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Spatial and Temporal Growth Variation of *Pinus heldreichii* Christ. Growing along a Latitudinal Gradient in Kosovo and Albania

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ABSTRACT

Background and Purpose: Trees growing at high elevations are particularly sensitive to climate variability. In this study, tree-ring chronologies of *Pinus heldreichii* Christ. have been developed to examine their dynamism along a 350 km latitudinal gradient.

Materials and Methods: Sampling was conducted in 6 high elevation sites along a latitudinal gradient from Kosovo and Albania. Two opposite cores from 148 healthy and dominant *P. heldreichii* trees were taken using an increment borer. The cores were mounted and sanded, and after a rigorous cross-dating, the ring widths were measured to a resolution of 0.01 mm using the LINTAB 6 measuring device. The ARSTAN program was used for tree-ring series detrending and site chronologies' development. The relationship between radial growth and climate, as well as between temporal patterns of *P. heldreichii* growth were investigated using simple correlation analysis and principal component analysis (PCA) over the common period 1951-2013.

Results: Radial growth variability of Bosnian pine increased with latitude and elevation. Significant correlations among our chronologies and others from neighbouring countries indicated that our chronologies possess a good regional climatic signal. *P. heldreichii* growth at all sampling sites was significantly influenced by seasonal and mean annual temperatures, as well as by the July drought. Thus, temperature was the main driving force of species growth, showing a larger control at spatial scale than precipitation. The difference in species growth patterns along the latitudinal gradient is implicated by the common action of climatic and non-climatic factors (age and human activity). With continued warming and precipitation decrease during the second half of the 20th century, *P. heldreichii* growth from these high elevation sites resulted in being more sensitive to drought. This climatic signal is assumed to be stronger in the future due to climate change.

Conclusions: *P. heldreichii* chronologies developed in our study possess a good local and regional climatic signal. Temperature was the main driving force of *P. heldreichii* growing in these high elevations sites. The reduction of *P. heldreichii* growth during the second half of the 20th century due to temperature rise and rainfall decrease imposes the necessity to continue investigations on potential impacts of climate warming on species growing near the tree-line.

Keywords: high-elevation, latitudinal gradient, tree-ring growth, spatial analysis, principal component

INTRODUCTION

Tree-ring records provide valuable information for understanding the spatial and temporal patterns of tree-growth variability induced by environmental factors. Tree-ring data from high elevation sites are considered to be highly sensitive to climate variations, providing evidences about the impact of climate in the past [1]. In addition, these sites have a great potential to build long tree-ring chronologies for exploring the environmental changes at a variety time-scales [2, 3]. Bosnian pine (*Pinus heldreichii* Christ.) is a long-living, high elevation species situated in the Balkan (including Kosovo and Albania) and southern Italy [4]. The overall area covered by Bosnian pine in Kosovo is accounted 2150 ha, mostly mixed with silver fir (*Abies alba* Mill.). Some of the natural forest stands of this species in Kosovo are situated in Prevalla, Koritnik and Decani mountanious regions. In Albania, coniferous species occupy an area of 245 thousands hectares, but there is a lack of information regarding forest area covered by *P. heldreichii*. Several studies have been conducted using *P. heldreichii* tree- ring variables for temperature reconstruction and for exploring climate-growth relationship in neighbouring countries. In Bulgaria, maximum latewood density of *P. heldreichii* trees from a high-elevation stand in the Pirin Mountains is used for reconstruction of summer temperatures for the period 1768-2008 [3]. Other studies conducted in Bulgaria [5, 6], Greece [7], Kosovo [8] and Albania [9], have addressed the dynamism of climate–growth relationship of this high elevation species at various scales. In Albania, a 1391-year tree-ring width (TRW) chronology (617–2008) was developed and maximum density measurements were acquired on living and dead *P. heldreichii* trees [9]. Such dendroclimatological studies on *P. heldreichii* growth at high elevation sites are based on the fundamental axiom that tree growth represents a reaction to climate conditions [10]. Therefore, a comprehensive analysis of the spatial and temporal patterns of *P. heldreichii* radial growth along a latitudinal gradient and its response to monthly and seasonal climate by means of dendroclimatological techniques is needed. The aim of this paper is: (i) to identify the dominant spatial and temporal patterns of *P. heldreichii* radial growth over a 350 km latitudinal gradient in Kosovo and Albania; (ii) to compare the newly developed chronologies with other *P. heldreichii* chronologies from neighbouring countries; (iii) to analyse the spatial and temporal patterns of temperature and precipitation variability in all sampled sites, as well as to study the spatial and temporal climate-growth relationship.

MATERIALS AND METHODS

Research Locations

During 2014 and 2015 we sampled 148 healthy living *P. heldreichii* trees growing in six high elevation sites along a 350 km latitudinal gradient with a northeast to southwest direction from Kosovo and Albania (Figure 1). The sampling

FIGURE 1. Research sites along latitudinal gradient. Red circles show locations where *P. heldreichii* samples were collected (Decani - DE; Prevalla - PRE; Koritinik - KOR; Theth - THE: Korab - KO: Llogara - LLO).

sites represent the boundary area between forest vegetation and alpine pastures. Cold temperate coniferous forests in the research area are dominated by Bosnian pine (*P. heldreichii* Christ.) mixed with Silver fir (*A. alba* Mill.). Due to landscape patterns these forest stands are situated between 1450 and 1945 m (m a.s.l.) (Table 1). All natural forest stands from Kosovo are growing under the influence of continental climate with some influences of Mediterranean climate in the Koritnik (KOR) site. The Decani (DE) sampling site is located on a relatively steep rocky slope with south-west exposure in the Strelca area. Elevation of the site is 1830 m a.s.l and soil type is carbonate brown soil on limestone bedrocks. The mean annual temperature of the site is 8.1°C and the annual rainfall 792 mm. The Prevalla (PRE) and Koritinik (KOR) sampling sites represent natural forest stands

TABLE 1. Location and altitude of the sampled sites.

Code	Name	Latitude (N)	Longitude (E)	Elevation (m a.s.l)	Slope aspect
PRE	Prevalle	42°11'01.3"	20°57'42.0"	1945	SW
DE	Decan	42°36'19.8"	20°14'52.5"	1830	SW
KOR	Koritnik	42°04'46.5"	20°31'58.6"	1815	NE
THE	Theth	42°23'05.0"	19°43'02.6"	1640	SW
KO	Korab	41°47'38.8"	20°28'56.0"	1670	NW
LLO	Llogara	40°12'57.7"	19°35'34.4"	1450	W

of Bosnian pine located in the south of Kosovo inside the Sharri National Park. The sampled forest stands are located on ultrabasic bedrocks growing on deep carbonate brown soils. The research site in PRE is a pure Bosnian pine stand, while the KOR site represents a mixed Bosnian pine - Silver fir stand situated at an altitudes of 1945 and 1815 m a.s.l respectively. The forest stands are situated on SW (PRE) and NE (KOR) slope exposure. The mean annual temperature range is between 8°C (PRE) and 8.3°C (KOR), while annual rainfall varies from 874 mm to 1024 mm repectively. The Thethi (THE) research site is located in the north of Albania inside the area of Thethi National Park. The sampling site elevation is 1640 m a.s.l located on a relatively steep, rocky area with SW (south-west) exposure. Bosnian pine trees on that site grow on typical brown soils developed on limestone bedrocks. The Korabi (KO) sampling site is situated in eastern Albania, while Llogara (LLO) is the southernmost site, located in the SW of Albania inside the Llogara National Park. Most of the Bosnian pine trees grow on slopes with moderate to relatively steep inclination with NW (KO) to W exposure. The soils in THE and LLO sites are relatively shallow, while soils in KO site are moderately deep. Bosnian pine forest stands in Albania are growing under the influence of mountainous Mediterranean climate with annual mean temperature between 10°C (KO) and 15.5°C (LLO). Llogara site is the driest (870 mm) and warmest site compared to other sites from Albania, while THE site is the wettest with 1447 mm rainfall per year. Increment cores were taken from trees with a diameter at breast height (dbh) from 33 cm to 98 cm and height between 20 and 35 m. The average diameter of the sampled trees varies between sites and ranges from 46.6 cm (KO) to 63 cm (LLO) (Table 3). Ground vegetation in all sampled sites comprises (mostly) of the following species: *Sesleria autumnalis* Ard., *Brachypodium sylvaticum* Huds., *Carex humilis* Leyess., *Thymus balcanus* L., *Fragaria vesca* L., *Festuca heterophylla* Lam., *Dactylus glomerata* L. etc. Annual temperatures along the latitudinal gradient increase from NE to SW, while precipitation decreases and becomes more irregular throughout the year. The climate data in Figure 2 shows the lack of drought period in each sampled site during the summer season. Mean annual temperature decreases along rising elevation at any given latitude, while the rainfall is less influenced.

