MAIN PATTERNS OF VARIABILITY IN BEECH TREE-RING CHRONOLOGIES FROM DIFFERENT SITES IN SLOVENIA AND THEIR RELATION TO CLIMATE

Katarina ČUFAR1, Martin DE LUIS2, Eva BERDAJS3, Peter PRISLAN4

Abstract

Fourteen local tree-ring chronologies of beech (Fagus sylvatica L.) from different sites in Slovenia, elevations 300-1,415 m a.s.l., were constructed. Basic statistics of the chronologies (raw, standard and residual), climatic influence on tree growth, and growth variability among the sites are presented in the article. Dendroclimatological analysis showed that summer (particularly June) temperatures have negative and precipitation positive effect on tree-ring widths of beech on eleven sites in central, SE and SW Slovenia. The beech from highly elevated site in the Julian Alps above Tolmin (elevation 1200-1,450 m) showed positive response to summer temperatures. The whole variability in studied beech chronologies can be resumed in three sources of variation (principal components - PC): (PC_1) response of trees to June climate, (PC_2) altitude, and (PC_3) biogeographical differences.

Key words: beech, Fagus sylvatica, Slovenia, dendrochronology, tree-rings, local chronologies, climate

European beech (Fagus sylvatica L.) is the basic structural element of Slovenian forests. It grows in most forest associations from the lowlands up to the high mountains (MARINČEK 1987). It forms more than one third of the wood stock and its proportion is still increasing (BRUS 2005). It has recently been reported that future competitiveness of beech might be considerably reduced due to climate change (e.g. GEBLER et al. 2007) or that the changing climate might even cause a retreat of beech populations (e.g. JUMP / PEÑUELAS 2006). For Slovenia, the climate change scenario predicts a rise in temperature and more uneven distribution of precipitation associated with more frequent droughts and extreme rainfall events (BERGANT / KAJFEŽ-BOGATAJ 2005). This might affect the survival of beech, particularly on more extreme and marginal sites (e.g. DIACI 2007).

Wood forming capacity is an important indicator of tree physiology. Therefore long-term tree-ring chronologies are frequently used to evaluate current and past relationships of growth and climate in different tree species and bioclimatological units, and to estimate future prospects and possible ecological risks associated with climate change (e.g. SCHWEINGRUBER 1989). The beech is appropriate for dendroecological tree-ring studies (e.g. SCHWEINGRUBER 1990). Due to its frequency and ability to grow on sites of wide ecological variability, networks of beech tree-ring chronologies have been developed in different parts of Europe (e.g. BIONDI 1992, ROZAS 2001, DITTMAR / ZECH / ELLING...
Among others, it was found that the longevity of beech can exceed 500 years (PIOVESAN et al. 2003), which makes it even more suitable for long-term dendrochronological studies.

Tree-ring studies of beech in Slovenia have been in the last years part of different projects of the Department of Wood Science and Technology. Recently completed graduation theses contributed to the construction of local chronologies of trees (RUTAR 2003, NEKIČ 2005, ERCEK 2006, BERDAJS 2008), their prolongation with mean curves of historical buildings (KOBE 2005, ERCEK 2006), and generally contributed to our knowledge of wood formation (PRISLAN 2007).

Tree-ring data from Slovenian beech sites have also been employed to study bioclimatological units in the Eastern Alps (DI FILIPPO et al. 2007). They also proved to be useful to put the studies of wood formation within one growth period into long-term context (ČUFAR / PRISLAN / GRIČAR 2008, ČUFAR et al. 2008c).

The purpose of this study is to present the current stand of beech chronologies of the Department of Wood Science and Technology, to describe their main characteristics and their relation to climate, as well as to evaluate the differences among them. This would help to use them in different future studies with different aims.

