

1 Dendroclimatic analysis of *Pinus peuce* Griseb. at subalpine
2 and treeline locations in Pirin Mountains, Bulgaria

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7 **Abstract**

8 Tree rings are a natural archive containing valuable information about
9 environmental changes. Among the most sensitive ecosystems to such changes are
10 high-mountain forests. Tree-ring series from such locations are exceptionally
11 valuable both for climate reconstructions and for studying the effects of climate
12 changes on forest ecosystems.

13 The objective of our study is to present new long tree-ring width chronologies
14 of *Pinus peuce* Griseb. from several locations at Pirin Mountains in southwestern
15 Bulgaria, to explore their correlation with monthly temperatures and precipitation in
16 the research area and to assess their potential for climate reconstruction.

17 We built three long-term index chronologies for the radial increment of *P.*
18 *peuce* from treeline locations in the study region. The longest chronology spans 675
19 years. We studied the impact of monthly air temperature and precipitation on its
20 growth for the past 86 years using multiple regression analysis. Our analysis shows
21 that *P. peuce* growth is positively influenced by high temperatures at the end of the
22 previous growing season, especially at the two sites in Banderitsa valley until the
23 middle of the 1970s, and negatively affected by cold winters. In some of the sample
24 plots its growth was also positively correlated with high summer temperatures.
25 However, even at these high altitudes in some of the locations on steep slopes *P.*
26 *peuce* showed signs of negative impact of drought during the hottest summer months
27 (especially in August).

28 Our chronologies contribute to the paleoclimatic record for southwestern
29 Bulgaria, which could provide baseline information about past climate variability and
30 improve our understanding of current and future environmental changes.

31 *Keywords:* tree-ring width; time series; climate impact; *Pinus peuce* Griseb.

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341. Introduction

35 Tree-ring data from long-lived species growing in locations where trees are
36 sensitive to variation in temperature or precipitation are among the most important
37 sources of proxy climate data (Fritts, 1976). Based on them, numerous climate
38 reconstructions have been produced and are continuously being updated (Bräuning,
39 2001; Mirtchev et al., 2003; Cook et al., 2010; Esper et al., 2012; Cook et al., 2015;
40 Leonelli et al., 2017). These climate proxies help understand climate variation in
41 different parts of the world and the driving factors behind it, which is particularly
42 important in the context of rising air temperatures in recent decades (IPCC, 2014).

43 Despite the importance of the Balkan Peninsula from a natural and climatic
44 point of view, high-resolution proxy climate data are only limitedly available for this
45 region (Xoplaki et al., 2001; Luterbacher and Xoplaki, 2003; Popa and Kern, 2009;
46 Trouet et al., 2012; Cook et al., 2015; Klesse et al., 2015; Klippel et al., 2018a,b;
47 Trouet et al., 2018; Esper et al., 2019). The recent advances in these studies were
48 based mostly on *Pinus heldriechii* Christ. from treeline locations in the mountains in
49 Bulgaria, Greece, and Albania. However, *Pinus peuce* Griseb., which is a long-lived
50 species with trees frequently reaching ages of more than 500 years (Panayotov and
51 Yurukov, 2007), has not been studied in such detail. There have been only few
52 attempts to reconstruct climate based on this species (Vakarelov et al., 2001,
53 Mirtchev and Zafirov, 2008). One of the reasons for the lack of climate
54 reconstructions is probably the fact that some of the studies performed so far found
55 mixed climate signals in *P. peuce* tree-ring width series (Panayotov et al., 2010).
56 More attention has been paid to eco-physiological studies (Lyubenova et al., 2005;
57 Ivanova et al., 2013; Anev and Tzvetkova, 2018), testing the performance in ex-situ
58 experimental locations (Bachmann et al., 2015) and recent fast advances in treeline
59 regeneration (Meshinev et al., 2000; Velkovski et al., 2013) of this species. They show
60 that *P. peuce* has high plasticity in response to climate variability and potential for
61 increasing future importance in subalpine locations in relation to treeline shifts.
62 However, recent first tests with blue intensity of scanned tree-ring images of *P. peuce*
63 show strong potential for summer temperature reconstruction (Tsvetanov et al.,
64 2020). In addition, different approaches to tree-ring width signal processing might

65 reveal stronger signals compared to previous attempts.

66 The objective of our study is to present new long tree-ring width chronologies
67 of *Pinus peuce* Griseb. from the Pirin Mountains in southwestern Bulgaria, to explore
68 their correlation with regional temperature and precipitation variability and to assess
69 their potential for climate reconstruction.