Data Collection, Chronology Development, and Statistics

Two opposite cores from dominant trees were taken at dbh using increment borers, where the number of sampled trees varied from 11 to 38. The cores were extracted along the slope contour to avoid reaction wood. The cores were then mounted and sanded following the standard dendrochronological procedures [11].

After rigorous cross-dating of the tree-ring cores, the ring widths were measured to a resolution of 0.01 mm using the LINTAB 6 (RINNTECH, Heidelberg) measuring device and the TSAP-Win Scientific software [12]. The quality of the time series measurement and cross-dating was examined and confirmed statistically using the COFECHA program [13]. The tree-ring width (TRW) measurements were standardized to remove the age-related growth trends. The TRW measurement series were converted into dimensionless indices [14]. For that, the ARSTAN,41b program was used [15].

Firstly, a negative exponential curve was fitted to each measured tree-ring series and ratios between the observed values and fitted growth curves were calculated. Secondly, a more flexible detrending was applied using a cubic smoothing spline with a 50% frequency response of 32 years to reduce non-climatic variation [16]. The persistence of the detrended series was removed by autoregressive modelling and the resulting residual series were averaged to a mean site chronology by computing the bi-weight robust mean [16]. In order to assess the temporal variability in the strength of the common variation in each site chronology, which reflects common responses to climatic influences, we used the running series of average correlations (R_{bar}) and expressed population signal (EPS) statistics [17]. R_{bar} is the mean correlation coefficient for all possible pairings among tree-ring series from individual cores, computed for a specific common time interval. The running EPS statistics computed from R_{bar} indicates to what extent the sample size is representative of a theoretical infinite population. Running EPS values were calculated over a 50-year window with a 25-year overlap. A threshold value for EPS≥0.85 for any given site chronology was considered adequate to reflect a common growth signal [17]. Several statistical parameters, such as the mean sensitivity (MS), the standard deviation (SD), first-order autocorrelation (AC1), the average correlation among all series (R_{bar}) and the expressed population signal (EPS) were calculated to assess the qualities of the six site chronologies.

In order to assess the similarity between the chronologies (tele-connection) from distant sites [18], regional chronologies were compared by t_{BP}-values and Gleichlauigkeit values (GLK) with the nearest existing tree-ring data available via the NOAA International Tree-Ring Data Bank (www.ncdc.noaa.gov/paleo/treering.html). The available Bosnian pine chronologies from the International Tree-Ring Data Bank were: Katara Pass (Greece, elevation 1750 m a.s.l, 1673-1981), Olympos Oros (Greece, elevation 2250 m a.s.l, 1583-1981), Sierra da Crispo (Italy, elevation 2000 m a.s.l, 1441-1980), Vihren (Bulgaria, elevation 1920 m a.s.l, 1721-1981), Pirin Mountain (Bulgaria, 2150 m a.s.l, 1288-2005). Additionally, we used the tree-ring chronology for Mount Smolikas (Greece, 575-2012) site provided by Paul Krusic (personal communication, 2017).

To assess the spatio-temporal patterns among six residual site chronologies the principal components analysis (PCA) [19] was applied over the common period 1840-2014. All principal components (PCs) with eigenvalues greater than 1 were retained for correlation analysis using the Minitab 17 program [20].

Spatial and Temporal Patterns of Temperature and Precipitation Variation

Instrumental climate records are spatially and temporally limited in these high mountain areas, and therefore the updated CRU TS 3.22 0.5°×0.5°- gridded monthly temperature and precipitation data sets were used [21] (www.climexp.knmi.nl). The climate data were extracted from the database for the region encompassed by the coordinates 40°25’-42°25’N and 19°25’-20°75’E (Table 2).

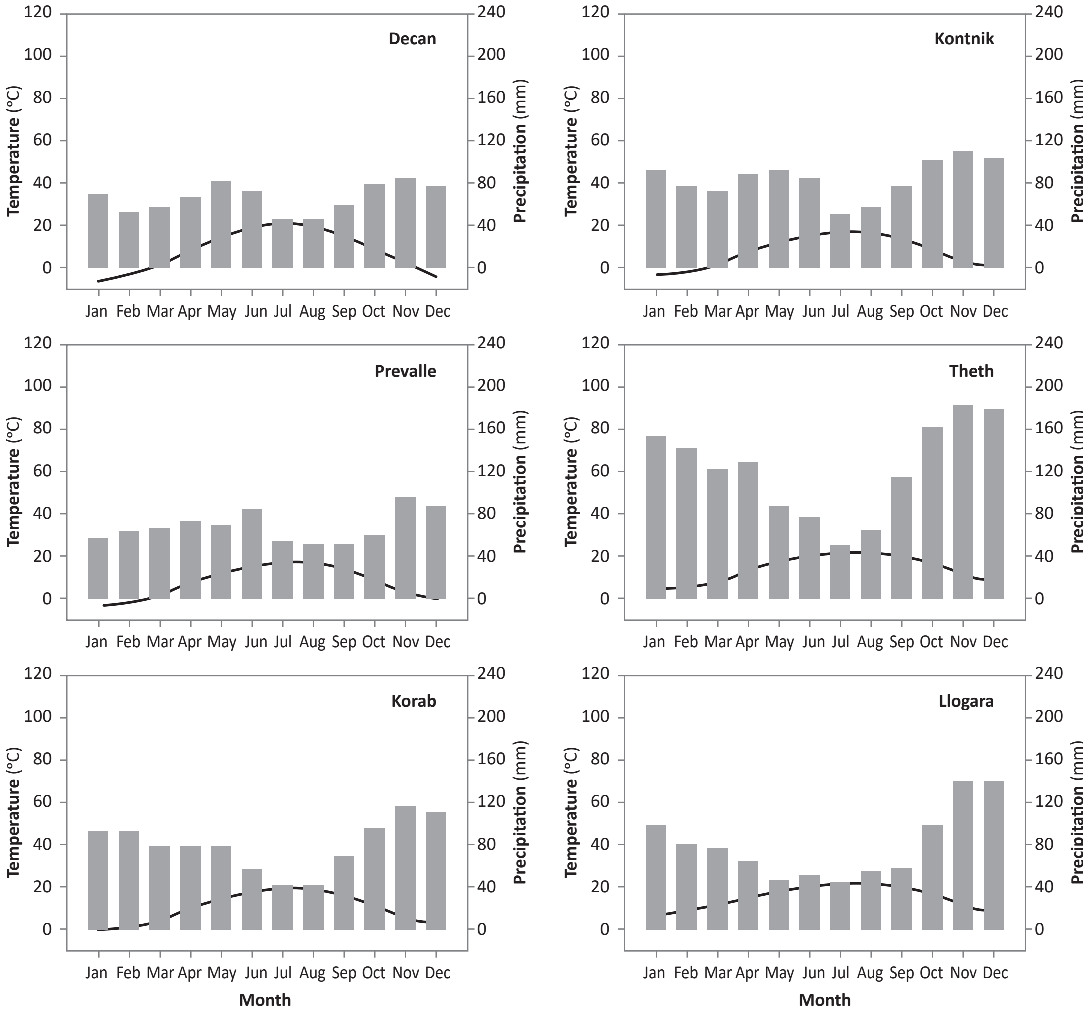

FIGURE 2. Climatic diagrams of the studied sites based on the CRU TS 3.22 data for the 1951-2013 period. Solid lines show temperature, while histograms show precipitation values.

