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ASSESSING CLIMATE-GROWTH RELATIONSHIPS WITH DAILY AND MONTHLY OBSERVATIONAL AND GRIDDED METEOROLOGICAL DATA

PRIMERJAVA KORELACIJ ŠIRIN BRANIK Z DNEVNIMI IN MESEČNIMI IZMERJENIMI IN MODELIRANIMI METEOROLOŠKIMI PODATKI

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Abstract / Izvleček

Abstract: We compared climate-growth relationships by correlating tree-ring variation with daily and monthly meteorological data obtained from the stations of the Slovenian Environment Agency (ARSO) and modelled data from the SLOCLIM database. Tree-ring width series for analyses were obtained from previously collected European beech (*Fagus sylvatica*) tree-ring data from 30 sites all over Slovenia. Climate-growth correlations were calculated to evaluate whether daily meteorological data exhibits stronger correlations than monthly data. We also compared the maximum correlation coefficients using meteorological station data and gridded SLOCLIM data. The analysis was conducted using the *dendroTools* R package, incorporating data on daily and monthly average air temperatures and precipitation sums from the period 1960–2018. Our findings revealed significantly higher maximum correlation coefficients for daily data compared to monthly data, underscoring the importance of using daily data, particularly for precipitation. However, no significant difference was observed between maximum correlation coefficients using the meteorological station and modelled data, and the difference did not change significantly with increasing altitude.

Keywords: observational data, gridded data, tree rings, correlation analysis, dendroclimatology

Izvleček: V raziskavi smo primerjali korelacije med širinami branik in dnevnimi oziroma mesečnimi meteorološkimi podatki, pridobljenimi iz meteoroloških postaj (ARSO) ali iz modelirane baze SLOCLIM. Uporabili smo podatke o dnevnih in mesečnih povprečnih temperaturah zraka in vsotah padavin za obdobje 1960–2018. V analize smo vključili 30 kronologij širin branik navadne bukve (*Fagus sylvatica*) iz celotne Slovenije. Raziskali smo tudi, kako na korelacije vpliva uporaba podatkov iz meteoroloških postaj ali iz baze SLOCLIM. Naše ugotovitve so pokazale značilno višje maksimalne korelacijske koeficiente, ko smo uporabili dnevne meteorološke podatke, kot če smo uporabili mesečne. Glede na to je priporočljiva uporaba dnevnih podatkov v dendroklimatoloških analizah, zlasti pri padavinah. Pri primerjavi korelacij s podatki iz meteoroloških postaj in modeliranimi podatki nismo ugotovili statistično značilnih razlik. Razlike med uporabo dnevnih in mesečnih podatkov ter podatkov iz dveh baz se z nadmorsko višino rastišč bukve niso značilno spreminjale.

Ključne besede: meteorološki podatki, modelirani podatki, branike, korelacijska analiza, dendroklimatologija

1 INTRODUCTION
1 UVOD

The use of meteorological data to explain variations in tree-ring widths has long been a cornerstone of dendrochronology, with traditional analyses relying on monthly data. However, over the past decade, authors have begun to emphasize the importance of daily data (Beck et al., 2013; Liang et al., 2013; Pritzkow et al., 2014), which has led to the increasing use of daily meteorological datasets (Castagneri et al., 2015; Kaczka et al., 2017). Daily data better captures weather hazards which last several days such as heatwaves, heavy rainfall events or sudden frost, which significantly affect the formation of tree rings. These effects can remain obscured in monthly averages. This is espe-

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cially relevant for precipitation data, which has an unpredictable occurrence pattern with low autocorrelation. Daily meteorological data also have a stronger relation to phenological phases (Kaczka et al., 2017), as the growth of a tree is not confined to the first and last day of a calendar month (Nagavciuc et al., 2019). Recently, a study by Jevšenak (2019) examined the question of the importance of using daily data in tree-ring analysis, and reported that the correlation coefficients calculated using the daily data compared to monthly data are on average by 0.076 higher for precipitation and 0.060 for air temperature data. However, these differences were generally not statistically significant, although still important with regard to capturing stronger climate signals.

Gridded meteorological series with daily resolution are less common and not available in all regions worldwide. However, high resolution gridded climate datasets have already been developed regionally, e.g. for Spain (Serrano-Notivoli et al., 2017, 2019), Norway (Lussana et al., 2018), Africa (Chaney et al., 2014) and certain large areas, e.g. E-OBS, ERA5, CHELSA, and the Berkeley Earth climate dataset. E-OBS is a commonly used daily gridded land-only observational dataset covering Europe, with a spatial resolution of 0.1° x 0.1° and 0.25° x 0.25° (Haylock et al., 2008). ERA5 is a global climate reanalysis dataset providing hourly estimates of atmospheric, land-surface and sea-state parameters from 1940, with a spatial resolution of 0.25° x 0.25° (or 0.1° for ERA5-Land) (Copernicus Climate Change Service, 2023). CHELSA is also global downscaled climate dataset with climate layers for various time periods and variables and a spatial resolution of 1 km (Karger et al., 2017). The Berkeley Earth climate dataset provides high-resolution land and ocean time series data and gridded temperature data from 1850 (Rohde & Hausfather, 2019). These datasets provide meteorological data for evenly spaced locations across a defined area, overcoming the limitations of station-based datasets, which are sometimes incomplete and have low spatial resolution.

In Slovenia, the Slovenian Environment Agency (ARSO) provides nationwide daily meteorological data collected from meteorological stations, with the earliest records dating back to 1850 (Nadbath, 2015). The distribution of these stations is uneven, with a higher density found in urban areas and at lower altitudes, while more forested regions have limited coverage. In recent years, there has been a significant decline in the number of traditional meteorological stations with observers, while the number of automatic meteorological stations has increased (Nadbath, 2015). All the data is being regularly validated and is publicly available. Although such data is of great value, there are still some downsides. For example, the data provided by the stations is of varying length and often partly incomplete. Moreover, many stations have been relocated in the past, resulting in altitudinal variations and corresponding climate discrepancies. However, these issues have been resolved through the homogenization of temperature and precipitation data, which can be obtained upon request. For dendrochronological studies, access to a comprehensive and consistent dataset is essential to ensure accurate climate reconstructions or climate-related dendroecological investigations. The SLOCLIM – Slovenian Modelled Climate Database was created (Škrk et al., 2021) to address these challenges, using available measurement data from ARSO, incorporating latitude, longitude, altitude and distance from the coast. Generalized linear mixed models (GLMMs) and generalized linear models (GLMs) were applied in the calculation process. The dataset has a spatial resolution of 1 x 1 km and contains daily data on maximum and minimum air temperatures, as well as precipitation amounts for the period 1950-2018. It offers modelled local meteorological data, ensuring continuous coverage without missing values.