MATERIALS AND METHODS

STUDY AREA AND WOOD FOR TREE-RING RESEARCH

The samples for local beech tree-ring chronologies originated from old-grown trees at various locations: (1) Brezova Reber, (2) Gorjanci, (3) Čermošnice, (4) Senovo, (5, 6) SE of Celje (two locations), (7) Cinkov Rog, (8) Knežja Lipa, (9) Kočevska Reka, (10) Draga, (11, 12, 13) surroundings of Tolmin (three locations), (14) Panška Reka near Ljubljana, (15) Mašun, (16) Pivka jama, and (17) Mokronog, Jelscevec (Figure 1, Table 1). Analyses were performed on discs taken from tree stems (1–4 m above ground) during regular harvesting in the 2001-2007 period.

DENDROCHRONOLOGICAL ANALYSES

Tree-ring widths were measured to the nearest 0.01 mm using TSAP/X and TSAP-Win programmes for data acquisition. The tree-ring series were visually and statistically cross-dated and compared with each other by calculating the $t_{BP}$ (t-value after BAILLIE / PILCHER 1973) using TSAP/X and TSAP-Win. We checked the intercorrelation among the tree-ring series of individual trees and finally assembled them into a local chronology for each location. Eventually, we calculated three versions of each chronology, a non-detrended, raw-data, and a detrended standard and residual chronology using the program ARSTAN (HOLMES 1994). The agreement among the chronologies was also checked by calculating the $t_{BP}$.

TREE-RING WIDTHS AND CLIMATE

The climatic influence on tree growth was studied using residual versions of the chronologies obtained by ARSTAN program (HOLMES 1994). Hereby, the individual raw tree-ring series were standardized to remove the age-related growth trends and potential disturbance or competition effects in mean ring widths. We applied a two-step procedure as recommended by COOK and PETERS (1997). First, the long-term trend was removed by fitting a negative exponential function or a regression line to each tree-ring series. Second, a more flexible detrending was done by a cubic smoothing spline with a 50% frequency response of 60 years to filter-out the effect of localized potential disturbance events and then reduce further non-climatic variance in tree-ring series. Then, autoregressive modelling of the residuals and a bi-weight robust estimation of the mean were applied (COOK / PETERS 1997).

The meteorological data used were the monthly high-resolution grids of mean temperature and precipitation for the 1901-2000 period from CRU TS 1.2 that is publicly available (http://www.cru.uea.ac.uk/) (MITCHELL et al. 2004). This database is constructed with a 10 minute resolution for the whole Europe, also including some territories from the surrounding areas; the dataset covers 11°W to 32°E longitude and 34°N to 72°N latitude. For each location of a chronology, we used the closest grid-point from this database.
Climate-growth relationships were calculated using the DendroClim2002 program through correlation function analysis (BIONDI / WAIKUL 2004), whereby the residual version of the tree-ring chronology was the dependent variable and the monthly mean temperatures and the monthly sums of precipitation for each biological year from the previous September to the current September were the regressors. The program applies a bootstrap process (GUIOT 1991) to assess the statistical significance of the correlation coefficients.

Common variability in tree-ring chronologies was represented by principal component (PC) scores (DI FILIPPO et al. 2007). Component loadings (eigenvectors), which display the pattern of association of chronologies with each component, were employed to detect groupings in the tree-ring network. Selection of PCs was guided by Kaiser’s Rule (KAISER 1992).

The spatial extent of the common signals was investigated by correlating PC scores with each local beech standard chronology. Thereafter, we looked for explanation of these different sources of variability by comparing the obtained loading components of each significant PC with general characteristics of each site of the chronology (e.g. altitude, climate, and distance from the sea).

RESULTS AND DISCUSSION
REZULTATI IN RAZPRAVA
THE CHRONOLOGIES
KRONOLOGIJE

We constructed 14 local chronologies based on at least 5 tree-ring series each. On 3 sites, the wood contained growth anomalies, therefore we could not build a chronology (Table 1). The basic statistics for raw non-detrended and detrended
ARSTAN standard and residual chronologies is given in Table 2. The results show that the chronologies were from 83 to 271 years long and spanned the 1731-2007 period. The longest chronologies were constructed for locations 13, 10, 9 and 2 (Tolmin C - Planina Kal, Draga, Kočevska Reka and Gorjanci) (Figure 2). The oldest trees were found at the sites 13, 10 and 9, where some of them aged 250 years or more. In raw chronologies, the mean ring widths varied from 1.1 to 3.0 mm and the standard deviation was 0.40 to 1.04. The mean sensitivity (MS) from residual chronologies varied from 0.15 to 0.50.

