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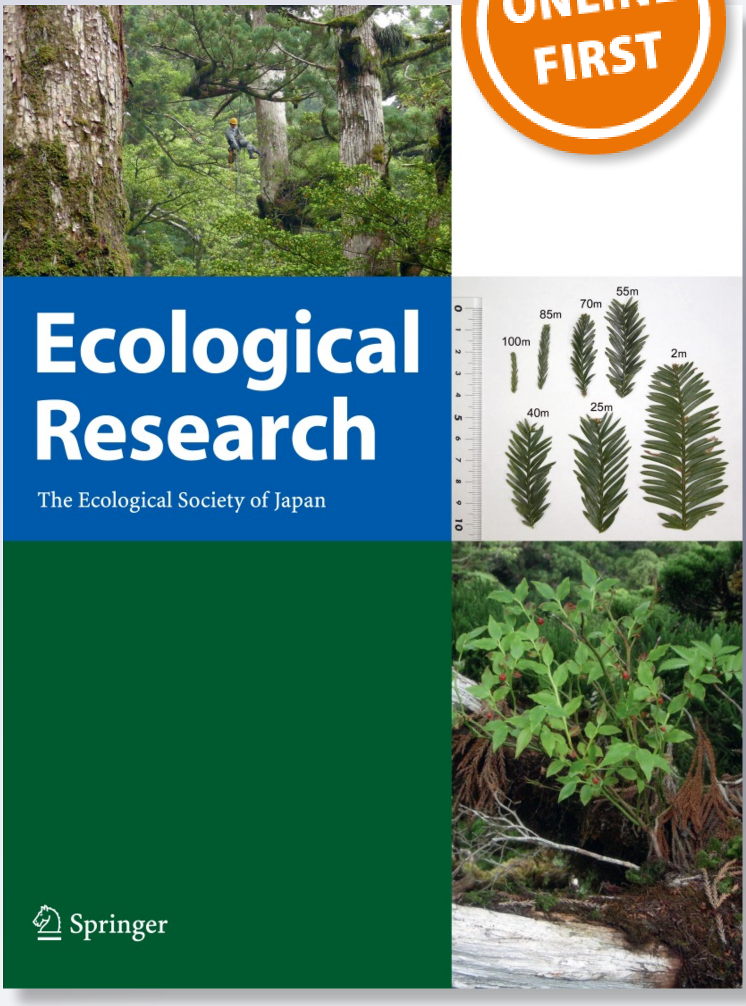

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ORIGINAL ARTICLE

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Abstract Radial growth of boreal tree species is only rarely studied in riparian habitats. Here we investigated chronologies of earlywood, latewood, and annual ring widths and blue intensity (BI; a surrogate to latewood density) from riparian lake shore and upland forest interior pines (*Pinus sylvestris* L.) growing in boreal forest in eastern Finland. Riparian and upland chronologies were compared to examine differences in the pine growth variability and growth response to climatic variation in the two habitats. It was found that the climatic variables showing statistically significant correlations with the tree-ring chronologies were related to snow conditions at the start of the growing season. Deeper snowpack led to reduced upland pine growth, possibly due to delayed snowmelt and thus postponed onset of the growing season. Warm late winters were followed by increased riparian pine growth because of earlier start of the snow-melt season and thus a lower maximum early summer lake level. Moreover, riparian pines reacted negatively to increased rainfall in June, whereas the upland pines showed a positive response. Latewood growth reacted significantly to summer temperatures. The BI chronology showed a strong correlation with warm-season temperatures, indicating an encouraging possibility of summer temperature reconstruction using middle/south boreal pine tree-ring archives.

Keywords Blue intensity · Dendrochronology · Radial growth · Lake shore · *Pinus sylvestris* · Tree ring

Introduction

Ongoing change in our climate and environment poses stress for ecosystems. Northern Europe has experienced precipitation increase by 10–40 % in the 20th century (Dore 2005). Uncertainties related to future climate change remain with different aspects of hydroclimate (Frei et al. 2006; Räisänen 2007). Even with these uncertainties, however, many climate models predict increasing risk of extreme precipitation events in the coming decades (Räisänen and Joelsson 2001; Palmen and Räisänen 2002). These changes may be of special importance for vegetation in northern and central Europe where an increase in precipitation in the early stage of the growing season has been predicted (Ylhäisi et al.

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2010). Vegetation of riparian zones, at the interface between terrestrial and aquatic systems, is exposed to sharp gradients in environmental processes (Naiman and Decamps 1997). Such zones, important for high productivity of biomass, biodiversity, ecological services, and as habitats for birds and mammals (Kozlowski 2002), are sensitive to hydroclimate anomalies.