The aim of this study was to evaluate whether daily meteorological data better explains the climate-growth relationship compared to monthly data, as daily data offers more precise weather information and is less constrained by temporal averaging. Our first hypothesis was that daily meteorological data will yield significantly stronger climate-growth correlations than monthly data, and differences will be greater for precipitation data. To test this, we employed selected sites from a Slovenian tree-ring database of European beech (*Fagus sylvatica*) (Čufar et al., 2008a; Dolar et al., 2023), the predominant tree species in Slovenia, comprising approximately 33% of the country's wood stock (Skudnik et al., 2021). The extensive coverage of tree-ring data from beech across Slovenia also provides a robust foundation for our analysis.

Additionally, we sought to compare data derived from traditional meteorological stations with that obtained from a gridded dataset, i.e. SLOCLIM, which feature higher spatial resolution and more comprehensive data. We hypothesized that gridded meteorological data for a given site explain the influence of weather conditions on the variation of tree-ring widths better than the commonly used data from meteorological stations (Hypothesis 2). Notably, there is a lack of studies that have systematically compared data from meteorological stations with gridded datasets in the context of dendrochronological research. This comparison is critical for understanding how different data sources influence dendrochronological analysis.

We further hypothesized that at higher altitudes the differences in maximum correlation coefficients between gridded and observational meteorological data, as well as between daily and monthly data, would be more pronounced (Hypothesis 3). This is attributed to the shorter growing season at higher altitudes, making daily data more significant than monthly data. Additionally, meteorological stations are predominantly located at lower altitudes, with fewer stations at higher altitudes, and we thus expected that the altitudinal correction of meteorological data should reveal stronger climate-growth effects.

2 MATERIALS AND METHODS
2 MATERIALI IN METODE
2.1 TREE-RING CHRONOLOGIES
2.1 KRONOLOGIJE ŠIRIN BRANIK

Tree-ring data of selected European beech (*Fagus sylvatica*) sites in Slovenia from the collection of the Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana (Čufar et al., 2008a; Dolar et al., 2023) were used in this study. The data contains raw tree-ring measurements from 30 sites across Slovenia with altitudes ranging between 230 and 1330 m a.s.l. (Figure 1, Table 1). Sites are located in three different climatic zones: Subcontinental, Subalpine, and Sub-Mediterranean. For each site, we calculated first-order autocorrelation (AR1), Gleichläufigkeit coefficient (%GLK) and mean interseries correlation (rbar) (Table 2). AR1 represents the impact of growth from the previous to the current year (Fritts, 1976). High positive values close to 1 indicate strong positive

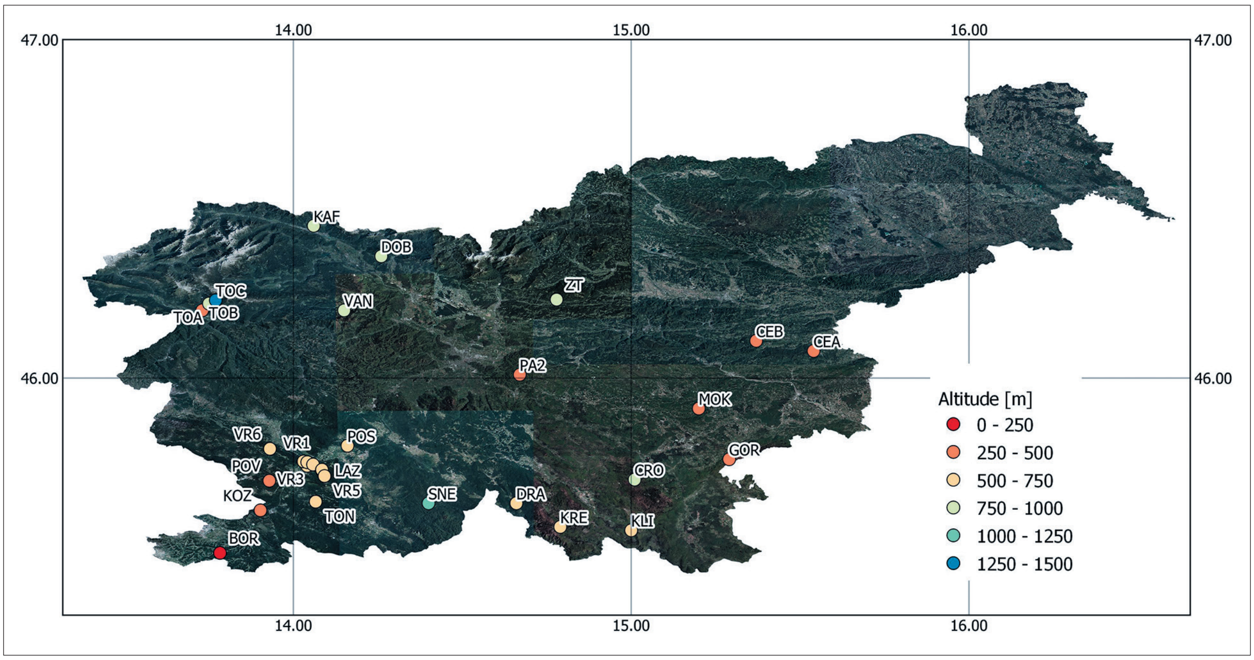

Figure 1. Selected European beech (*Fagus sylvatica*) sites for tree-ring analyses in Slovenia with respective altitudes in metres above sea level.

Slika 1. Izbrane lokacije s kronologijami širin branik navadne bukve (*Fagus sylvatica*) in njihove nadmorske višine.

Table 1. Basic site information for chronologies: altitude (m a.s.l.) (ALT), latitude (LAT), longitude (LON), ARSO nearest meteorological station (ARSO MS), mean annual air temperature (TAVG), annual precipitation sum (PCP). ARSO – data from Slovenian Environment Agency; SLOCLIM (Škrk et al., 2021). Meteorological data is calculated for the period 1960-2018.
Preglednica 1. Osnovni podatki o rastiščih: nadmorska višina (m) (ALT), zemljepisna širina (LAT), zemljepisna dolžina (LON), kronologiji najbližja ARSO meteorološka postaja (ARSO MS), povprečna letna temperatura zraka (TAVG), letna količina padavin (PCP). ARSO – podatki Agencije Republike Slovenije za okolje; SLOCLIM (Škrk et al., 2021). Meteorološki podatki so izračunani za obdobje 1960–2018.

