Science*, *12*. https://doi.org/10.3389/fpls.2021.669229

Aunon, F. J., Barrio, J. M. G. D., Mancha, J. A., Vries, S. M. G. D., & Alia, R. (2011). *Regions of provenance of European beech (Fagus sylvatica L.) in Europe. Genetic resources of European beech (Fagus sylvatica L.) for sustainable forestry*. (141–148). https://research.wur.nl/en/publications/regions-of-provenance-of-european-beech-fagus-sylvatica-l-in-euro

Barka, I., Bucha, T., Molnár, T., Móricz, N., Somogyi, Z., & Koreň, M. (2019). Suitability of MODIS-based NDVI index for forest monitoring and its seasonal applications in Central Europe. *Central European Forestry Journal*, *65*(3–4), 206–217. https://doi.org/10.2478/forj-2019-0020

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

Berra, E. F., & Gaulton, R. (2021). Remote sensing of temperate and boreal forest phenology: A review of progress, challenges and opportunities in the intercomparison of in-situ and satellite phenological metrics. *Forest Ecology & Management*, *480*, 118663. https://doi.org/10.1016/j.foreco.2020.118663

Blundo, C., Gasparri, N. I., Malizia, A., Clark, M., Gatti, G., Campanello, P. I., Grau, H. R., Paolini, L., Malizia, L. R., Chediack, S. E., MacDonagh, P., & Goldstein, G. (2018). Relationships among phenology, climate and biomass across subtropical forests in Argentina. *Journal of Tropical Ecology*, *34*(2), 93–107. https://doi.org/10.1017/S026646741800010X

Bucha, T., & Koren, M. (2017). Phenology of the beech forests in the Western Carpathians from MODIS for 2000-2015. iForest -. *IForest - Biogeosciences & Forestry*, *10*(3), 537–546. https://doi.org/10.3832/ifor2062-010

Bucha, T., Koren, M., Sitková, Z., Pavlendová, H., & Z Snopková, Z. (2023, prosinec 31). Trends and driving forces of Spring phenology of oak and beech stands in the Western Carpathians from MODIS times series 2000-2021. *IForest - Biogeosciences & Forestry*, *16*(6), 334–344. https://doi.org/10.3832/ifor4121-016

Bucha, T., Sitková, Z., Pavlendová, H., & Snopková, Z. (2022). Spring phenology of oak stands in the Western Carpathians: Validation of satellite metrics from MODIS using ground-based observations. *Central European Forestry Journal*, *68*(4), 191–202. https://doi.org/10.2478/forj-2022-0014

Caparros-Santiago, J. A., Rodriguez-Galiano, V., & Dash, J. (2021). Land surface phenology as indicator of global terrestrial ecosystem dynamics: A systematic review. *ISPRS Journal of Photogrammetry & Remote Sensing*, *171*, 330–347. https://doi.org/10.1016/j.isprsjprs.2020.11.019

Čater, M., Adamič, P. C., & Dařenova, E. (2024). Response of beech and fir to different light intensities along the Carpathian and Dinaric mountains. *Frontiers in Plant Science*, *15*, 1380275. https://doi.org/10.3389/fpls.2024.1380275

Čater, M., & Levanič, T. (2019). Beech and silver fir's response along the Balkan's latitudinal gradient. *Scientific Reports*, *9*(1), Article 1. https://doi.org/10.1038/s41598-019-52670-z

Claverie, M., Ju, J., Masek, J. G., Dungan, J. L., Vermote, E. F., Roger, J.-C., Skakun, S. V., & Justice, C. (2018). The harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote Sensing of Environment*, *219*, 145–161. https://doi.org/10.1016/j.rse.2018.09.002

Cook, B. I., Smith, T. M., & Mann, M. E. (2005). The north Atlantic oscillation and regional phenology prediction over Europe. *Global Change Biology*, *11*(6), 919–926. https://doi.org/10.1111/j.1365-2486.2005.00960.x