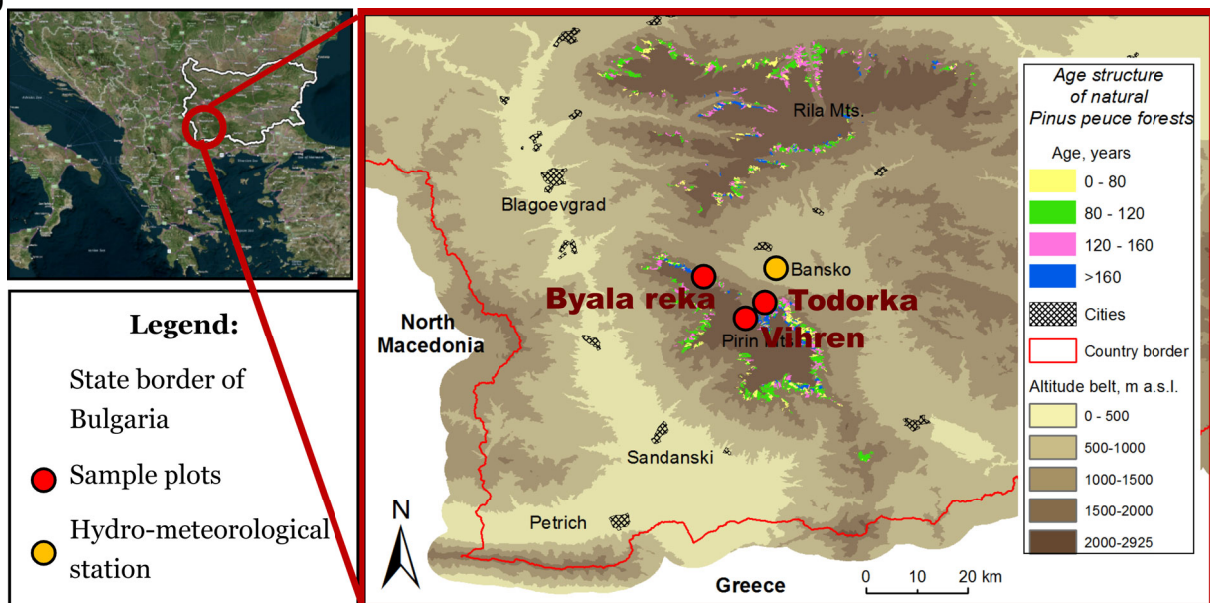
70 2. Material and methods

71 2.1. Study area

72 Tree-ring samples were collected from three subalpine locations (1850–2250
73 m a.s.l.) in Banderitsa and Byala Reka valleys in the Pirin Mountains, SW Bulgaria
74 (fig. 1; table 1). The trees were located mostly on steep northeast-, northwest- and
75 north-facing slopes covered with Umbric and Modic Cambisols on granite bedrock.
76 All locations are protected in Pirin National Park (UNESCO World Heritage) due to
77 the high conservation value of *P. peuce* and *P. heldreichii* forests.

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80 **Fig. 1.** Distribution of the natural *P. peuce* forests in Rila and Pirin Mountains in Bulgaria and location
81 of the three sample plots

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85

86Table 1

87Location of the sample plots

Sample plot	Valley	Mean altitude, m a.s.l.	Site exposure	Coordinates (dec. degrees)		Number of samples
				Latitude	Longitude	
Vihren	Banderitsa	1950	northeast	41.757279	23.417352	31
Todorka	Banderitsa	2000	northwest	41.763903	23.429092	112
Byala reka	Byala reka	2000	north	41.818974	23.351102	19

88

89 2.2. Tree-ring data and chronology development

90 Samples (in total 162 cores) were collected at breast height (1.3 m) with an
91 increment borer from dominant and codominant trees. The cores were mounted on
92 wooden holders and progressively sanded to obtain very smooth and clearly visible
93 surfaces. The ring widths were measured using Lintab 6 equipment and post-
94 scanning processing with CooRecorder computer program. All samples were cross-
95 dated visually, and the cross-dating was then statistically verified using COFECHA
96 software (Grissino-Mayer, 2001). Then the measured data were standardized by
97 applying cubic smoothing splines (50 % frequency cut-off, 50 % of each series
98 length), using the programs ARSTAN (Cook, 1985) and DendroStat (Zafirov, 2006).
99 Due to the different lengths of the tree-ring width series, the spline lengths ranged
100 mainly from 100 to 325 years. With this procedure we aimed to remove the age-
101 related growth trends and preserve the climate signal. We calculated several
102 statistical parameters commonly used in dendrochronology – Expressed Population
103 Signal (EPS), R-Bar, First Order Autocorrelation (1st AC), and Mean Sensitivity (MS).

104 2.3. Climate data

105 The climate in the study region is transitional-continental and influenced by
106 Mediterranean air masses. The mean annual temperature (Vihren chalet climate
107 station, 1970 m a.s.l.) is 3.5°C. It ranges from a mean monthly temperature of -4.7°C
108 in January to +12.2°C in August. The annual precipitation is 1378 mm, with an
109 autumn-winter maximum. However, these precipitation values were observed in the
110 middle of the 20th century, whereas in recent decades precipitation has decreased in
111 autumn and winter coupled with increased temperatures (Grunewald et al., 2009;
112 Nojarov, 2012). Precipitation reaches its annual minimum in summer, when it is
113 often lower than in other parts of Bulgaria (Brown and Petkova, 2007). The dry
114 summers, combined with shallow soil profiles on steep rocky sites, might cause local

115drought conditions that can be reflected in the tree-ring width series (Panayotov et
116al., 2010).

117 Climate data for the analysis were provided for three Hydro-Meteorological
118Stations (HMS): Bansko (936 m a.s.l.), Vihren chalet (1970 m a.s.l.) and Musala
119(2925 m a.s.l.). The source of the data is the Bulgarian National Hydro-
120Meteorological Institute. HMS Bansko is located at the foot of the Pirin Mountains,
121approximately 10–12 km away from the study sites, and provides a continuous record
122since the end of 1931. HMS Vihren chalet is situated in Banderitsa valey at the closest
123altitude to the sample plots. However, it was operated only for a short period of time
124(25 years) and was therefore mainly used to characterize the climate in the study
125area. HMS Musala is located in a high-mountain area and has been operated since
1261932. However, it is situated in the Rila Mountains at a distance of about 50 km from
127the study sites. Because of this it was used mainly for additional analysis and
128comparison of the climatic signal in the tree-growth chronologies.