Code / Oznaka	ALT	LAT	LON	ARSO MS	TAVG (ARSO) [°C]	PCP (ARSO) [mm]	TAVG (SLOCLIM) [°C]	PCP (SLOCLIM) [mm]
CEA	450	46.1	15.5	BIZELJSKO	10.4	1031	10.2	955
CEB	450	46.1	15.4	MALKOVEC	10.4	1126	9.5	1033
CRO	1000	45.7	15.0	KOČEVJE	8.8	1502	8.5	1331
DOB	1000	46.4	14.3	BRNIK–LETA-LIŠČE	9.0	1344	9.0	1515
DRA	750	45.6	14.7	BABNO POLJE	6.5	1688	7.9	1569
GOR	450	45.8	15.3	MALKOVEC	10.4	1126	7.9	1293
KAF	950	46.5	14.1	KREDARICA	-1.1	2025	6.8	1656
KLI	531	45.6	15.0	KOČEVJE	8.8	1502	9.2	1373
KRE	568	45.6	14.8	KOČEVJE	8.8	1502	8.3	1524
MOK	400	45.9	15.2	MALKOVEC	10.4	1126	9.6	1068
PA2	380	46.0	14.7	LJUBLJANA–BEŽIGRAD	10.6	1390	9.6	1215
POS	640	45.8	14.2	POSTOJNA	9.1	1557	9.6	1449
SNE	1100	45.6	14.4	BABNO POLJE	6.5	1688	7.3	1709
TOA	355	46.2	13.7	KREDARICA	-1.1	2025	11.0	1991
TOB	821	46.2	13.8	KREDARICA	-1.1	2025	8.2	2015
TOC	1328	46.2	13.8	KREDARICA	-1.1	2025	7.0	2010
VAN	1000	46.2	14.2	VOJSKO	6.6	2379	7.9	1879
KOZ	380	45.6	13.9	GODNJE	11.3	1411	11.1	1167
LAZ	650	45.7	14.1	POSTOJNA	9.1	1557	9.3	1382
POT	690	45.7	14.0	POSTOJNA	9.1	1557	9.2	1401
POV	500	45.7	13.9	GODNJE	11.3	1411	10.7	1236
TON	590	45.6	14.1	POSTOJNA	9.1	1557	9.8	1269
VR1	570	45.8	14.0	POSTOJNA	9.1	1557	10.0	1353
VR2	615	45.8	14.0	POSTOJNA	9.1	1557	9.5	1383
VR3	690	45.7	14.1	POSTOJNA	9.1	1557	9.4	1395
VR4	638	45.7	14.1	POSTOJNA	9.1	1557	9.3	1382
VR5	650	45.7	14.1	POSTOJNA	9.1	1557	8.9	1404
VR6	515	45.8	13.9	GODNJE	11.3	1411	10.3	1398
ZT1	900	46.2	14.8	KRVAVEC	3.6	1476	6.8	1207
BOR	230	45.5	13.8	GODNJE	11.3	1411	12.0	1148

Table 2. Basic characteristics of the tree-ring width chronologies of European beech: first-order autocorrelation (AR1), Gleichläufigkeit coefficient (%GLK), mean interseries correlation (rbar).

Preglednica 2. Osnovni podatki o izbranih kronologijah navadne bukve: avtokorelacija prve stopnje (AR1), koeficient ujemanja Gleichläufigkeit (% GLK), drseča korelacija med zaporedji širin branik kronologije (rbar).

Code / Oznaka	Number of trees / Število dreves	First year / Prvo leto	Last year / Končno leto	%GLK	rbar	AR1
BOR	13	1939	2022	0.75	0.43	0.62
CEA	5	1840	2001	0.69	0.45	0.82
CEB	4	1883	2001	0.66	0.30	0.74
CRO	6	1831	2004	0.69	0.47	0.70
DOB	12	1840	2013	0.63	0.33	0.72
DRA	7	1752	2004	0.67	0.38	0.75
GOR	11	1830	2005	0.65	0.33	0.73
KAF	7	1859	2010	0.63	0.30	0.83
KLI	6	1845	2004	0.69	0.48	0.62
KOZ	13	1935	2022	0.69	0.28	0.68
KRE	7	1775	2004	0.61	0.29	0.80
LAZ	17	1921	2020	0.66	0.45	0.50
MOK	27	1854	2007	0.64	0.34	0.65
PA2	7	1911	2020	0.65	0.33	0.68
POS	8	1840	2007	0.63	0.24	0.74
POT	18	1886	2020	0.66	0.44	0.72
POV	13	1919	2022	0.69	0.37	0.67
SNE	24	1844	2008	0.60	0.25	0.72
TOA	7	1880	2001	0.70	0.29	0.76
TOB	4	1924	2001	0.77	0.43	0.74
TOC	10	1731	2001	0.66	0.32	0.74
TON	7	1911	2021	0.62	0.19	0.73
VAN	16	1927	2016	0.58	0.17	0.80
VR1	7	1914	2014	0.71	0.47	0.51
VR2	4	1928	2014	0.74	0.47	0.72
VR3	5	1927	2014	0.66	0.36	0.77
VR4	4	1889	2014	0.64	0.18	0.76
VR5	5	1872	2015	0.66	0.32	0.70
VR6	4	1910	2014	0.67	0.39	0.75
ZT1	10	1896	2021	0.68	0.43	0.68

autocorrelation, reflecting stronger lag effects related to previous tree-ring growth. GLK is a non-parametric measure of growth similarity when comparing two tree-ring series (Speer, 2010). GLK can reach a maximum of 100, indicating a complete agreement between two series, while values above 60 are usually considered to indicate good agreement (Geijer et al., 2024). Rbar represents the average correlation between individual tree-ring chronologies within each site (Cook & Kairiukstis, 2013), where higher values represent a stronger underlying common signal. The raw tree-ring data was detrended using the *detrend()* function from the dplR package, using a spline with a 50% frequency cutoff response at 32 years (Popa et al., 2024). We used pre-whitening to remove biological trends and temporal autocorrelation from each tree-ring width series. Finally, we built 30 site chronologies by robust bi-weight averaging of individual detrended tree-ring width series, used in subsequent analyses.

2.2 METEOROLOGICAL DATA

2.2 METEOROLOŠKI PODATKI

For each site, daily and monthly meteorological data was extracted based on the shortest distance between the site and the location of meteorological stations or grid points. For the modelled meteorological data, the SLOCLIM database was used (Škrk et al., 2021) for the period 1960-2018, extracting daily maximum (TMAX) and minimum air temperature (TMIN), and daily precipitation (PCP). The same daily data (TMAX, TMIN, PCP) were extracted from the Slovenian Environment Agency's observational database (ARSO, 2024), considering only the nearest meteorological stations that have a complete dataset for the period from 1960 to 2018. The period from 1960 to 2018 was chosen because it offers comprehensive meteorological data coverage from both ARSO and SLOCLIM. The mean air temperature (T) was calculated as the average of the maximum and minimum temperature. The differences in monthly values between ARSO and SLOCLIM datasets for both temperature and precipitation were also computed.

