Izvirni znanstveni članek / Original scientific paper

INFLUENCE OF METEOROLOGICAL CONDITIONS AND CROWN DEFOLIATION ON TREE PHENOLOGY IN INTENSIVE FOREST MONITORING PLOTS IN SLOVENIA

VPLIV VREMENSKIH SPREMENLJIVK IN OSUTOSTI KROŠENJ NA FENOLOŠKE FAZE DREVES NA PLOSKVAH INTENZIVNEGA MONITORINGA GOZDNIH EKOSISTEMOV V SLOVENIJI

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ABSTRACT

Data from the forest monitoring programme in Slovenia were used to assess the relationship between tree phenology, crown defoliation and meteorological conditions in *Fagus sylvatica*, *Quercus robur* and *Picea abies* forests in the 2004–2013 period. We hypothesized a species-specific response of first leaf unfolding, general leaf colouring, the length of the growing season to crown defoliation, air temperature, precipitation and soil water.

In accordance with the hypothesis, we found a high sensitivity of first leaf unfolding to air temperature and precipitation for all species, exhibiting contrasting responses. We observed strong sensitivity of beech defoliation to precipitation and soil water conditions. Oak crown defoliation and next-year phenology were correlated, with higher crown defoliation contributing to earlier leaf unfolding, later autumn leaf colouring and longer growing season of oak in next year. Correlation between crown defoliation and phenology was found neither for beech nor spruce.

Key words: forest monitoring, tree phenology, crown defoliation, air temperature, precipitation, soil water content, Slovenia

IZVLEČEK

V naši raziskavi smo na podlagi podatkov spremljanja stanja gozdnih ekosistemov v Sloveniji ugotavljali povezanost fenofaz dreves, osutosti krošenj dreves in vremenskih razmer v gozdovih bukve, doba in smreke v letih 2004–2013. Predpostavili smo, da je odziv fenofaz prvih listov in iglic, splošnega rumenenja listja in dolžine vegetacijskega obdobja na osutost krošenj, temperaturo zraka, padavine in vsebnost vode v tleh vrstno specifičen.

Ugotovili smo veliko odzivnost nastopa fenofaze prvih listov in iglic na temperaturo zraka in padavine za vse obravnavane drevesne vrste, vendar so se odzivi razlikovali. Ugotovili smo tudi veliko odzivnost osutosti krošnje bukve na količino padavin in vsebnost vode v tleh. Osutost krošenj in fenofaze doba v sledečem letu so bile korelirane, pri čemer je večja osutost krošenj prispevala k zgodnejšemu nastopu fenofaze prvih listov, splošnega rumenenja listja in dolžine vegetacijskega obdobja za dob v sledečem letu. Nismo pa ugotovili povezanosti med osutostjo krošenj in fenofazami bukve ali smreke.

Ključne besede: monitoring gozdnih ekosistemov, fenologija dreves, osutost krošenj, temperatura zraka, padavine, vsebnost vode v tleh, Slovenija

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1 INTRODUCTION

1 UVOD

Long-term studies of phenological phases of trees are of increasing importance as an indicator of global climate change and associated biological responses in forests. Tree phenological data have been proved to be an efficient tool in studies on the impact of climate change (Donnelly A. et al., 2004; Lebourgeois F. et al., 2010; Menzel A. et al., 2006), as they are relatively easy to collect (Vliet A. H. et al., 2003), have a long history of observations (Menzel A., 2005; Menzel A. and Dose V., 2005) and have in certain regions established networks over a larger geographical area, mostly run by national meteorological networks (Askeyev O. V. et al., 2005; Chen X. and Xu L., 2012; Menzel A. et al., 2006; Vliet A. H. et al., 2003). When studying tree phenology, we need to understand how different species interacts with the environment. Temperature appears to be the main driver of leaf development of tree species (Lebourgeois F. et al., 2010; Linkosalo T., 1999), although the effect of photoperiod (Vitasse Y. and Basler D., 2012) and soil water content (Peñuelas

J. et al., 2004) are sometimes evoked. Various experimental studies have shown that cessation of winter dormancy and subsequent leaf unfolding are affected by chilling during dormancy, as well as forcing temperatures and photoperiod during reactivation (Caffarra A. and Donnelly A., 2011). Because of tight relationship between altitudinal gradients and temperatures, it is also important to know how local topography and altitude affects tree phenology (Dittmar C. and Elling W., 2006; Pellerin M. et al., 2012; Vitasse Y. et al., 2009). Leaf colouring and leaf fall have been less studied than leaf unfolding, although various authors have reported that mainly lower temperatures, shorter day length and summer drought promote senescence of deciduous trees (Črepinšek Z. et al., 2006; Delpierre N. et al., 2009; Dragoni D. and Rahman A. F., 2012). Less attention has been devoted to other climatic factors than air temperature, such as rainfall (Peñuelas J. et al., 2004) or soil water content (Sheffield M. C. P. et al., 2003). Rainfall is known to affect leaf and flower phenology even in regions with good water supply such as Norway or seasonal tropical forests (Peñuelas J. et al., 2004). However, rainfall and soil water content are more determinant in dry regions.

Tree crown defoliation is an indicator of forest health in response to several stressors including air pollutants, and therefore one of the most important parameters monitored in the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) (De Marco A. et al., 2014). This program is one of the largest programs for monitoring air pollution effects on European forests (Ferretti M. and Fischer R., 2013) an aims to assess the spatial-temporal variation of forest condition in relation to natural and anthropogenic factors (in particular air pollution) and to gain a better understanding of the cause-effect relationship between these factors and the condition of forest ecosystems (Lorenz M., 2010).

Understanding the relationship between tree phenology, crown defoliation and meteorological conditions is crucial for a better understanding of indicators used to assess forest health and long-term changes of forest vitality.

Our objective was to evaluate potential relationship between the observed tree phenology and tree crown defoliation in beech, pedunculate oak and spruce forest stands and their sensitivity to meteorological conditions. We hypostatize a species-specific response of first leaf unfolding, general leaf colouring, the length of the growing season and crown defoliation to air temperature, precipitation and soil water. In addition, we want to test whether tree phenology is related to crown defoliation.

The Level II forest monitoring plots for Intensive Monitoring of Forest Ecosystems by the Slovenian Forestry Institute were used as a case study. Slovenia is characterized by fairly large gradients of climatic factors due to its position between the Alps, the Mediterranean and continental Europe (Čufar K. et al., 2012). Consequently, a great variety of forest habitats, from lowlands to high mountains (Kutnar L. et al., 2002),