Growth–Climate Spatial and Temporal Relationship

Climate sensitivity of *P. heldreichii* at spatial and temporal scale was assessed over the common period 1951-2013 using correlation analysis. The Pearson correlation analysis was performed between the principal components (PCs) of tree-ring residual chronologies and monthly, seasonal and annual climate variables to determine which climatic variables had the strongest influence on the radial growth of species growing in different sites along the latitudinal gradient. The *P. heldreichii* radial growth may be influenced by the current year's climatic conditions and that of the previous years. Thus, a period of 18 months, from previous May to current October, was involved in the following analysis [22]. The growth-climate relationship was quantified using the PCA. First a correlation matrix among each site chronology was estimated. In addition, three main principal components (PCs) were extracted from PCA, using the Kaiser criterion (eigenvalue>1). We applied the Varimax method for components rotation in order to minimize the number of variables that have high loadings and that have the main contribution in the final explained variance [23]. To detect which climatic factors affect the growth patterns as well as the spatial variation of this influence along the latitudinal gradient, correlation analysis was used between the first three PCs loadings and climate data [22]. To test the relationship at spatial and temporal scale we calculated the correlation coefficients among principal components of *P. heldreichii* residual chronologies and climate variables for the common period 1951-2013. Additionally, we selected the PCs which showed the strongest relationship with climate variables and plotted them graphically against each other to examine their coherence in temporal scale over the common period 1951-2013.

RESULTS

Sampling Site Characteristics

Sampling sites have a considerable difference in altitude (c.a. 495 m a.s.l.) along the latitudinal gradient. Elevation decreased southward along the latitudinal gradient and the correlation between elevation and latitude was 0.77 ($p<0.05$). The difference in elevation among sampling sites was associated with a northward decrease of mean annual temperature (c.a 1.6°C per 100 m elevation increase). Furthermore, a significant correlation ($R<0.85$, $p<0.05$) was found between mean annual temperatures and elevation at all research sites, while a weaker correlation was reached with precipitation. Based on climate data it was noticeable that aridity is increased with decreasing latitude (Figure 2).

Descriptive Statistics of the Tree-Ring Width Chronologies

Table 3 shows the descriptive statistics of each ring-width chronology. The longest chronology is from DE site spanning through the period from 1474 to 2014 with a replication of 35 trees, while the shortest chronology belongs to KOR site with 175 years (Figure 3). The mean ring-width values of built chronologies decreased with age indicating the presence of a biological trend in *P. heldreichii* radial growth. Mean sensitivity, characterizing the year-to-year variability in tree-ring records, ranges between 0.17 and 0.25, whereas the standard deviation varies from 0.50 to 1.32. Mean sensitivity is significantly affected by latitudinal and elevation gradients indicating that intra-annual variability in TRW increases with latitude and altitude. General patterns show that *P. heldreichii* chronologies located in the northern portion of the latitudinal range have higher sensitivity as compared to the southern ones. Tree-growth patterns through time vary among the site chronologies. The EPS values above the threshold (EPS>0.85) for all chronologies were reached after 1933, indicating a strong climate signal and a good temporal stability for all chronologies during the 1951-2013 common period.

Comparison among Chronologies

Correlations between site chronologies in the study area resulted depending on site characteristics and distance among sites. Correlation matrix displayed a greater similarity among site chronologies that are geographically situated in the central-northern and southern part of the latitudinal gradient, while a low correlation was found between the two most distant sites (Table 4). LLO chronology displayed significant correlations with most of the site chronologies except with DE-site. The highest correlations were found between LLO and THE, as well as between KOR and KO site chronologies. The correlation between KOR and PRE chronologies was statistically significant but not very high

TABLE 2. Climatic variables used for comparison with radial growth at a spatial and temporal scale.

Site	Latitude (N)	Longitude (E)	Record period	Parameter	Source
PRE	42° 25'	20° 75'	1951-2013	T ; P	https://climexp.knmi.nl/select.cgi?id
DE	42° 25'	20° 25'	1951-2013	T ; P	https://climexp.knmi.nl/select.cgi?id
KOR	42° 25'	20° 25'	1951-2013	T ; P	https://climexp.knmi.nl/select.cgi?id
THE	42° 25'	19° 25'	1951-2013	T ; P	https://climexp.knmi.nl/select.cgi?id
KO	41°25'	20° 25'	1951-2013	T ; P	https://climexp.knmi.nl/select.cgi?id
LLO	40° 25'	19° 25'	1951-2013	T ; P	https://climexp.knmi.nl/select.cgi?id

T - temperature; P - precipitation

TABLE 3. Descriptive statistics of the six ring-width chronologies.

Code	Name	Sampled trees	Period	Mean dbh (cm)	Mean ring-width (mm)	SD	MS[a]	AC1[a]	R_{bar}	EPS>0.85
PRE	Prevalle	30	1776-2014	52.0	2.13	0.91	0.21	0.78	0.55	1920
DE	Decan	38	1474-2014	62.6	1.06	0.50	0.22	0.77	0.56	1770
KOR	Koritnik	30	1840-2014	60.4	1.81	0.87	0.25	0.75	0.61	1876
THE	Theth	11	1575-2014	54.5	1.08	0.50	0.23	0.79	0.36	1726
KO	Korab	22	1833-2014	46.6	2.16	1.32	0.20	0.75	0.47	1933
LLO	Llogara	17	1597-2014	63.0	1.65	0.76	0.17	0.77	0.41	1765

SD - standard deviation; MS - mean sensitivity; AC1- first-order autocorrelation; R_{bar} - mean inter-series correlation; EPS - expressed population signal

[a] - Calculated for the standardized chronologies prior to autoregressive modelling

(R=0.22, p<0.01) due to the difference in tree age (c.a. 64 yr) and the influence of slope aspect on solar radiation budget.

PCA revealed that the first three rotated PCs have eigenvalues >1 and account for 35%, 20% and 15% of the total variance respectively, or cumulatively 70% of the total variance (Figure 4). The remaining components explain only 30% of the total variance. According to the loadings of the first three PCs, the site chronologies can be divided into three groups. This division is consistent with the results of the correlation analyses. The loadings of PC1 describe the environmental signals that are common between the *P. heldreichii* chronologies for KOR and DE with a clear pattern of decreasing towards the KO site.

PC2 represents the common variances of three high-elevation sites (LLO, KO and PRE) with a clear decreasing northwards (the PRE site). THE chronology showed the highest loadings of PC3-growth (>0.6). Temporal patterns of *P. heldreichii* radial growth are shown in Figure 5. The PC1 growth pattern shows a considerable variability of intra-annual values during the common period 1951-2013. The most negative factor scores were noted in several years: 1840, 1861, 1874, 1907, 1908, 1929, 1942 and 1947. This pattern is related to the northern chronologies (DE and KOR), which have the highest loadings. The PC2 growth pattern indicates a double decrease of negative values at KO site chronology where most of the negative values in factor scores were recorded after the year 1905. The negative score values of PC3 growth indicate the existence of lower variability. The most negative values were reached in 1853, 1869, 1993 and 1996 and this growth pattern is related to THE chronology.