As shown in Figure 2, the average distance from the chronology site to the nearest meteorological station provided by the Slovenian Environment Agency (ARSO) was 15044 m (± 6405.2 m), whereas

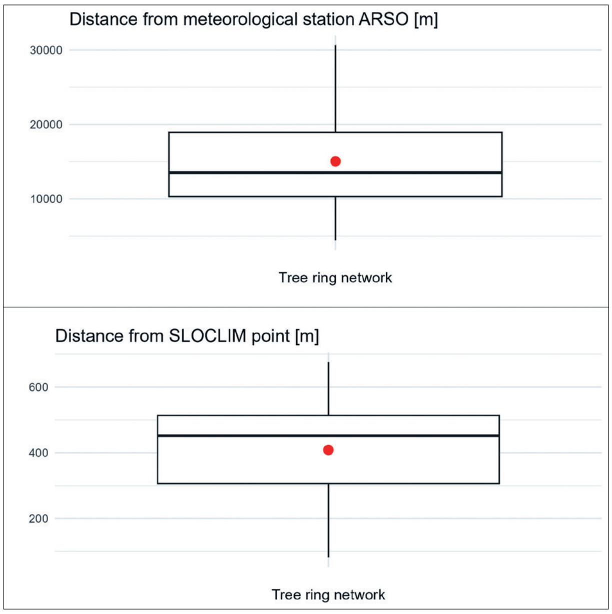

Figure 2. The boxplots of distances between site chronologies and the nearest meteorological station (ARSO) or gridded point (SLOCLIM). The red dots represent the average distance.
Slika 2. Okvir z ročaji za razdalje med lokacijami kronologij in najbližjo meteorološko postajo (ARSO) ali točko na mreži modeliranih podatkov (SLOCLIM). Rdeči piki predstavljata povprečno razdaljo.

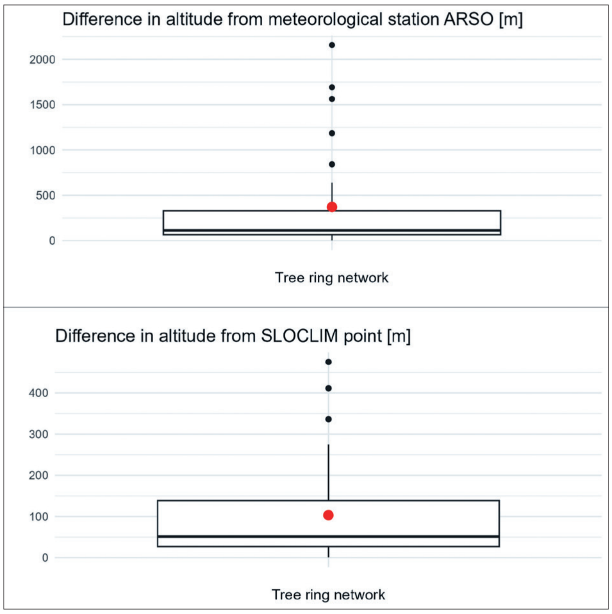

Figure 3. Difference between the altitude of the chronology site and the altitude of the ARSO meteorological station or gridded point (SLOCLIM). The red dots represent the average distance.
Slika 3. Okvir z ročaji za razlike med nadmorskimi višinami lokacij kronologij in nadmorskimi višinami najbližjih meteoroloških postaj (ARSO) ali točke na mreži modeliranih podatkov (SLOCLIM). Rdeči piki predstavljata povprečno razliko.

the average distance to the modelled climate data from SLOCLIM was only 409 m (± 141.6 m). This indicates the often-discussed inadequate spatial coverage of meteorological datasets in contrast to gridded datasets, underscoring their limited ability to accurately represent local climate conditions (e.g. Škrk et al., 2021).

The average difference between the altitude of a chronology site and the altitude of the nearest meteorological station was 370 m (± 559.1 m), while the average difference with regard to the altitude of SLOCLIM point was 103 m (± 122.2 m) (Figure 3).

2.3 STATISTICAL ANALYSES
2.3 STATISTIČNA ANALIZA

Climate-growth relationships were calculated using the *daily_response()* function for daily meteorological data and *monthly_response()* for monthly data from the dendroTools R package (Jevšenak & Levanič, 2018). Both functions work by sliding moving windows with variable lengths and calculating the correlation coefficient between the aggregated meteorological data of interest and the selected tree-ring chronology. We performed these calculations for the growing season, spanning from March to September to cover the entire period of cambial production, which for European beech in Slovenia mainly starts in April and ends in August (Čufar et al., 2008b; Prislan et al., 2013, 2019). This time frame was chosen because it is presumed that climate has the greatest influence on growth during this period. For each site, the highest absolute Pearson correlation coefficient was extracted and used for the comparison, calculated separately for mean air temperatures and precipitation sums, and for meteorological observational ARSO and gridded SLOCLIM datasets. Pairwise statistical significance was assessed using the Wilcoxon-rank sum test (Wilcoxon, 1992).

To test whether meteorological daily data exhibit significantly higher correlations with variations in tree-ring widths than monthly data, we compared daily and monthly data correlations with tree-ring widths for both meteorological stations (ARSO) and the gridded dataset (SLOCLIM), with separate calculations for precipitation and air temperature (Hypothesis 1). To test whether modelled meteorological data for a given site better explain the influence of climate conditions on tree-ring width variation than the commonly used meteorological station data, we compared ARSO and SLOCLIM data for daily and monthly air temperature and precipitation (Hypothesis 2). Furthermore, this study aimed to investigate whether altitude has an influence on the magnitude of the difference in the maximum correlation coefficient between data from meteorological stations and gridded datasets. We also sought to determine if altitude impacts the magnitude of the difference in maximum correlation coefficients between monthly and daily data (Hypothesis 3). To address the altitude effects, we first calculated differences between daily and monthly correlations with tree-ring data and also differences between SLOCLIM and ARSO correlations with tree-ring data (separately for temperature and precipitation variables), and afterwards fitted linear models where these differences are regressed as a function of altitude.

3 RESULTS AND DISCUSSION
3 REZULTATI IN DISKUSIJA

When comparing climate-growth relationships using daily and monthly meteorological data, the results show significantly higher maximum correlation coefficients between tree-ring data and meteorological data, if daily data of SLOCLIM or ARSO is used compared to monthly data for both the temperature and precipitation variables (Figure 4). The mean absolute maximum correlation coefficient with daily temperature was 0.30 for both ARSO and SLOCLIM (Figure 4). For daily precipitation, it was 0.44 for ARSO and 0.43 for SLOCLIM. For the monthly data, the absolute maximum correlation coefficient for temperature was 0.22 for ARSO and 0.21 for SLOCLIM, while for precipitation it was 0.34 for both ARSO and SLOCLIM. The correlations for temperature data were on average lower than the correlations in a study by Jevšenak (2019), where they were 0.47 for daily data and 0.41 for monthly data. Similarly, they were lower for precipitation data. However, the data in Jevšenak (2019) mainly included conifers (82%), which are known to be generally more sensitive to the climate. The advantage of using daily data applies especially for precipitation, which was also confirmed in the aforementioned study. This is due to the higher autocorrelation of temperatures compared to precipitation, and therefore the relative position of time windows for temperature is less important. The stronger correlation between daily meteorological data and tree-ring proxies, compared to monthly data, was also confirmed in a study by Nagavciuc et al. (2019).

