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# TREE-RING CHRONOLOGIES OF *PICEA ABIES*, *LARIX DECIDUA* AND *FAGUS SYLVATICA* ALONG ALTITUDINAL GRADIENTS

# KRONOLOGIJE ŠIRIN BRANIK DREVESNIH VRST *PICEA ABIES, LARIX DECIDUA* IN *FAGUS SYLVATICA* VZDOLŽ GRADIENTOV NADMORSKE VIŠINE

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## *Abstract / Izvleček*

**Abstract:** The dendrochronological climate signal of Norway spruce (*Picea abies*), European larch (*Larix decidua*), and European beech (*Fagus sylvatica*), among others, depends on altitude, therefore we have to collect dendrochronological data systematically for each species along altitude gradients. To this end, we established local tree-ring chronologies for the three species along two elevation gradients: (1) Kokra – Jezersko with sites at 750, 780, 950, 1200, 1250, 1380, 1600 m a.s.l., and (2) Bled – Radovna – Krma with sites at 518, 550, 580, 700, 750, 900, 950, 1000, 1200, 1400, 1600, 1760, 1900, 2040 m a.s.l. We present the main characteristics of the chronologies and the results of the dendroclimatological analyses, which show how the climatic factors influence the variation of the tree rings in dependence of altitude and species. We also present the agreement of the different chronologies in terms of standard dendrochronological parameters such as the t-value and discuss the potential use of the presented database.

**Keywords:** Norway spruce (*Picea abies*), European larch (*Larix decidua*), European beech (*Fagus sylvatica*), tree rings, dendrochronology, altitudinal gradients, climate, Slovenia

**Izvleček:** Dendrokronološki signal navadne smreke (*Picea abies*), evropskega macesna (*Larix decidua*) in navadne bukve (*Fagus sylvatica*) je med drugim odvisen od nadmorske višine, zato moramo za razumevanje dendrokronološkega signala sistematično zbirati podatke o posamezni vrsti vzdolž višinskih gradientov. V ta namen smo zbrali vzorce lesa in sestavili lokalne kronologije širin branik omenjenih treh vrst z območij vzdolž dveh gradientov: (1) Kokra – Jezersko, ki vključuje lokacije na 750, 780, 950, 1200, 1250, 1380 in 1600 m nadmorske višine, in (2) Bled – Radovna – Krma z rastišči na 518, 550, 580, 700, 750, 900, 950, 1000, 1200, 1400, 1600, 1760, 1900, 2040 m n. v. Predstavljamo glavne značilnosti kronologij in rezultate dendroklimatoloških analiz, ki so potrdile, da se podnebni dejavniki, ki vplivajo na variiranje širin branik, spreminjajo z nadmorsko višino in da je to spreminjanje širin branik različno pri posamezni drevesni vrsti. Predstavljamo tudi ujemanje različnih kronologij z vidika standardnih dendrokronoloških parametrov, kot je t-vrednost, in razpravljamo o možni uporabi predstavljene podatkovne baze.

**Ključne besede:** navadna smreka (*Picea abies*), evropski macesen (*Larix decidua*), navadna bukev (*Fagus sylvatica*), branike, dendrokronologija, gradient nadmorske višine, podnebje, Slovenija

## 1 INTRODUCTION
## 1 UVOD

Norway spruce (*Picea abies*), European larch (*Larix decidua*), and European beech (*Fagus sylvatica*) in Slovenia have particular species-specific tree-ring characteristics in relation to climatic factors which affect the importance of each species in dendrochronology. Since the climatic signal depends on altitude, the construction of local chronologies of trees from known sites along altitudi-

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nal gradients represents an important step in their dendrochronological characterization, including the issues of teleconnection (similarity of the dendrochronological signal of the same species over longer distances) and heteroconnection (similarity of the dendrochronological signal between different species).

European beech has a wide natural range and grows on a great variety of sites (Euforgen, 2022), and is important for dendroecological studies throughout Europe (e.g., Di Filippo et al., 2007; Martinez del Castillo et al., 2022). The dendrochronological signal of beech shows a variable response to climatic factors depending on altitude and latitude (Čufar et al., 2008; Di Filippo et al., 2007; Martinez del Castillo et al., 2018). In temperate zones of Central Europe, including Slovenia, lowland beech responds mainly negatively to hot and dry late spring and early summer (May, June, July) weather, while at higher elevations and cold sites it responds positively to summer temperatures (e.g., Čufar et al., 2008; Di Filippo et al., 2007). Numerous studies have also shown that frequent climatic extremes such as ice storms, late frosts, and excessive summer heat negatively affect beech growth (Bascietto et al., 2018; Decuyper et al., 2020; Gazol et al., 2019; Martinez del Castillo et al., 2022; Roženbergar et al., 2020). It is thus assumed that beech might decline at numerous sites as climate change progresses (Martinez del Castillo et al., 2022).

Beech is currently the most common forest tree species in Slovenia, accounting for 32.9% in the wood stock (ZGS, 2021). Its wood is a highly valued industrial timber for numerous uses (Čufar et al., 2017). Despite this, it is rarely found in historical objects, and we do not have long composed regional chronologies for dating (Čufar et al., 2012).

Norway spruce is one of the most important coniferous tree species with a wide distribution area (Euforgen, 2022). Basically, it is a species of cold environments, which has been widely artificially spread in Central Europe (including Austria, Germany, Czech Republic, Switzerland, Slovenia) even in lowland areas (e.g., Caudullo et al., 2016; Jansen et al., 2017; Kolář et al., 2020; Marincek et al., 2003). It is an important wood species for various uses (Straže et al., 2022), wood formation and dendroecology (e.g., Kolář et al., 2020; Martinez del Castillo et al., 2018), dendrochronology and for dating historical objects, including musical instruments (Bernabei et al., 2017; Cherubini, 2021; Wilson et al., 2004).

Norway spruce is currently the second most common forest tree species in Slovenia, accounting for 30.2% of the wood stock (ZGS, 2021). Its natural range in Slovenia is restricted to high altitudes, mainly in the Alps and the Dinaric Mountains (Brus, 2012; ZGS, 2022). Since the early 19$^{th}$ century, the species has been artificially spread throughout Slovenia, including the lowlands (ZGS, 2022), where it is currently severely affected by climate change and associated bark beetle infestations (e.g., de Groot et al., 2021).

The dendroclimatological signal of spruce is strongly influenced by local climatic conditions and varies considerably with altitude. This variability is particularly high in Slovenia, where we lack an adequate collection of chronologies for dating historical objects (e.g., Bernabei et al., 2018; Čufar et al., 2020). In Slovenia, spruce is found in numerous objects that are often difficult to date, therefore the knowledge of its signal along elevational gradients is particularly important.

European larch is a pioneer tree species, able to colonize open land on disturbed soils; it can tolerate very cold temperatures during winter. Its natural range is mainly limited to high mountains, especially the Alps (Euforgen, 2022). In Slovenia it has a share of 1.2% in the wood stock (ZGS, 2021). Its wood is highly valued for its high density and durable heartwood (Čufar, 2006; Gričar & Prislan, 2021). It is and was valued for modern and historical constructions, and can be found in many prominent buildings of the Venetian Republic (Levanič et al., 2001). Therefore, long composed tree-ring chronologies have been constructed for this species, based on wood from trees and historical constructions (Bebber, 1990; Nicolussi, 1995; Siebenlist-Kerner, 1984). Using subfossil stems preserved in bogs and glaciers it was possible to construct one of the longest multimillennial chronologies of conifers, including *Larix decidua*, *Pinus cembra* and *Picea abies*, spanning 9,111 years (7109 BC to AD 2002) (Nicolussi et al., 2009).

Larch from high elevation shows excellent teleconnection over larger areas (Levanič, 2005a; Levanič et al., 2001). However, detailed studies in Slovenia have shown that its dendrochronological signal also depends on altitude (Levanič, 2005b) which often makes the dating of historical objects made of "lowland larch" extremely difficult.