The comparison of our chronologies with others from neighbour countries showed a strong dependence on the distance between sampled sites. Thus, the correlations of our *P. heldreichii* chronologies from DE, THE and KO sites with the Mount Smolikas (Greece) and Lure (Albania) were statistically significant (Table 5). Moreover, Bosnian pine chronology from KOR site showed a good agreement with Bulgarian chronologies from Pirin and Vihren sites. Tables 5 indicates that agreement was stronger between chronologies from the closest sites (Table 6). Thus, LLO chronology showed a good connection with chronology from Sierra del Crispo in Italy, while our *P. heldreichii* chronologies from THE site and KO site displayed good agreement with chronologies from Thethi and Lure built earlier by Seim et al. [9]. These results show that our *P. heldreichii* chronologies

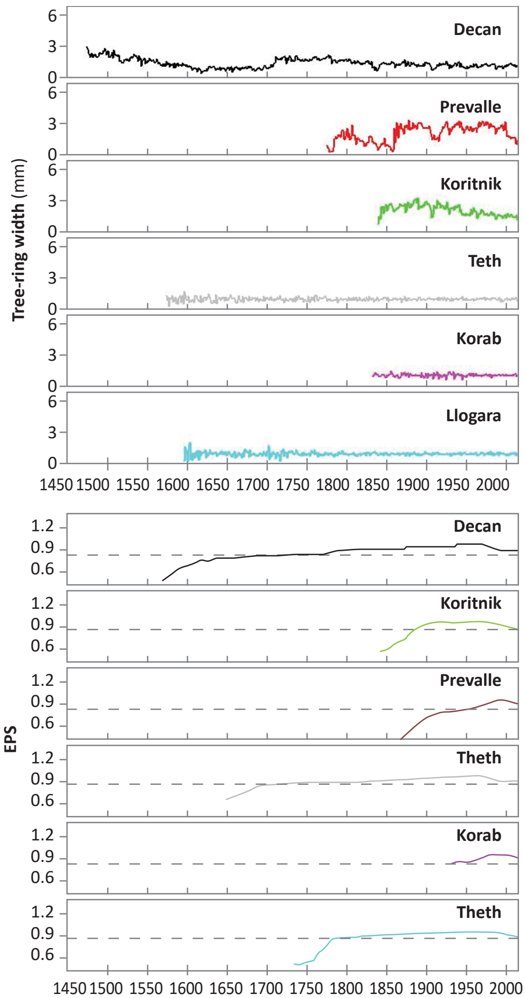

FIGURE 3. Raw tree-ring width chronologies of Bosnian pine (*P. heldreichii* Christ.) from research sites along latitudinal gradient. The upper part in the graph shows the raw ring width chronologies, while the lower part shows EPS value for each site chronology (dashed line shows EPS threshhold >0.85).

TABLE 4. Correlation between 6 site ring-width chronologies along the latitudinal gradient over the 1840–2014 common period.

Sampled sites	Pearson's correlation coefficients among site tree-ring chronologies					
	Decan	Prevalle	Koritnik	Theth	Korab	Llogara
Decan	1.00	0.08	0.48**	-0.18	-0.13	- 0.14
Prevalle		1.00	0.22**	0.11	-0.07	0.25**
Koritnik			1.00	-0.56**	-0.61**	-0.23**
Theth				1.00	0.58**	0.67**
Korab					1.00	0.19*
Llogara						1.00

** - correlation is significant at the 0.01 level (2- tailed)
* - correlation is significant at the 0.05 level (2 tailed)

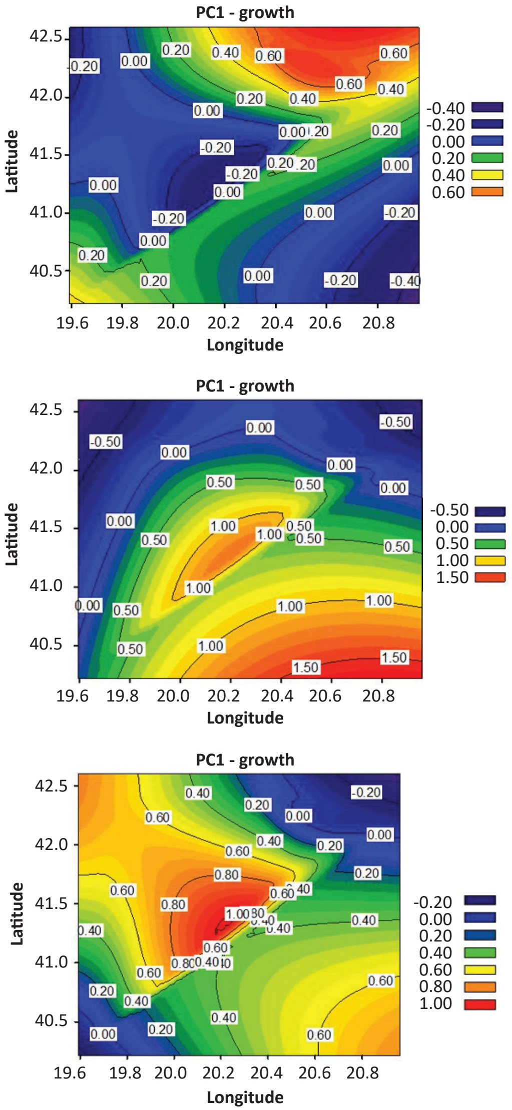

FIGURE 4. Spatial patterns of *P. heldreichii* tree growth along their latitudinall range. Site chronologies are plotted along longitudinal (X) and latitudinal (Y) location of respective sampling sites (DE 42.60 N - 20.26E; PRE 42.18 N - 20.96; KOR 42.08 N - 20.54 E; THE 42.38 N - 19.07 E; KO 41.79 N - 20.48 E; LLO 40.21 N- 19.59 E) . Isolines represent factor scores for the first three principal components for radial growth.

posses a good regional signal and may be included into a Bosnian pine dendrochronological network covering the whole geographical distribution of the species.

Spatial and Temporal Patterns of Temperature and Precipitation

Spatial and temporal patterns of temperature and precipitation were analysed for the period 1951-2013 which

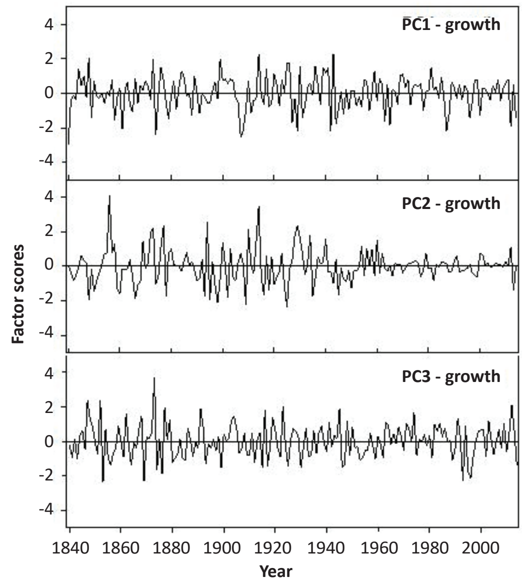

FIGURE 5. Temporal variations in factor scores of the first three principal components of *P.* heldreichii growth (from top to bottom: PC1-growth, PC2-growth and PC3-growth) extracted from the 6 site chronologies over the 1840–2014 common period.

is considered reliable from the climate data point of view. The first two PCs for mean annual temperature (PC1-temp and PC2-temp) explain 81% and 16% of the variance respectively (cumulative value 97%). The two stations (DE and KO) had the highest loadings for PC1-temp (>0.45) with a decreasing trend toward southern Kosovo. PC2-temp shows the opposite trend with the highest loadings (>0.9) in the KOR-site, and decreasing values northward Albania with negative loadings for THE-site (Figure 6). Regarding precipitation the first two PCs (PC1-prec and PC2-prec) explain 87% and 8% of the total variance respectively (cumulative value 95%). PC1-prec loadings reached high values (>0.41) for the sampled sites located in the north and central part of the latitudinal transect, whereas PC2-prec showed the highest loadings (>0.8) for LLO, which is the southernmost site along latitudinal gradient. The temporal patterns of temperature and precipitation in Figure 7 display the variability of PC1 and PC2 loadings. PC1-temp shows a temporal fluctuation of mean annual temperatures associated with a sustained positive trend in specific years (1984-1987; 1995-1998; 2000-2002 and 2010-2013) attributed to DE and KOR climate data. On the other hand, the PC2-temp shows a sustained decrease over the 1967-1997 period, associated with an increase of PC loadings during the 1998-2004 and 2006-2013 periods. Such trends reflect temperature variations at KOR site, which is located in southern Kosovo. The temporal patterns for both principal components of precipitation show a typical intra-annual variability over the 1951-2013 period. The long-term annual pattern for PC1-prec shows a distinct fluctuation in certain periods and a sustained decrease in precipitation during the period 1966-1979. The

TABLE 5. The comparison of all six *P. heldreichii* chronologies from Albania and Kosovo with others from neighbour countries.