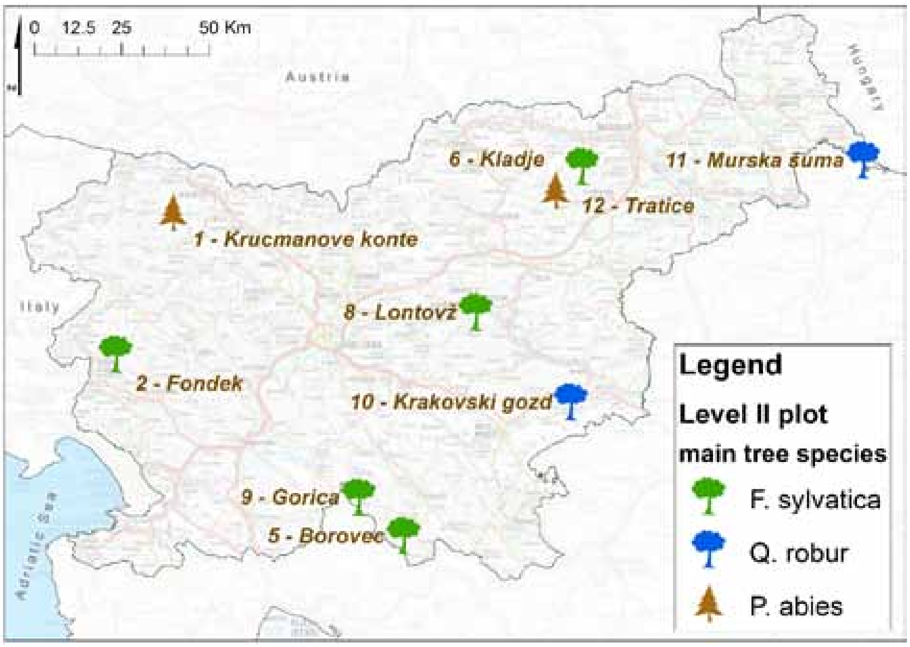


Fig. 1: Nine intensive forest ecosystem monitoring plots in Slovenia

Slika 1: Devet ploskev intenzivnega monitoringa gozdnih ekosistemov v Sloveniji can be found in the country. The present study is using sub-regional data from a relatively small area with high geographic variability, which could be extended and applied to other monitoring plots and tree species, provided that a sufficiently long time series of monitoring data are available.

2 MATERIALS AND METHODS
2 MATERIALI IN METODE
2.1 Study areas and species
2.1 Območje raziskav in obravnavane drevesne vrste

This study was conducted on Level II forest monitoring plots for Intensive Monitoring of Forest Ecosystems by the Slovenian Forestry Institute, established in 2004 (Krajnc N. et al., 2006) in accordance with the International Co-operative Program on Assessment and Monitoring of Air pollution Effects on Forests (ICP Forests), United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution (Ferretti M. et al., 2010; Lorenz M., 2010). Nine monitoring plots distributed throughout Slovenia were included, ranging from 170 to 1397 m a.s.l. and with different site and climatic characteristics (Figure 1, Table 1). At five plots, the main tree species was European beech (*Fagus sylvatica* L.), at two plots pedunculate oak (*Quercus robur* L.) and at two plots Norway spruce (*Picea abies* (L.) Karst.). The period of observation was from 2004 until 2013, but for some monitoring plots data on certain parameters were available for shorter period (Appendix 1).

2.2 Phenological observations
2.2 Fenološka opazovanja

We used phenological data on first leaf and needle unfolding (LU) of European beech (*Fagus sylvatica* L.), pedunculate oak (*Quercus robur* L.) and Norway spruce (*Picea abies* (L.) Karst.) in Slovenia. In addition, the general leaf colouring (LC) was considered for the broadleaved trees and the length of the growing season (LGS) calculated as the difference between LC and LU. The data originated from 9 forest monitoring plots for Intensive Monitoring of Forest Ecosystems by the Slovenian Forestry Institute (Vilhar U. et al., 2013b). The selection of trees on monitoring plots and the observations were made in accordance with the ICP Forests Manual (Beuker E. et al., 2010; Vilhar U., 2010; Vilhar U. et al., 2013a). Phenological monitoring was carried out on 19 to 20 individual trees located inside 75 m x 75 m area on 9 monitoring plots from 2004 till 2013, but for some monitoring plots data were available for shorter period (Appendix 1). The assessments were always done on the same trees. If one of the selected trees died or was removed, it was replaced with a new, nearest tree, as per criteria of the phenological monitoring manual. In comparison to the nearby trees, the social class of selected trees were dominant or co-dominant. The upper part of the tree crowns was observed. In case the upper part of the crowns was not visible, the middle part of the crown was assessed. The use of binoculars was recommended. The same part of the crown was considered for subsequent phenological observations throughout the observation years. Biotic (pests and/or diseases) and abiotic damage (e.g. frost, wind, hail) relevant to phenological development of trees were considered. The observations during leaf and needle unfolding and leaf colouring were carried out weekly. The week of needle and leaf unfolding (LU) was recorded as the first regular surfaces of leaves and needless were becoming infrequent or slightly visible, up to 33% of the observed part of the crown. For broadleaved trees, the week of leaf colouring (LC) was recorded as leaves

Table 1: Geographic locations and main characteristics of 9 intensive forest monitoring plots in Slovenia

Preglednica 1: Geografska lokacija in glavne značilnosti ploskev intenzivnega monitoringa gozdnih ekosistemov

Tree species *Drevesna vrsta*	Plot name *Ime ploskve*	Longitude *Zemljepisna dolžina** (°)	Latitude *Zemljepisna širina** (°)	Elevation *Nadmorska višina** (m)	Ecological region *Ekološka regija*
Spruce / *Smreka* (*Picea abies*)	1 - Krucmanove konte	+13°56´36˝	+46°22´04˝	1397	Alpine / *Alpska*
	6 – Kladje	+15°23´51˝	+46°28´26˝	1304	Pohorje / *Pohorska*
Beech / *Bukev* (*Fagus sylvatica*)	2 - Fondek	+13°44´16˝	+45°59´55˝	827	Dinaric / *Dinarska*
	5 - Borovec	+14°48´16˝	+45°32´12˝	705	Dinaric / *Dinarska*
	8 - Lontovž	+15°04´13˝	+46°06´51˝	950	Pre-Alpine / *Predalpska*
	9 – Gorica	+14°38´18˝	+45°38´12˝	955	Dinaric / *Dinarska*
	12 - Tratice	+15°23´12˝	+46°27´48˝	1289	Pohorje / *Pohorska*
Pedunculate oak / *Dob* (*Quercus robur*)	10 - Krakovski gozd	+15°24´59˝	+45°52´55˝	160	Pre-Pannonian / *Predpanonska*
	11 - Murska šuma	+16°30´46˝	+46°29´49˝	170	Pre-Pannonian / *Predpanonska*

* plot center / *center ploskve*

become coloured in autumn in more than 66% of the observed part of the crown. Observations of the first needle and leaf unfolding and the autumn leaf colouring were synchronized to week of the year (WOY).

2.3 Crown defoliation
2.3 Osutost krošenj

Tree crown defoliation was obtained for 9 monitoring plots from 2004 to 2013, but for some monitoring plots data were available for shorter period (Appendix 1). In total, crown defoliation was assessed for 6,335 trees (Appendix 1). Tree crown defoliation describes the amount of foliage missing in comparison to a full-leaved reference tree and is estimated in 5% classes for individual trees. In the field, the assessment was done each year in August. Only trees from 1-3 social class were considered. Assessment was performed according to the guidelines of the UN-ECE ICP Forests program (Eichhorn J. et al., 2010) by two field teams. In order to minimize the differences between the two teams, calibration seminar was organized each year for both teams, and local photo album with different percentage of defoliation for main tree species was used (Kovač M. et al., 2014).

2.4 Meteorological measurements
2.4 Meritve vremenskih spremenljivk

For this study we used a dataset of daily averaged or summed meteorological data from 2004 – 2013 for 8 monitoring plots (Appendix 1). Meteorological data were collected using automated weather stations in the open area according to ICP Forests (Raspe S. et al., 2010) with average distance of 1.5 km from forest monitoring plots. The distance between plots 6 – Kladje and 12 – Tratice is only 1.2 km, therefore the same automated weather station in open area was used for both plots. Automated weather stations collected data on wind speed, wind direction and global radiation sensors at 10 m (all from Davis Instruments). At 2 m, the standard 0.2 mm precipitation gauge (Davis Instruments), air pressure (Freescale Semiconductor), air temperature and relative humidity sensor (Sensirion) were installed. Data on air temperature and relative humidity were measured and logged by USB datalogger Voltcraft DL-120TH; all other sensors were connected to the CR200 datalogger (Campbell Scientific) (Sinjur I. et al., 2010). On 6 monitoring plots located in forest stands, 2 soil water content sensors (EC-05, Decagon Devices) were additionally installed at 10 and 30 cm soil depth and connected to SFI datalogger developed in Laboratory for Electronic Devices (LED) established by the Slovenian Forestry Institute. All meteorological measurements were performed every 30 minutes.