Table 1: Description of beech locations (see also Figure 1).

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Code</th>
<th>Location</th>
<th>No. of trees</th>
<th>Altitude (m)</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
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<td>Gorjanci</td>
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<td>300-600</td>
<td>45.76°</td>
<td>15.29°</td>
</tr>
<tr>
<td>3</td>
<td>CER</td>
<td>Čemerničjce**</td>
<td>5</td>
<td>300-600</td>
<td>45.66°</td>
<td>15.09°</td>
</tr>
<tr>
<td>4</td>
<td>SEN</td>
<td>Senovo**</td>
<td>5</td>
<td>300-600</td>
<td>46.01°</td>
<td>15.50°</td>
</tr>
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</tr>
<tr>
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<td>CEB</td>
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<td>300-600</td>
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<td>15.37°</td>
</tr>
<tr>
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<td>Cinkov Rog</td>
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<td>700</td>
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<td>15.01°</td>
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<td>Knežja Lipa</td>
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<td>15.00°</td>
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<td>KRE</td>
<td>Kočevska Reka</td>
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<td>Draga</td>
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<td>750</td>
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<td>14.66°</td>
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<td>Tolmin A, V Lazu</td>
<td>12</td>
<td>290-420</td>
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<td>TOB</td>
<td>Tolmin B, Pod Zagonom</td>
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<td>797-854</td>
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<td>Pivka jama</td>
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<td>Mokronog, Jelševci</td>
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<td>45.91°</td>
<td>15.20°</td>
</tr>
</tbody>
</table>

* Number of trees collected / Število vzorčnih dreves
** Tree ring chronology could not be constructed / Kronologija širin branik ni bila sestavljena

Fig. 2: The longest tree-ring chronologies (raw versions) and their replication (i.e. number of trees used to build them).

Slika 2: Najdaljše kronologije širin branik (neindeksirane verzije) in njihova pokritost (število dreves vključenih v kronologijo).
Table 2: Descriptive statistics of beech chronologies: time span and length (in years), number of trees used to build a climate. Namely, the study presented here is the first one on how the beech at different sites in Slovenia responds to climate. By June temperature and positively by June precipitation at 15 and 17 had SS greater than 0.85 and could therefore be considered representative for dendroclimatological analysis. These chronologies were based on 10 trees or more. Despite the insufficient SS and replication at the other 6 sites, we used all 14 chronologies to obtain an indication of how the beech at different sites in Slovenia responds to climate. Namely, the study presented here is the first one on the response of beech tree-rings to climate in Slovenian sites and additional sampling and analyses are planned to improve and confirm the current results.

t-values (t_{fig}) calculated to test the similarity among the chronologies showed that tree-ring variation in beech from the central and southern parts of Slovenia is governed by a common factor (Table 3), for chronologies are considered to be similar when t_{fig} ≥ 4 (e.g. LEVANIČ 1996). On the other hand, the chronologies from the surroundings of Tolmin showed nearly no similarity with the other ones. Poor replication of the chronologies from sites 11 and 12, and high elevation of the site 13 could possibly be among the main reasons for such results. It should be noted that the chronology from site 13 had been previously used in another study and that it agreed significantly with 3 beech chronologies from the high elevation Alpine sites in NE Italy (Paularo, Lateis) and in Austria (Hallstatt) (DI FILIPPO et al. 2007).

**CLIMATE / GROWTH RELATIONSHIPS**

**KLIMA IN VARIIRANJE ŠIRIN BRANIK**

Year to year tree-ring variation was negatively affected by June temperature and positively by June precipitation at

### Table 2: Descriptive statistics of beech chronologies: time span and length (in years), number of trees used to build a climate.