Site	Mt. Smolikas, Greece		Lure, Albania		Olympos-Oros, Greece		Sierra da Crispo, Italy		Pirin, Bulgaria		Vihren Park, Bulgaria		Tomorr, Albania		Katara Pass, Greece		Theth, Albania (Seim)	
	t_{BP}	GLK%	t_{BP}	GLK%	t_{BP}	GLK%	t_{BP}	GLK%	t_{BP}	GLK%	t_{BP}	GLK%	t_{BP}	GLK%	t_{BP}	GLK%	t_{BP}	GLK%
Decan, Kosovo	6.29*	65*	6.29*	65*	8.29	60	2.33	52	3.59	54	14.11	62	4.52*	66*	2.19	59	1.67	45
Koritink, Kosovo	6.59	59	6.59*	65*	2.67	62	3.71	57	9.60*	66*	6.28*	69*	2.64	60	1.31	54	1.95	46
Prevalle, Kosovo	4.13	59	4.13	51	1.29	53	6.79	57	2.29	60	5.32	62	1.07	52	2.92	49	0.91	57
Theth, Albania	24.42*	69*	4.42	48	2.00	47	12.24	49	3.36	47	12.05	58	2.73	49	2.3	52	6.94*	68*
Llogara, Albania	9.69	53	9.69	51	1.77	53	6.60*	65*	0.61	54	3.62	53	0.81	51	3.58	54	2.24	52
Kala Dodes, Albania	10.01*	68*	10.01*	70*	4.98	53	6.26	46	3.23	51	5.59	57	7.41	45	3.13	48	1.72	55

* - significant correlations (p<0.05)

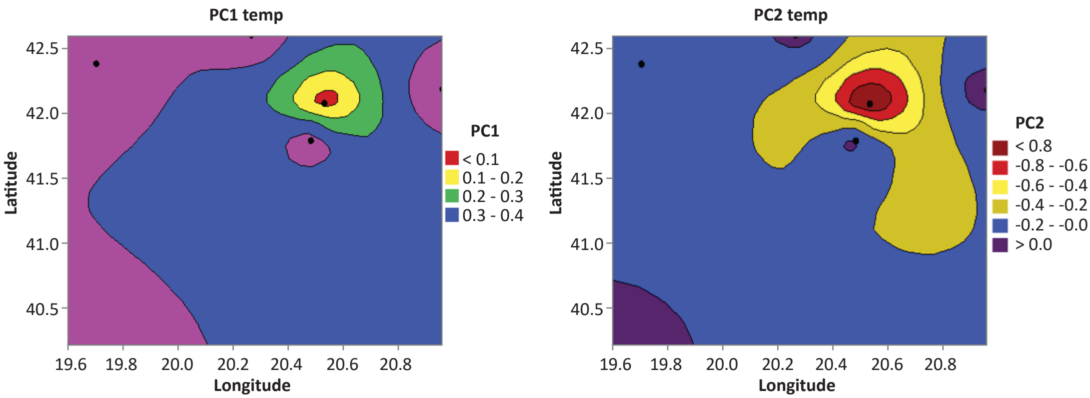

FIGURE 6. Spatial patterns of mean annual temperature variability for all research sites along their longitudinal (X) and latitudinal (Y) geographic range over the 1951–2013 period. Isolines represent factor scores of the first two principal components for mean annual temperature (left: PC1-temp and right: PC2-temp).

opposite patterns were observed from 1986 to 1992, as well as from 2007 to 2010. The long-term pattern for PC2-prec shows a higher variability than the first component associated with only two periods of precipitation decrease after the 1960s (1960-1964 and 1994-1998).

Growth-Climate Spatial Relationship

According to the available climatic data, all *P. heldreichii* chronologies were truncated over the common period 1951–2003, and then used for the growth-climate analysis. Correlation analysis indicated that our Bosnian pine chronologies were negatively correlated with temperatures in the summer and autumn prior to growth and in the spring, summer and autumn of the growing season (Figure 8). The growth-climate response for DE chronology (PC1) shows significant negative correlation to monthly temperatures from May prior to growth to current October, as well as to seasonal and annual temperatures. The climatic response of KOR chronology resulted as being weaker than the response showed by DE chronology. The KOR chronology was negatively correlated with previous July and August temperatures, as well as with current spring (MAM), summer (JJA) and early-mid autumn (September and October) temperatures of the growing year. The same response was also noted with seasonal and annual temperatures. The distinct drought signal in these two chronologies is supported by positive correlations with current July and August precipitation and with current summer precipitation ($r=0.24$, $p<0.05$) and negative correlation with summer (JJA) temperatures ($r=0.46$, $p<0.05$). The DE chronology was the only which showed significant positive correlation to annual sum precipitation. Similar correlation patterns with previous July, August, September and October temperatures were also noted for the second PCs, which represents the growth variability at KO, PRE and LLO sites. Our chronology from LLO site showed a stronger response against temperature than the previous ones. Thus, *P. heldreichii* trees responded negatively against to the previous June, July, October as

TABLE 6. Distance between our sampling sites and others from neighbouring countries

Site	Mt. Smolikas, Greece	Lure, Albania	Olympos-Oros, Greece	Sierra da Crispo, Italy	Pirin, Bulgaria	Vihren Park, Bulgaria	Tomorr, Albania	Katara Pass, Greece	Theth, Albania (Seim)
Decan, Kosovo (DE)	n.a	91.96	334.98	449.19	294.25	274.23	213.78	330.58	46.48
Koritink, Kosovo (KOR)	n.a	39.05	270.92	433.10	241.23	238.80	152.03	259.60	73.22
Prevalle, Kosovo (PRE)	n.a	75.64	265.16	469.44	224.80	205.86	175.99	268.30	101.75
Theth, Albania (THE)	n.a	77.89	341.96	399.26	330.77	312.14	188.07	317.30	6.40
Llogara, Albania (LLO)	n.a	183.03	240.63	289.01	366.82	362.96	69.07	148.00	249.00
Kala Dodes, Albania (KO)	n.a	22.58	248.30	413.63	257.20	241.61	126.80	233.21	90.49

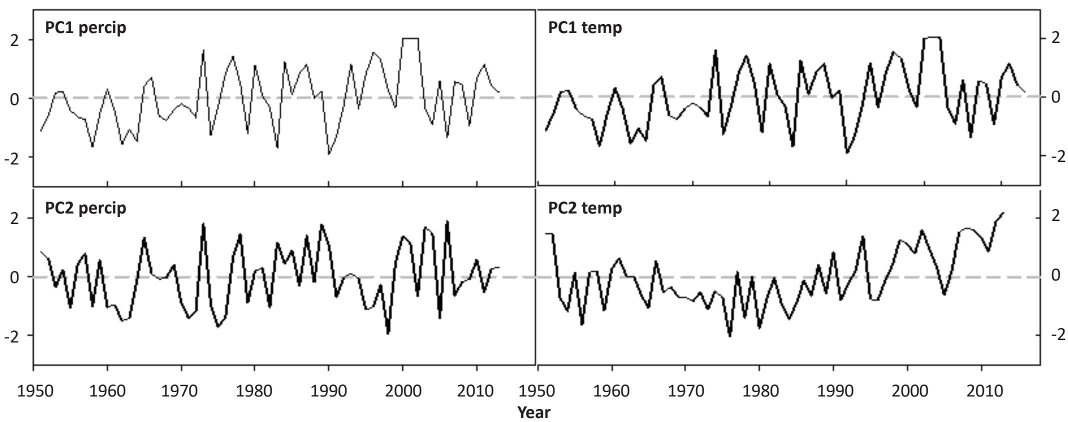

FIGURE 7. Temporal variations in factor scores of the first two principal components of annual precipitation (left) and mean annual temperature (right) extracted from CRU climate data for respective research sites.