129 The relationships between the tree-ring width chronologies of *P. peuce* and
130monthly climate data were explored using multiple linear regression analysis. We
131built regression models for the entire 86-year period of overlap between the tree-
132growth and climate data (1933–2018) and for two non-overlapping sub-periods
133(1933–1975 and 1976–2018) to determine if climate-growth relationships changed
134over time.

135**3. Results and discussion**

136 We developed three representative radial increment chronologies for *Pinus*
137*peuce* forest stands in the Pirin Mountains (Vihren, Todorka, and Byala reka) that
138reflect the growth dynamics and health status of the studied tree species (table 2).
139Several missing and partially missing rings were found during the cross-dating of the
140core samples. This demonstrates that the environmental conditions in the studied
141sites during some of the years were unfavorable enough to cease the radial increment
142of *P. peuce* trees.

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148**Table 2**

149Characteristics of the mean index chronologies for the radial increment of *P. peuce*

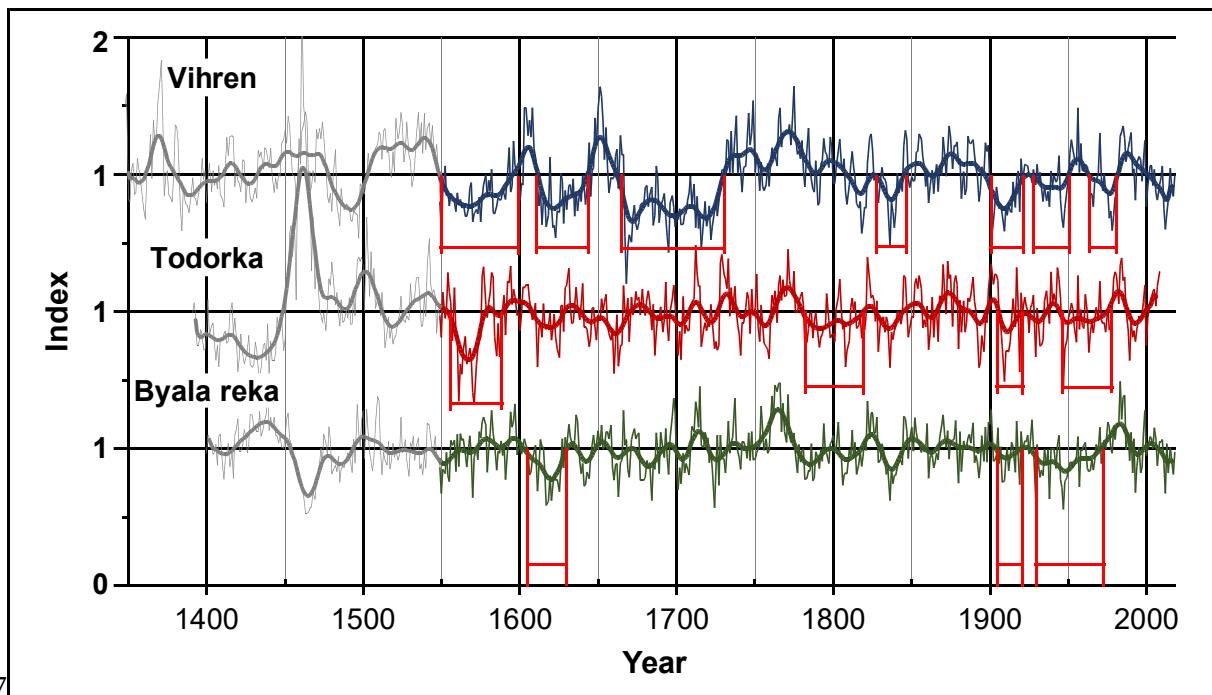
Sample plot	Number of samples	Start year	End year	Length (years)	First order AC	Mean sensitivity	Mean EPS	EPS \geq 0.85 (year)
Vihren	31	1344	2018	675	0.72	0.145	0.87	1800
Todorka	112	1391	2008	617	0.71	0.156	0.95	1650
Byala reka	19	1399	2018	620	0.52	0.130	0.85	1800

150

151 All three *P. peuce* chronologies are longer than 600 years, with the longest one
 152(Vihren) spanning 675 years. Its time span covers the period from 1344 until 2018.
 153However, the common period of high replication for the three chronologies (more
 154than 5 samples) covers the years after 1550. The correlation coefficients between the
 155chronologies for this period are: Vihren–Todorka $r = 0.37$, Vihren–Byala reka
 156 $r = 0.34$, and Todorka–Byala reka $r = 0.57$, all of which are significant ($p \leq 0.05$).

157 The parallel graphical analysis of the smoothed *P. peuce* chronologies (21-year
 158moving averages) showed similarities in the growth dynamics at the three sites (fig.
 1592). Some of the most pronounced periods with prolonged reduction of the ring-width
 160indices below 1 (stress periods) coincide between the three chronologies. During the
 16120th century such stress periods were: from 1900 until the beginning of 1920s, at the
 162end of 1940s and from the beginning of 1960s until the beginning of 1970s. In the
 163course of the previous centuries there were several other such common periods, for
 164example, in the 1720s and in the 1830s. We found also several common prolonged
 165periods with increased tree-ring widths for the three chronologies during the last
 166three centuries: from the beginning of 1760s until the end of 1770s, in the 1870s and
 167the final one was in the 1980s. These periods of decreased or increased tree growth
 168were most likely caused by common environmental factors in all three studied
 169locations such as unfavorable or favorable climatic conditions, respectively.