In case of missing data, meteorological data from the nearest climatological station of the Slovene Environment Agency were used (SEA Archive). In order to gap-fill the missing data, linear regression for each parameter was performed for the common years (2010-2012) of the recorded and SEA data. All R2 were found higher than 0.90 and linear regressions were applied to SEA (2004 – 2010) to minimize the location difference (corrected SEA data). Gap-filling of missing data followed the procedure: (1) for air temperature and global radiation, the datasets from SFI, USB or CR200 (in all combinations) were used to gap-fill the missing data. On average over all plots, 9.1% of data were gap-filled using this procedure; (2) for other parameters or if air temperatures were still missing, the corrected SEA data were used. On average over all plots, 2.3% of data were gap-filled using this procedure; (3) if data were still missing, appropriate multiple regression was performed for the missing parameter. On average over all plots, 0.4% of data were gap-filled using this procedure; (4) in the last step, all gaps were filled using linear interpolation. On average over all plots, 0.2% of data were gap-filled using this procedure. After gap-filling, data were averaged or summed to daily values. For final dataset presented and used in this study, the corrected SEA data (2004 – 2010) and recorded data (2010 – 2012) were merged.

2.5 Relative extractable soil water
2.5 Relativna dostopna voda v tleh

Soil water content (SWC) and soil temperature were measured on six plots. SWC was measured every 30 minutes using frequency domain soil water content sensors (EC-05, Decagon Devices Inc.) connected to data logger developed in LED. Four-year dataset (2010-2013) was used in the presented study. During the growing seasons, SWC was analysed using relative extractable soil water (REW). REW was computed as follows (Bréda N. et al., 2006a; Granier A. et al., 2007):

$$REW = \frac{SWC_{day} - SWC_{min}}{SWC_{max} - SWC_{min}} \qquad (1)$$

where SWC_{min} and SWC_{max} are the daily minimum and maximum soil water content (m^3 m^{-3}). REW varies between 1.0 (maximum soil water content) and 0 (minimum soil water content). Mean monthly REW was computed for 6 monitoring plots from 2004 – 2013, but for some monitoring plots data were available for shorter period (Appendix 1).

2.6 Data evaluation

2.6 Vrednotenje podatkov

Meteorological data were aggregated to monthly sums and means, with the following parameters used in further analysis and comparisons with phenological data: monthly and three-monthly sums of precipitation (P), monthly and three-monthly sums of air temperature (T), monthly means of T and relative extractable water (REW). Meteorological datasets were merged with yearly means for phonological observations (WOY) and tree crown defoliation (%). Pearson's correlation coefficients (r) between meteorological data and phonological data were calculated and only significant coefficients ($p<0.05$) were taken for further analyses. All data elaboration was done using R (A language and environment for statistical computing) (R Development Core Team, 2013).

3 RESULTS

3 REZULTATI

3.1 Meteorological conditions

3.1 Vremenske razmere

In the 2004–2013 period, the average annual T on 5 beech monitoring plots ranged from 4.7°C (minimum 3.4°C; maximum 5.8°C) on plot 12 to 11.2°C (minimum 8.6°C; maximum 12.7°C) on plot 2 (Figure 2). Annual P on beech plots was lowest on plot 12 (898 mm) and highest on plot 2 (1988 mm). The differences in average annual T on beech plots are due to altitudinal gradient of monitoring plots ranging from 705 m to 1,289 m a.s.l.. The differences in annual P are mainly the result of heterogeneous topography.

For the two pedunculate oak plots, average annual T were lower on plot 10: 9.7°C (minimum 8.7°C; maximum 10.6°C) compared to 10.4°C (minimum 8.6°C; maximum 11.3°C) on plot 11. However, annual P was much higher on plot 10 (1,278 mm) compared to plot 11 (659 mm). Average annual T for spruce plots were the lowest and ranged from 4.4°C (minimum 3.5°C; maximum 5.2°C) on plot 1 to 4.9°C (minimum 3.4°C; maximum 5.8°C) on plot 6. Annual P on spruce plots ranged from 1,153 mm on plot 6 to 1,448 mm on plot 1. Average annual REW was highest on beech plots, ranging from 0.76 on plot 8 to 0.35 on plot 12. Average annual REW was 0.41 on pedunculate oak plot 11 and 0.35 on spruce plot, respectively.

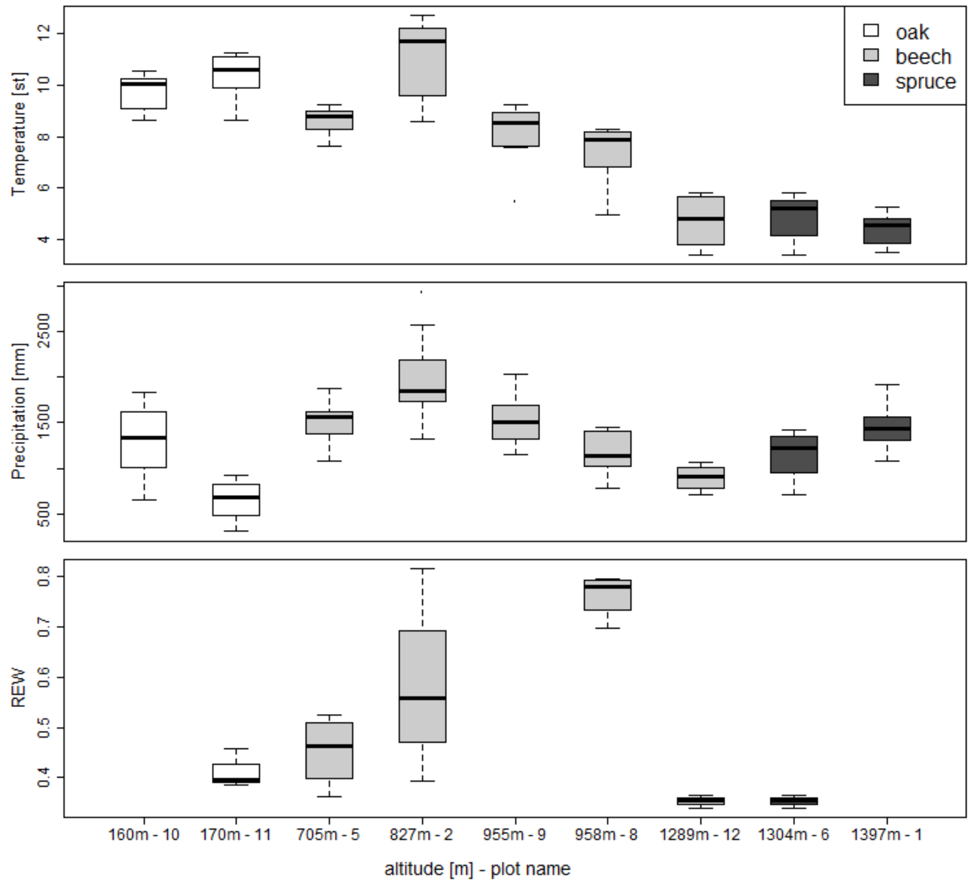


Fig. 2: Average annual a) air temperature (T), b) precipitation (P) and c) relative extractable soil water (REW) for nine Intensive forest monitoring plots in Slovenia in the 2004–2013 period