The main objective of this study is to present the tree-ring chronologies of Norway spruce (*Picea abies*), European larch (*Larix decidua*), and European beech (*Fagus sylvatica*) along two altitudinal gradients in the Kamnik-Savinja Alps and the Julian Alps, starting from the lowlands to the altitudinal limit of species distribution in the studied areas. We present (1) the constructed tree-ring chronologies and their main characteristics, (2) how climatic

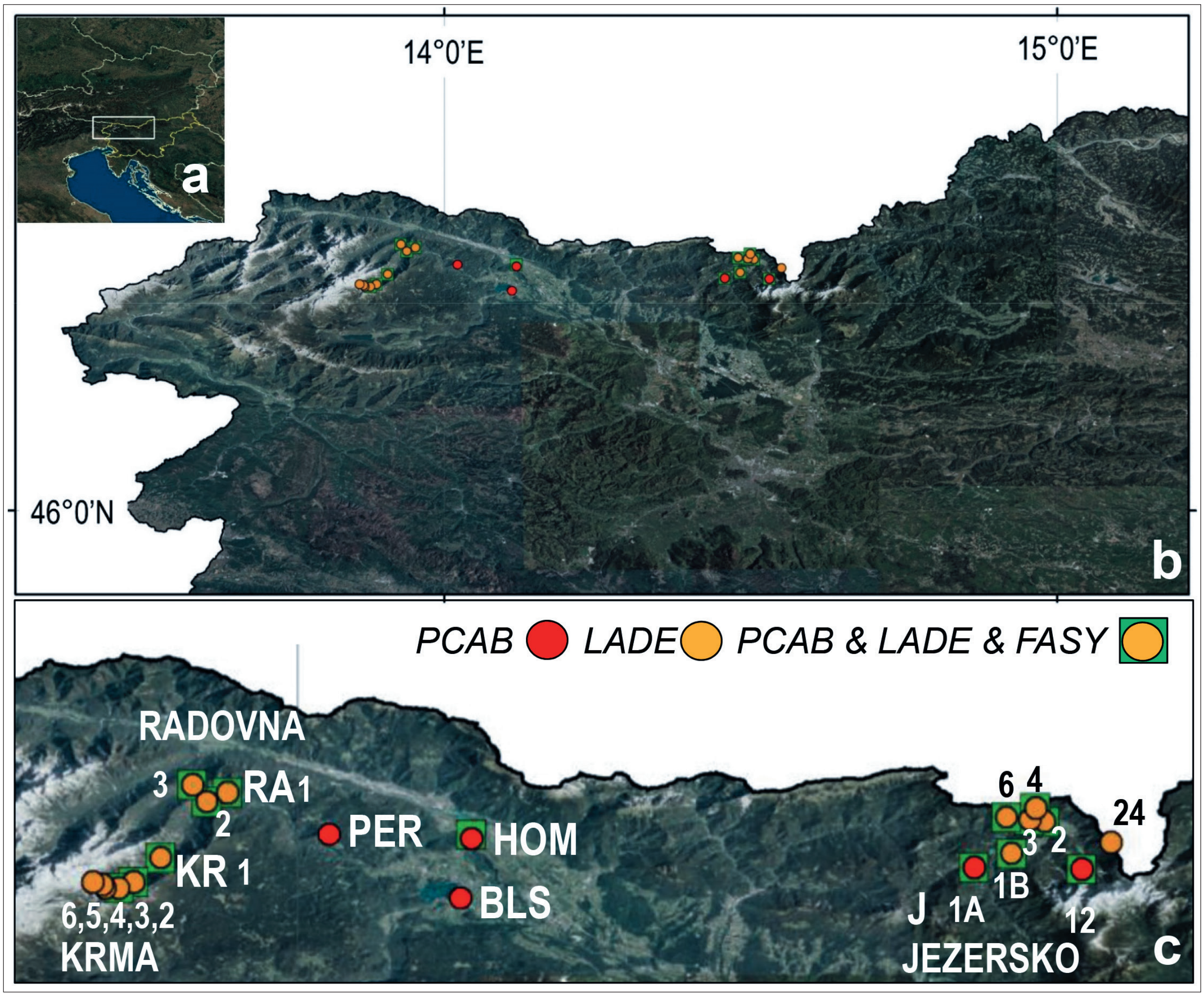



*Figure 1. Sampling areas with (a) map of Slovenia, (b) Kokra – Jezersko, and Bled – Radovna – Krma with sampling locations and (c) detailed views of site locations along the altitudinal gradients for three tree species: European beech (Fagus sylvatica) – FASY; European larch (Larix decidua) – LADE; and Norway spruce – (Picea abies), PCAB. For details see Tables 1 and 2.*
*Source of maps: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGrid, IGN, and the GIS User Community.*
*Slika 1. Mesta vzorčenja (a) zemljevid Slovenije, (b) Kokra – Jezersko in Bled – Radovna – Krma z oznakami lokacij vzorčenja ter (c) mesta vzorčenja vzdolž višinskih gradientov za tri vrste: navadno bukev (Fagus sylvatica)–FASY, evropski macesen (Larix decidua)–LADE in navadno smreko (Picea abies)–PCAB. Za podrobnosti primerjajte preglednici 1 in 2.*
*Vir zemljevidov: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGrid, IGN, and the GIS User Community.*


*Figure 2. Selected locations from two areas with similar site characteristics: (a) Kokra – Jezersko with sampling locations J02, J03, J04 and J06, and (b) Krma with sampling locations KR1, KR2, KR3 and KR4.*
*Slika 2. Izbrane lokacije z dveh območij s podobnimi rastiščnimi razmerami: (a) Kokra – Jezersko z lokacijami vzorčenja J02, J03, J04 in J06 in (b) Krma z lokacijami vzorčenja KR1, KR2, KR3 and KR4.*

factors influence tree-ring variations, (3) the variation of their dendrochronological signal, and (4) the potential of the database for future studies addressing various issues related to ecology, climate, and cultural heritage.

## 2 MATERIALS AND METHODS
## 2 MATERIAL IN METODE
### 2.1 STUDY SITES AND TREES
### 2.1 RAZISKOVALNE PLOSKVE IN DREVESA

The experimental design was based on a selection of mature dominant or codominant trees of Norway spruce, European larch, and European beech felled in the areas of Kokra – Jezersko, between the Karawanks and Kamnik-Savinja Alps, and Bled – Radovna – Krma, Julian Alps in northwestern Slovenia (Figure 1).

The sampling area Kokra – Jezersko is oriented south-east in the Kamnik-Savinja Alps. The sampling was performed on localities at 750, 780, 950, 1200, 1250, 1380, 1600 m a. s. l.) (Figures 1, 2a, Table 1).

The area Bled – Radovna – Krma included localities on 518, 550, 580, 700, 750, 900, 950, 1000, 1200, 1400, 1600, 1760, 1900, 2040 m a. s. l. (Figures 1, 2b, Table 2).

### 2.2 SAMPLE COLLECTION AND PREPARATION
### 2.2 VZORČENJE IN OBDELAVA VZORCEV

The fieldwork with the collection of samples was carried out from March until November 2019 in cooperation with forest owners, the Slovenia Forest Service, local foresters, the Triglav National Park in the area Bled – Radovna – Krma, and the Municipality of Jezersko in the area Kokra – Jezersko with corresponding permissions. We aimed to collect 15 trees per site. After regular felling we collected discs at the lower part of the trees (mainly 4 m above ground level). If the number of felled trees was not sufficient, additional samples were collected by coring from the nearby living trees. For this purpose, two cores per tree were extracted at the breast height, perpendicular to the tree axis from the bark to the pith using a Haglöf increment corer combined with a Haglöf increment borer chuck and a cordless drilling machine (Milwaukee, M18 FDD2-502X FUEL-135 Nm).

The samples were labelled with the identifying system of the codes, which contained information on sampling site, tree species, tree number and the radius.

The sampled discs and cores fixed on wooden supports were transported to the workshop and air dried. Their transversal surfaces were sanded with the belt sander using progressively finer sandpaper, from 80, 120, 180, 220, 280, and 360 grit until the tree rings and individual cells in the wood on the transversal section were perfectly visible under a stereo microscope.

The wood surface was scanned with a Mustek S-series 2400 Plus flatbed scanner with the resolution set at 1200 dpi and the images were processed with Adobe Photoshop Elements 2020. In the case of extremely narrow rings the structure of wood was additionally checked under an Olympus stereo microscope S2 11 or images were obtained with the help of confocal laser scanning microscope CLSM (Balzano et al., 2019).

### 2.3 DATA ACQUISITION AND PROCESSING
### 2.3 ZAJEM IN OBDELAVA PODATKOV

Tree-ring widths were measured using calibrated high-resolution digital photos along two radii of each tree, to the nearest 0.01 mm using the CDendro / CooRecorder 9.5 image analysis program (Cybis Elektronik, 2022 http://www.cybis.se/forfun/dendro/helpcoorecorder7/index.php). The TSAP-Win program (Frank Rinn, Heidelberg, Germany) and R Studio program using the dplR library (Bunn, 2010) were used for visual and statistical cross-dating and verification.

Cross-dated tree-ring series were assembled into local chronologies using R Studio and the dplR package (Bunn, 2008).