170 However, some differences are also evident between the three sites. For
 171example, during the 1930s and at the beginning of 1940s *P. peuce* in Vihren and
 172Byala reka had low radial increment, while in Todorka its indices were above 1.
 173Likewise, in the 1950s the radial increment in Vihren was high, while in the other two
 174sample plots its indices were below 1. During the last several years – at the beginning
 175of 21st century, the indices for the radial increment of *P. peuce* in the two locations
 176whose chronologies reach 2018 (Vihren and Byala reka) are also below average.



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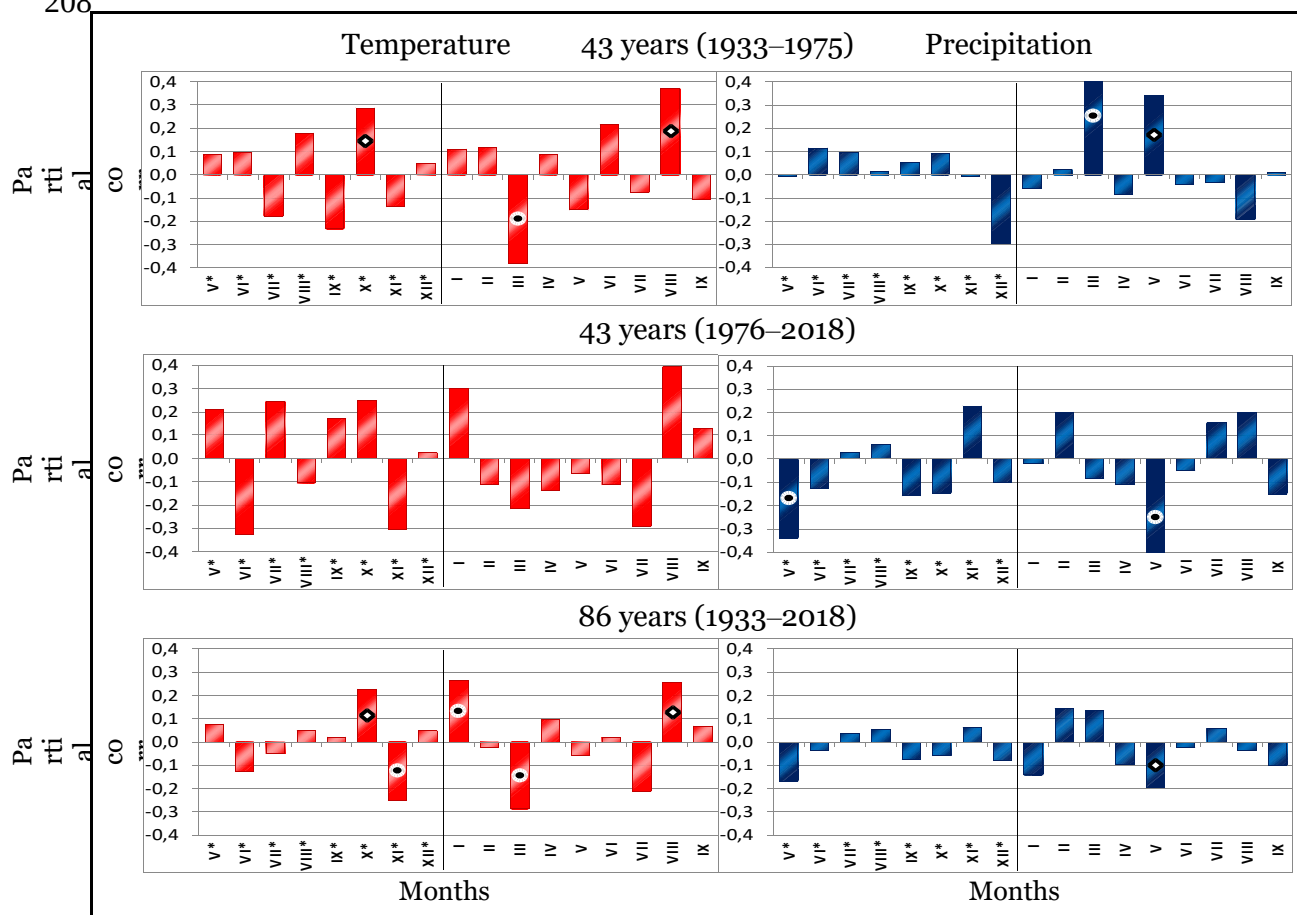
178 **Fig. 2.** Dynamics of the *P. peuce* chronologies after calculating, 21-year moving averages, and stress
 179 periods longer than 20 years (indicated by arrows) in the three sample plots in the Pirin Mountains.
 180 The colored parts of the curves represent the common period of high replication for the chronologies
 181 (more than 5 samples).

182 We found relatively strong autocorrelation in all three Standard tree-ring
 183 width chronologies (see table 2). However, we used these versions of the mean series
 184 to study the climatic signal in *P. peuce* growth variation instead of the Residual and
 185 Arstan ones in order to retain as much as possible of the original low-frequency
 186 variation. One explanation for the strong autocorrelations could be a strong impact of
 187 environmental factors during the previous growing seasons on the radial increment
 188 in the following years. Because of this, we included mean air temperatures and
 189 precipitation for all months from May of the previous year until September of the
 190 current year as predictors in the multiple regression model.