Slika 2: Povprečne letne a) temperature zraka (T), padavine (P) in c) relativna dostopna voda v tleh (REW) za devet ploskev intenzivnega monitoringa v Sloveniji v obdobju 2004–2013

3.2 Tree phenology

3.2 Fenologija dreves

For the 2004–2013 period, the pedunculate oak LU started on average in 15 WOY, which corresponds to the beginning of April. LC of pedunculate oak started on average in 44 WOY, which corresponds to the end of October. Thus, the length of the pedunculate oak growing season 198 days was on average. For beech, LU started in 17 WOY on average, which corresponds to the end of April. LC of beech started in 44 WOY on average, which corresponds to the end of October. Thus, the length of the beech growing season was 189 days on average. The latest LU was observed for spruce, specifically in 22 WOY, which corresponds to the end of May.

Beech / Bukev

The LU of beech occurred earlier with higher P in winter and spring (January till April) T (Figure 4a). In addition, higher T, in particular May – June – July and October – November – December, induced earlier LU of beech in the ensuing year. Furthermore, LU occurred earlier with higher P in winter (January till March). Higher P in spring (March – April – May) induced earlier LU of beech in the ensuing year. We found no significant relation between LU of beech and REW. LC of beech started later with higher T in spring (March – April – May) (Figure 4b). We found no significant relation between LC of beech and P. However, higher REW in August, indicating well watered soils, induced later LC of beech in the following year. LGS of beech was influenced mainly by spring T (from March till May) (Figure 4c). In addition, higher spring and summer T and higher spring P induced longer LGS of beech in the year.

Pedunculate oak / Dob

LU of pedunculate oak started earlier with higher winter and spring T (from January till April) (Figure 4a). In addition, higher T in July induced earlier LU of pedunculate oak in the following year. However, LU of pedunculate oak started later with higher P in April. Furthermore, higher P in autumn (October – November - December) induced later LU of pedunculate oak in the following year. We found no significant relation between LU of pedunculate oak and REW.

LC of pedunculate oak started later with higher

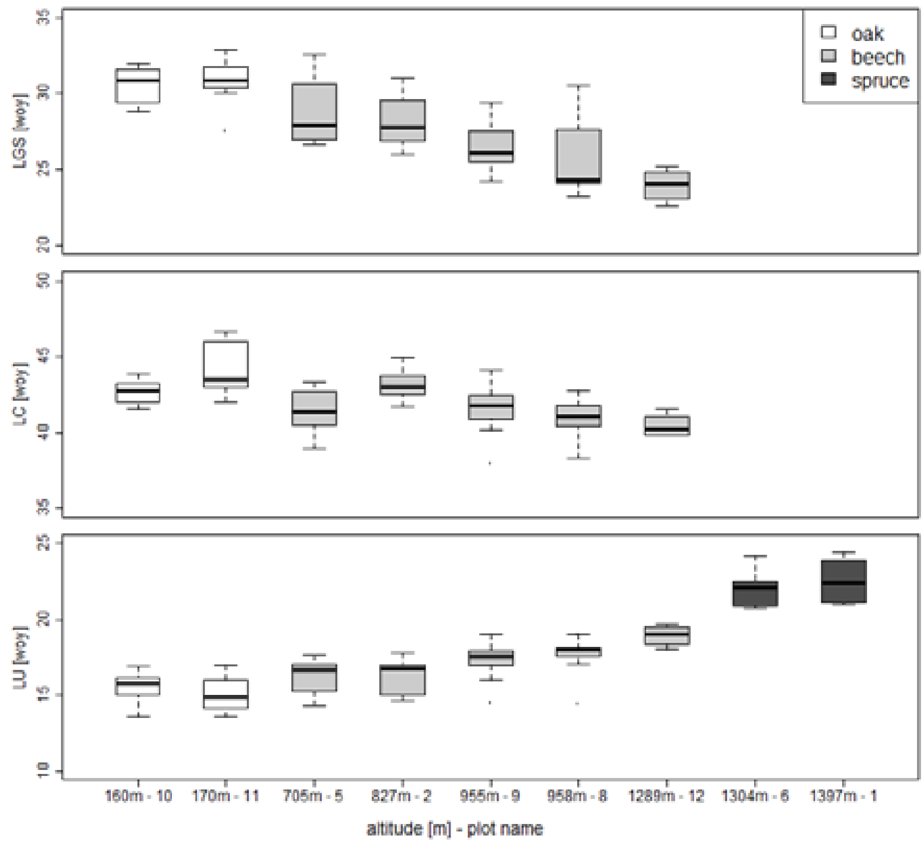


Fig. 3: First leaf and needle unfolding (LU) for pedunculate oak, beech and spruce; the general leaf colouring (LC) and the length of the growing season (LGS) for pedunculate oak and beech in relation to altitude on the nine Intensive forest monitoring plots in Slovenia in the 2004–2013 period. (WOY – week of the year)

Slika 3: Fenofaze prvih listov in iglic (LU) za dob, bukev in smreko; splošno rumenenje listov (LC) in dolžina vegetacijskega obdobja (LGS) za dob in bukev glede na nadmorsko višino na devetih ploskvah intenzivnega monitoringa v Sloveniji v obdobju 2004–2013. (WOY – teden v letu)