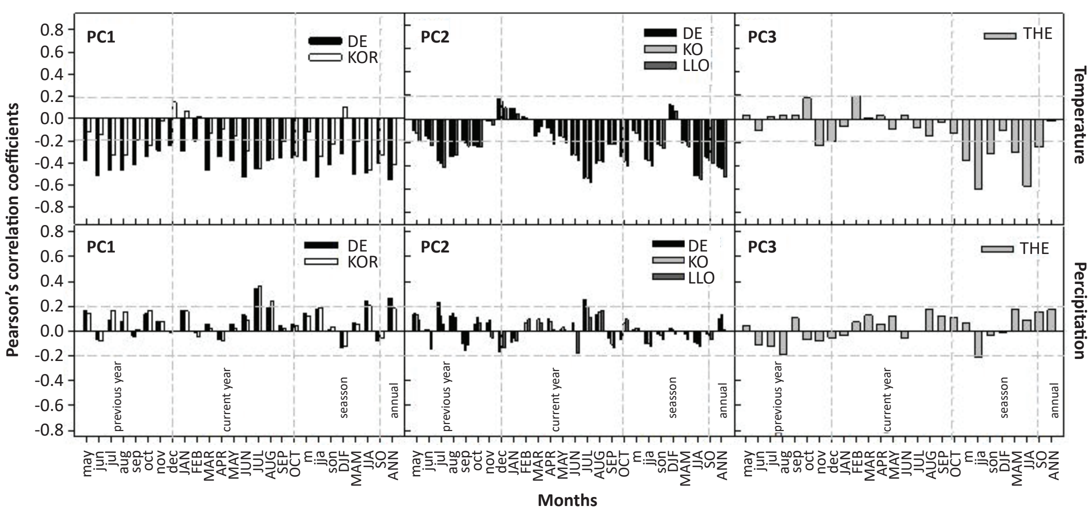

FIGURE 8. The correlation between monthly, seasonal and annual values of temperature and precipitation with first three principal components of *P. heldreichii* radial growth. The correlation coefficients were calculated from previous year May to current year October over the common period 1951–2013. The horizontal dash lines in each graph indicate the significance level of Pearson's correlation coefficients ($p<0.05$).

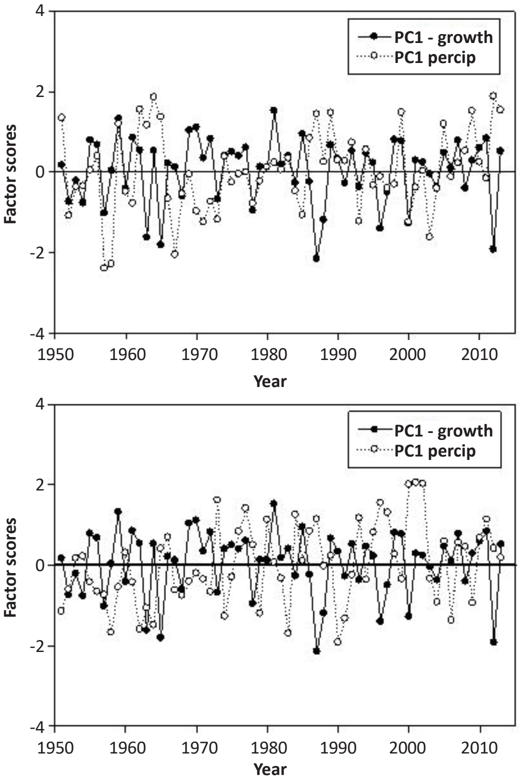

FIGURE 9. Temporal patterns of tree growth variability for the selected principal components extracted from 6 research sites for the 1951-2013 period compared with PCs of temperature and precipitation. The graphs show factor scores between PC1-growth and PC1-temp (left graph) and PC1-growth and PC1-precip (right graph).

well as current JJA and SO temperature at those three sites. The PRE chronology was positively correlated with previous and current July precipitation, while KO chronology showed positive correlation only with current July precipitation. The growth of *P. heldreichii* trees from THE site (PC3) has been negatively influenced by November temperatures of the previous year, as well as by seasonal temperatures except in winter. This is the only chronology which showed inverse correlation with summer (JJA) precipitation of the previous growing season ($r<-0.21$, $p<0.05$).

Growth–Climate Temporal Relationships

The correlation analysis revealed a significant correlation ($r=-0.24$, $p<0.05$) between *P. heldreichii* growth (PC1-growth) and mean annual temperatures, while the relationship with annual precipitation was weaker (Figure 9). Long-term gridded mean annual temperature data showed an increasing trend, whereas species growth has decreased ($p<0.05$) since 1951. The annual air temperature calculated from gridded data set showed a decreasing trend during the 1951-1985 period and a steady increasing trend from 1986 to 2013 for both countries. The air temperature has risen during May-August period. Furthermore, long-term annual precipitation data showed a decreasing trend for the 1951-2013 period characterized by a year-to-year variation and an uneven monthly distribution for both countries. The precipitation decline (c.a. 50 mm) in Kosovo was especially accounted for July, November, and May, whereas in Albania the annual sum of precipitation decline was two times higher than in Kosovo and the largest decline in rainfall was recorded during January, February, March, May, October, and November. Over the past 30 years, both countries experienced several extreme drought events (e.g. 1990; 2000; 2003; 2008 and 2011) which might have affected the Bosnian pine's radial growth [24].