191 The partial regression coefficients for the effect of each independent variable
 192 (monthly temperature and precipitation) on the dependent variable (tree-ring width
 193 chronology) for Vihren, with the influence of all the remaining variables held
 194 constant, are shown on fig. 3. During the first 43-year period (1933–1975) we
 195 obtained significant regression coefficients ($p \leq 0.05$) for the influence of air
 196 temperature (negative) and precipitation (positive) in March. Temperature in
 197 preceding October (positive) and in August (positive), as well as precipitation in May

198(positive) also had considerable effect ($p \leq 0.1$). This result shows that prolonged
 199previous growing seasons had a positive impact on *P. peuce* growth during these
 200years. The negative influence of lower temperatures and positive of higher
 201precipitation in March is probably connected with the need of a larger snowpack
 202during this time of the year, which contributes to higher soil moisture. The absence of
 203significant positive coefficients for the influence of precipitation during the summer
 204and the positive coefficients for the air temperature in August indicate that there were
 205likely no strong summer droughts at this location in this period and that the trees
 206benefitted from high temperatures during the period of highest rate of tracheid
 207formation, which is in July–August (Ivanova et al., 2013).

208



209 **Fig. 3.** Partial correlation coefficients for the relationship between tree-ring width of *P. peuce* in Vihren
 210 and temperature (left, red color) / precipitation (right, blue color) for the three periods (asterisks mark
 211 the months of the previous year, circles indicate the months with $p \leq 0.05$, diamonds – months with
 212 $p \leq 0.1$)

213 For the later 43-year period (1976–2018), we found no significant coefficients
 214for monthly air temperature, but significant negative influence of precipitation of

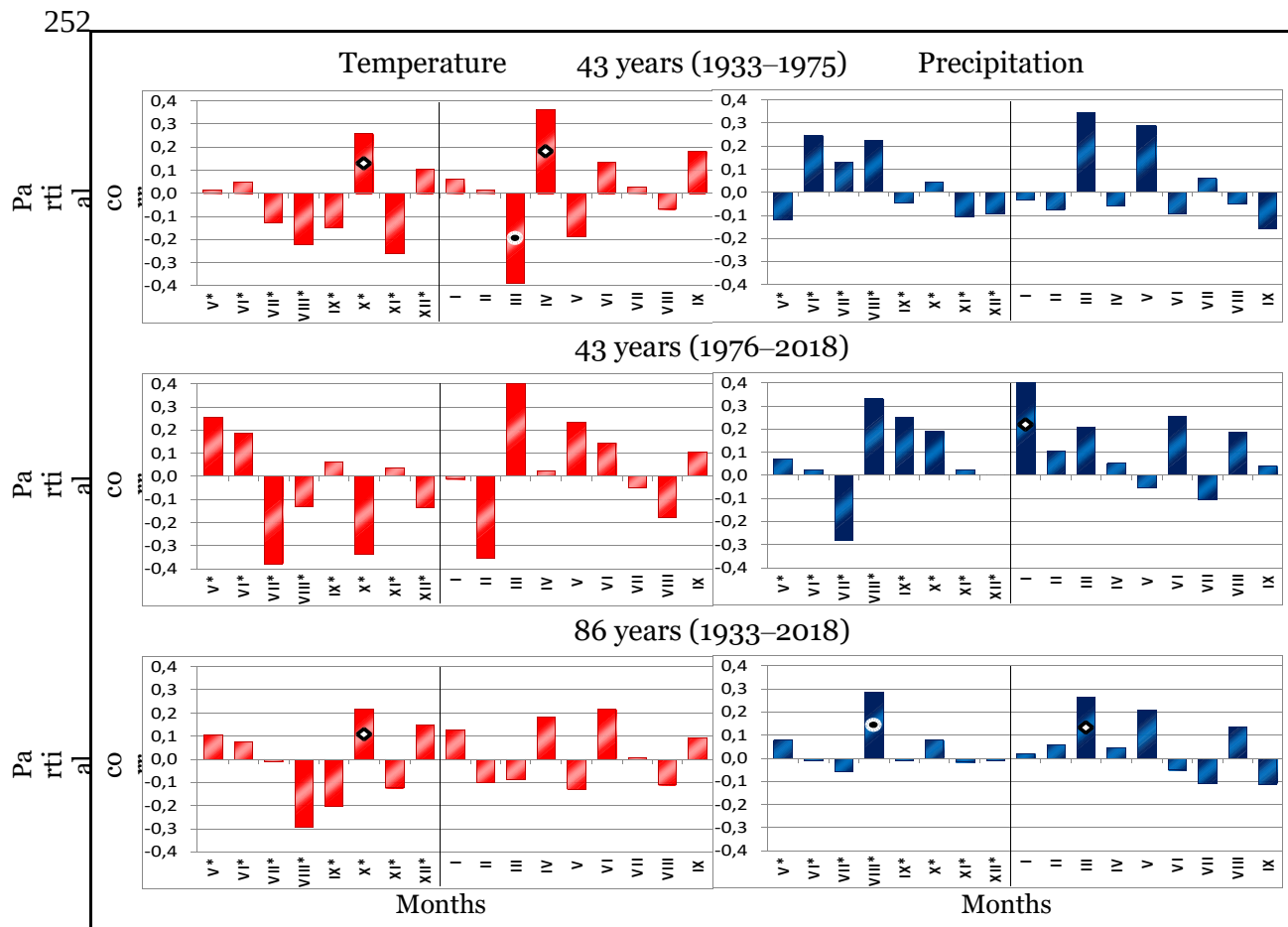
215 May of the previous year and May of the current year. This could be related to
216 prolonged winters and therefore delay of the start of the growing seasons. Recent
217 studies of xylogenesis of *P. peuce* showed that in the years with cold and moist
218 conditions in May, the onset of cambial activity is delayed (Ivanova et al., 2013;
219 Ivanova, 2016).