### 2.4 TREE RING CHRONOLOGIES AND CLIMATE
### 2.4 KRONOLOGIJE ŠIRIN BRANIK IN KLIMA

The climatic influence on tree growth was analysed using the residual version of each chronology with R Studio. For this purpose, the original tree-ring width series were standardized in a two-step procedure. First, the long-term trend was removed by fitting a negative exponential function (regression line) to each tree-ring series. Second, more flexible detrending was carried out by applying a cubic smoothing spline with a 50% frequency response of 30 years to further reduce non-climatic variance. Subsequently, autoregressive modelling of the residuals and bi-weight robust estimation of the mean were applied (Cook & Peters, 1997).

Local climatic data for calculation were obtained from the SLOCLIM data base (Škrk et al., 2021) which is a publicly available modelled climatic database which contains a daily gridded dataset of maximum and minimum temperature and precipitation data with 1×1 km spatial resolution covering the entire territory of Slovenia from 1950 to 2018. The data are available on zenodo (Škrk et al., 2020, 2021) and on the web page www.sloclim.eu. For each sampling location we extracted the climatic data of the nearest grid point and aggregated the daily data into monthly mean values.

Pearson correlation function coefficients (CFC) were calculated by using the residual version of each tree-ring chronology as a dependent variable and the regressors monthly minimum and maximum temperatures and the monthly sums of precipitation for each biological year from the previous January to current December, as well as for the past and current spring, summer, autumn and current winter for the period 1950-2018. The climate and growth relationships were calculated using the program packages library("dplR"), library("stringr"), and library("plyr"). The CFC values were considered statistically significant when $p<0.05$.

### 2.5 TELECONNECTION AND HETEROCONNECTION
### 2.5 TELEKONEKCIJA IN HETEROKONEKCIJA

To test the potential of the chronologies with regard to establishing regional chronologies for dating purposes, we made basic comparisons among the chronologies by calculating standard statistical values, including the t-value after Baillie and Pilcher (tBP) and sign test (Gleichläufigkeit–Glk) using the TSAP-Win program.

We also tested the chronologies for teleconnection (agreement between the chronologies of the same species from different sites) and for heteroconnection (agreement between different tree species from the same site).

## 3 RESULTS AND DISCUSSION
## 3 REZULTATI IN RAZPRAVA

### 3.1 TREE-RING DATA AND THE CHRONOLOGIES
### 3.1 KRONOLOGIJE ŠIRIN BRANIK

The database consists of 47 chronologies of three species along two altitudinal gradients in the Alps of Slovenia. We present their locations and time spans (Table 1 and 2). The local chronologies had average lengths of 156 (69-296) years for *European beech*, 139 (57-355) years for *Norway spruce*, and 191 (56-378) years for *European larch.*

At Kokra – Jezersko the corresponding averages (minimum-maximum) for seven *beech* chronologies were 133 (69-296) years, for seven *spruce* chronologies 135 (57-246) years, and for six *larch* chronologies 156 (56-214) years (Table 1).

At Bled – Radovna – Krma the averages (minimum-maximum) for seven *beech* chronologies were 179 (69-296) years, for 11 *spruce* chronologies 142 (81-355) years, and for nine larch chronologies 215 (84-378) years. The oldest trees were sampled in Krma (KR*) (Table 2).

### 3.2 TREE-RINGS AND CLIMATE
### 3.2 ŠIRINE BRANIK IN KLIMA

Correlation function coefficients (CFCs) for residual chronologies and monthly minimum (Tmin) and maximum temperatures (Tmax) and precipitation (PCP) (Figures 3 and 4) from the previous January to current December and from the previous and current spring, summer, autumn and current winter show that each of the species has a unique response to climate and that the response varies with elevation.

For example, in Kokra – Jezersko (Figure 3) beech shows a negative response to June temperatures (especially Tmax) and a positive response to June precipitation. The values of the CFCs generally decrease from lower to higher altitude, while at 1600 m a.s.l. we observe a positive response to temperatures in July, August and September. Spruce shows a negative response to temperatures in July and August and a positive response to precipitation in July at the same gradient, while at 1600 m a.s.l. a positive response to temperatures in May and August is observed. Larch shows a negative response to Tmax in March and a positive response to summer temperatures, while at altitudes above 1250 m a.s.l. we observe a positive response to May temperatures, especially Tmax, and a pos-

| Code / Koda | Species / Drevesna vrsta | Altitude / Nadmorska višina | Latitude / Zemljepisna širina | Longitude / Zemljepisna dolžina | Number of trees / Število dreves | Chronology Length / Kronologija Razpon | Start / Začetek | End / Konec |
|---|---|---|---|---|---|---|---|---|
| | | m | N / S | E / V | | Years / leta | Year / leto | Year / leto |
| J01A | FASY | 750 | 46.380118° | 14.457731° | 7 | 121 | 1899 | 2019 |
| J01B | FASY | 780 | 46.389231° | 14.483326° | 10 | 122 | 1898 | 2019 |
| J02 | FASY | 950 | 46.410676° | 14.505766° | 12 | 78 | 1941 | 2018 |
| J12 | FASY | 1200 | 46.378934° | 14.530259° | 18 | 130 | 1890 | 2019 |
| J03 | FASY | 1250 | 46.411992° | 14.494944° | 8 | 151 | 1869 | 2019 |
| J04 | FASY | 1380 | 46.419799° | 14.499313° | 11 | 169 | 1850 | 2018 |
| J06 | FASY | 1600 | 46.413493° | 14.479713° | 10 | 160 | 1860 | 2019 |
| J01B | LADE | 780 | 46.389231° | 14.483326° | 10 | 162 | 1858 | 2019 |
| J02 | LADE | 950 | 46.410676° | 14.505766° | 5 | 163 | 1856 | 2018 |
| J03 | LADE | 1250 | 46.411992° | 14.494944° | 4 | 153 | 1866 | 2018 |
| J04 | LADE | 1380 | 46.419799° | 14.499313° | 10 | 214 | 1805 | 2018 |
| J06 | LADE | 1600 | 46.413493° | 14.479713° | 13 | 189 | 1832 | 2020 |
| J24 | LADE | 1600 | 46.396635° | 14.550305° | 10 | 56 | 1964 | 2019 |
| J01A | PCAB | 750 | 46.380118° | 14.457731° | 18 | 145 | 1874 | 2018 |
| J01B | PCAB | 780 | 46.389231° | 14.483326° | 15 | 174 | 1846 | 2019 |
| J02 | PCAB | 950 | 46.410676° | 14.505766° | 30 | 89 | 1930 | 2018 |
| J12 | PCAB | 1200 | 46.378934° | 14.530259° | 17 | 138 | 1882 | 2019 |
| J03 | PCAB | 1250 | 46.411992° | 14.494944° | 14 | 133 | 1887 | 2019 |
| J04 | PCAB | 1380 | 46.419799° | 14.499313° | 15 | 97 | 1922 | 2018 |
| J06 | PCAB | 1600 | 46.413493° | 14.479713° | 12 | 246 | 1774 | 2019 |

*Table 1. Kokra – Jezersko, basic information on the sites and chronologies along the gradient (short code, species, altitude, latitude, longitude, number of trees, useful length of the chronology and its start and end date) for three tree species: European beech (Fagus sylvatica) – FASY: European larch (Larix decidua) – LADE, and Norway spruce (Picea abies) – PCAB.*

*Preglednica 1. Kokra – Jezersko, osnovni podatki o rastiščih in kronologijah vzdolž gradienta nadmorske višine (kratka koda, drevesna vrsta, nadmorska višina, zemljepisna širina, zemljepisna dolžina, število dreves, uporabna dolžina kronologije ter prvo in zadnje leto) za tri drevesne vrste: navadna bukev (Fagus sylvatica)–FASY, evropski macesen (Larix decidua)–LADE in navadna smreka (Picea abies)–PCAB.*

itive response to August temperatures with lower values of correlation coefficients.