DISCUSSION

Our study aims to reveal a comprehensive understanding of spatial and temporal patterns of *P. heldreichii* radial growth related to climate along the latitudinal gradient. We present a dataset of 148 living sample trees from six high elevation sites across Kosovo and Albania that used to build *P. heldreichii* radial growth chronologies. Such chronologies will contribute to a denser tree-ring network of Bosnian pine, providing a better understanding of the impact of climate on species growth along its geographic range. In comparison, the nearby *P. heldreichii* chronologies documented for the Balkan Peninsula and southern Italy, span periods of 1392 years (617 to 2008) in Albania [9], 762 years (1243 to 2004) in Greece [25], 758 years (1250 to 2008) in Bulgaria [6] and 827 years (1148 to 1974) in south Italy [26]. The comparison of our chronologies with others from neighbour countries showed a strong dependence on the distance between sampling sites. These results showed that our chronologies posses a good regional signal and that they could be integrated into a Bosnian pine dendrochronological network. Our *P. heldreichii* ring-width chronologies have different length, ranging from 174 to 541 years and a mean sensitivity ranging from 0.17 to 0.25. Mean sensitivity showed the suitability of *P. heldreichii* for dendroclimatic analyses. The presence of young trees in PRE, KO and KOR chronologies implies that such forest stands have been intensively managed and used by humans in the past. We analysed *P. heldreichii* growth patterns along a 350 km latitudinal gradient oriented toward northest-southwest direction. The sampling sites ranged in elevation from 1450 m to 1945 m a.s.l along latitudinal and longitudinal gradient associated with a northward decrease in mean annual temperature (c.a. 1.6°C per 100 m elevation). Although sampling was performed at the highest forested elevations, our research sites do not represent the typical tree - line conditions. Körner [27] stated that high elevation sites in Mediterranean region do not show a clear temperature control in radial growth pattern as compared to the Alpine sites, but our study found that temperature was the main climate driver of *P. heldreichii* growth. Climatic sensitivity of Bosnian pine chronologies increased with latitude and elevation. Thus, those *P. heldreichii* chronologies located in the northern portion of the latitudinal range had a higher year-to-year variation as compared to the southern ones. The difference in climate-growth relationship might be due to the combined effect of local site conditions, tree age and human activity. Thus, *P. heldreichii* radial growth showed stronger significant negative correlation with temperature at the northernmost site (DE) of the latitudinal gradient and an opposite relationship with precipitation. The significance of the growth-climate relationship is diminished towards the southern limit of the latitudinal gradient. The intra annual variability in radial growth from these sites has increased, not only by local climate conditions, but also by non-climatic factors. The diversity noted in Bosnian pine growth patterns (especially for PRE and KOR sites) and the relationship with climate variables might be caused by the presence of in-situ natural processes (e.g. rockfall, landslide, thunderclap) and anthropogenic activity (slash-and-burn for grazing, wood cutting for heating). It is known that shepherds and goatherds have been using the pastures close to the sampling sites in summer for grazing for many centuries and that the wood of Bosnian pine is traditionally used for cottage building and heating. *P. heldreichii* response versus climate seems to be age dependent because the oldest trees growing in DE, THE and LLO sites, resulted more sensitively against temperature than the youngest trees. Previous studies have shown that in old conifer trees the duration of wood formation is shorter than in younger ones [28]. It is well-known that tree ageing affects carbon allocation to different parts of the plant, reduces the foliar efficiency and gas attributes [29, 30]. Thus, decline of photosynthetic rate in old conifer species induce the increasing of climatic sensitivity, especially towards temperatures [31]. Although our sampling sites represent high elevation ecotones, the climate diagrams show the presence of a moderate water stress during the summer season. The inverse relationship noted at most of the sites between temperature and precipitation of the current July displays the presence of a distinct drought signal in Bosnian pine growth. Young trees are able to face with water stress which directly reduces their stomatal conductance, showing a higher sensitivity to drought. These moderate water deficits have a direct impact by reducing the foliar efficiency due to earlier stomatal closure, as well as the potential assimilation [32, 33]. Furthermore, young Bosnian pine trees do not have a deep root system, which makes them unable to utilize water sources in the deepest and wettest soil layers and meet their demands during the summer season [34].

Considering the latitudinal gradient we found that temperatures have greater control on Bosnian pine growth than precipitation, as indicated by negative correlations with PCs of species growth. This finding is supported by other authors' works on high elevation showing that radial growth of *P. heldreichii* correlates well with mean or seasonal temperatures [35, 36]. We found that all correlations between principal components and climate variables over the 1951-2013 period were relatively strong, exceeding the 95% significance level. Similar patterns of temperature and precipitation change over the 1951-2013 period have been observed at both countries. The climate data used here showed an overall decrease of annual temperature during the 1951-1985 period, followed by a prominent increase over the 1986-2013 period. Precipitation declined throughout the 1951-2013 period, which is associated with inter-annual variation and uneven monthly distribution for both countries. These important evidence of climate variables in both countries has been reported earlier by other authors. Thus, [37] stated a mean temperature increase by 1°C in Albania during the 20th century. They reported in their study a temperature decrease by 0.6°C during the 1900-1975 period associated with a warming by 2°C up to the present. The warming period in Albania during the 20th century is accompanied with changes of the rainfall regime, wind speed and wetness. They reported a decrease by 200-400 mm in the annual rainfall quantity [37]. Within the study area, spatial variability in *P. heldreichii* response to climate noted during the 20th century supports the conclusion that global warming possibly lead to differences among sites in sensitivity and climate variation [38]. Recently, other studies conducted in the European Alps have shown that global warming has potentially increased radial growth of conifer species growing in high elevations [39]. The decrease of *P. heldreichii* growth noted in our study during the second half of the 20th century implies that species growth is limited by humidity. The adequate explanation might be that hot dry summers recorded in the 1990s (1990; 2000; 2003; 2008 and 2011) caused drought stress where water storage capacity is limited because of shallow soil depth. Earlier studies have shown that *P. heldreichii* trees displayed higher sensitivity to summer drought, which was probably a result of increased summer temperatures and decreased winter precipitation [6].

It is assumed that there will not be any competition for the Bosnian pine by other tree species of the upper mountain level zone during the course of shifting of vegetation zones due to climate warming, which means that *P. heldreichii* would be the winner of climatic changes [40, 41]. However, ongoing and future research focused on *P. heldreichii* behavior to current and predicted climate change along its geographic range is required to improve the current level of knowledge of dendroclimatological studies.

CONCLUSIONS

P. heldreichii chronologies developed in our study possess a good local and regional climatic signal. Growth-climate relationship indicated that temperature is the main driving force of *P. heldreichii* growing in these high elevations sites. The difference in Bosnian pine growth patterns along the latitudinal gradient is implicated by common action of climatic and non climatic factors (age and human activity). The reduction of *P. heldreichii* growth during the second half of the 20th century due to the temperature rise and precipitation/rainfall decrease impose the necessity to continue investigations on potential impacts of climate warming on species growing near the tree-line.