220 Many of the previously discussed significant climate factors also showed
221 strong effects on the growth of *P. peuce* over the entire 86-year period. In addition,
222 we found significant coefficients for the influence of air temperature in previous
223 November (negative) and in January (positive). The negative influence of November
224 temperature shows that the beginning of the dormant period should not be
225 postponed during this month. The positive influence for January indicates that the
226 trees were negatively affected by low air temperatures during the coldest month of
227 the year.

228 In Todorka, we also found a significantly ($p \leq 0.05$) negative influence of
229 March temperature during the first 43-year period (1933–1975; fig. 4). Temperatures
230 in previous October and current April have a positive influence ($p \leq 0.1$), indicating
231 the need for prolonged previous year growing seasons. There are no significant
232 positive coefficients for the influence of precipitation or negative ones for
233 temperatures impacts during the summer, which indicates also for this site that there
234 were no considerable summer droughts at this location in this earlier period. We
235 would like to note that although the Todorka study site is located on a steep slope, its
236 exposure is northwestern, which retains relatively more moisture than southern
237 exposures, and therefore the effects of potential short-term droughts are expected to
238 be comparatively lower. Moreover, if the winter soil moisture reserves were higher,
239 the trees would have sufficient moisture for the growing season. This is confirmed by
240 the positive, albeit statistically not significant, coefficients for precipitation in March
241 and May. Negative effects of summer drought at this altitude are expected only in
242 extreme cases, as previously reported by Panayotov et al. (2010) for the same
243 location.

244 For the second 43-year period (1976–2018), we only found a considerable
245 positive effect ($p \leq 0.1$) on the growth of *P. peuce* of precipitation in January, which
246 shows that trees need more precipitation during winter. Regression coefficients were
247 similar, albeit not statistically significant, for the other winter months at this location.
248 The regression coefficient for the effect of precipitation in August of the previous year

249is also positive and relatively high. This indicates that summer droughts during this
 250period could have some negative impact on the growth of the trees even at this more
 251mesic site.