Finland is "a land of a thousand lakes". There are 187,888 lakes within the country, including 215,000 km of shorelines. In addition, the combined length of the inland shorelines is 314,000 km including the riverine habitats (Kuusisto 2006). As some predictions show an increase in precipitation in the early stage of the growing season (Ylhäisi et al. 2010), large areas of riparian ecosystems may therefore be directly influenced by hydroclimatic changes. Understanding the impact of climatic and hydrologic variability on the riparian ecosystems necessitates enhanced understanding of riparian versus upland forest responses to these variations. Invaluable insights into forest health and growth in the context of climate variability can be unveiled using dendroecological methods (Fritts 1976; Fritts and Swetnam 1989). To do so, tree-ring chronologies are typically correlated against temperature and precipitation records to quantify the response of tree growth to climate parameters. In boreal environments, snowfall data have also proven to be an important complement in these analyses, as the snow conditions may considerably influence tree growth (Vaganov et al. 1999; Kirdyanov et al. 2003; Helama et al. 2013).

Scots pine (*Pinus sylvestris* L.) is a common species over large areas of Eurasian boreal forests. However, riparian pine growth around lake environments has rarely been studied, and little comparison with the growth responses of upland trees has been made. In Sweden and Finland, the growth of pines growing in riparian habitats has previously been compared with levels of flooding (Eriksson 1951; Tuononen et al. 1981). It was found that high-standing water during the earliest part of the growing season did not impair tree growth, while the high water conditions during the later part of the season may indeed cause a negative effect on pines (Tuononen et al. 1981). These studies did not, however, investigate dendroclimatic responses to a multitude of climatic parameters, which is now routine in modern dendroclimatology (Biondi and Waikul 2004). More recently, riparian pines were found to experience less drought stress and, accordingly, showed a stronger dendroclimatic response to summer temperatures in northern Norway (Hundhausen 2004). In Scotland, waterlogging was seen as probably the primary restriction on the radial growth of pine on bog and lakeshore sites (Moir et al. 2011). Lakeshore and upland pine tree-ring chronologies were also compared in northern Scandinavia, where the July temperature was found to be a time-independent climatic factor affecting the growth as analyzed from tree rings of standing pines growing in inland habitats as well as from subfossil pine logs recovered from lake sediments, thus originating from riparian habitat (Helama et al. 2004a). Moreover, the latewood density growth of riparian pines was enhanced in comparison to inland pines over the most recent centuries (Esper et al. 2012). Herein, we aim to build upon these relatively few studies by studying a riparian setting of Scots pine growth in eastern Finland, around Lake Linnalampi, and comparing the growth of the trees growing in the riparian zone with the growth in the upland habitat adjacent to the same lake. By detailing the possible growth differences in these habitats, our analyses aim at identifying the dominant temperature and hydroclimate variables controlling growth.

One more important reason to study the tree rings around Lake Linnalampi is the possibility of recovering the subfossil trunks lying in the lacustrine sediments of the same lake for dendroclimatic investigations (Dr. Jouko Meriläinen, pers. comm.). Dendrochronological exploration of these subfossil pine trunks could result in a considerably elongated tree-ring chronology, similar to the studies of subfossil tree rings carried out in different parts of Fennoscandia (Eronen et al. 2002; Grudd et al. 2002; Linderholm and Gunnarson 2005; Helama et al. 2005, 2008a, b; Esper et al. 2012). These multi-centennial and even multi-millennial tree-ring chronologies have provided estimates of past temperature and precipitation variability (Grudd et al. 2002; Linderholm and Gunnarson 2005; Helama et al. 2010a, b, 2012a), yet it has been suggested that these chronologies ought to be calibrated using lake edge riparian trees (Hundhausen 2004; Esper et al. 2012). Thus, the collection of riparian pine tree-ring chronologies around Lake Linnalampi serve as the most suitable modern counterpart for the ancient tree rings that could potentially be recovered from this lacustrine archive.

Materials and methods

Tree-ring samples

Lake Linnalampi is located at 62.73°N and 31.01°E, 146 m above sea level (Fig. 1), in the municipality of Ilomantsi, the province of North Karelia, eastern Finland, approx. 5 km south-southeast of the Mekrijärvi Research Station (University of Eastern Finland). The study site is located between the middle and southern boreal zones (sensu Ahti et al. 1968). The lake is north–south oriented, has a surface area of 20.14 ha, and a maximum depth of 18 m. It is surrounded by pine forests, growing on sandy ridges, reaching 150 m a.s.l., with correspondingly well-drained soils.