Cui, X., Xu, G., He, X., & Luo, D. (2022). Influences of seasonal soil moisture and temperature on vegetation phenology in the Qilian mountains. *Remote Sensing*, *14*(15), 3645. Article 15. https://doi.org/10.3390/rs14153645

Czernecki, B., Nowosad, J., & Jabłońska, K. (2018). Machine learning modeling of plant phenology based on coupling satellite and gridded meteorological dataset. *International Journal of Biometeorology*, *62*(7), 1297–1309. https://doi.org/10.1007/s00484-018-1534-2

Dantec, C. F., Vitasse, Y., Bonhomme, M., Louvet, J.-M., Kremer, A., & Delzon, S. (2014). Chilling and heat requirements for leaf unfolding in European beech and sessile oak populations at the southern limit of their distribution range. *International Journal of Biometeorology*, *58*(9), 1853–1864. https://doi.org/10.1007/s00484-014-0787-7

Darenova, E., Adamič, P. C., & Čater, M. (2024). Effect of temperature, water availability, and soil properties on soil CO2 efflux in beech-fir forests along the Carpathian Mts. *Catena*, *240*, 107974. https://doi.org/10.1016/j.catena.2024.107974

De Beurs, K. M., & Henebry, G. M. (2005). Land surface phenology and temperature variation in the international geosphere-biosphere program high-latitude transects. *Global Change Biology*, *11*(5), 779–790. https://doi.org/10.1111/j.1365-2486.2005.00949.x

De Beurs, K. M., Wright, C. K., & Henebry, G. M. (2009). Dual scale trend analysis for evaluating climatic and anthropogenic effects on the vegetated land surface in Russia and Kazakhstan. *Environmental Research Letters*, *4*(4), 045012. https://doi.org/10.1088/1748-9326/4/4/045012

Didan, K. (2021a). *MODIS/Aqua vegetation indices 16-day L3 global 250m SIN grid V061 [dataset]*. NASA EOSDIS Land Processes Distributed Active Archive Center. https://doi.org/10.5067/MODIS/MYD13Q1.061

Didan, K. (2021b). *MODIS/Terra vegetation indices 16-day L3 global 250m SIN grid V061 [dataset]*. NASA EOSDIS Land Processes Distributed Active Archive Center. https://doi.org/10.5067/MODIS/MOD13Q1.061

Didan, K., & Munoz, A. B. (2019). *MODIS vegetation index user's guide (MOD13Series)*. The University of Arizona. https://lpdaac.usgs.gov/documents/621/MOD13_User_Guide_V61.pdf

Donnelly, A., Yu, R., Caffarra, A., Hanes, J., Liang, L., Desai, A. R., Liu, L., & Schwartz, M. D. (2017). Interspecific and interannual variation in the duration of spring phenophases in a northern mixed forest. *Agricultural and Forest Meteorology*, *243*, 55–67. https://doi.org/10.1016/j.agrformet.2017.05.007

Duguay-Tetzlaff, A., Bento, V. A., Göttsche, F. M., Stöckli, R., Martins, J. P. A., Trigo, I., Olesen, F., Bojanowski, J. S., Da Camara, C., & Kunz, H. (2015). Meteosat land surface temperature climate data record: Achievable accuracy and potential uncertainties. *Remote Sensing*, *7*(10), 13139–13156. Article 10. https://doi.org/10.3390/rs71013139

Ellenberg, H. (1988). *Vegetation ecology of Central Europe*. Cambridge University Press.