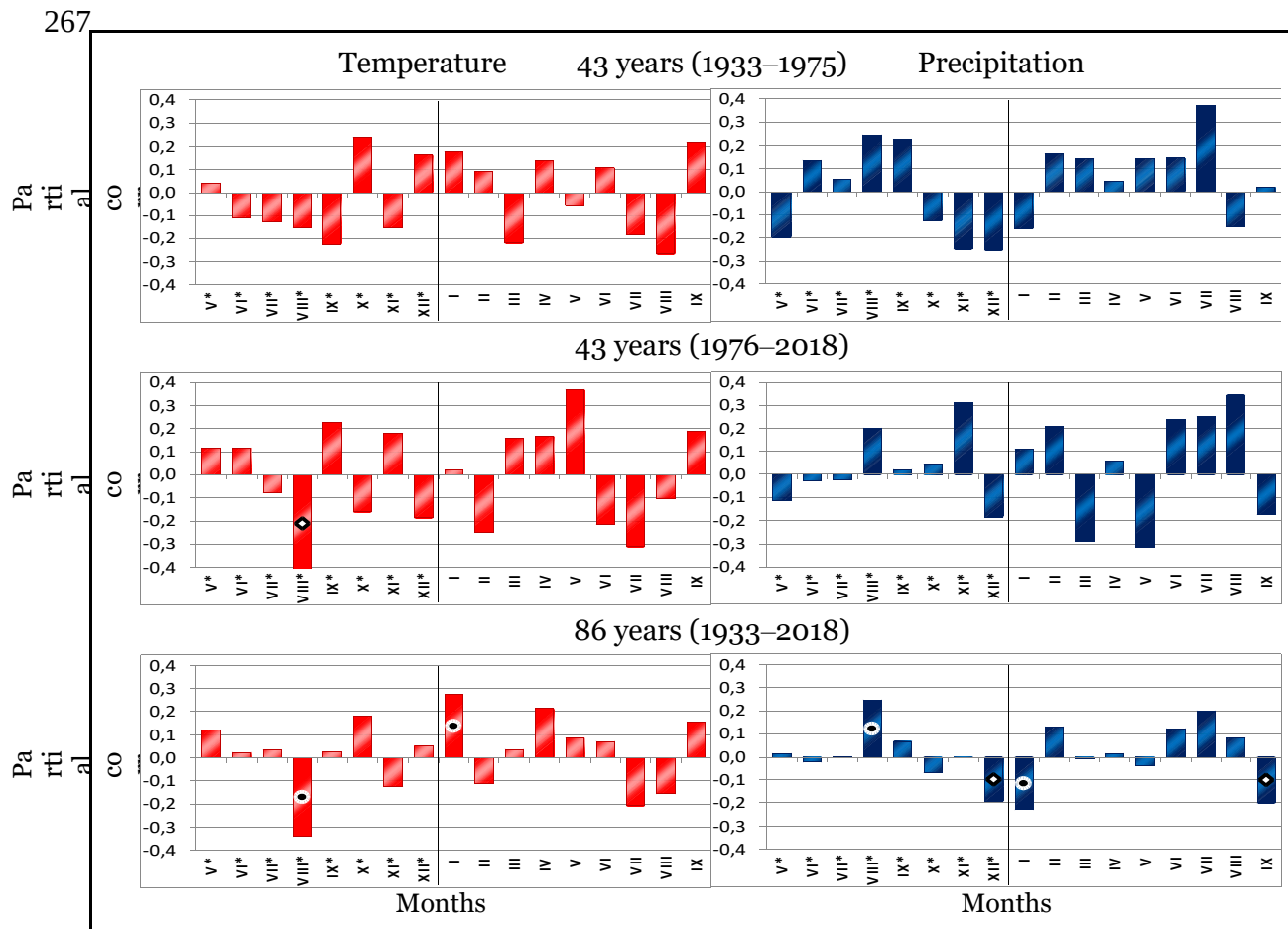


253 **Fig. 4.** Partial correlation coefficients for the relationship between tree-ring widths of *P. peuce* in
 254 Todorka and temperature (left, red color) / precipitation (right, blue color) for the three periods
 255 (asterisks mark the months of the previous year, circles indicate the months with $p \leq 0.05$, diamonds –
 256 months with $p \leq 0.1$)

257 For the entire 86-year period, higher temperatures at the end of the previous
 258growing season have a positive influence ($p < 0.1$) and so does more precipitation
 259during most of the year, especially in previous August ($p < 0.05$) and in March
 260($p < 0.1$).

261 At the Byala reka site, partial regression coefficients for the effect of monthly
 262air temperature and precipitation on *P. peuce* growth were insignificant ($p > 0.05$) for
 263the two 43-year periods (fig. 5). Nevertheless, this is the only site for which we found
 264a negative influence of summer (July and August) temperature and a positive
 265($p > 0.1$) influence of July precipitation. The negative effect of summer temperature

266on tree growth is strongest ($r = -0.42, p < 0.1$) in previous August in the later period.

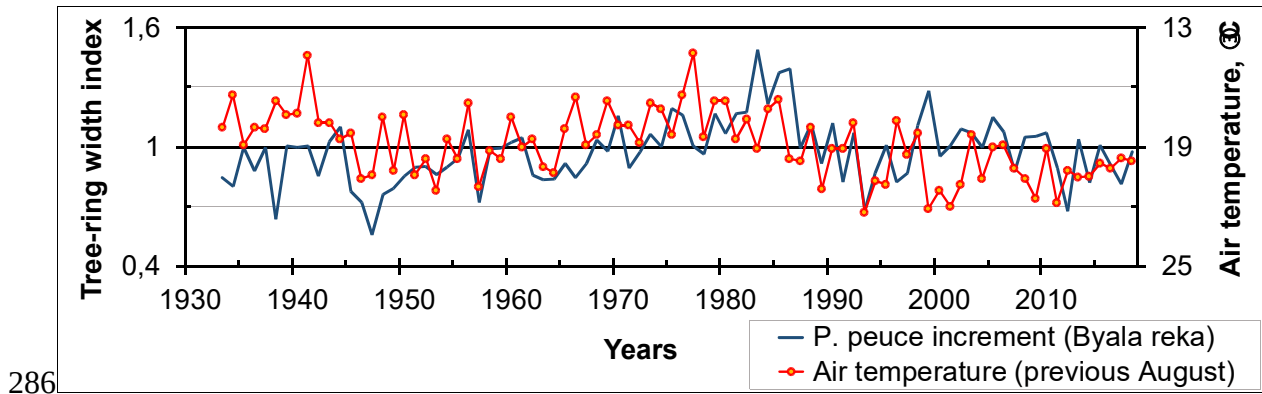


268 **Fig. 5.** Partial correlation coefficients for the relationship between tree-ring widths of *P. peuce* in Byala
 269 reka and temperature (left, red color) / precipitation (right, blue color) for the three periods (asterisks
 270 mark the months of the previous year, circles indicate the months with $p \leq 0.05$, diamonds – months
 271 with $p \leq 0.1$)

272 Over the whole 86-year period, *P. peuce* generally benefitted from lower
 273 temperatures in previous summer (August), but from higher temperatures in winter
 274 (January). The trees also benefitted from more precipitation in previous August, but
 275 less snow in winter (December and January).

276 In order to visually evaluate the correspondence between periods of low and
 277 high tree-growth and climate variations, we plotted *P. peuce* radial increment against
 278 the instrumental data of the highest correlation (fig. 6). For this graph, we selected
 279 the variables for which we obtained the highest partial correlation coefficient for the
 280 entire 86-year period – indices for the tree-ring widths in Byala reka and air
 281 temperature in previous August ($r = -0.34, p < 0.05$). Since the correlation found was
 282 negative, we plotted the air temperature values in reverse order. The period of

283 increased temperature between the mid-1940s and the mid-1960s (below the line on
 284 the graph) can be seen to correspond to decreased *P. peuce* growth. The same is valid
 285 for the period after the end of the 1980s.



286
 287 **Fig. 6.** Dynamics of *P. peuce* radial increment in Byala reka and mean monthly air temperature in
 288 previous August (the air temperature values are plotted in reverse order)

289 The described effects of air temperature and precipitation on the radial
 290 increment of *P. peuce* at the three sites are confirmed by the coefficients of
 291 determination (R^2) of the multiple regressions (table 3). During the first 43-year
 292 period air temperature had a stronger impact than precipitation on the growth of the
 293 trees at Vihren ($R^2 = 46.7\%$ and 37.5% , respectively), while during the second period
 294 their impact is reversed ($R^2 = 38.9\%$ and 55.6% , respectively). This change in the
 295 role of the two climatic factors is even more pronounced at Todorka. In Byala reka the
 296 effect of air temperatures on tree growth was also stronger than precipitation during
 297 the first 43-year period ($R^2 = 47.5\%$) and its greater impact at this location is
 298 retained even during the second period ($R^2 = 48.3\%$).