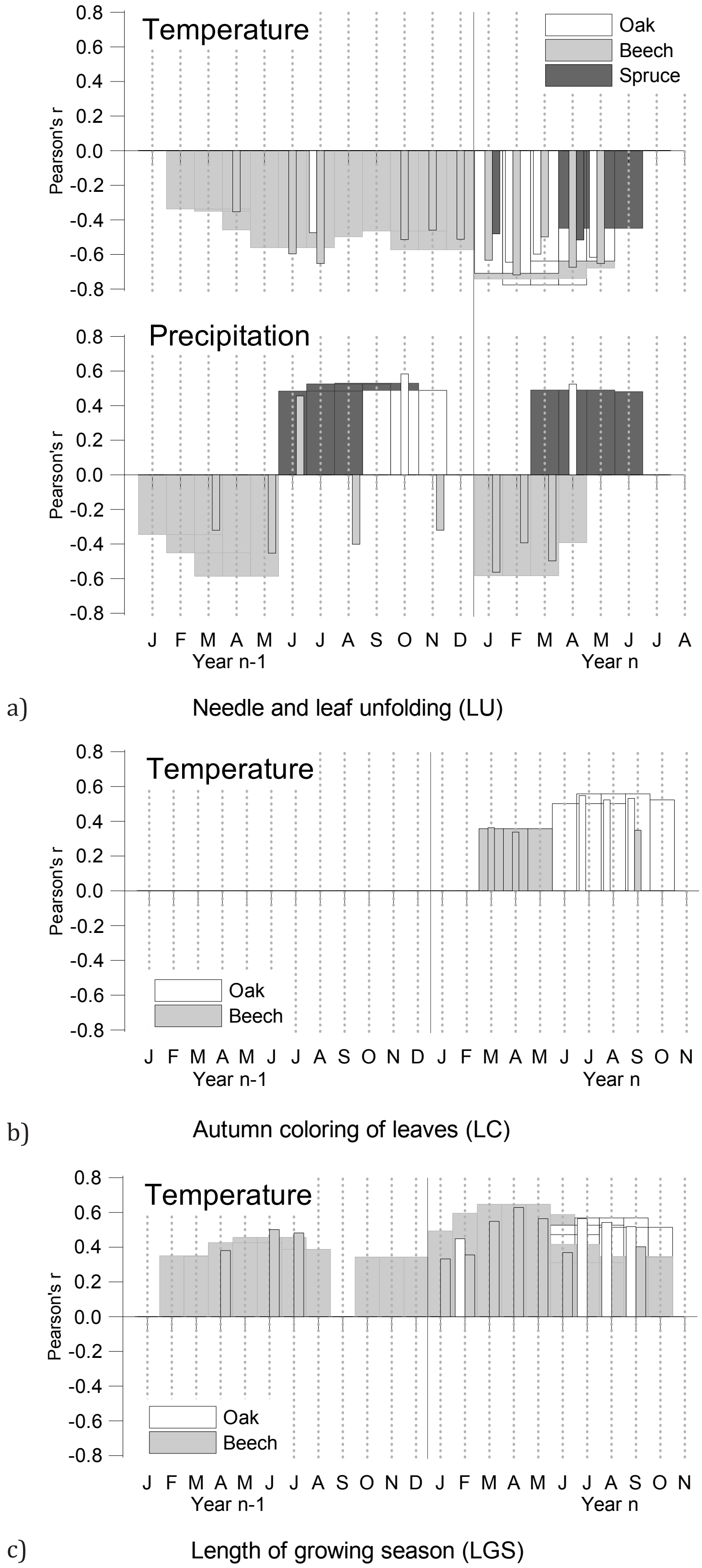


Fig. 4: Significant Pearson's correlation coefficients r (at 95% level) calculated between the monthly (bars) and three-month (shadow) air temperature sums (T) and precipitation (P) and a) the first leaf and needle unfolding (LU) for pedunculate oak, beech and spruce; b) the general leaf colouring (LC) for pedunculate oak and beech and c) the length of the growing season (LGS) for pedunculate oak and beech at Intensive forest monitoring plots in Slovenia in the period 2004– 2013

Slika 4: Značilni Pearsonovi koeficienti korelacije r (na 95-odstotni ravni), izračunani med mesečnimi (stolpci) in trimesečnimi (osenčeno) vsotami temperature zraka (T) in padavinami (P) in a) fenofazo prvih listov in iglic (LU) za dob, bukev in jelko; b) dolžina vegetacijskega obdobja (LGS) za dob in bukev na ploskvah intenzivnega monitoringa v Sloveniji v obdobju 2004–2013 summer T (from June till October). However, LC started earlier with higher T in October and November (Figure 4b). LGS of pedunculate oak was longer at higher T from May till October (Figure 4c). However, we observed shorter LGS with higher T in autumn (from October till December), most likely inducing late LC. We found no significant relation between LC or LGS of pedunculate oak and P nor REW.

Spruce / Smreka

LU of spruce started earlier with higher winter and spring T (from January till June) (Figure 4a). In addition, higher T in May – June – July induced earlier LU of spruce in the following year. However, LU of spruce started later at higher spring P (from March till June). Furthermore, higher P from June till October induced later LC of spruce in the following year. We found no significant relation between LU of spruce and REW.

3.3 Crown defoliation and meteorological conditions

3.3 Osutost krošenj in vremenske razmere

Crown defoliation of beech was not sensitive to monthly T but to P and REW (Figure 5). Higher P in spring and summer months (from May till July) induced higher crown defoliation of beech in the current and the following year (Figure 6). However, higher P in August induced lower crown defoliation for beech in the following year ($r = -0.321$, $p < 0.05$). Crown defoliation was higher at higher REW in May, indicating increased crown defoliation of beech in wet soil water conditions. Furthermore, higher REW through several months (January, February, March, April, May, June, August, October) induced higher crown defoliation of beech in the following year. Crown defoliation of pedunculate oak was higher with higher T in May. In addition, higher REW in January induced higher crown

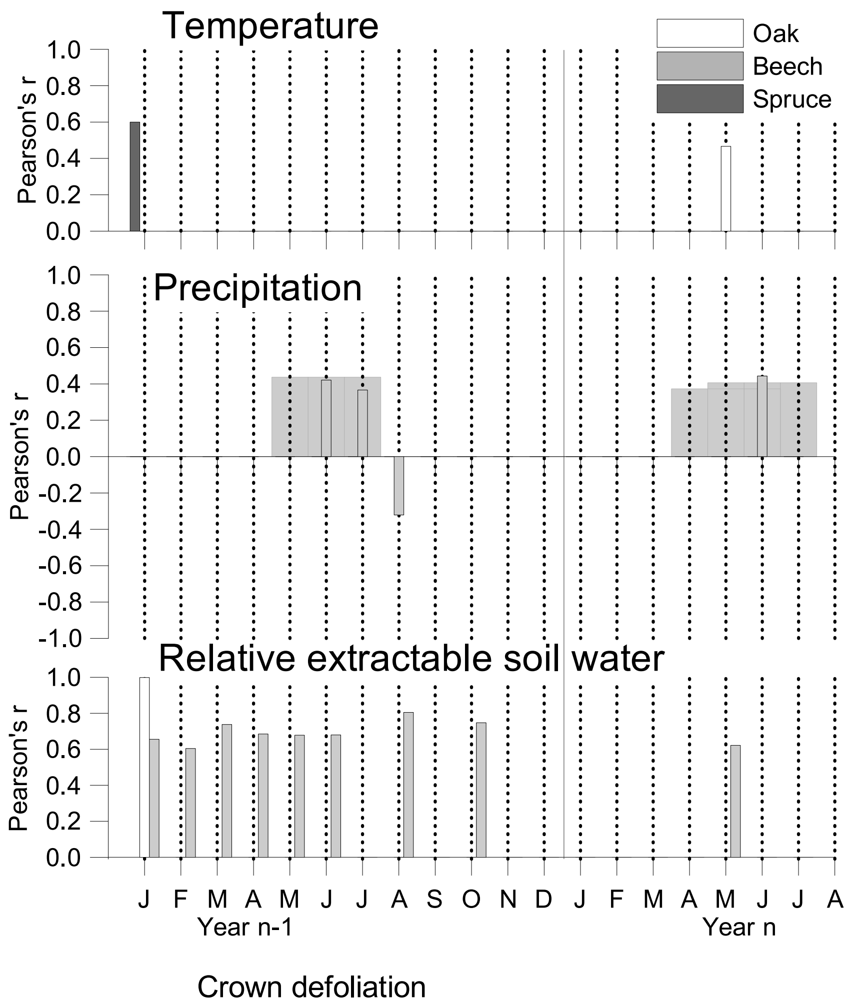


Fig. 5: Significant Pearson's correlation coefficients r (at 95 % level) calculated between crown defoliation for pedunculate oak, beech and spruce and monthly (bars) and three-month (shadow) air temperature sums (T), precipitation (P) and relative extractable soil water (REW) on Intensive forest monitoring plots in Slovenia in the 2004–2013 period

Slika 5: Značilni Pearsonovi koeficienti korelacije r (na 95-odstotni ravni), izračunanimi med osutostjo krošenj za dob, bukev in smreko in mesečnimi (stolpci) in trimesečnimi (osenčeno) vsotami temperature zraka (T), padavinami (P) in relativno dostopno vodo v tleh (REW) na ploskvah intenzivnega monitoringa v Sloveniji v obdobju 2004–2013