Ermida, S. L., Soares, P., Mantas, V., Göttsche, F. M., & Trigo, I. F. (2020). Google earth engine open-source code for land surface temperature estimation from the landsat series. *Remote Sensing*, *12*(9), 1471. Article 9. https://doi.org/10.3390/RS12091471

European Environment Agency. (2020). *Forest type 2018 (raster 10 m), Europe, 3-yearly, Oct. 2020 (Version 01.00) [GeoTIFF]*. https://doi.org/10.2909/59B0620C-7BB4-4C82-B3CE-F16715573137

Golonka, J., Pietsch, K., & Marzec, P. (2018). The North European platform suture zone in Poland. *Geology, Geophysics and Environment*, *44*(1), 5. Article 1. https://doi.org/10.7494/geol.2018.44.1.5

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google earth engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

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

Griffiths, P., Kuemmerle, T., Baumann, M., Radeloff, V. C., Abrudan, I. V., Lieskovsky, J., Munteanu, C., Ostapowicz, K., & Hostert, P. (2014). Forest disturbances, forest recovery, and changes in forest types across the Carpathian ecoregion from 1985 to 2010 based on Landsat image composites. *Remote Sensing of Environment*, *151*, 72–88. https://doi.org/10.1016/j.rse.2013.04.022

Guo, Z., Zhang, K., Lin, H., Majcher, B. M., Lee, C. K. F., Still, C. J., & Wu, J. (2023). Plant canopies exhibit stronger thermoregulation capability at the seasonal than diurnal timescales. *Agricultural and Forest Meteorology*, *339*, 109582. https://doi.org/10.1016/j.agrformet.2023.109582

Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2014). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 dataset. *International Journal of Climatology*, *34*(3), 623–642. https://doi.org/10.1002/joc.3711

Harris, I., Osborn, T. J., Jones, P., & Lister, D. (2020). Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific Data*, *7*(1), Article 1. https://doi.org/10.1038/s41597-020-0453-3

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4–10. https://doi.org/10.1016/j.wace.2015.08.001

Heide, O. M. (1993). Dormancy release in beech buds (Fagus sylvatica) requires both chilling and Long Days. *Physiologia plantarum*, *89*(1), 187–191. https://doi.org/10.1111/j.1399-3054.1993.tb01804.x

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, *83*(1), 195–213. https://doi.org/10.1016/S0034-4257(02)00096-2

Jump, A. S., Hunt, J. M., Martínez-Izquierdo, J. A., & Peñuelas, J. (2006). Natural selection and climate change: Temperature-linked spatial and temporal trends in gene frequency in Fagus sylvatica. *Molecular Ecology*, *15*(11), 3469–3480. https://doi.org/10.1111/j.1365-294X.2006.03027.x

Kholiavchuk, D., Gurgiser, W., & Mayr, S. (2023). Carpathian forests: Past and recent developments. *Forests*, *15*(1), 65. https://doi.org/10.3390/f15010065

Klimek, B., Jaźwa, M., Choczyński, M., Stolarczyk, M., & Niklińska, M. (2020). The drivers of soil microbial communities structure on forest stands along the altitudinal gradient in western carpathians. *Acta Oecologica*, *108*, 103643. https://doi.org/10.1016/j.actao.2020.103643

Kong, D., McVicar, T. R., Xiao, M., Zhang, Y., Peña-Arancibia, J. L., Filippa, G., Xie, Y., & Gu, X. (2022). Phenofit: An R package for extracting vegetation phenology from time series remote sensing. *Methods in Ecology and Evolution*, *13*(7), 1508–1527. https://doi.org/10.1111/2041-210X.13870

Körner, C., Möhl, P., & Hiltbrunner, E. (2023). Four ways to define the growing season. *Ecology Letters*, *26*(8), 1277–1292. https://doi.org/10.1111/ele.14260

Kruhlov, I., Thom, D., Chaskovskyy, O., Keeton, W. S., & Scheller, R. M. (2018). Future forest landscapes of the Carpathians: Vegetation and carbon dynamics under climate change. *Regional Environmental Change*, *18*(5), 1555–1567. https://doi.org/10.1007/s10113-018-1296-8

Larcher, W. (2003). *Physiological plant ecology*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-05214-3