Species responses along the Bled – Radovna – Krma slope differ from those at Jezersko. Beech shows a negative response to June temperatures in Hom (518 a.s.l.), while the Radovna and Krma sites respond mainly positively to May temperatures and negatively to March temperatures. Spruce at lower elevations shows a positive influence of January, February and March temperatures, while at elevations above 1000 m a positive influence of May temperatures is observed. Larch shows a negative response to Tmax in March and a positive response to temperatures in May.

| Code / Koda | Species / Drevesna vrsta | Altitude / Nadmorska višina | Latitude / Zemljepisna širina | Longitude / Zemljepisna dolžina | Number of trees / Število dreves | Chronology Length / Kronologija Razpon | Start / Začetek | End / Konec |
|---|---|---|---|---|---|---|---|---|
| | | m | N / S | E / V | | Years / leta | Year / leto | Year / leto |
| HOM | FASY | 550 | 46.401975° | 14.117478° | 15 | 146 | 1874 | 2019 |
| RA01 | FASY | 700 | 46.430571° | 13.952667° | 14 | 69 | 1951 | 2019 |
| RA02 | FASY | 750 | 46.423824° | 13.938677° | 15 | 115 | 1905 | 2019 |
| RA03 | FASY | 900 | 46.435654° | 13.928797° | 20 | 188 | 1833 | 2020 |
| KR01 | FASY | 1000 | 46.386683° | 13.907620° | 18 | 239 | 1780 | 2018 |
| KR02 | FASY | 1200 | 46.370348° | 13.888781° | 10 | 198 | 1822 | 2019 |
| KR03 | FASY | 1400 | 46.366540° | 13.879257° | 10 | 296 | 1724 | 2019 |
| RA01 | LADE | 700 | 46.430571° | 13.952667° | 20 | 174 | 1846 | 2019 |
| RA02 | LADE | 750 | 46.423824° | 13.938677° | 12 | 195 | 1824 | 2018 |
| RA03 | LADE | 900 | 46.435654° | 13.928797° | 7 | 84 | 1936 | 2019 |
| KR01 | LADE | 1000 | 46.386683° | 13.907620° | 15 | 181 | 1833 | 2013 |
| KR02 | LADE | 1200 | 46.370348° | 13.888781° | 10 | 154 | 1866 | 2019 |
| KR03 | LADE | 1400 | 46.366540° | 13.879257° | 16 | 141 | 1880 | 2020 |
| KR04 | LADE | 1600 | 46.366383° | 13.869982° | 7 | 328 | 1692 | 2019 |
| KR05 | LADE | 1760 | 46.368392° | 13.867702° | 12 | 378 | 1642 | 2019 |
| KR06 | LADE | 1900-2040 | 46.370559° | 13.861593° | 12 | 303 | 1717 | 2019 |
| HOM | PCAB | 518 | 46.359262° | 14.110083° | 11 | 110 | 1910 | 2019 |
| BLS | PCAB | 580 | 46.399197° | 14.117837° | 12 | 98 | 1922 | 2019 |
| RA01 | PCAB | 700 | 46.430571° | 13.952667° | 20 | 107 | 1913 | 2019 |
| RA02 | PCAB | 750 | 46.423824° | 13.938677° | 23 | 155 | 1864 | 2018 |
| RA03 | PCAB | 900 | 46.435654° | 13.928797° | 12 | 110 | 1909 | 2018 |
| PER | PCAB | 950 | 46.402138° | 14.021151° | 15 | 81 | 1939 | 2019 |
| KR01 | PCAB | 1000 | 46.386683° | 13.907620° | 19 | 164 | 1855 | 2018 |
| KR02 | PCAB | 1200 | 46.370348° | 13.888781° | 9 | 172 | 1848 | 2019 |
| KR03 | PCAB | 1400 | 46.366540° | 13.879257° | 15 | 116 | 1904 | 2019 |
| KR04 | PCAB | 1600 | 46.366383° | 13.869982° | 11 | 355 | 1665 | 2019 |
| KR05 | PCAB | 1760 | 46.368392° | 13.867702° | 4 | 95 | 1925 | 2019 |

*Table 2. Bled – Radovna – Krma, basic information on the sites and chronologies along the gradient (short code, species, altitude, latitude, longitude, number of trees, useful length of the chronology and its start and end date) for three tree species: European beech (Fagus sylvatica) – FASY, European larch (Larix decidua) – LADE, and Norway spruce (Picea abies) – PCAB.*
*Preglednica 2. Bled – Radovna – Krma, osnovni podatki o rastiščih in kronologijah vzdolž gradienta nadmorske višine (kratka koda, drevesna vrsta, nadmorska višina, zemljepisna širina, zemljepisna dolžina, število dreves, uporabna dolžina kronologije ter prvo in zadnje leto) za tri drevesne vrste: navadna bukev (Fagus sylvatica)–FASY, evropski macesen (Larix decidua)–LADE in navadna smreka (Picea abies)–PCAB.*

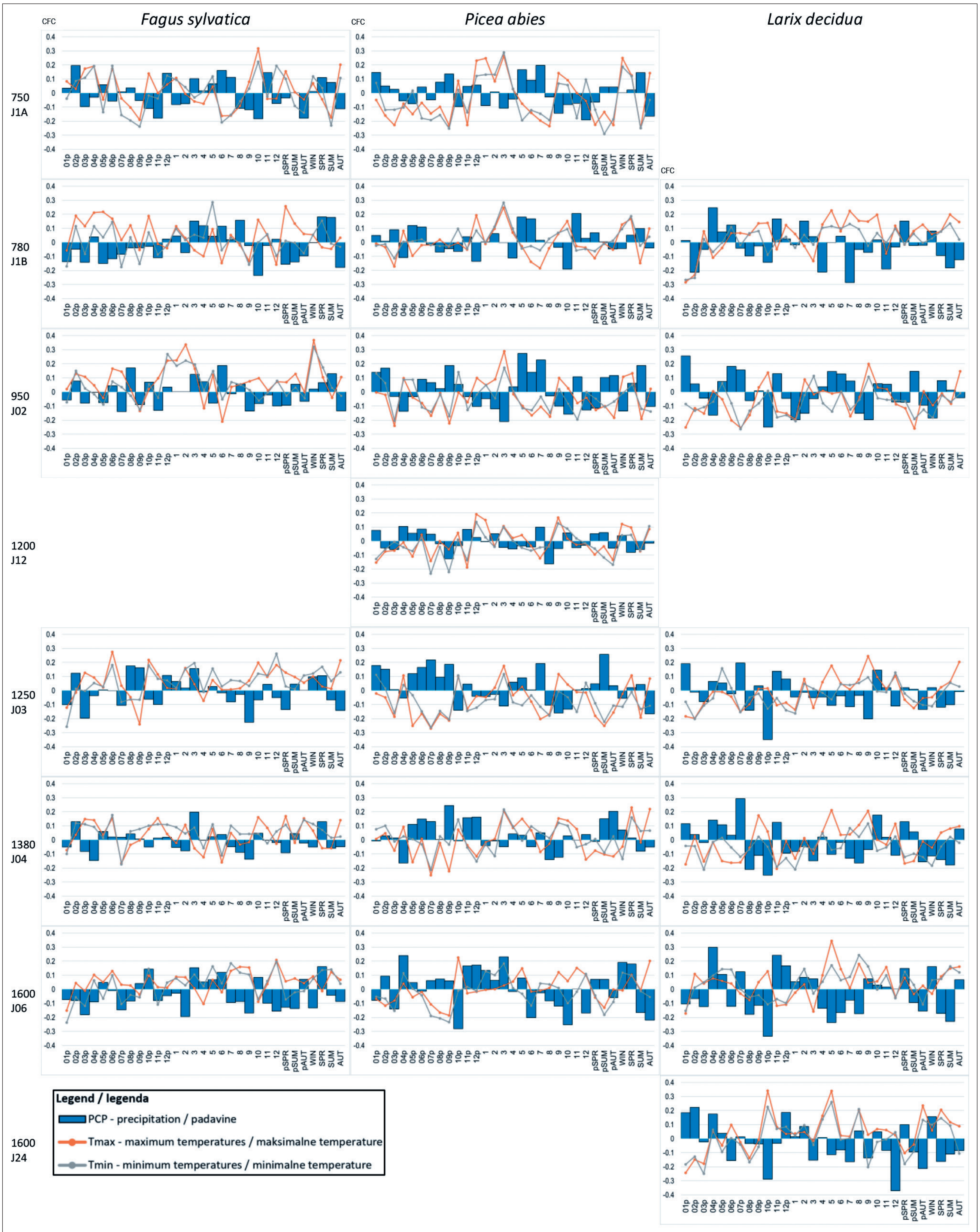
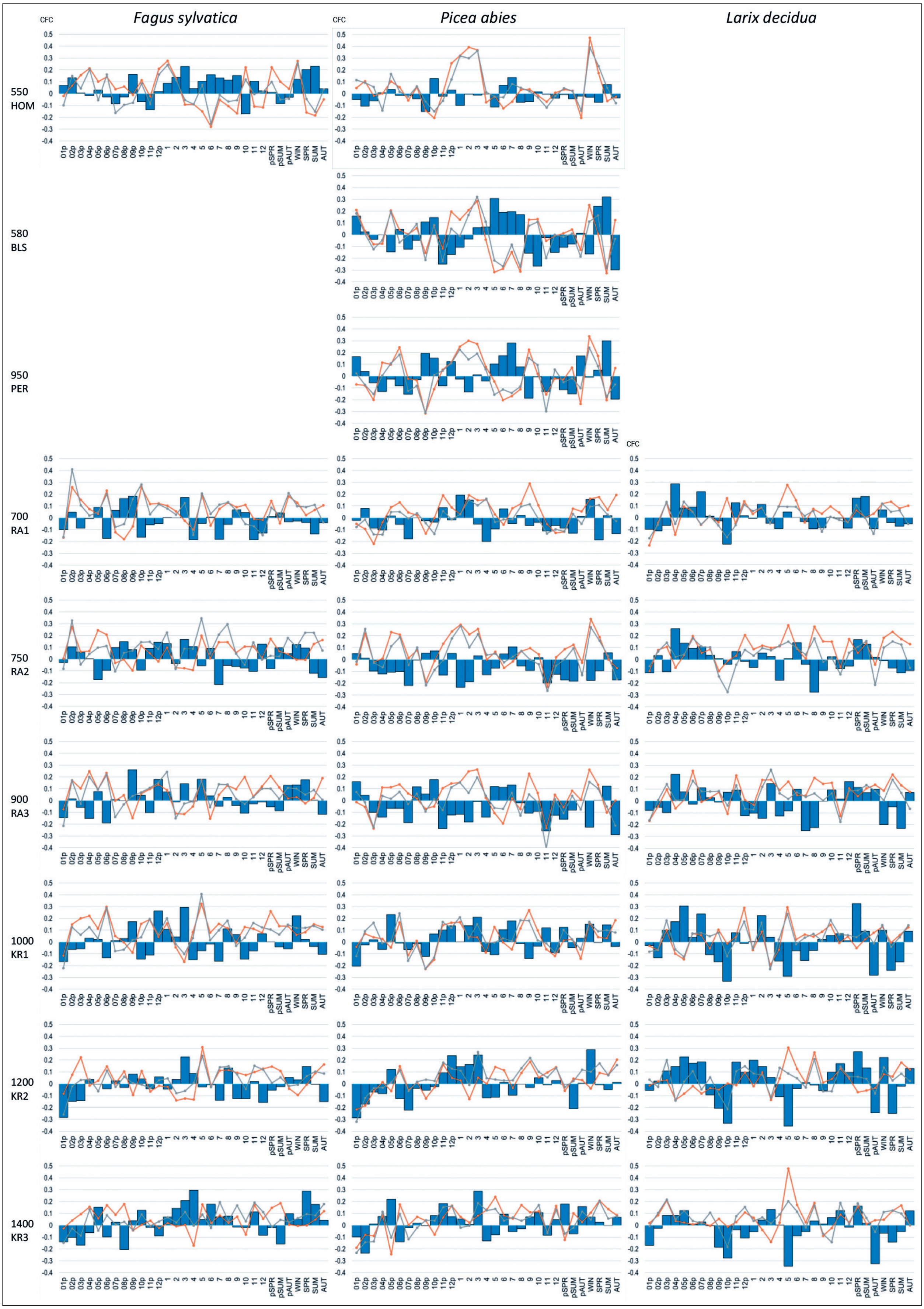



