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Phenological trends of European beech stands along the Carpathian arc: A 20-year MODIS based analysis

KEYWORDS: European beech, phenology, remote sensing, time series, vegetation index

Introduction

Phenology, the study of biological life cycle events and their climate relationships, is vital in the context of global environmental change. Forest phenology provides insights into tree events and their environmental responses. The Carpathian Mountains offer significant ecological services, and understanding their forest phenology is essential for managing ecosystem services under changing conditions.

Personal visual observations and local ground stations are typically used to study forest phenology, but these methods can be time- and resource-intensive. Satellite remote sensing (RS) offers a valuable alternative for long-term phenological studies at larger scales. Recent satellite-based studies have observed phenological shifts in Carpathian forests, such as delayed leaf unfolding and extended growing seasons, linked to increased air temperatures. Air and soil temperatures significantly influence the growing season's start and duration. Beech trees, for instance, begin leaf unfolding when mean daily temperatures exceed 10 °C.

Further research is needed to explain spatial phenological variations, especially in the less-studied regions of the Carpathians. Geographic gradients may help predict climate change impacts on tree species. Previous studies have shown different growth responses of beech and fir to climatic conditions and spatial variability of soil respiration.

This study uses MODIS satellite data to analyze phenology metrics for European beech forests from 2003 to 2022. It aims to assess seasonal and inter-annual changes and examine the relationship between phenological metrics, precipitation and air temperature to better understand phenological responses to climate change in the Carpathians.

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Methods

The study focused on eight forest sites dominated by European beech (*Fagus sylvatica* L.) along the Carpathian Arc, covering various altitudes (830 to 1038 meters above sea level) and climatic conditions. These sites were selected to represent a geographical gradient with minimal human intervention, ensuring a consistent ecological context.

We utilized MODIS Terra and Aqua vegetation indices product for the period 2003-2022 to derive the Enhanced Vegetation Index (EVI). Meteorological data, including monthly mean temperatures and total precipitation, were obtained from the CRU TS 4.01 dataset.

The phenofit software package for R was employed to extract key phenological metrics, namely the start (SOS), length (LOS), and end (EOS) of the growing season. The time series of EVI were split into individual growing seasons, followed by curve fitting and extraction of phenological indicators. The derivative method was used for determining these metrics.

Results

The analysis revealed varied responses across the sites, with significant site-specific differences in the start, length, and end of the growing season (Figure 1). Salajka exhibited the earliest mean SOS (DOY 105), while Livovska Huta and Zagon had the latest mean SOS (DOY 119). Trends in SOS showed delays in some sites like Zagon, whereas Salajka experienced earlier SOS over the years.

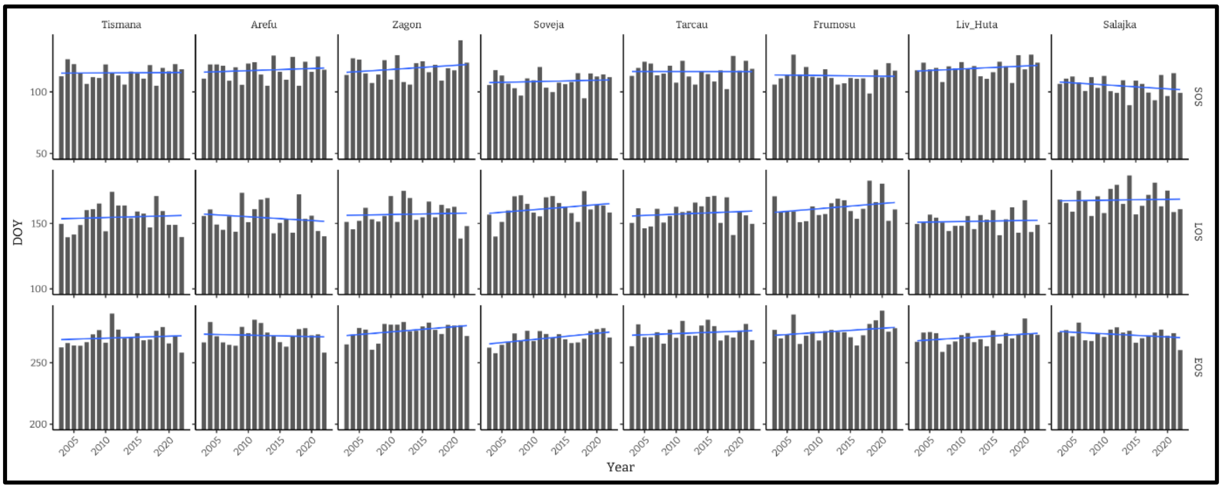

Fig. 1. Day of year of start, end and length of season on eight research sites between the years 2003 and 2022 with linear trend (blue line)

The EOS varied, with Zagon and Soveja having later EOS compared to other sites. Soveja showed a statistically significant extension of the growing season by approximately half a day each year. The LOS was longest at Salajka (168 days) and shortest at Livovska Huta (152 days), indicating spatial variability in phenological responses.