<table>
<thead>
<tr>
<th>Code</th>
<th>Time span</th>
<th>Length</th>
<th>No. of trees</th>
<th>Ring width Mean sensitivity</th>
<th>AC1 Mean sensitivity</th>
<th>ARSTAN chronologies</th>
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<td></td>
<td></td>
<td></td>
<td>Raw</td>
<td>stan</td>
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<tr>
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<td></td>
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<td>MS</td>
<td>AC1</td>
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<td>16</td>
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<td>1840</td>
<td>2001</td>
<td>162</td>
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<td>1883</td>
<td>2001</td>
<td>119</td>
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<tr>
<td>7</td>
<td>CRO</td>
<td>1832</td>
<td>2004</td>
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<td>1775</td>
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<td>1752</td>
<td>2004</td>
<td>253</td>
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<td>1854</td>
<td>2007</td>
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<td>1.79</td>
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</table>
Slightly less pronounced but still consistent was the positive effect of July precipitation and negative effect of July temperature. May or August precipitation and temperature had in some cases significantly positive and negative effects as well. Precipitation and temperatures of previous autumn and winter months in some cases affected tree-ring variability, too, but their influence differed from site to site.

June is an important month for growth of plants due to the longest photoperiod. As evaluated by ČUFAR et al. (2008a), June weather conditions in Slovenia can differ considerably from year to year. Mean precipitation and mean temperature in June are around 37 mm and 20°C in dry years, 236 mm and 16°C in moist and cold years, and 129 mm and 18°C in normal years.

Recent studies on wood formation in beech at site 14 near Ljubljana showed that the highest monthly amount of wood, i.e. 35% of the entire tree-ring, was produced in June (ČUFAR/PRISLAN / GRIČAR 2008, ČUFAR et al. 2008c). Other studies demonstrated that June conditions have a great effect on wood formation in Picea abies and Abies alba from different sites in Slovenia (GRIČAR 2007) and on trees from many other sites in Europe and North America (ROSSI / DESLAURIERS / ANFODILLO 2006). June conditions also proved to have crucial and temporally stable effect on tree-ring variation in oak from SE Slovenia (ČUFAR et al. 2008b).

The temperature and precipitation effect on tree-ring variation in oak was proved to be so significant and stable in time, that it could be used for reconstruction of June conditions in SE Slovenia for the last 500 years (ČUFAR et al. 2008a).

Moist and not too hot June conditions therefore positively influence tree-ring widths in beech and other tree species. June conditions are also crucial for agriculture, for example maize and other grain crops as well as for many other cultivated plants (e.g. AŽNIK / KAJFEŽ-BOGATAJ 1982).

Positive effects of precipitation and negative effect of temperatures in May, July and August indicate that the trees can use favourable conditions for increased wood production not only in June, but also in the period from May to August.

The climatic response of beech in Slovenia compared with that of SE Slovenian oak and beech from other European sites indicates that June climatic conditions at our sites are most likely optimal for beech growth and contribute less to inter-annual tree-ring variation than in other regions.

The response of trees to climate at the high elevation site 13 differs from all other sites. The tree-ring variation here is positively affected by late spring and summer temperatures, particularly by May temperature. This site has with its 1,240-1,415 m a.s.l. the highest elevation of all sites (Table 1) and the beech grows here at its altitudinal limit. At such elevation the growing season begins later than at lower elevated sites, most likely in May, and the beech here is more frequently

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Table 3: Cross-dating parameters ($t$) of raw data chronologies. Only statistically significant values of $t \geq 4$ are given.

<table>
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<tr>
<td>17</td>
<td>MOK</td>
<td>CEB</td>
<td>6.8</td>
<td>9.4</td>
<td>7.3</td>
<td>9.2</td>
<td>8.6</td>
<td>4.2</td>
<td>5.0</td>
<td>10.7</td>
<td>5.8</td>
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Chronology codes / Oznake kronologij: 2 GOR, Gorjanci; 5, CEA, Celje A; 6, CEB, Celje B; 7, CRO, Cinkov Rog; 8, KLI, Knežja Lipa; 9, KRE, Kočevska Reka; 10, DRA, Draga; 11, TOA, Tolmin A; 12, TOB, Tolmin B; 13, TOC, Tolmin C; 14, PAN, Panška Reka; 15, MAS, Mašun; 16, PIV, Pivka jama; 17, MOK, Mokronog.
affected by late-frost damage (DITTMAR et al. 2006, DI FILIPPO et al. 2007). All this could help to explain why the late spring and summer warmth promotes the tree-ring growth.