A total of 65 Scots pine trees (*Pinus sylvestris* L.), were cored around the lake in June of 2010. The upland pines (34 trees) were cored through random sampling along the western, southern, and eastern sides of the lake, and tended to be at the highest landscape positions created by the sandy ridges. The sampled riparian pines (31 trees) were located immediately downslope from

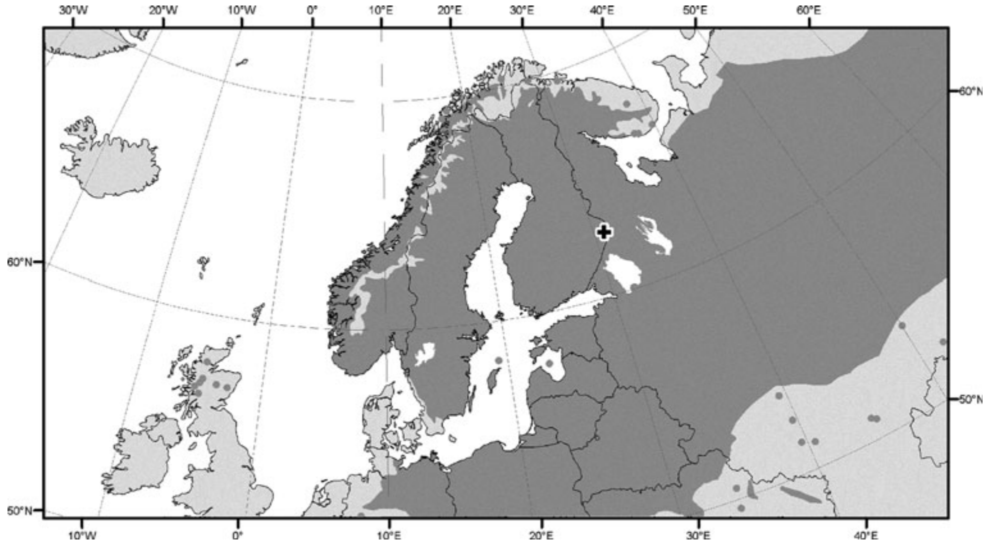


Fig. 1 Distribution map of Scots pine and the studied site (*cross*). The map was modified following the initial compilation by the members of the EUFORGEN Conifers Network (Mátyás et al. 2004)

each of the upland pine sites. For riparian pines, we tried to sample trees with their roots clearly reaching the lake water. One core was obtained from each tree, at breast height, using Finnish and Swedish increment borers. The samples were glued into wood mounts and prepared using standard methods. Prepared samples were scanned at 1200 dpi resolution using an Epson Expression 1640 XL scanner (Seiko Epson Corp, Nagano, Japan).

Chronology construction

Dendrochronological cross-dating was performed using the list method (Yamaguchi 1991) to ensure the correct dating of the samples before measuring the ring properties. This is done by listing the narrow rings from the outermost (nearest to bark) to the innermost (nearest the pith) ring and comparing the lists for shared narrow rings. The upland and riparian chronologies, consisting of trees from the western, southern, and eastern sides of the lake, cover the period 1890–2009 and 1841–2009, respectively. Multiple tree-ring parameters were measured on the digitized sample images using CooRecorder 7.2 (Cybis Elektronik & Data AB, Stockholm, Sweden). Annual ring boundaries and earlywood/latewood divisions were recorded to construct three types of time-series of annual and intra-annual ring width properties for each tree: annual ring width (ARW), earlywood width (EWW) and latewood width (LWW). The intra-annual earlywood/latewood boundaries for the species are typically more gradual than the inter-annual latewood/earlywood borders but can be detected from the intra-annual color/density profile (Helama et al. 2008b). Moreover, surface reflectance of the wood was determined from scanned images and the minimum blue channel light intensity (BI) of the latewood portion of each annual ring was obtained. Previously, BI has been shown to provide a highly skilled surrogate for latewood density of pine tree rings, in particular Scots pine (McCarroll et al. 2002; Campbell et al. 2007; Wilson et al. 2011). It has been shown that the radial density variations in the Scots pine tree-rings are positively associated with the changes in cell wall thickness and cell wall proportion and negatively with the radial tracheid size (Helama et al. 2010c). The BI data were thus utilized as indicators of corresponding wood quality and anatomy. In this study, no attempt was made to control for the extractive (e.g., resin) and moisture content in the wood. Since these circumstances may influence the trends and variability of estimated growth (Helama et al. 2010c, 2012a), the data were processed to remove trends and stabilize variance. Tree-ring series are known to contain non-climatic trends that should be eliminated from the series prior to computing the mean chronology for dendroclimatic analyses. In this study, a curve in the form of a modified exponential function (Fritts et al. 1969) or a trendline with negative or zero slope was fitted to each series. Tree-ring indices were extracted by dividing the observed tree-ring value (ARW, EWW, LWW, or BI) by the value expected by the curve. Further, a cubic smoothing spline function (Cook and Peters 1981) was fitted to the series of these indices and a new series of tree-ring indices were extracted from this curve as ratios. The rigidity of the spline was determined to be 67 % of the length of each individual time series (50 % frequency response cut-off). The first detrending was expected to remove the long-term growth trend from the tree-ring measurement series and to stabilize their variance, whereas the second detrending was is expected to remove growth variation related to possible disturbance caused by forest dynamics with additional variance stabilization (Fritts 1976; Cook et al. 1990a; Helama et al. 2004b). These ‘‘double-detrended’’ series were used in the subsequent dendrochronological and dendroclimatic analyses. Tree-ring chronologies of riparian and upland pines were produced separately by averaging the annual values of indices using a biweight robust mean (Mosteller and Tukey 1977; Cook et al. 1990b). Tree-ring index series were further pre-whitened using Box and Jenkins (1970) methods of autoregressive and moving-average time-series modeling (Henttonen 1984; Cook 1985; Monserud 1986; Biondi and Swetnam 1987). The order of the autoregressive-moving average process was determined using Akaike (1974) information criteria. The process of pre-whitening transforms autocorrelated series into a series of independent observations by extracting residuals from the modeled process. Again, tree-ring chronologies were produced by averaging the annual values of indices by biweight robust mean (Mosteller and Tukey 1977; Cook 1985). Expressed population signal (EPS) was used as indication of chronology reliability and to measure the expression of common variability among the available tree-ring series through time and considering EPS > 0.85 as a reasonable albeit objective value for an acceptable level of chronology confidence (Wigley et al. 1984).