*Figure 3. Kokra-Jezersko correlation function coefficients between tree-ring width indices and climate variables (for details, see Figure 4 caption).*

*Slika 3. Kokra – Jezersko korelacijski koeficienti med indeksi širin branik in klimatskimi spremenljivkami (za podrobnosti glejte napis pod sliko 4).*


CFC
Fagus sylvatica
Picea abies
Larix decidua
550
HOM
580
BLS
950
PER
700
RA1
750
RA2
900
RA3
1000
KR1
1200
KR2
1400
KR3
01p
02p
03p
04p
05p
06p
07p
08p
09p
10p
11p
12p
pSPR
pSUM
pAUT
WIN
SPR
SUM
AUT

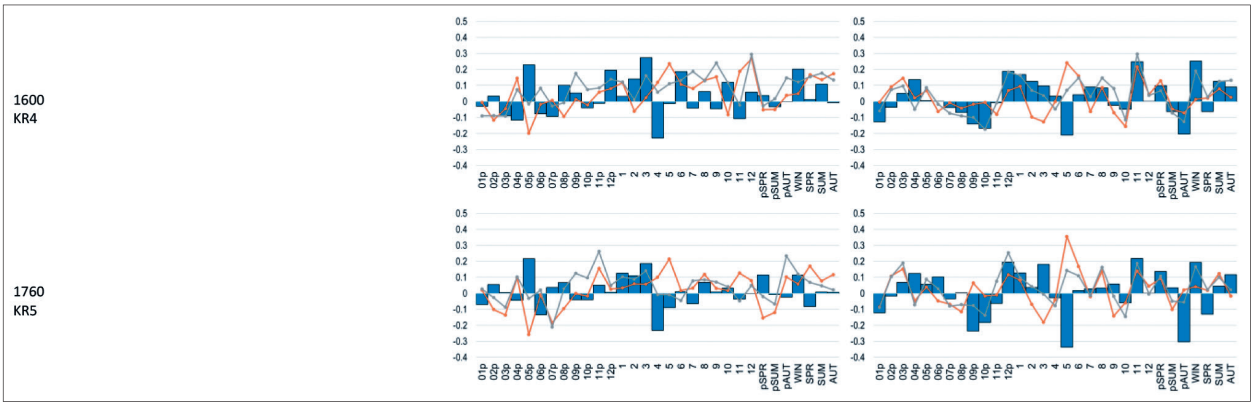



*Figure 4. Bled – Radovna – Krma: correlation function coefficients for the residual chronologies of European beech (FASY), Norway spruce (PCAB), European larch (LADE) from various elevations and monthly minimum (Tmin, gray lines) and maximum temperatures (Tmax, orange lines) and precipitation (PCP, bars) from the previous January (01p) to current December (12) and the past and current spring (pSPR, SPR), summer (pSUM, SUM), autumn (pAUT, AUT) and current winter (WIN) for the period 1950-2018. CFC values are statistically significant (p<0.05) if >0.2084 or <-0.2084 (for legend, see Figure 3).*
*Slika 4. Bled – Krma: korelacijski koeficienti med rezidualnimi verzijami kronologij za navadno bukev (FASY), navadno smreko (PCAB) in evropski macesen (LADE) ter mesečnimi minimalnimi (Tmin, sive črte) in maksimalnimi temperaturami (Tmax, oranžne črte) ter padavinami (PCP, stolpci) od preteklega januarja (01p) do decembra (12) tekočega leta, ter za preteklo in tekočo pomlad (pSPR, SPR), poletje (pSUM, SUM), jesen (pAUT, AUT) in zimo (WIN) za obdobje 1950–2018.Vrednosti koeficientov so statistično značilne (p<0,05), če so manjše od -0,2084, ali večje od 0,2084 (za legendo glejte sliko 3).*

The presented complex response to climatic parameters with similarities and differences among species and sites requires confirmation with further studies using principal component analysis (e.g., Čufar et al., 2014, 2008) or other methods.

### 3.2 COMPARISONS OF CHRONOLOGIES
### 3.2 PRIMERJAVA KRONOLOGIJ

The comparison of chronologies using tBP values shows that at the Kokra – Jezersko gradient most of the chronologies of the same species showed tBP≥4, which is considered to indicate statistically significant similarity (Table 3). Comparison of the chronologies J2, J3, J4 and J6 from locations on the same slope (Figure 2a) showed the highest similarity between nearby altitudes and smallest between the two extreme altitudes at 950 and 1600 m a.s.l. Heteroconnection, i.e. similarity between the chronologies of different species, is observed only occasionally (Table 3).

The cross-correlations at the Bled – Radovna – Krma gradient of the same species generally show some similarity between nearby locations and no similarity between lowest and highest elevations (Table 4). Highest similarity between the chronologies KR1, KR2, KR3 and KR4 could be partly explained by the location of the sites in the valley (Figure 2b) Heteroconnection is observed only occasionally (Table 4).

## 4 CONCLUSIONS
## 4 ZAKLJUČKI

The 47 tree-ring chronologies of Norway spruce (*Picea abies*), European larch (*Larix decidua*), and European beech (*Fagus sylvatica*) for two altitudinal ranges in the Kamnik-Savinja Alps and the Julian Alps, starting from the lowlands to the altitudinal limit of species distribution, show variability in tree-ring response to climate.