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REFERENCES

1. VILLALBA R, BONINSEGNA JA, VEBLEN TT, SCHMELTER A, RUBULIS S 1997 Recent trends in tree-ring records from high elevation sites in the Andes of Northern Patagonia. *Clim Chang* 36 (3-4): 425-454. DOI: https://doi.org/10.1023/A:1005366317996
2. TROUET V 2014 A Tree-Ring Based Late Summer Temperature Reconstruction (AD 1675-1980) for the Northeastern Mediterranean. *Radiocarbon* 56 (4): S69-S78. DOI: https://doi.org/10.2458/azu,rc.56.18323
3. TROUET V, PANAYOTOV M, IVANOVA A, FRANK D 2012 A Pan-European summer teleconnection mode recorded by a new temperature reconstruction from the eastern Mediterranean (1768-2008). *Holocene* 22 (8): 887-898. DOI: https://doi.org/10.1177/0959683611434225
4. BARBERO M, LOISEL R, QUEZEL P, RICHARDSON DM, ROMANE F 1998 Pines of the Mediterranean Basin. *In*: Richardson DM (*ed*) Ecology and biogeography of Pinus. Cambridge University Press, Cambridge, UK, pp 153-170
5. PANAYOTOV M, BEBI P, KRUMM F, YURUKOV S 2009 *Pinus peuce* and *Pinus heldreichii* tree rings as a key to past mountain climate in Southeastern Europe. *In*: Kaczka RJ, Malik I, Owczarek P, Gärtner H, Heinrich I, Helle G, Schleser G (*eds*) Tree rings in archaeology, climatology and ecology, TRACE 7: 71-77.
6. PANAYOTOV M, BEBI P, KRUMM F, YURUKOV S 2010 Climate signals in *Pinus peuce* and *Pinus heldreichii* tree-ring width chronologies from the Pirin Mountains in Bulgaria. *Trees* 24 (3): 479-490. DOI: https://doi.org/10.1007/s00468-010-0416-y
7. BRANDERS R 2007 Waldgrenzen griechischer Hochgebirge: unter besonderer berücksichtigung des Taygetos, Südpeloponnes [Timberlines of Greek high mountains: With special regard to the Taygetos mountains, southern Peloponnese (forest dynamics, fir die-back, dendrochronological research on *Pinus nigra*)] (*in German with English summary*). PhD thesis, University of Erlangen, Germany, 259 p
8. BOJAXHI F, TOROMANI E 2016 The Growth of Bosnian Pine (*Pinus heldreichii* Christ.) at Tree Line Locations from Kosovo and its Response to Climate. *South-east Eur for* 7 (2): 109-118. DOI: https://doi.org/10.15177/seefor.16-10
9. SEIM A, BUNTGEN U, FONTI P, HASKA H, HERZIG F, TEGEL F, TROUET V, TREYDTE K 2012 Climate sensitivity of a millennium-long pine chronology from Albania. *Clim Res* 51 (3): 217-228. DOI: https://doi.org/10.3354/cr01076
10. SCHWEINGRUBER FH 1996 Tree Rings and Environment. Dendroecology. Swiss Federal Institute for Forest, Snow and Landscape Research/Paul Haupt: Berne, Switzerland
11. STOKES MA, SMILEY TL 1968 An introduction to tree-ring dating. University of Chicago Press, Chicago, IL, USA, 73 p
12. RINN F 2005 Time Series Analysis and Presentation software (TSAP-Win). User Reference (Version 0.55), RinnTech, Heidelberg, Germany
13. HOLMES RL 1983 Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull* 44: 69-75
14. FRITTS HC 1976 Tree rings and climate. Academic Press, London, UK, 567 pp
15. COOK ER, KRUSIC PJ 2007 ARSTAN a Tree-Ring Standardization Program Based on Detrending and Autoregressive Time Series Modelling, with Interactive Graphics. Tree Ring Laboratory, Lamont Doherty Earth Observatory of Columbia University, Palisades, NY, USA
16. COOK ER 1985 A time series analysis approach to tree-ring standardization. PhD Thesis, University of Arizona, Tucson, AZ, USA
17. WIGLEY TML, BRIFFA KR, JONES PD 1984 On the average value of correlated time- series, with applications in dendroclimatology and hydrometeorology. *J Clim Appl Meteorol* 23 (2): 201-213. DOI: https://doi.org/10.1175/1520-0450(1984)023<0201:OTAVOC>2.0.CO;2
18. KAENNEL M, SCHWEINGRUBER FH 1995 Multilingual Glossary of Dendrochronology. Paul Haupt: Berne, Switzerland. URL: http://www.wsl.ch/dienstleistungen/produkte/glossare/dendro,glossary/index,EN (10 February 2017)
19. COOLEY WW, LOHNES PR 1971 Multivariate data analysis. Wiley, New York, USA, 364 p
20. MINITAB 17 STATISTICAL SOFTWARE 2010 [Computer software]. State College, PA: Minitab, Inc, URL: http://www.minitab.com/en-us/ (10 February 2017)
21. HARRIS I, JONES PD, OSBORN TJ, LISTER DH 2014 Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 dataset. *Int J Climatol* 34 (3): 623-642. DOI: https://doi.org/10.1002/joc.3711
22. BLASING TJ, SOLOMON AM, DUVICK DN 1984 Response functions revisited. *Tree-Ring Bull* 44: 1-17.
23. RICHMAN BM 1986 Rotation of principal components. *Int J Climatol* 6 (3): 293-335. DOI: https://doi.org/10.1002/joc.3370060305
24. SPINONI J, NAUMANN G, VOGT JV, BARBOSA P 2015 The biggest drought events in Europe from 1950 to 2012. *J Hydrol: Regional Studies* 3: 509-524. DOI: https://doi.org/10.1016/j.ejrh.2015.01.001
25. KUNIHOLM PI, STRIKER CL 1987 Dendrochronological inves tigations in the Aegean and neighboring regions, 1983–1986. *J Field Archaeol* 10 (4): 385-398. DOI: https://doi.org/10.2307/529464
26. SERRE-BACHET F 1985 Une chronologie pluriséculaire du Sud de l'Italie. *Dendrochronologia* 3: 45-66
27. KÖRNER C 1998 A re-assessment of high elevation tree-line positions and their explanation. *Oecologia* 115 (4): 445-459. DOI: https://doi.org/10.1007/s004420050540
28. CARRER M, URBINATI C 2004 Age-dependent tree ring growth responses to climate of *Larix decidua* and *Pinus cembra* in the Italian Alps. *Ecology* 85 (3): 730-740. DOI: https://doi.org/10.1890/02-0478
29. KULL O, KOPPEL A 1987 Net photosynthetic response to light intensity of shoots from different crown positions and age of *Picea abies* (L.) Karst. *Scand J For Res* 2 (1-4): 157-166. DOI: https://doi.org/10.1080/02827588709382454
30. RICHARDSON AD, BERLYN GP, ASHTON PMS, THADANI R, CAMERON IR 2000 Foliar plasticity of hybrid spruce in relation to crown position and stand age. *Can J Bot* 78 (1-2): 305-317
31. BOND BJ 2000 Age-related changes in photosynthesis of woody plants. *Trends Plant Sci* 5 (8): 349-353. DOI: https://doi.org/10.1016/S1360-1385(00)01691-5
32. RYAN MG, YODER BJ 1997 Hydraulic limits to tree height and tree growth. *BioScience* 47 (4): 235-242. DOI: https://doi.org/10.2307/1313077
33. DAY ME, GREENWOOD MS, WHITE SA 2001 Age related changes in foliar morphology and physiology in red spruce and their influence on declining photosynthetic rates and productivity with tree age. *Tree Physiology* 21 (16): 1195-1204. DOI: https://doi.org/10.1093/treephys/21.16.1195
34. VALENTINI R, AANDOFILLO T, EHLRINGER J 1994 Water sources utilization and carbon isotope compositions ($d^{13}C$) of co-occurring species along an altitudinal gradient in the Italian Alps. *Can J For Res* 24 (8): 1575-1578. DOI: https://doi.org/10.1139/x94-205

35. KÖRNER C 2012 Alpine Tree-lines. Functional Ecology of the Global High Elevation Tree Limits. Springer, Basel, Switzerland, 220 p. DOI: https://doi.org/10.1007/978-3-0348-0396-0
36. LENZ A, VITASSE Y, HOCH G, KÖRNER C 2014 Growth and carbon relations of temperate deciduous tree species at their upper elevation range limit. *J Ecol* 102 (6): 1537-1548. DOI: https://doi.org/10.1111/1365-2745.12307
37. FRASHËRI A, PANO N 2003 Impact of the climate change on Adriatic Sea hydrology. *Elsev Oceanogr Serie* 69: 92-96. DOI: https://doi.org/10.1016/S0422-9894(03)80015-6
38. OBERHUBER W, KOFLER W 2003 Effects of climate and slope aspect on radial growth of Cembran pine (*Pinus cembra* L.) at the alpine timberline ecotone on Mt. Patscherkofel (Tyrol, Austria). *Aust J For Sci* 120: 39-50
39. HARTL-MEIER C, DITTMAR C, ZANG C, ROTHE A 2014 Mountain forest growth response to climate change in the Northern Limestone Alps. *Trees* 28 (3): 819-829. DOI: https://doi.org/10.1007/s00468-014-0994-1
40. GRUNEWALD K, SCHEITHAUER J 2008 Untersuchungen an der alpinen Waldgrenze im Piringebirge (Bulgarien). *Geo-Öko Band* 29 (1-2): 1-32
41. SCHEITHAUER J, GRUNEWALD K, HELLE G, GÜNTHER B, GIKOV A 2009 Bosnian pine (*Pinus heldreichii)* as geoarchive at the timberline in the Pirin mountains and on the Balkan Peninsula. *Biotechnol Equip* 23: 96-99. DOI: https://doi.org/10.1080/13102818.2009.10818374