Li, Z.-L., Tang, B.-H., Wu, H., Ren, H., Yan, G., Wan, Z., Trigo, I. F., & Sobrino, J. A. (2013). Satellite-derived land surface temperature: Current status and perspectives. *Remote Sensing of Environment*, *131*, 14–37. https://doi.org/10.1016/j.rse.2012.12.008

Li, Z.-L., Wu, H., Duan, S.-B., Zhao, W., Ren, H., Liu, X., Leng, P., Tang, R., Ye, X., Zhu, J., Sun, Y., Si, M., Liu, M., Li, J., Zhang, X., Shang, G., Tang, B.-H., Yan, G., & Zhou, C. (2023). Satellite remote sensing of global land surface temperature: Definition, methods, products, and applications. *Reviews of Geophysics*, *61*(1), e2022RG000777. https://doi.org/10.1029/2022RG000777

Löw, M., & Koukal, T. (2020). Phenology modelling and forest disturbance mapping with Sentinel-2 time series in Austria. *Remote Sensing*, *12*(24), 4191. https://doi.org/10.3390/rs12244191

Martinez Del Castillo, E., Zang, C. S., Buras, A., Hacket-Pain, A., Esper, J., Serrano-Notivoli, R., Hartl, C., Weigel, R., Klesse, S., Resco de Dios, V., Scharnweber, T., Dorado-Liñán, I., van der Maaten-Theunissen, M., van der Maaten, E., Jump, A., Mikac, S., Banzragch, B.-E., Beck, W., Cavin, L., . . . de Luis, M. (2022). Climate-change-driven growth decline of