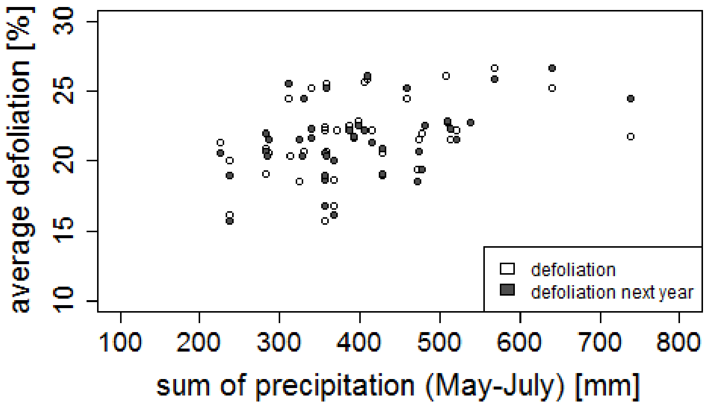


Fig. 6: Crown defoliation of beech in relation to precipitation (P) in months from May till July in the current year (white dots) and the following year (black dots) on Intensive forest monitoring plots in Slovenia in the period 2004–2013

Slika 6: Osutost krošenj bukve glede na padavine (P) v mesecih od maja do julija v tekočem (beli krožci) in naslednjem letu (črni krožci) na ploskvah intenzivnega monitoringa v Sloveniji v obdobju 2004–2013

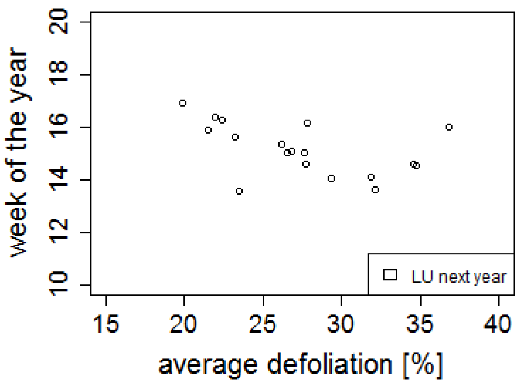
defoliation of pedunculate oak in year ($r = 0.999$, $p < 0.05$). For spruce, higher T in January induced higher crown defoliation of spruce in the following year ($r = 0.600$, $p < 0.05$). However, we found no significant relation between P and crown defoliation of pedunculate oak and spruce.

3.4 Tree crown defoliation and phenology
3.4 Osutost krošenj in fenologija

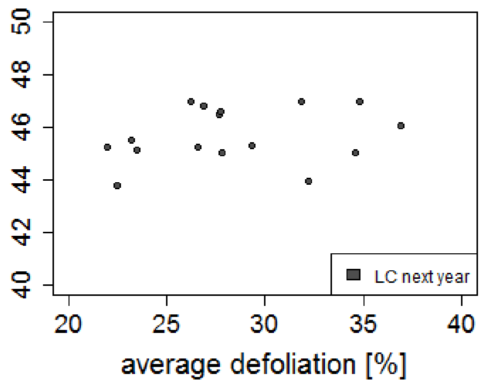
The results of this study clearly demonstrate that crown defoliation and next-year phenology of pedunculate oak were correlated, although neither for beech nor spruce. We found negative correlation between pedunculate oak LU and crown defoliation in the following year ($r = -0.479$ $p = 0.044$) (Figure 7). In addition, pedunculate oak LC and crown defoliation in the following year were positively correlated ($r = 0.510$ $p = 0.031$). Furthermore, LGS and pedunculate oak crown defoliation were also positively correlated in the following year ($r = 0.532$ $p = 0.023$), indicating that higher crown defoliation might contribute to earlier LU, later LC and longer LGS of pedunculate oak in the following year.

4 DISCUSSION
4 RAZPRAVA

This study allowed us to evaluate potential relationship between the observed tree phenology and crown defoliation in beech, pedunculate oak and spruce forest stands and their sensitivity to meteorological conditions. We found high correlations between LU and monthly T and P for all species. However, we observed that T and P sensitivity of tree phenology was highly species-dependent. In particular, the three dominant species of European forests, i.e. beech, pedunculate oak and spruce, exhibited very contrasting responses.



a)



b)

Fig. 7: Pedunculate oak a) first leaf unfolding (LU) in the following year and b) general leaf colouring (LC) in the following year in relation to crown defoliation

Slika 7: Dob a) fenofaza prvih listov (LU) v naslednjem letu in b) splošno rumenenje listov (LC) v naslednjem letu glede na osutost krošenj

Then, our results indicated sensitivity of crown defoliation to P and soil water conditions for beech, whereas pedunculate oak showed only sensitivity to T and soil water. Finally, we found high correlations between tree phenology and crown defoliation of pedunculate oak, although neither for beech nor spruce.

4.1 Tree phenology

4.1 Fenologija dreves

We found significant relationships between LU and spring T for all species. These results support the hypothesis that in temperate climates the timing of tree flushing is mainly sensitive to T at the end of winter and beginning of spring (Vitasse Y. et al., 2009). Penuelas et al. (2004) also showed that LU in Mediterranean forests was correlated to the increase in T during the winter / spring period, especially T from January to April, which corresponds to the period of tree bud quiescence. In our study, LU of beech occurred earlier with higher winter and spring T. Čufar et al. (2012) also report on higher March and April T promoting earlier LU of beech across the phenological network in Slovenia. Our results also show great sensitivity of pedunculate oak LU to winter and spring T, with warmer winter T hastening leaf unfolding (Lebourgeois F. et al., 2010). The results of this study clearly demonstrate that higher T in spring / summer promoted earlier next year LU for all tree species. In particular spruce next year LU demonstrated high sensitivity to May – June – July T, whereas for beech and pedunculate oak next year LU was highly sensitive to T in July. In addition to T, LU indicated sensitivity to P of all tree species. In particular higher P in spring induced earlier current and next year LU of beech. However, spruce LU was later if P in spring was higher. Furthermore, higher P in autumn (October – November - December) induced later pedunculate oak LU in next year and high P during the growing season (from June till October) induced later spruce LU in next year. This might arise from the fact that higher P could contribute to reduced global solar radiations, which appeared to play an important role for spring tree phenology, in particular for coniferous (Lebourgeois F. et al., 2010).

Leaf colouring and leaf fall have been less studied than leaf unfolding, although various authors have reported that the timing of leaf senescence shows less year-to-year variability and is concomitant with less favourable conditions for photosynthesis (Delpierre N. et al., 2009). The end of the growing season variability and response to climate variability across deciduous forests of the Eastern USA was in general correlated with latitude of the forest with clear relation to summer T, but no clear relationship between LC and P was found (Dragoni D. and Rahman A. F., 2012). Leaf colouring process started earlier and was sensitive to higher T for *Fagus sylvatica*, *Quercus robur* and *Quercus petrea* in France (Delpierre N. et al., 2009). Menzel (2003) reported positive correlation between August and September mean T and LC in *Fagus sylvatica* and *Quercus robur*. In our study, the general LC of pedunculate oak was sensitive to summer and autumn T with higher T from June till October, inducing later LC. In addition, beech LC was sensitive to spring T (March – April – May). Apart from T, global solar radiations appeared to play an important role for LC of *Fagus sylvatica*, *Quercus robur* and *Quercus petrea* in France (Lebourgeois F. et al., 2010).

The LGS of beech was influenced mainly by spring T. Also higher summer P (July – August – September) induced longer LGS of beech in the following year. LGS of pedunculate oak was longer at higher T from May till October, which might be a consequence of higher T promoting later LC, but shorter with higher T from October till December.