Correlation function coefficients (CFCs) for residual chronologies and monthly minimum (Tmin) and maximum temperatures (Tmax) and precipitation from the previous January to current December and from the previous and current spring, summer, autumn and current winter vary along the altitudinal gradient.

*Table 3. Cross-correlation values of tBP (t-value after Baillie and Picher) between Kokra – Jezersko raw chronologies (J1A-J6, maximum overlap) of Norway spruce, Picea abies, PCAB, European larch, Larix decidua, LADE, and European beech, Fagus sylvatica, FASY, from different altitudes. Values tBP≥4 with statistically significant similarity are marked.*

*Preglednica 3. Korelacijske vrednosti tBP (t-vrednost po Baillieju in Picherju) med surovimi kronologijami Kokra – Jezersko (J1A-J6, maksimalno prekrivanje) smreke, Picea abies, PCAB, evropskega macesna, Larix decidua, LADE in evropske bukve, Fagus sylvatica, FASY, z različnih nadmorskih višin. Vrednosti tBP≥4 so statistično značilne in so označene.*

| | J1A | J1B | J02 | J12 | J03 | J04 | J06 | J1B | J02 | J03 | J04 | J06 | J24 | J1A | J1B | J02 | J12 | J03 | J04 | J06 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| J1A | 100 | | | | | | | | | | | | | | | | | | | | 750 PCAB |
| J1B | 6.7 | 100 | | | | | | | | | | | | | | | | | | | 780 PCAB |
| J02 | 8.5 | 3.1 | 100 | | | | | | | | | | | | | | | | | | 950 PCAB |
| J12 | 6.5 | 6.1 | 4.8 | 100 | | | | | | | | | | | | | | | | | 1200 PCAB |
| J03 | 7.5 | 7.7 | 6.9 | 6.3 | 100 | | | | | | | | | | | | | | | | 1250 PCAB |
| J04 | 6.4 | 3.9 | 6.5 | 4.6 | 5.3 | 100 | | | | | | | | | | | | | | | 1380 PCAB |
| J06 | 6.4 | 5.6 | 1.7 | 6.7 | 5.5 | 4.0 | 100 | | | | | | | | | | | | | | 1600 PCAB |
| J1B | 2.9 | 1.7 | 0.9 | 2.4 | 2.0 | 1.6 | 5.9 | 100 | | | | | | | | | | | | | 780 LADE |
| J02 | 6.6 | 4.8 | 3.6 | 4.2 | 6.5 | 4.5 | 5.5 | 5.8 | 100 | | | | | | | | | | | | 950 LADE |
| J03 | 4.5 | 2.3 | 0.9 | 3.5 | 3.4 | 4.1 | 4.6 | 6.5 | 7.7 | 100 | | | | | | | | | | | 1250 LADE |
| J04 | 3.4 | 3.6 | 1.0 | 3.8 | 3.3 | 3.9 | 4.1 | 6.0 | 10.5 | 9.8 | 100 | | | | | | | | | | 1380 LADE |
| J06 | 1.7 | 0.9 | 1.4 | 4.4 | 1.1 | 2.2 | 6.0 | 4.3 | 3.5 | 5.5 | 4.9 | 100 | | | | | | | | | 1600 LADE |
| J24 | 1.7 | 0.9 | 0.7 | 2.1 | 1.9 | 2.8 | 3.9 | 1.6 | 1.0 | 2.8 | 2.5 | 4.2 | 100 | | | | | | | | 1600 LADE |
| J1A | 3.1 | 2.1 | 2.7 | 1.1 | 1.8 | 3.5 | 2.5 | 1.6 | 3.0 | 1.0 | 0.9 | 1.0 | 0.0 | 100 | | | | | | | 750 FASY |
| J1B | 2.2 | 2.4 | 0.7 | 0.4 | 2.1 | 2.9 | 3.1 | 1.8 | 2.4 | 1.1 | 0.8 | 1.5 | 0.0 | 5.3 | 100 | | | | | | 780 FASY |
| J02 | 3.2 | 1.2 | 2.4 | 1.6 | 2.4 | 1.8 | 2.5 | 1.2 | 1.5 | 0.6 | 0.5 | 0.1 | 1.4 | 4.7 | 4.9 | 100 | | | | | 950 FASY |
| J12 | 2.5 | 3.1 | 0.1 | 2.1 | 1.5 | 2.2 | 5.5 | 2.5 | 1.5 | 1.2 | 0.6 | 3.0 | 1.5 | 3.5 | 6.6 | 4.0 | 100 | | | | 1200 FASY |
| J03 | 3.8 | 6.2 | 2.2 | 2.6 | 2.7 | 2.7 | 6.5 | 2.5 | 4.5 | 1.5 | 3.2 | 1.4 | 1.5 | 8.1 | 4.4 | 8.5 | 6.3 | 100 | | | 1250 FASY |
| J04 | 3.3 | 1.9 | 0.7 | 2.3 | 1.9 | 3.7 | 2.8 | 2.8 | 4.5 | 1.4 | 2.9 | 1.3 | 0.8 | 6.7 | 9.2 | 7.6 | 8.2 | 7.2 | 100 | | 1380 FASY |
| J06 | 1.5 | 1.7 | 0.7 | 0.7 | 1.6 | 2.6 | 2.9 | 3.6 | 0.9 | 2.4 | 2.1 | 2.6 | 1.8 | 2.8 | 4.8 | 4.9 | 6.4 | 3.2 | 4.4 | 100 | 1600 FASY |
| | 750 PCAB | 780 PCAB | 950 PCAB | 1200 PCAB | 1250 PCAB | 1380 PCAB | 1600 PCAB | 780 LADE | 950 LADE | 1250 LADE | 1380 LADE | 1600 LADE | 1600 LADE | 750 FASY | 780 FASY | 950 FASY | 1200 FASY | 1250 FASY | 1380 FASY | 1600 FASY | |

Standard dendrochronological parameters (tBP) calculated between the chronologies from the Kokra–Jezersko gradient showed that most of the chronologies of the same species along the gradient showed similarity (tBP≥4). In the subset of chronologies from locations on the same slope the greatest similarity was found between the nearby altitudes and smallest between the two extreme altitudes at 950 and 1600 m a.s.l. Heteroconnection, i.e. similarity between the chronologies of different species, was observed only occasionally. The relationships between the Bled – Radovna – Krma chronologies seem to be more complex, and require a detailed study.

The presented results show that the relationship between tree growth and climate is not only affected by altitude and the corresponding climatic conditions. The complex relationships need to be further investigated with an appropriate methodology, such as principal component analysis.

The database shows great potential for future studies of *spruce*, *larch*, and *beech* from cold environments in the southern Alps in a time of changing climate. The local chronologies with average lengths of 156 (69-296) years for *beech*, 139 (57-355) years for *spruce*, and 191 (56-378) years for *larch* also provide a basis for the construction of master chronologies for dating cultural heritage objects. In Slovenia and in the surrounding areas such

*Table 4. Cross-correlation values of tBP (t-value after Baillie and Picher) between Bled – Radovna – Krma raw chronologies (HOM-KR6, common period 1900-2020) of Norway spruce, Picea abies, PCAB, European larch, Larix decidua, LADE, and European beech, Fagus sylvatica, FASY, from different altitudes. Values of tBP≥4 with statistically significant similarity are marked.*