Since most of the beech sites elevated up to 1,000 m a.s.l. showed negative response to summer drought and high temperatures, and the high elevated site 13 showed an opposite pattern (i.e. positive response to summer warmth), the transition from one pattern to another possibly occurs at the elevation from 1,000 to 1,200 m a.s.l. This should also be confirmed in the near future by additional studies.

Principal component (PC) analysis indicates that the whole variability in presented beech chronologies can be resumed in three significant sources of variation, i.e. principal components PC_1, PC_2 and PC_3. PC_1 explains 49% of total
variability, showing that an important common signal exists among the chronologies. It also explains more than 50% of variability in all chronologies except the ones from the surroundings of Tolmin, sites 11, 12 and 13 (Figure 4 a). At sites 2, 5, 6, 7, 8, 9, 10, 14, 15, 16 and 17, this common signal seems to be related to common sensitivity to June temperature and precipitation (Figure 4 b).

PC_2 explains 11% of total variability, showing that another important common signal exists among the chronologies. Its importance greatly varies among the sites (Figure 4c). It highly correlates with chronology at site 13, but is also relatively important at sites 15, 9, 10, 5 and 12. This common signal seems to be at least partially explained by altitudinal gradient (Figure 4d).

Fig. 4: Principal component (PC) analysis for eleven sites in Slovenia: (a, c) loading of PC_1 and its correlation with June temperature and precipitation, (b, d) loading of PC_2 and its correlation with altitude, (e) loading of PC_3.

Slika 4: Analiza osnovnih komponent (PC) za enajst rastišč v Sloveniji: (a, c) vpliv PC_1 ter njena korelacija z junijskimi temperaturami in padavinami, (b, d) vpliv PC_2 in njena korelacija z nadmorsko višino, (e) vpliv PC_3.

Chronology codes / Oznake kronologij: 2 GOR, Gorjanci; 5, CEA, Celje A; 6, CEB, Celje B; 7, CRO, Cinkov Rog; 8, KLI, Knežja Lipa; 9, KRE, Kočevska Reka; 10, DRA, Draga; 11, TOA, Tolmin A; 12, TOB, Tolmin B; 13, TOC, Tolmin C; 14, PAN, Panška Reka; 15, MAS, Mašun; 16, PIV, Pivka jama; 17, MOK, Mokronog.
PC_3 explains 7.5% of total variability, but is important only locally (merely at sites 11 and 12) (Figure 4e). This result can be explained with location of the chronologies in different biogeographical regions with different climate conditions. PC_3 may be affected by the distance from the sea (c.f. DI FILIPPO et al. 2007). The sites 11, 12 and 13 are located on the border between the Sub-Mediterranean and Alpine phytogeographical areas (MARTINČIČ et al. 1999). These Alpine sites are connected to the 50 km distant Adriatic coast by the Soča river valley and are therefore strongly affected by the interference between the Sub-Mediterranean and Alpine climatic influence.

CONCLUSIONS

The results indicate that generally known differences among beech populations growing at various sites, forest associations and elevations in Slovenia are also reflected in response of their tree-rings to climate.

The tree-ring variation in beech at eleven sites in central, SE and SW Slovenia proved to be negatively affected by June temperature and positively by June precipitation. Similar but less pronounced effect may also have July, May and August conditions.

The climatic response of beech in SE and SW Slovenia compared with that of beech from other European sites indicates that June climatic conditions here are optimal for beech growth and contribute less to inter-annual tree-ring variation than in other European regions.

The response to June conditions mentioned above cannot be confirmed for beech from sites above Tolmin (11, 12, 13). At site 13, elevation 1,200-1,450 m a.s.l., the beech responds positively to late spring/summer temperatures.