The comparative analysis revealed no significant differences between daily and monthly data for SLOCLIM and ARSO data for either temperature or precipitation variables (Figure 4). Although the SLOCLIM database was developed on the basis of data from ARSO meteorological stations across Slovenia (considering also altitude, latitude, longitude and distance to the coast), the result remains surprising. Given SLOCLIM's higher spatial resolution, it was expected to more accurately reflect local climate conditions and their influence on tree-ring variations.

Furthermore, the analysis of monthly temperature and precipitation differences between the ARSO and SLOCLIM databases revealed that the medians of the differences are consistently close to zero throughout the year (Figure 5). Nevertheless, in certain months (July to October), ARSO recorded lower temperature values than SLOCLIM in some years, suggesting occasional discrepancies during these months which could explain the lack of significant differences between ARSO and SLOCLIM meteorological data in climate-growth analysis.

Linear regression was applied to describe the statistical relationship between altitude and differences in absolute maximum climate-growth correlations between gridded data and meteorological station data, as well as between daily and monthly data. The results indicate that none of the dependent variables are significantly influenced by altitude (Table 3, Figure 6).

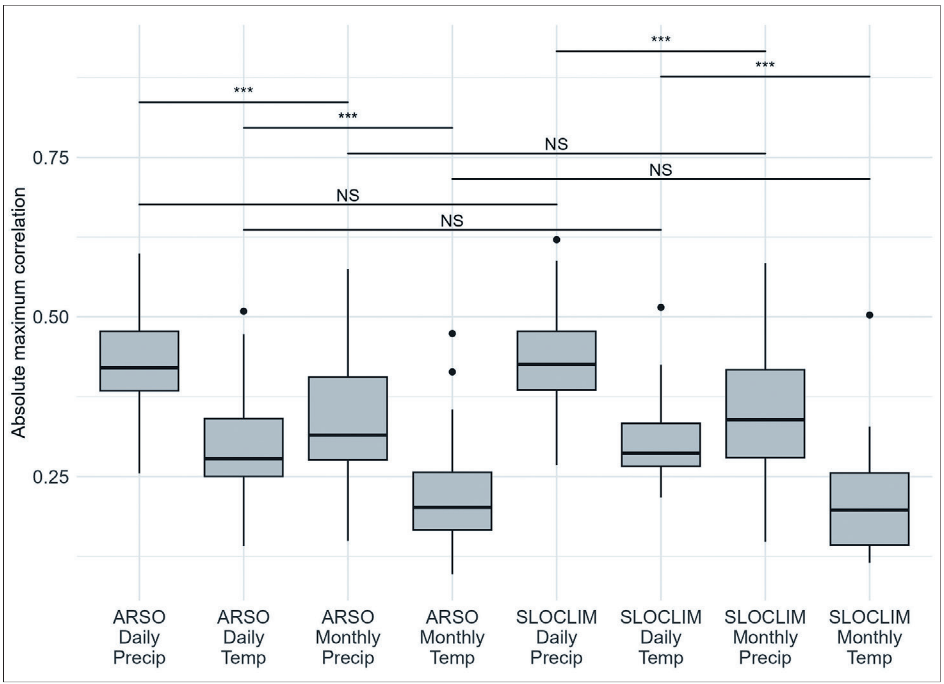

Figure 4. Boxplots of absolute maximum correlation coefficients, calculated between tree-ring data and daily or monthly meteorological data, calculated separately for gridded data (SLOCLIM) and data from meteorological stations (ARSO). Horizontal lines indicate statistical significance of pairwise comparisons. Significance levels: NS not significant at p >0.05; significant: *(0.01 < p ≤ 0.05); **(0.001 < p ≤ 0.01); ***(p ≤ 0.001).

Slika 4. Okvirji z ročaji za prikaz vrednosti absolutnih maksimalnih korelacijskih koeficientov, izračunani med širinami branik in dnevnimi oziroma mesečnimi meteorološkimi podatki, ki so pridobljeni iz modelirane baze SLOCLIM ali iz meteoroloških postaj (ARSO). Ravne črte predstavljajo statistično značilnost pri parnih primerjavah. Stopnje značilnosti: NS ni značilno pri p >0.05; značilno: *(0.01 < p ≤ 0.05); **(0.001 < p ≤ 0.01); ***(p ≤ 0.001).

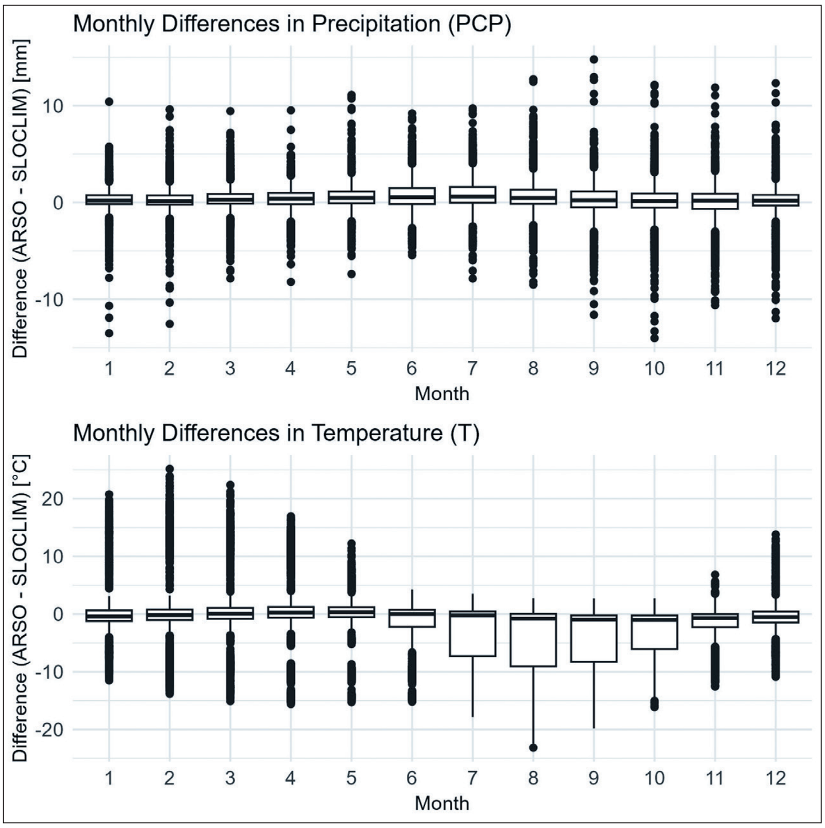

Figure 5. Boxplots of monthly differences between ARSO and SLOCLIM datasets for precipitation (PCP) and temperature (T). The difference is calculated as ARSO – SLOCLIM for the period 1960-2018.

Slika 5. Okvirji z ročaji za prikaz razlik v mesečnih vrednostih med meteorološkimi podatki SLOCLIM ali ARSO za padavine in povprečne temperature. Razlika je izračunana kot ARSO – SLOCLIM v obdobju 1960–2018.