4.2 Tree crown defoliation

4.2 Osutost krošenj

The cause and effect relationships between tree crown defoliation and meteorological parameters is difficult to identify due to a mixture of stress factors currently acting on the response variable (De Marco A. et al., 2014). The results of this show that crown defoliation of beech was not sensitive to T but to P and REW. Increased spring and summer P (from March till July) (but not August) increase beech crown defoliation in current and the following year. In addition, higher REW in May, indicating wet soil water conditions, induced higher beech crown defoliation. Physiologically increasing defoliation should be the response of tree on drier and hotter years (Carnicer J. et al., 2011). Trees affected by drought reduce transpiration through adjustments in total leaf area (Bréda N. et al., 2006b). In spite of this, our results show no direct relation between defoliation of beech and climatic data. We assume that the correlation between the meteorological conditions and defoliation is not direct and could be explained by establishing better conditions for different pathogenic agents during wet growing seasons, which might contribute to increased summer tree defoliation (Waller M., 2013). In areas where water is not a limiting factor, defoliators and diseases are important for the increase of tree defoliation (Ozolinčius R. and Stakenas V., 1996), in contrary to the water-limited forests where the main driver of defoliation could be drought

(Carnicer J. et al., 2011). During our study, drought was not the limiting factor on forest monitoring plots in Slovenia, dominated by beech (Figure 2).

The results of this study show weak crown defoliation sensitivity of spruce and pedunculate oak to T and only for pedunculate oak also to soil water conditions. However, these correlations were significant for single months only, without clear seasonal pattern. For spruce in southeast Norway, summer drought, i.e. unusually dry and warm weather, has been a significant stress factor causing increases in defoliation, discolouration of foliage, cone formation and mortality (Solberg S., 2004). In addition, crown defoliation of Norway spruce in Swedish Scandes is reported to increase due to severe and prolonged ground freezing, which invoked winter desiccation (xylem cavitation) and reduced radial growth, implying increasing sensitivity of spruce to climatic stress and decreasing ability to take advantage of positive climatic anomalies (Kullman L., 1996). Furthermore, crown defoliation of Norway spruce in the Polish Sudety and Carpathian mountains is linked to the accumulation of pollutants, the exhaustion of self-regulation capacity of older trees and the destabilization of sensitive spruce ecosystems (Modrzyński J., 2003). For pedunculate oak, changes in P patterns and droughts seem to be frequently associated with aggravated decline and, in particular, fluctuations between dry and wet periods may interact with biotic agents such as *Phytophthora* spp., thus increasing disease severity (Jönsson U. et al., 2005). The interpretation of the correlation between crown condition and P is complicated, since P also includes deposition of certain elements, such as N and S. These elements may have direct effects on the trees, or influence them indirectly through their effects on the microbial activity in the soil (*ibid*.).

4.3 Tree crown defoliation and phenology

4.3 Osutost krošenj in fenologija

Correlation between crown defoliation and phenology was found neither for beech nor spruce, which is in contrast to the results presented by Kaitaniem et al. (1997) who found the relationship between defoliation and the timing of budburst for mountain birch. Increased defoliation could influence the amounts of nutrients and carbon needed for leaf unfolding (Tuomi J. et al., 1984) and additionally defoliation could prolong the ability of buds to take up stored nutrients (Honkanen T. and Haukioja E., 1994). In contrast to beech and spruce, the results of this study show that pedunculate oak crown defoliation and next-year phenology are correlated, indicating that higher crown defoliation contributed, at least partially, to earlier leaf unfolding, later autumn leaf colouring and, consequently, longer growing season of pedunculate oak in the following year. Results indicate that the correlation between defoliation and phenology is species-specific and we assume that site conditions also play an important role, in particular availability of nutrients. Further investigations involving a larger number of sites are therefore needed before any conclusions about the role of crown defoliation and meteorological conditions in tree phenology in Slovenia can be drawn.

4.4 Conclusions

4.4 Zaključki

The present study is using sub-regional data from a relatively small area with high geographic variability, showing that temperature and precipitation sensitivity of tree phenology was highly species-dependent with beech, pedunculate oak and spruce exhibiting contrasting responses.

Crown defoliation of beech was not sensitive to air temperature but to precipitation and relative extractable soil water. For spruce and pedunculate oak, only weak sensitivity of crown defoliation to air temperature, and only for pedunculate oak also to soil water conditions, was found for single months, without clear seasonal pattern.

Higher crown defoliation of pedunculate oak contributed to earlier leaf unfolding, later autumn leaf colouring and longer growing season in next year. Relation between tree phenology and crown defoliation was found neither for beech nor spruce.

To assess the influence of crown defoliation and meteorological conditions on tree phenology, longer time series are needed, involving a larger number of sites.

5 RAZŠIRJEN POVZETEK V SLOVENŠČINI

Dolgoletno spremljanje fenoloških faz dreves je pomemben kazalnik globalne podnebne spremenljivosti in z njimi povezanih bioloških odzivov v gozdovih. Fenološki podatki dreves so učinkovito orodje v raziskavah o podnebni spremenljivosti, saj je njihovo zbiranje razmeroma enostavno, imajo dolgo zgodovino opazovanj, hkrati pa ponekod obstaja množična mreža opazovalnih ploskev, ki pokrivajo širša geografska območja. Raziskave fenologije dreves vključujejo razumevanje medsebojnih vplivov različnih drevesnih vrst in okolja. Temperatura zraka je glavno gonilo razvoja listov in iglic pri drevesnih vrstah, nekatere raziskave pa poudarjajo tudi pomemben vpliv sončevega sevanja, padavin in vsebnosti vode v tleh. Osutost krošenj dreves v gozdovih je kazalnik zdravstvenega stanja gozdov in njihovega odziva na stresne dejavnike, vključno z onesnaževali v zraku. Zato je osutost krošenj dreves eden izmed najpomembnejših kazalnikov v sklopu spremljanja stanja gozdnih ekosistemov v skladu z mednarodnim programom ICP Forests (The International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests), ki deluje v okviru Konvencije Ekonomske komisije za Evropo pod pokroviteljstvom Združenih narodov o onesnaževanju zraka prek meja na velike razdalje (UNECE CLTRAP). Ta program je eden izmed največjih programov za spremljanje učinkov onesnaženosti zraka na evropske gozdove, katerega namen je ovrednotiti prostorsko in časovno spremenljivost stanja gozdov v odvisnosti do naravnih in antropogenih dejavnikov, zlasti onesnaževanja zraka.

V naši raziskavi smo ugotavljali povezanost fenofaz doba (*Quercus robur* L.), bukve (*Fagus sylvatica* L.) in smreke (*Picea abies* (L.) Karst.) z osutostjo krošenj in vremenskimi razmerami na ploskvah spremljanja stanja gozdnih ekosistemov v Sloveniji v letih 2004–2013. Za smreko smo upoštevali fenofazo prvih iglic, za bukev in dob pa fenofaze prvih listov, splošnega rumenenja listja in dolžine vegetacijskega obdobja v skladu z metodologijo ICP Forests. Fenološka opazovanja dreves se v gozdni krajini, oddaljeni od urbanih središč, redko opravljajo, čeprav so pomemben podatek o procesih v gozdnih ekosistemih. Nastop fenofaz dreves med leti smo primerjali z mesečnimi in trimesečnimi vsotami za temperaturo zraka, padavine in vsebnostjo vode v tleh, ki so bile merjene na ploskvah v gozdu ali na prostem v neposredni bližini opazovanih dreves. Na podlagi merjene vsebnosti vode v tleh smo izračunali tudi kazalnik relativne dostopne vode v tleh (angl. relative extractable soil water). Predpostavili smo, da je odziv fenofaz ter osutosti krošenj na vremenske razmere vrstno specifičen. Dodatno smo želeli tudi ugotoviti, ali obstaja povezava med nastopom fenofaz izbranih drevesnih vrst ter osutostjo njihovih krošenj.