*Preglednica 4. Korelacijske vrednosti tBP (t-vrednost po Baillieju in Picherju) med surovimi kronologijami Bled – Radovna – Krma (HOM-KR6, skupno obdobje 1900–2020) smreke, Picea abies, PCAB, evropskega macesna, Larix decidua, LADE, in evropske bukve, Fagus sylvatica, FASY, z različnih nadmorskih višin. Vrednosti tBP≥4 so statistično značilne in so označene.*

| | HOM | BLS | RA1 | RA2 | RA3 | PER | KR1 | KR2 | KR3 | KR4 | KR5 | RA1 | RA2 | RA3 | KR1 | KR2 | KR3 | KR4 | KR5 | KR6 | HOM | RA1 | RA2 | RA3 | KR1 | KR2 | KR3 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HOM | 100 | | | | | | | | | | | | | | | | | | | | | | | | | | | 518 PCAB |
| BLS | 7.5 | 100 | | | | | | | | | | | | | | | | | | | | | | | | | | 580 PCAB |
| RA1 | 3.4 | 3.7 | 100 | | | | | | | | | | | | | | | | | | | | | | | | | 700 PCAB |
| RA2 | 4.0 | 4.9 | 5.0 | 100 | | | | | | | | | | | | | | | | | | | | | | | | 750 PCAB |
| RA3 | 5.0 | 6.5 | 2.8 | 5.5 | 100 | | | | | | | | | | | | | | | | | | | | | | | 900 PCAB |
| PER | 5.0 | 6.3 | 5.7 | 8.5 | 9.4 | 100 | | | | | | | | | | | | | | | | | | | | | | 950 PCAB |
| KR1 | 2.1 | 2.5 | 3.2 | 7.3 | 2.3 | 4.7 | 100 | | | | | | | | | | | | | | | | | | | | | 1000 PCAB |
| KR2 | 0.6 | 0.4 | 1.6 | 3.8 | 0.1 | 3.0 | 8.8 | 100 | | | | | | | | | | | | | | | | | | | | 1200 PCAB |
| KR3 | 1.4 | 0.5 | 0.9 | 1.8 | 1.3 | 1.0 | 4.5 | 2.9 | 100 | | | | | | | | | | | | | | | | | | | 1400 PCAB |
| KR4 | 0.0 | 0.0 | 2.6 | 0.7 | 0.7 | 2.1 | 2.4 | 5.9 | 2.6 | 100 | | | | | | | | | | | | | | | | | | 1600 PCAB |
| KR5 | 1.9 | 0.5 | 3.3 | 1.5 | 0.9 | 4.0 | 2.1 | 3.9 | 2.8 | 6.7 | 100 | | | | | | | | | | | | | | | | | 1760 PCAB |
| RA1 | 1.8 | 0.9 | 0.7 | 1.8 | 0.5 | 0.1 | 3.4 | 2.1 | 0.8 | 0.1 | 1.5 | 100 | | | | | | | | | | | | | | | | 700 LADE |
| RA2 | 2.5 | 2.9 | 3.9 | 6.3 | 3.2 | 3.2 | 5.2 | 2.4 | 0.8 | 0.4 | 1.2 | 6.7 | 100 | | | | | | | | | | | | | | | 750 LADE |
| RA3 | 3.2 | 2.0 | 3.1 | 2.6 | 2.4 | 2.6 | 2.2 | 3.0 | 1.2 | 1.6 | 2.3 | 4.7 | 5.6 | 100 | | | | | | | | | | | | | | 900 LADE |
| KR1 | 0.2 | 1.7 | 0.3 | 1.3 | 0.9 | 0.5 | 3.6 | 2.6 | 2.1 | 1.8 | 1.1 | 4.3 | 3.7 | 2.6 | 100 | | | | | | | | | | | | | 1000 LADE |
| KR2 | 1.0 | 0.8 | 1.1 | 0.1 | 0.8 | 0.7 | 4.6 | 4.3 | 3.5 | 3.6 | 2.2 | 4.3 | 3.1 | 2.2 | 5.7 | 100 | | | | | | | | | | | | 1200 LADE |
| KR3 | 3.3 | 3.1 | 0.6 | 0.6 | 1.3 | 1.6 | 3.3 | 3.1 | 3.6 | 3.2 | 0.4 | 2.3 | 0.8 | 1.0 | 3.9 | 7.7 | 100 | | | | | | | | | | | 1400 LADE |
| KR4 | 1.7 | 1.7 | 0.4 | 0.7 | 1.7 | 0.7 | 3.0 | 4.9 | 1.9 | 4.5 | 1.1 | 2.0 | 2.3 | 0.2 | 3.5 | 8.9 | 11.4 | 100 | | | | | | | | | | 1600 LADE |
| KR5 | 2.0 | 0.8 | 0.2 | 0.0 | 2.2 | 0.3 | 2.9 | 5.4 | 2.3 | 3.4 | 1.4 | 2.3 | 2.5 | 0.7 | 2.6 | 8.2 | 9.0 | 16.9 | 100 | | | | | | | | | 1760 LADE |
| KR6 | 2.4 | 1.5 | 1.6 | 3.2 | 1.7 | 1.3 | 0.9 | 3.2 | 1.3 | 3.6 | 1.7 | 0.3 | 0.1 | 1.2 | 0.8 | 4.9 | 5.3 | 8.7 | 9.0 | 100 | | | | | | | | 1950 LADE |
| HOM | 2.9 | 4.3 | 0.1 | 3.1 | 2.2 | 2.8 | 2.5 | 0.7 | 1.0 | 0.4 | 1.2 | 1.1 | 1.2 | 0.4 | 2.4 | 0.3 | 1.0 | 0.5 | 0.0 | 0.6 | 100 | | | | | | | 550 FASY |
| RA1 | 2.4 | 1.7 | 2.9 | 3.8 | 2.3 | 2.1 | 1.5 | 2.0 | 0.7 | 2.0 | 2.3 | 0.8 | 1.8 | 2.2 | 1.1 | 0.6 | 0.3 | 0.4 | 1.0 | 0.3 | 2.0 | 100 | | | | | | 700 FASY |
| RA2 | 0.1 | 0.1 | 0.7 | 3.0 | 1.2 | 1.1 | 2.1 | 2.6 | 0.6 | 1.3 | 0.2 | 0.7 | 1.3 | 1.3 | 0.5 | 2.1 | 1.0 | 2.4 | 2.2 | 0.5 | 3.2 | 5.4 | 100 | | | | | 750 FASY |
| RA3 | 0.4 | 0.4 | 0.1 | 2.5 | 0.9 | 0.9 | 2.7 | 2.5 | 0.8 | 1.6 | 0.6 | 0.8 | 2.3 | 2.5 | 1.6 | 1.8 | 2.1 | 2.6 | 2.4 | 1.0 | 2.4 | 1.9 | 5.0 | 100 | | | | 900 FASY |
| KR1 | 0.8 | 1.3 | 0.7 | 2.6 | 0.8 | 0.4 | 2.9 | 3.0 | 1.1 | 1.9 | 1.2 | 1.5 | 1.7 | 0.8 | 4.0 | 2.4 | 2.8 | 2.9 | 2.4 | 1.5 | 3.5 | 3.4 | 5.4 | 7.7 | 100 | | | 1000 FASY |
| KR2 | 1.2 | 0.7 | 0.8 | 0.0 | 1.3 | 0.9 | 3.5 | 4.7 | 2.2 | 3.2 | 1.5 | 1.5 | 0.5 | 0.6 | 3.9 | 4.7 | 4.7 | 4.6 | 4.4 | 5.8 | 2.4 | 1.5 | 3.4 | 4.0 | 6.3 | 100 | | 1200 FASY |
| KR3 | 0.1 | 1.2 | 0.4 | 0.2 | 1.3 | 1.0 | 3.0 | 4.7 | 1.4 | 4.6 | 2.4 | 2.1 | 0.4 | 1.1 | 2.6 | 3.4 | 3.6 | 5.4 | 5.1 | 5.7 | 1.4 | 2.5 | 2.2 | 1.6 | 3.1 | 9.4 | 100 | 1400 FASY |
| | 518 PCAB | 580 PCAB | 700 PCAB | 750 PCAB | 900 PCAB | 950 PCAB | 1000 PCAB | 1200 PCAB | 1400 PCAB | 1600 PCAB | 1760 PCAB | 700 LADE | 750 LADE | 900 LADE | 1000 LADE | 1200 LADE | 1400 LADE | 1600 LADE | 1760 LADE | 1950 LADE | 550 FASY | 700 FASY | 750 FASY | 900 FASY | 1000 FASY | 1200 FASY | 1400 FASY | |

chronologies are particularly needed for spruce (e.g., Bernabei et al., 2017; Čufar et al., 2020).

The sampling material and data are stored in the archive of the Chair for Wood Science at the Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana.