Table 3. The results of the linear regression analyses for the relationship between altitude (independent variable) and the difference (Diff) in absolute maximum correlation coefficient between tree-ring data and meteorological data when observational data (ARSO) versus gridded data (SLOCLIM) is used for temperature (T) and precipitation (PCP), as well as difference in daily and monthly meteorological data from ARSO or SLOCLIM (dependent variables). The table presents the beta coefficient (β), standard error (SE), t-value, p-value, and the coefficient of determination (R^2).

Preglednica 3. Rezultati linearne regresije, kjer je neodvisna spremenljivka nadmorska višina, odvisne spremenljivke pa so razlike v maksimalnih korelacijskih koeficientih med širinami branik in dnevnimi oziroma mesečnimi meteorološkimi podatki ter podatki iz meteoroloških postaj (ARSO) ali baze SLOCLIM za temperature (T) in padavine (PCP). Beta – koeficient β, standardna napaka (SE), t-vrednost, p-vrednost in koeficient determinacije (R^2).

Dependent Variable / Odvisna spremenljivka	Beta (β)	SE	t-value	p-value	R^2
Diff between ARSO and SLOCLIM in daily T	0.000	0.000	0.418	0.679	0.006
Diff between ARSO and SLOCLIM in daily PCP	0.000	0.000	0.543	0.591	0.010
Diff between ARSO and SLOCLIM in monthly T	0.000	0.000	0.339	0.738	0.004
Diff between ARSO and SLOCLIM in monthly PCP	0.000	0.000	0.160	0.874	0.001
Diff between daily and monthly data in ARSO T	0.000	0.000	-1.156	0.258	0.046
Diff between daily and monthly data in SLOCLIM T	0.000	0.000	-1.105	0.279	0.042
Diff between daily and monthly data in ARSO PCP	0.000	0.000	0.768	0.449	0.021
Diff between daily and monthly data in SLOCLIM PCP	0.000	0.000	0.352	0.728	0.004

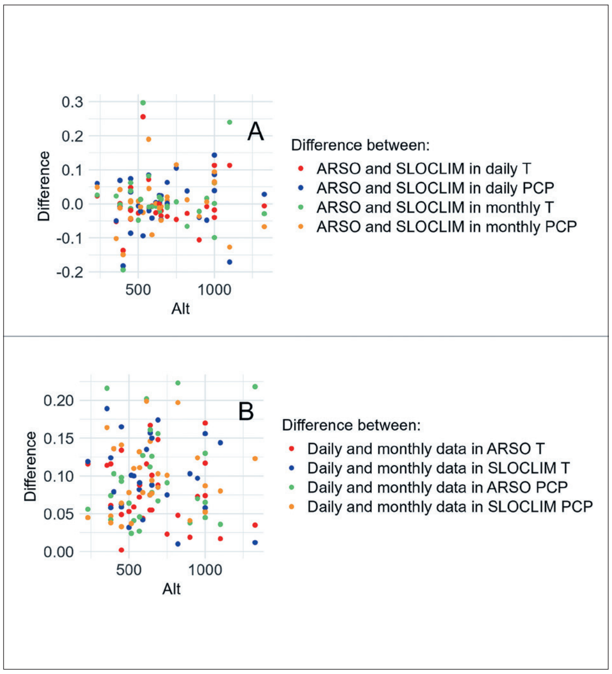

Figure 6. Difference in absolute maximum correlation coefficient between tree-ring data and meteorological data when observational data (ARSO) versus gridded data (SLOCLIM) is used for temperature (T) and precipitation (PCP) regarding altitude (A). Difference in maximum correlation coefficient between tree-ring data and meteorological data when daily versus monthly data is used from ARSO and SLOCLIM regarding altitude (B). Altitude (x-axis) refers to the elevation of the specific site.

Slika 6. Razlike v maksimalnih korelacijskih koeficientih med širinami branik in meteorološkimi podatki, glede na to, ali uporabimo podatke iz meteoroloških postaj (ARSO) ali modelirane podatke (SLOCLIM) pri temperaturah (T) in padavinah (PCP) glede na nadmorsko višino (A), ter ali uporabimo dnevne ali mesečne meteorološke podatke (B) glede na nadmorsko višino. Nadmorska višina (x os) se nanaša na nadmorsko višino posameznega rastišča.

4 CONCLUSIONS
4 ZAKLJUČEK

In this study we compared the climate-growth relationship of European beech from selected sites in Slovenia, based on newly compiled tree-ring chronologies (with the recommended detrending procedure) and meteorological data from the meteorological stations of the Slovenian Environment Agency (ARSO) and gridded data from the SLOCLIM database. Our results show that daily meteorological data provided a significantly higher maximum correlation coefficients with tree-ring data compared to monthly data, which underlines the advisability of using daily data (if available) over monthly data in dendrochronological analyses. This advantage is particularly pronounced for precipitation, and agrees with results reported by other studies. Hypothesis 1 is thus supported.

Using these particular tree-ring data and the statistical approach, no statistically significant difference was found in correlations between tree-ring data and the meteorological data from meteorological stations and the gridded data from SLOCLIM, with a high spatial resolution. This confirms that the observations from ARSO, which were also used to interpolate SLOCLIM database, adequately reflect the actual climate variability in Slovenia as already discussed by Škrk et al. (2021). Boxplots of the differences in monthly meteorological data between the ARSO and SLOCLIM databases revealed that both datasets report similar values for precipitation and temperature, indicating that the datasets are largely consistent. We thus reject Hypothesis 2.

The advantage of using daily data over monthly data applies to both lower and higher altitudes. However, the difference in absolute maximum climate-growth correlations between daily or monthly data does not significantly vary with altitude. Furthermore, the difference between gridded and observational meteorological data remains fairly constant across different altitudes. As such, Hypothesis 3 is not supported.

These results suggest the importance of further studies with a larger tree-ring network, possibly also including other tree species to gain a more comprehensive understanding of the benefits of daily and gridded meteorological data, particularly in regions with sparse meteorological station coverage, such as forested areas and higher altitudes, and in cases with many gaps in meteorological data. High spatial resolution of meteorological data is also crucial for the calibration of process models. When interpreting the climate-growth relationships, it should also be considered that the tree-ring width integrates the effect of climatic and other ecological influences, and that these reactions recorded in the tree-ring width cannot simply be described by the selected climate data alone.

5 SUMMARY
5 POVZETEK

V dendrokronoloških študijah se za analizo vpliva podnebnih dejavnikov na variiranje širin branik tradicionalno uporabljajo mesečni meteorološki podatki. V mesečnih povprečjih pa pogosto ostanejo prezrti ekstremni vremenski dogodki, ki pomembno vplivajo na rast dreves in se v zadnjem času zaradi podnebnih sprememb pojavljajo pogosteje. Zato se v zadnjih letih vedno bolj poudarja pomen uporabe dnevnih meteoroloških podatkov (Beck et al., 2013; Jevšenak, 2019; Liang et al., 2013; Pritzkow et al., 2014), ki lažje zajamejo tudi različne fenološke faze, ki jih beležimo v dnevnih intervalih.