European beech forests. *Communications Biology*, *5*(1), 1–9. https://doi.org/10.1038/s42003-022-03107-3
Micu, D., Dumitrescu, A., Cheval, S., & Birsan, M.-V. (2014). *Climate of the Romanian Carpathians-variability and trends*. https://doi.org/10.1007/978-3-319-02886-6
Mirek, Z., & Piekos-Mirkowa, H. (1992). Flora and vegetation of the Polish Tatra mountains. *Mountain Research and Development*, *12*(2), 147–173. https://doi.org/10.2307/3673788
Misra, G., Buras, A., & Menzel, A. (2016). Effects of different methods on the comparison between land surface and ground phenology—A methodological case study from South-Western Germany. *Remote Sensing*, *8*(9), 753. Article 9. https://doi.org/10.3390/rs8090753
Park, C.-E., & Jeong, S. (2023). Land surface temperature sensitivity to changes in vegetation phenology over northern deciduous forests. *Journal of Geophysical Research Biogeosciences*, *128*(12), e2023JG007498. https://doi.org/10.1029/2023JG007498
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
Piao, S., Sitch, S., Ciais, P., Friedlingstein, P., Peylin, P., Wang, X., Ahlström, A., Anav, A., Canadell, J. G., Cong, N., Huntingford, C., Jung, M., Levis, S., Levy, P. E., Li, J., Lin, X., Lomas, M. R., Lu, M., Luo, Y., . . . Zeng, N. (2013). Evaluation of terrestrial carbon cycle models for their response to climate variability and to CO2 trends. *Global Change Biology*, *19*(7), 2117–2132. https://doi.org/10.1111/gcb.12187
Pikl, M., Brovkina, O., Zemek, F., Ladyka, M., & Starodubtsev, V. (2024). Effects of urbanization and Kaniv Reservoir on the thermal characteristics in the region. *European Journal of Environmental Sciences*, *14*(1), 33–42. https://doi.org/10.14712/23361964.2024.4
Popescu, R., & Şofletea, N. (2020). Spring and autumn phenology in sub-mesothermal beech stands from the southwestern extremity of the Carpathians. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *48*(2), 1057–1069. https://doi.org/10.15835/nbha48211897
Qin, J., Ma, M., Shi, J., Ma, S., Wu, B., & Su, X. (2023). The time-lag effect of climate factors on the forest enhanced vegetation index for subtropical humid areas in China. *International Journal of Environmental Research and Public Health*, *20*(1), Article 1. https://doi.org/10.3390/ijerph20010799
Rădulescu, D. P., & Săndulescu, M. (1973). The plate-tectonics concept and the geological structure of the Carpathians. *Tectonophysics*, *16*(3–4), 155–161. https://doi.org/10.1016/0040-1951(73)90010-3
Reyes-González, E. R., Gómez-Mendoza, L., Barradas, V. L., & Terán-Cuevas, Á. R. (2021). Cross-scale phenological monitoring in forest ecosystems: A content-analysis-based review. *International Journal of Biometeorology*, *65*(12), 2215–2227. https://doi.org/10.1007/s00484-021-02173-2
Scheifinger, H., Menzel, A., Koch, E., Peter, C., & Ahas, R. (2002). Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in central Europe. *International Journal of Climatology*, *22*(14), 1739–1755. https://doi.org/10.1002/joc.817
Schieber, B., Kubov, M., & Janík, R. (2017). Effects of climate warming on vegetative phenology of the common beech Fagus sylvatica in a submontane forest of the western Carpathians: Two-decade analysis. *Polish Journal of Ecology*, *65*(3), 339–351. https://doi.org/10.3161/15052249PJE2017.65.3.003
Seyednasrollah, B., Young, A. M., Hufkens, K., Milliman, T., Friedl, M. A., Frolking, S., & Richardson, A. D. (2019). Tracking vegetation phenology across diverse biomes using Version 2.0 of the PhenoCam dataset. *Scientific Data*, *6*(1), Article 1. https://doi.org/10.1038/s41597-019-0229-9
Škrk Dolar, N., Črepinšek, Z., & Čufar, K. (2020). Phenology of leaf development in European beech (Fagus sylvatica) on a site in Ljubljana, Slovenia in 2020. *Les*, *69*(1), 5–19. https://doi.org/10.26614/les-wood.2020.v69n01a07
Skvareninova, J., Sitko, R., Vido, J., Snopková, Z., & Skvarenina, J. (2024). Phenological response of European beech (Fagus sylvatica L.) to climate change in the Western Carpathian climatic-geographical zones. *Frontiers in Plant Science*, *15*. https://doi.org/10.3389/fpls.2024.1242695
Smigaj, M., Agarwal, A., Bartholomeus, H., Decuyper, M., Elsherif, A., de Jonge, A., & Kooistra, L. (2024). Thermal infrared remote sensing of stress responses in forest environments: A review of developments, challenges, and opportunities. *Current Forestry Reports*, *10*(1), 56–76. https://doi.org/10.1007/s40725-023-00207-z
Sun, D., Pinker, R. T., & Basara, J. B. (2004). *Land surface temperature estimation from the next generation of geostationary operational environmental satellites: GOES M-Q*. https://journals.ametsoc.org/view/journals/apme/43/2/1520-0450_2004_043_0363_lsteft_2.0.co_2.xml
Templ, B., Koch, E., Bolmgren, K., Ungersböck, M., Paul, A., Scheifinger, H., Rutishauser, T., Busto, M., Chmielewski, F.-M., Hájková, L., Hodzić, S., Kaspar, F., Pietragalla, B., Romero-Fresneda, R., Tolvanen, A., Vučetič, V., Zimmermann, K., & Zust, A. (2018). Pan European phenological database (PEP725): A single point of access for European data. *International Journal of Biometeorology*, *62*(6), 1109–1113. https://doi.org/10.1007/s00484-018-1512-8
Zhang, X., Wang, J., Gao, F., Liu, Y., Schaaf, C., Friedl, M., Yu, Y., Jayavelu, S., Gray, J., Liu, L., Yan, D., & Henebry, G. M. (2017). Exploration of scaling effects on coarse resolution land surface phenology. *Remote Sensing of Environment*, *190*, 318–330. https://doi.org/10.1016/j.rse.2017.01.001