299 The coefficients of determination are above 75 % for the combined influence of
 300 all 34 factors (both air temperatures and precipitation from previous May until
 301 September of the current growing season) during the 43-year periods for all three
 302 sites. *P. peuce* in Vihren was equally affected by air temperature and precipitation
 303 during both periods ($R^2 = 75.7\%$). At the other two sites, the effect of the climate
 304 factors was slightly higher in the mid-20th century than in the later 43-year period
 305 ($R^2 = 92.9\%$ and 91.2% , respectively in Todorka; $R^2 = 85.1\%$ and 82.9% ,
 306 respectively in Byala reka). However, none of the three coefficients of determination
 307 for the entire 86-year period is higher than 50 %.

308

309**Table 3**

310Influence of the temperature-precipitation regimes – coefficients of determination
 311(R^2) in percent from the multiple regression analysis (data from HMS Bansko)

Sample plot	Period	R^2 , % – air temperatures, 17 months, prev. May–Sep	R^2 , % – precipitation, 17 months, prev. May–Sep	R^2 , % – combined, 34 factors, prev. May–Sep
Vihren	1933–1975	46.7	37.5	75.7
	1976–2018	38.9	55.6	75.7
	1933–2018	29.4	19.3	40.0
Todorka	1933–1975	54.6	26.3	92.9
	1976–2018	26.3	53.3	91.2
	1933–2018	25.0	24.5	44.2
Byala reka	1933–1975	47.5	39.6	85.1
	1976–2018	48.3	41.8	82.9
	1933–2018	27.8	23.4	42.6

312

313 Since HMS Bansko is located at a lower altitude than the study sites, we also
 314performed multiple regression analysis with data from a high-mountain hydro-
 315meteorological station – HMS Musala. Although we received similar coefficients of
 316determination for the influence of air temperature and precipitation on *P. peuce*
 317growth, none of them were higher than those obtained with the climate data from
 318HMS Bansko. This indicates that the data used from the closer HMS Bansko,
 319although located at a lower altitude, are more suitable for studies of climate-growth
 320relationships in the research area.

321 In terms of the potential future work for studying past climate variations, we
 322consider that the created chronologies and their further development will contribute
 323to a better understanding of the long-term autumn-winter climate in the region. This
 324could be of high value given the fact that most of the recent advances of tree-ring
 325analysis in the area have focused on the reconstruction of temperature (Trouet et al.,
 3262012; Klesse et al., 2015; Klippel et al., 2018b), drought (Cook et al., 2015; Klippel et
 327al., 2018a), or atmospheric circulation patterns (Trouet et al., 2018) variation in
 328summer only. The observed differences between the Vihren and Todorka
 329chronologies, which are relatively close to each other but with different exposures, is

330in our opinion an additional indication that by careful planning and collection of tree-
331ring cores we can reveal varying climate signals in the radial increment series.

332**4. Conclusions**

333 The longevity of *Pinus peuce* allows the development of long tree-ring width
334chronologies. The longest chronology we developed for this species in the Pirin
335Mountains covers 675 years, with a common period of high replication for all three
336chronologies for the study region after 1550.

337 During the 20th century common prolonged stress periods for *P. peuce* at the
338three sites were: from 1900 until the beginning of 1920s, in the end of 1940s and
339from the beginning of 1960s until the beginning of 1970s.

340 The regional temperature-precipitation regime is a major factor for the growth
341of *P. peuce* in this region. Despite the proximity of the three sites, we found some
342differences in their relation to climate. *P. peuce* trees at the two sites in Banderitsa
343valley were positively influenced by high temperatures at the end of the previous
344growing season, especially until the middle of 1970s, and negatively affected by cold
345winters. Their growth was also positively influenced by high summer temperatures.
346However, even at these high altitudes, on steep slopes *P. peuce* showed signs of
347negative drought impacts during the hottest summer months (especially in August).

348 Our chronologies contribute importantly to the paleoclimatic record of
349southwestern Bulgaria. A long record of climate variability will provide baseline
350information about its natural dynamics, which will improve our understanding of
351current environmental changes. Rising temperatures in recent decades in the Pirin
352Mountains require a more in-depth analysis of the likely future climate change and its
353impact on pine ecosystems. The developed long tree-ring width chronologies could
354potentially be extended even further back in time with dead or mainly with
355construction wood. However, care must be taken that this wood comes from nearby
356locations because of the found specifics of *P. peuce* increment in the studied sites.

357**Acknowledgments**

358 The study was supported by projects “Dendrochronology – A Thousand Years
359Master Chronology Building to Date the Material and Cultural Heritage of the
360Balkans”, financed by the Bulgarian National Science Fund with partnering
361organizations: National Archeological Institute with Museum at the Bulgarian
362Academy of Sciences, Forest Research Institute at the Bulgarian Academy of Sciences

363and University of Forestry (Agreement № ДН 20/7 / 11.12.2017), and by the National
364Science Program "Environmental Protection and Reduction of Risks of Adverse
365Events and Natural Disasters", approved by the Resolution of the Bulgarian Council
366of Ministers № 577/17.08.2018 and supported by the Ministry of Education and
367Science of Bulgaria (Agreement № D01-230/06.12.2018).

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