Ker meteorološke postaje, ki beležijo dnevne podatke, običajno niso gosto in enakomerno razporejene po prostoru, so bile razvite različne interpolirane in/ali modelirane podatkovne baze, ki nudijo tudi dnevne meteorološke podatke z visoko prostorsko ločljivostjo, tako na evropski (E-OBS) kot tudi svetovni ravni (CHELSA, ERA5). V Sloveniji imamo v okviru Agencije Republike Slovenije za okolje (ARSO) dobro razvito mrežo meteoroloških postaj. Število klasičnih postaj z opazovalci v zadnjih letih sicer upada, veča pa se število samodejnih postaj (Nadbath, 2015). Gostota teh postaj je manjša na gozdnatih in višje ležečih predelih, lokacije postaj pa so bile v preteklosti tudi večkrat spremenjene. Da bi zagotovili meteorološke podatke z visoko časovno in prostorsko ločljivostjo, je bila razvita modelirana baza SLOCLIM (Škrk et al., 2021), ki smo jo uporabili tudi v tej raziskavi.

Glavni cilj raziskave je bil preučiti, ali dnevni podatki bolje pojasnijo vpliv podnebnih razmer na variiranje širin branik kot doslej običajno uporabljeni mesečni podatki (hipoteza 1). Poleg tega smo želeli preveriti tudi, ali se korelacijski koeficienti med širinami branik in meteorološkimi podatki razlikujejo, če uporabimo podatke iz meteoroloških postaj ali iz baze SLOCLIM (hipoteza 2). Zanimalo nas je še, ali se te razlike značilno spreminjajo z nadmorsko višino (hipoteza 3).

Uporabili smo 30 na novo sestavljenih kronologij navadne bukve (*Fagus sylvatica* L.) iz celotne Slovenije z razponom nadmorskih višin med 230 in 1330 metri. Izračunali smo maksimalne absolutne korelacijske koeficiente med širinami branik in dnevnimi oziroma mesečnimi meteorološkimi po-

datki iz meteoroloških postaj ARSO ali baze SLOCLIM. Meteorološka postaja ARSO ali točka na mreži SLOCLIM je bila izbrana glede na oddaljenost od lokacije kronologije, pri čemer smo upoštevali najkrajšo razdaljo. Pri analizah smo uporabili knjižnico dendroTools (Jevšenak & Levanič, 2018) s funkcijama *daily_response*() za dnevne meteorološke podatke in *monthly_response*() za mesečne podatke. Analize so vključevale povprečne temperature zraka ter količino padavin za obdobje od 1960 do 2018.

Rezultati so pokazali, da so maksimalni korelacijski koeficienti med širinami branik in meteorološkimi podatki statistično značilno višji, če uporabimo dnevne, kot pa če uporabimo mesečne podatke. To potrjuje smiselnost uporabe dnevnih podatkov v dendroklimatoloških analizah. Korelacijski koeficienti so bili višji tako pri temperaturah kot pri padavinah. Uporabo dnevnih podatkov še posebej priporočamo pri korelacijah širin branik s padavinami, kar je pokazal tudi Jevšenak (2019). Temperaturni podatki imajo namreč veliko stopnjo avtokorelacije, ki je padavine nimajo. Hipotezo 1 smo torej potrdili. V primerjavi z raziskavo, kjer so bili vključeni predvsem iglavci (Jevšenak, 2019), so bili maksimalni korelacijski koeficienti v naši študiji z bukvijo nekoliko nižji, verjeto zato, ker so iglavci na splošno občutljivejši na podnebne razmere.

Čeprav je bila povprečna oddaljenost meteorološke postaje ARSO od lokacije s kronologijo približno 15 km, točke SLOCLIM, ki temeljijo na podatkih več okoliških postaj, pa le okoli 409 m, rezultati niso potrdili statistično značilnih razlik v maksimalnih korelacijskih koeficientih med širinami branik in meteorološkimi podatki iz dveh različnih baz podatkov. Tudi analize razlik v mesečnih meteoroloških podatkih so pokazale, da ni večjih razlik med bazama tako pri padavinah kot temperaturah. Hipotezo 2 smo zato zavrnili.

Z višanjem nadmorske višine se razlike med korelacijami s širinami branik glede na to, ali smo uporabili dnevne ali mesečne podatke, tako pri temperaturah kot tudi padavinah niso statistično značilno spreminjale. Prav tako se z višanjem nadmorske višine niso značilno spreminjale razlike v korelacijah s kronologijami med bazama. Predvidevamo, da je med razlogi za to manjše število proučenih kronologij z višjih nadmorskih višin, kjer bi pomanjkanje meteoroloških postaj lahko privedlo do večjih razlik. Hipotezo 3 smo prav tako zavrnili.

Naši rezultati so potrdili pomembnost izbire načina izračuna korelacijskih koeficientov. Delno smo potrdili ugotovitve predhodnih študij, pokazali pa tudi, da so merjeni meteorološki podatki, čeprav oddaljeni od lokacij rastišč v Sloveniji, še vedno zanesljiv vir za zajem variabilnosti podnebja kot dejavnika pri rasti bukve. Rezultati so pokazali neznačilen vpliv nadmorske višine na razlike v korelacijah.

V prihodnjih raziskavah bi lahko analize razširili s širšim naborom kronologij bukve in drugih drevesnih vrst ter tako pridobili še celovitejše razumevanje pomena uporabe meteoroloških podatkov z visoko prostorsko in časovno ločljivostjo, še posebej na območjih, kjer je meteoroloških postaj malo, npr. v gozdnatih in višje ležečih predelih. Kljub temu je potrebno poudariti, da na širino branik vplivajo tudi ekološki in drugi individualni dejavniki in zato variacij med širinami branik ni možno pojasniti izključno z izbranimi meteorološkimi podatki.

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REFERENCES
VIRI

Beck, W., Sanders, T. G. M., & Pofahl, U. (2013). CLIMTREG: detecting temporal changes in climate–growth reactions–a computer program using intra-annual daily and yearly moving time intervals of variable width. Dendrochronologia, 31(3), 232–241.

Castagneri, D., Petit, G., & Carrer, M. (2015). Divergent climate response on hydraulic-related xylem anatomical traits of *Picea abies* along a 900-m altitudinal gradient. Tree Physiology, 35(12), 1378–1387. DOI: https://doi.org/10.1093/treephys/tpv085

Chaney, N. W., Sheffield, J., Villarini, G., & Wood, E. F. (2014). Development of a high-resolution gridded daily meteorological dataset over sub-Saharan Africa: Spatial analysis of trends in climate extremes. Journal of Climate, 27(15), 5815–5835. DOI: https://doi.org/10.1175/JCLI-D-13-00423.1

Cook, E. R., & Kairiukstis, L. A. (2013). Methods of dendrochronology: applications in the environmental sciences. Springer Science & Business Media.