V skladu s hipotezo smo ugotovili veliko odzivnost nastopa fenofaze prvih listov in iglic na temperaturo zraka in padavine za vse obravnavane drevesne vrste, vendar so se odzivi razlikovali.

Nastop fenofaze prvih listov bukve in doba ter iglic smreke je bil zgodnejši pri višjih temperaturah zraka v zimskih in spomladanskih mesecih. Višje temperature zraka spomladi in poleti pa so vplivale tudi na zgodnejši nastop fenofaze prvih listov in iglic v naslednjem letu. Več padavin v spomladanskih mesecih je vplivalo na zgodnejši nastop fenofaze prvih listov bukve v tekočem in naslednjem letu. V nasprotju z bukvijo pa je več spomladanskih padavin in padavin v preteklem vegetacijskem obdobju vplivalo na kasnejši nastop fenofaze prvih iglic smreke. Tudi pri več padavinah v jesenskih mesecih se je pokazal kasnejši nastop fenofaze prvih listov doba v naslednjem letu.

Fenofaze splošnega rumenenja listov in odpadanja so manj raziskane kot fenofaze prvih listov in iglic. Nastop fenofaze splošnega rumenenja listov naj bi bil po mnenju različnih avtorjev manj spremenljiv med leti ter vezan predvsem na manj ugodne razmere za fotosintezo. Rezultati naše raziskave nakazujejo, da so višje spomladanske temperature vplivale na kasnejši nastop splošnega rumenenja listov bukve ter višje temperature od junija do oktobra na kasnejši nastop splošnega rumenenja listov doba. Tudi dolžina vegetacijskega obdobja bukve in doba se je odzivala na temperaturo zraka in padavine. Višje temperature zraka predvsem v spomladanskih mesecih so vplivale na daljše vegetacijsko obdobje bukve. Več padavin spomladi pa je vplivalo na daljše vegetacijsko obdobje bukve v naslednjem letu. Za dob je bilo vegetacijsko obdobje daljše ob višjih temperaturah zraka od maja do oktobra.

Razmerja med vzrokom in posledico v primeru osutosti krošenj dreves in vremenskimi spremenljivkami je težko določiti zaradi različnih stresnih dejavnikov, ki trenutno vplivajo na obravnavano spremenljivko. Rezultati naše raziskave nakazujejo, da na osutost krošenj bukve niso vplivale temperature zraka, temveč padavine in relativna dostopna voda v tleh. Več padavin spomladi in poleti (od marca do junija, avgusta pa ne) je vplivalo na večjo osutost krošenj bukve. Tudi višje vrednosti relativne dostopne vode v tleh v maju, ki kažejo na veliko namočenost tal, so vplivale na povečano osutost krošenj bukve. Sklepamo, da ni neposredne povezave med vremenskimi spremenljivkami in osutostjo krošenj bukve, pač pa obstajajo posredni vplivi večje količine padavin na gradacijo defoliatorjev in patogenih organizmov, ki morda prispevajo k večji osutosti krošenj bukve. Za osutosti krošenj doba in smreke smo zaznali šibko občutljivost za temperaturo zraka in samo za dob tudi za vsebnost vode v tleh. Vendar pa so bile te korelacije značilne samo za posamezne mesece, brez jasnih sezonskih vzorcev. Ugotovili smo tudi veliko odzivnost osutosti krošnje bukve na količino padavin in vsebnost vode v tleh. Osutost krošenj in fenofaze doba v sledečem letu so bile korelirane, pri čemer je večja osutost krošenj prispevala k zgodnejšemu nastopu fenofaze prvih listov, splošnega rumenenja listja in dolžine vegetacijskega obdobja za dob v sledečem letu. Nismo pa ugotovili povezanosti med osutostjo krošenj in fenofazami bukve ali smreke.

Ugotavljamo, da povezava med nastopom fenofaz izbranih drevesnih vrst ter osutostjo njihovih krošenj obstaja, vendar je vrstno specifična. Izsledke te raziskave iz razmeroma majhnega območja z veliko geografsko raznolikostjo bi lahko uporabili tudi na drugih ploskvah spremljanja stanja gozdnih ekosistemov v skladu z mednarodnim programom ICP Forests v Evropi ter za več drevesnih vrst in daljše časovne nize opazovanj.

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Appendix 1: Measured parameters and measurement periods

Dodatek 1: Izmerjeni parametri in obdobja meritev

Tree species	Plot name	Meteorology					Phenology			Defoliation		
		Air temperature		Precipitation		REW						
		Measurement period	Corrected SEA[1] measurement period	Measurement period	Corrected SEA*** measurement period	Measurement period	Observation period	No. of observed trees	No. of observations	Observation period	No. of observed trees	No. of observations
Drevesna vrsta	*Ime ploskve*	*Obdobje meritev*	*Obdobje uporabe prilagojenih SEA meritev*	*Obdobje meritev*	*Obdobje uporabe prilagojenih SEA meritev*	*Obdobje meritev*	*Obdobje opazovanj*	*Št. opazovanih dreves*	*Št. opazovanj*	*Obdobje opazovanj*	*Št. opazovanih dreves*	*Št. opazovanj*
Spruce (Picea abies)	1 - Kruc manove konte	2010-2013	2004-2010	2010-2013	2004-2010	/	2004-2013	19	155	2004 - 2013	87-90	882
	6 - Kladje	2010-2013	2004-2010	2010-2013	2004-2010	2010-2013	2004-2013	19	155	2004 – 2013**	118-119 (29)**	708 (145)**
Beech (Fagus sylvatica)	2 - Fondek	2010-2013	2004-2010	2010-2013	2004-2010	2010-2013	2004-2013	20	160	2004 - 2013	100-108	1026
	5 - Borovec	2010-2013	2004-2010	2010-2013	2004-2010	2010-2013	2004-2013	20	160	2004 - 2013	63-67	649
	8 - Lontovž	2010-2013	2004-2010	2010-2013	2004-2010	2010-2013	2004-2013	20	160	2004 - 2013	118-135	1245
	9 - Gorica	2010-2013	2004-2010	2010-2013	2004-2010	/	2004-2013	20	160	2004 - 2013	51-64	584
	12 – Tratice	2010-2013	2004-2010	2010-2013	2004-2010	2010-2013	2010-2013			2009 - 2013	58-60	293
Pedunculate oak (Quercus robur)	10 - Krakovski gozd	2010-2013	2004-2010	2010-2013	2004-2010	/	2004-2012*	20	136	2004 – 2013	13-14	136
	11 - Murska šuma	2010-2013	2004-2010	2010-2013	2004-2010	2010-2013	2004-2013	19	159	2004 - 2013	32-36	335

[1] Corrected meteorological data from the nearest climatological station of the Slovene Environment Agency were used (Corrected SEA).

* in years 2011 and 2012 only first leaf unfolding (LU) was observed

** from 2004 till 2009 defoliation of spruce was assessed, in 2010 this plot was abandoned and defoliation of spruce was assessed on plot 12 – Tratice (values in the brackets). The distance between plots is 1.2 km.