April and May temperatures had a strong influence on SOS, with warmer temperatures leading to earlier starts (Figure 2). Precipitation in April correlated positively with SOS and negatively with LOS, suggesting that increased spring precipitation may delay the onset of the growing season but shorten its length. September temperatures showed a positive correlation with EOS, indicating extended growing seasons in warmer early autumn conditions.

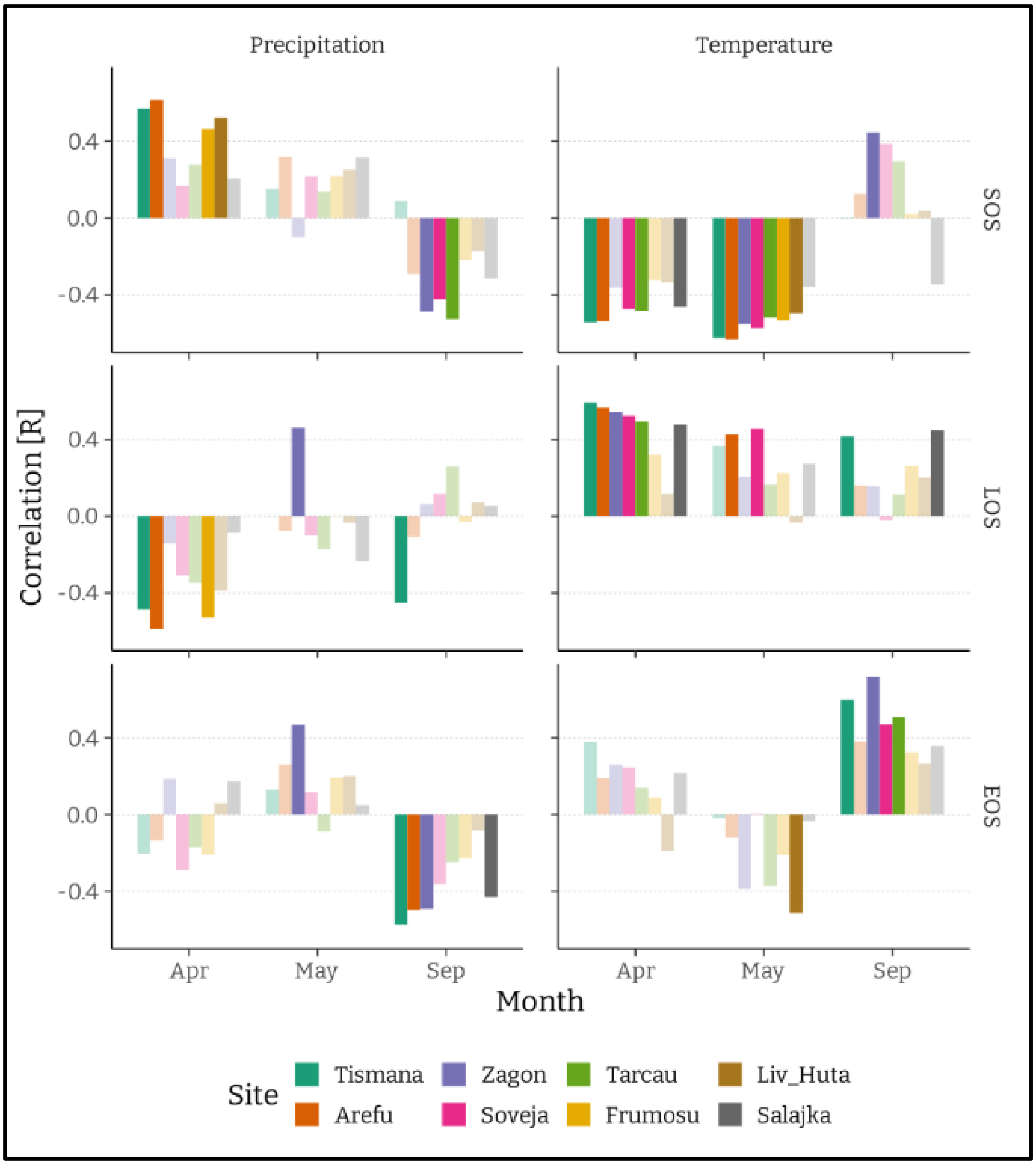

Fig. 2. Correlation between each phenological indicator and precipitation/temperature for individual sites for April, May and September. Darker color indicates significant correlation ($p < 0.1$)

Conclusions

This study highlights the complex interactions between climate variables and phenological responses of European beech forests in the Carpathian region. The observed phenological shifts are influenced significantly by both temperature and precipitation, with notable site-specific variations. The use of MODIS data combined with the phenofit R package provided a robust framework for long-term phenological monitoring. The findings underscore the need for continued long-term research and the integration of advanced remote sensing technologies to better understand and predict the impacts of climate change on forest ecosystems.

Future research should focus on refining data integration techniques and expanding the temporal and spatial scope of phenological studies to develop more accurate predictive models for forest management and conservation strategies in the face of global climate change.

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