## 5 SUMMARY
## 5 POVZETEK

Predstavljamo mrežo lokalnih kronologij navadne smreke (*Picea abies*), evropskega macesna (*Larix decidua*) in navadne bukve (*Fagus sylvatica*) vzdolž dveh gradientov nadmorskih višin na območju Kokra – Jezersko v Kamniško Savinjskih Alpah in Bled – Radovna – Krma v Julijskih Alpah v Sloveniji. Vsaka od izbranih vrst ima svoje posebnosti z vidika dendrokronologije. Bukev, ki je v Evropi in Sloveniji zelo razširjena, pogosto uporabljamo kot modelno vrsto v dendroekologiji ter za proučevanje učinkov klimatskih sprememb na vegetacijo (npr. Čufar et al., 2008; Di Filippo et al., 2007; Martínez del Castillo et al., 2019, 2022). Redkeje se srečamo z bukovimi predmeti iz preteklih obdobij, ki bi jih želeli dendrokronološko datirati (Čufar et al., 2012). Smreka je prav tako zelo razširjena v Evropi in Sloveniji. V splošnem je to vrsta hladnih okolij, ki so jo v zadnjih dvesto letih razširili tudi na manj primerna rastišča na nižjih nadmorskih višinah. Pogosto jo proučujemo kot modelno drevesno vrsto v dendroekologiji (npr. Martinez del Castillo et al., 2018). Smreka je pogosta v zgodovinskih konstrukcijah, predmetih in glasbenih inštrumentih. Dendrokronološki signal smreke po Sloveniji zelo variira, ker je v veliki meri odvisen od nadmorske višine, zato za Slovenijo še nismo uspeli sestaviti dobrih referenčnih kronologij za datiranje (npr. Bernabei et al., 2017; Čufar et al., 2020). Macesen je v Sloveniji manj razširjen kot bukev in smreka (ZGS, 2021), a je pomemben z vidika uporabe lesa, ter tudi za dendrokronološke raziskave. Kot cenjena lesna vrsta je pogost tudi v predmetih kulturne dediščine. Macesen z visokih nadmorskih višin, ki je bil uporabljen za prestižne konstrukcije Benečanov, ima dobro telekonekcijo (Levanič et al., 2001). Tudi dendrokronološki signal macesna je zelo odvisen od nadmorske višine, zato za nižje nadmorske višine še nimamo ustreznih kronologij za datiranje.

Cilj te študije je bil predstaviti (1) kronologije in njihove glavne značilnosti, (2) kako podnebni dejavniki vplivajo na variiranje širin branik, (3) kako se dendrokronološki signal posamezne vrste spreminja z nadmorsko višino in (4) kakšen potencial ima predstavljena podatkovna zbirka za bodoče raziskave na področju ekologije in kulturne dediščine.

Vzorce lesa za raziskave smo pridobili na različnih nadmorskih višinah: (1) Kokra-Jezersko, na 750, 780, 950, 1200, 1250, 1380 in 1600 m in (2) Bled – Radovna – Krma z rastišči na 518, 550, 580, 700, 750, 900, 950, 1000, 1200, 1400, 1600, 1760, 1900, 2040 m n. v.

Na vsakem rastišču smo v času redne sečnje iz posekanih dreves na nivoju 4 m od baze drevesa odžagali kolut. V kolikor število posekanih dreves ni bilo zadostno, smo iz rastočih dreves na posameznem rastišču odvzeli izvrtke.

Prečne prereze vzorcev smo gladko zbrusili in jih skenirali pri ločljivosti 1200 dpi. Na slikah smo izmerili širine branik s programom CDendro / Cooo Recorder 9.5 (Cybis Elektronik, 2022 http://www.cybis.se/forfun/dendro/helpcoorecorder7/index.php). Za vizualno in statistično sinhronizacijo smo uporabili program TSAP-Win (Frank Rinn, Heidelberg, Nemčija) in paket dplR v programu R Studio (Bunn, 2010).

Sinhronizirana in datirana zaporedja širin branik smo uporabili za sestavo lokalnih kronologij s programom R Studio z uporabo paketa dplR (Bunn, 2008). Izračunali smo tri različice kronologij: kronologijo širin branik ter standardno in rezidualno kronologijo. Za proučevanje vpliva klime na rast dreves smo uporabili rezidualno kronologijo z uporabo programa R Studio. Lokalni vremenski podatki za izračune so bili pridobljeni iz podatkovne baze SLOCLIM (Škrk et al., 2021).

Opravili smo osnovne primerjave med kronologijami z izračunom standardnih statističnih vrednosti (predvsem t-vrednost Baillie in Pilcher, tBP) s programom TSAP-Win.

Kronologije smo testirali tudi z vidika telekonekcije (ujemanje med kronologijami iste vrste z različnih lokacij) in heterokonekcije (ujemanje med kronologijami različnih drevesnih vrst z istega območja).

Za vseh 47 kronologij za 3 drevesne vrste smo predstavili natančne zemljepisne koordinate, število dreves, uporabno dolžino ter prvo in zadnje leto kronologije (preglednica 1 in 2).

Za vseh 47 kronologij 3 drevesnih vrst smo predstavili korelacijske koeficiente (CFC) med indeksi širin branik (rezidualne kronologije) ter mesečnimi minimalnimi (Tmin) in maksimalnimi temperaturami (Tmax), padavinami (PCP) od preteklega januarja do decembra tekočega leta, ter za preteklo in tekočo pomlad, poletje, jesen in zimo za obdobje 1950–2018.

Rezultati za Kokro – Jezersko (slika 3) kažejo, da se bukev negativno odziva na junijske temperature (zlasti Tmax), pozitivno pa na junijske padavine. Vrednosti korelacijskih koeficientov (CFC) se na splošno zmanjšujejo od nižje proti višji nadmorski višini, medtem ko na nadmorski višini 1600 m opažamo pozitiven odziv na temperature v juliju, avgustu in septembru. Smreka se negativno odziva na temperature julija in avgusta ter pozitivno na padavine julija na večini gradienta, medtem ko je na 1600 m nadmorske višine opazen pozitiven odziv na temperature v maju in avgustu. Macesen kaže negativen odziv na Tmax v marcu in pozitiven odziv na poletne temperature, medtem ko na nadmorski višini nad 1250 m opažamo pozitiven odziv na majske temperature, zlasti Tmax, in pozitiven odziv na avgustovske temperature z nižjimi vrednostmi korelacijskih koeficientov.

Rezultati na območju Bled – Radovna – Krma se razlikujejo od rezultatov na Jezerskem. Bukev kaže negativen odziv na junijske temperature na Homu (518 m n. v.), medtem ko se na rastiščih v Radovni in Krmi drevesa odzivajo večinoma pozitivno na majske temperature in negativno na marčevske.

Smreka na nižjih nadmorskih višinah kaže pozitiven odziv na januarske, februarske in marčevske temperature, medtem ko je na nadmorskih višinah nad 1000 m opazen pozitiven vpliv majskih temperatur. Macesen kaže negativen odziv na Tmax v marcu in pozitiven odziv na temperature v maju.

Ker je odziv različnih vrst na različnih nadmorskih višinah na dveh območjih zelo kompleksen, bi bilo dobljene podatke treba analizirati še z drugimi metodami, na primer z analizo glavnih komponent (npr. Čufar et al., 2008, 2014).

Navzkrižne korelacije z izračunom parametra tBP (kjer tBP≥4 pomeni statistično značilno podobnost), kažejo, da je na Jezerskem večina kronologij vsaj v določeni meri podobnih (tBP≥4) (preglednica 3). Primerjava kronologij J2, J3, J4 in J6 z lokacij z enako ekspozicijo (slika 2a) je pokazala največjo podobnost med bližnjimi nadmorskimi višinami in najmanjšo med dvema skrajnima nadmorskima višinama na 950 in 1600 m. Heterokonekcija, tj. primerjava kronologij različnih vrst, je pokazala, da imajo različne vrste na isti lokaciji podoben dendrokronološki signal samo v posameznih primerih (preglednica 3).

Korelacije med kronologijami vzdolž gradienta Bled – Radovna – Krma kažejo nekaj podobnosti iste vrste na bližnjih lokacijah. Med kronologijami z najnižjih in najvišjih nadmorskih višin pa ni bilo podobnosti v dendrokronološkem signalu (preglednica 4). Najbolj so si bile podobne kronologije KR1, KR2, KR3 in KR4, kar bi lahko delno pojasnili z lego rastišč v isti dolini (slika 2b). Podobnost dendrokronoloških signalov med vrstami (heterokonekcija) je bila zabeležena le v nekaj primerih (preglednica 4).

Predstavljeni rezultati kažejo, da na rast (variiranje širin branik) ne vplivajo le nadmorska višina in pripadajoče podnebne razmere. Kompleksne odnose med kronologijami bi bilo treba dodatno raziskati.

Prikazani rezultati kažejo na velik potencial podatkovne zbirke za prihodnje študije dendrokronoloških posebnosti vrst navadne smreke (*Picea abies)*, evropskega macesna (*Larix decidua)* in navadne bukve (*Fagus sylvatica)* iz hladnih okolij v južnih Alpah v spreminjajočem se podnebju. Lokalne kronologije, ki so v povprečju dolge 156 (69-296) let za bukev, 139 (57-355) za smreko in 191 (56-378) let za macesen, predstavljajo tudi osnovo za izdelavo sestavljenih referenčnih kronologij, ki jih zlasti za smreko potrebujemo za datiranje lesenih predmetov kulturne dediščine (prim. Čufar et al., 2020).

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