Copernicus Climate Change Service, C. D. S. (2023). ERA5 hourly data on single levels from 1940 to present. URL: https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview (28.11.2024)

Čufar, K., De Luis, M., Horvat, E., & Prislan, P. (2008a). Main patterns of variability in beech tree-ring chronologies from different sites in Slovenia and their relation to climate. Zbornik Gozdarstva in Lesarstva, 87, 123–134.

Čufar, K., Prislan, P., & Gričar, J. (2008b). Cambial activity and wood formation in beech (*Fagus sylvatica*) during the 2006 growth season. Wood Research, 53, 1–11.

Dolar, N. Š., Castillo, E. M. del, Serrano-Notivoli, R., Arrillaga, M. de L., Novak, K., Merela, M., & Čufar, K. (2023). Spatial and temporal variation of *Fagus sylvatica* growth in marginal areas under progressive climate change. Dendrochronologia, 81. DOI: https://doi.org/10.1016/j.dendro.2023.126135

Fritts, H. (1976). Tree rings and climate. Academic Press.

Geijer, H., Ndongozi, F., & Edvardsson, J. (2024). Dendrochronology with a medical X-ray photon counting computed tomography scanner. Dendrochronologia, 86, 126233. DOI: https://doi.org/10.1016/j.dendro.2024.126233

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D., & New, M. (2008). A European daily high-resolution gridded data set of surface temperature and precipitation for 1950-2006. Journal of Geophysical Research Atmospheres, 113(20). DOI: https://doi.org/10.1029/2008JD010201

Jevšenak, J. (2019). Daily climate data reveal stronger climate-growth relationships for an extended European tree-ring network. Quaternary Science Reviews, 221. DOI: https://doi.org/10.1016/j.quascirev.2019.105868

Jevšenak, J., & Levanič, T. (2018). DendroTools: R package for studying linear and nonlinear responses between tree-rings and daily environmental data. Dendrochronologia, 48, 32–39. DOI: https://doi.org/10.1016/j.dendro.2018.01.005

Kaczka, R. J., Janecka, K., Hulist, A., & Spyt, B. (2017). Linking the growth/climate response of daily resolution with annual ring formation of Norway spruce in the Tatra Mountains. Trace, 15, 13–22.

Karger, D. N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W., Zimmermann, N. E., Linder, H. P., & Kessler, M. (2017). Climatologies at high resolution for the earth's land surface areas. Scientific Data, 4(1), 1–20.

Liang, W., Heinrich, I., Simard, S., Helle, G., Liñán, I. D., & Heinken, T. (2013). Climate signals derived from cell anatomy of scots pine in NE Germany. Tree Physiology, 33(8), 833–844. DOI: https://doi.org/10.1093/treephys/tpt059

Lussana, C., Tveito, O. E., & Uboldi, F. (2018). Three-dimensional spatial interpolation of 2 m temperature over Norway. Quarterly Journal of the Royal Meteorological Society, 144(711), 344–364. DOI: https://doi.org/10.1002/qj.3208

Nadbath, M. (2015). Podnebna spremenljivost Slovenije v obdobju 1961-2011. Meteorološka opazovanja I. Ministrstvo za okolje in prostor, Agencija RS za okolje.

Nagavciuc, V., Roibu, C. C., Ionita, M., Mursa, A., Cotos, M. G., & Popa, I. (2019). Different climate response of three tree ring proxies of *Pinus sylvestris* from the Eastern Carpathians, Romania. Dendrochronologia, 54(October 2018), 56–63. DOI: https://doi.org/10.1016/j.dendro.2019.02.007

Popa, A., Jevšenak, J., Popa, I., Badea, O., & Buras, A. (2024). In pursuit of change: Divergent temporal shifts in climate sensitivity of Norway spruce along an elevational and continentality gradient in the Carpathians. Agricultural and Forest Meteorology, 358(July). DOI: https://doi.org/10.1016/j.agrformet.2024.110243

Prislan, P., Gričar, J., Čufar, K., de Luis, M., Merela, M., & Rossi, S. (2019). Growing season and radial growth predicted for *Fagus sylvatica* under climate change. Climatic Change, 153(1–2), 181–197. DOI: https://doi.org/10.1007/s10584-019-02374-0

Prislan, P., Gričar, J., de Luis, M., Smith, K. T., & Čufar, K. (2013). Phenological variation in xylem and phloem formation in *Fagus sylvatica* from two contrasting sites. Agricultural and Forest Meteorology, 180, 142–151. DOI: https://doi.org/10.1016/j.agrformet.2013.06.001

Pritzkow, C., Heinrich, I., Grudd, H., & Helle, G. (2014). Relationship between wood anatomy, tree-ring widths and wood density of *Pinus sylvestris* L. and climate at high latitudes in northern Sweden. Dendrochronologia, 32(4), 295–302. DOI: https://doi.org/10.1016/j.dendro.2014.07.003

Rohde, R., & Hausfather, Z. (2019). Berkeley Earth Combined Land and Ocean Temperature Field, Jan 1850-Nov 2019 [Data set]. Zenodo. DOI: https://doi.org/https://doi.org/10.5281/zenodo.3634713

Serrano-Notivoli, R., Beguería, S., & de Luis, M. (2019). STEAD: A high-resolution daily gridded temperature dataset for Spain. Earth System Science Data Discussions, 1–27. DOI: https://doi.org/10.5194/essd-2019-52

Serrano-Notivoli, R., Beguería, S., Saz, M. Á., Longares, L. A., & de Luis, M. (2017). SPREAD: A high-resolution daily gridded precipitation dataset for Spain. Earth System Science Data Discussions, 1–33. DOI: https://doi.org/10.5194/essd-2017-35

Škrk, N., Serrano-Notivoli, R., Čufar, K., Merela, M., Črepinšek, Z., Kajfež Bogataj, L., & de Luis, M. (2021). SLOCLIM: a high-resolution daily gridded precipitation and temperature dataset for Slovenia. Earth System Science Data, 13(7), 3577–3592. DOI: https://doi.org/10.5194/essd-13-3577-2021

Skudnik, M., Grah, A., Guček, M., Hladnik, D., Jevšenak, J., Kovač, M., Kušar, G., Mali, B., Pintar, A. M., Pisek, R., Planinšek, Š., Poljanec, A., & Simončič, P. (2021). Stanje in spremembe slovenskih gozdov med letoma 2000 in 2018: rezultati velikoprostorskega monitoringa gozdov in gozdnih ekosistemov. Gozdarski inštitut Slovenije, Silva Slovenica. DOI: https://doi.org/10.20315/SFS.181

Speer, J. H. (2010). Fundamentals of Tree-Ring Research. University of Arizona Press.

Wilcoxon, F. (1992). Individual comparisons by ranking methods. In *Breakthroughs in statistics: Methodology and distribution* (pp. 196–202). Springer.