The variation of beech tree-rings can be explained by three sources of variation, i.e. three principal components (PC). PC_1 is mainly explained by June climatic conditions, PC_2 by altitude and PC_3 possibly by climatic differences among phytogeographical regions.

The present study will hopefully contribute to better understand the physiology of beech as well as its possible flexibility and risks related to climate change in different bioclimatological units.

SUMMARY


Namen pričujočega prispeka je predstaviti trenutno stanje razvoja kronologije širin branik bukve na Oddelku za lesarstvo, njihove značilnosti, njihov odziv na klimatske dejavnike ter razlike med kronologijami z različnih območij v Sloveniji, vse to z namenom, da bi podatke kronologij v prihodnost dopolnili in jih bolje uporabili za različne študije.


Sestavili smo 14 lokalnih kronologij širin branik za nadmorske višine od 300 do 1415 m. Pri izboru osnovnih komponent (PC) smo uporabili Kaiserjevo pravilo (KAISER 1992).


Podoben pomen junijskih temperatur in padavin smo ugotovili tudi pri hrastih, predvsem gradnu (Quercus petraea) iz JV Slovenije (ČUFAR et al. 2008a, ČUFAR et al. 2008b), kjer so bile junijske razmere najpomembnejše za razlago meščene variabilnosti širin branik. Podobnost med kronologijami širin branik hrasta in bukve na osnovi rezultatov pričujočeega sestavka lahko razložimo s podobnim odzivom bukve in hrasta na junijsko klimo (ČUFAR et al. 2008b).

Bukove kronologije (verzija residual) so imele srednjo odzivnost (ang. mean sensitivity) 0.15-0.26, kar je več kot pri hrastu iz Slovenije in manj kot pri večini bukovih kronologij iz Evrope (prim. DITTMAR / ZECH / ELLING 2003). Denda okviru programske skupine Lesarstvo in programa P4-0015.

Opisani odziv ne velja za rastljača med Tolminom, kjer posebej bukve v zgornje gozdné meje na nadmorski višini 1200-1450 m kaže pozitiven odziv na temperature v času vegetacijske dobe.

Pričujoča študija naj bi pripomogla k boljšemu razumanju fiziologije bukve in odvisnosti nastanka lesa od klima, prednosti bubve in nevarnosti zaradi možnih sprememb klime v različnih bioklimatskih regijah.

Opisani odziv ne velja za rastljača med Tolminom, kjer posebej bukve v zgornje gozdné meje na nadmorski višini 1200-1450 m kaže pozitiven odziv na temperature v času vegetacijske dobe.

Avtorji se zahvaljujo javni agenciji za raziskovalno doseženo znanje, a podoben vpliv kot junijske razmere imajo temperature in padavine v maju, juliju in avgustu. Ta ugotovitev se dopolnjuje z našimi raziskavami nastanka lesa pri bukvi s Panške reke pri Ljubljani, kjer smo ugotovili, da je v juniju 2006 nastalo več kot 35 % branike, kar je največji mesečni prirastek branike (ČUFAR/ PRISLAN / GRIČAR 2008, ČUFAR et al. 2008c).

Podoben pomen junijskih temperatur in padavin smo ugotovili tudi pri hrastih, predvsem gradnu (Quercus petraea) iz JV Slovenije (ČUFAR et al. 2008a, ČUFAR et al. 2008b), kjer so bile junijske razmere najpomembnejše za razlago meščene variabilnosti širin branik. Podobnost med kronologijami širin branik hrasta in bukve na osnovi rezultatov pričujočeega sestavka lahko razložimo s podobnim odzivom bukve in hrasta na junijsko klimo (ČUFAR et al. 2008b).


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Na lokacijah, kjer je bilo podobnih podobnih, a podoben vpliv kot junijske razmere imajo tem prednosti bubve in nevarnosti znanje zaradi možnih sprememb klime v različnih bioklimatskih regijah.

Opisani odziv ne velja za rastljača med Tolminom, kjer posebej bukve v zgornje gozdné meje na nadmorski višini 1200-1450 m kaže pozitiven odziv na temperature v času vegetacijske dobe.
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