Climate data

Meteorological observations (since 1959) nearest to the tree-ring sampling site originate from the weather station in Ilomantsi operated by the Finnish Meteorological Institute (62.67ºN, 30.93ºE). Since 2000, the meteorological observations have been carried out at the Mekrijärvi Research Station (62.77ºN, 30.97ºE). We adopted these data as continuous meteorological records of mean monthly temperatures, monthly precipitation sums, and snow depth on the 15th and last day of each month. A small number of missing temperature values were estimated from a 10 × 10-km Finnish monthly mean temperature grid (Tietäväinen et al. 2010). Low temperatures are typically experienced in January and February, whereas the warmest month is July (Electronic Supplementary Material, Fig. A1). The wettest season is summer (June through August), while precipitation reaches its lowest values during the late winter season (February through April). The period of maximum snow depth occurs in February and March, and snow-melt takes place from April to May. In order to obtain the longest possible temperature time series for the study area, the Finnish monthly mean temperature grid data was used to excerpt the estimates of mean monthly temperatures from a grid point representing the study site (mid-point of the grid, 62.73ºN and 31.01ºE) starting from the year 1909. This was the year after which the monthly grid-point mean temperatures were judged unbiased following the elevated number of station records in the region and adjacent areas in eastern Finland and north-west Russia (see Tietäväinen et al. 2010).

Dendroclimatic analyses

Investigation of climatic variables that affected pine growth was achieved using the bootstrapped response function analyses producing the coefficients (computed between the tree-ring chronology and the series of monthly climatic variables) as multivariate estimates (Biondi and Waikul 2004). The series of mean monthly temperatures and precipitation sums were linearly detrended before dendroclimatic analyses. That is, a regression line was fitted to each monthly record of temperature and precipitation and the trendline was extracted from the series by subtraction. Response functions were computed separately for the ARW, EWW, LWW, and BI chronologies from upland (dry) and riparian (wet) habitats over the climatic study period (1960–2009). The climate data (Tietäväinen et al. 2010) were used for estimating the correlation of the BI chronologies (riparian and upland) with different warm-season temperature series over an extended period (1909–2009) as well as stability over the recent (1959–2009) and early (1909–1958) periods.

Results

Growth and growth variability

On average, the upland and riparian pine data contained 78 and 107 rings with mean radii (sum of measured ARWs) of 119 and 122 mm, respectively, these values translating into absolute growth rates of 1.7 and 1.2 mm/year. These findings indicate slower growth in riparian habitat. Chronologies from the upland and riparian habitats portrayed tree-ring growth variations on inter-annual to longer scales (Fig. 2). The two habitats showed fairly similar pine growth variability, although there appeared also dissimilarities. Although the two types of chronologies were generally similar in their growth characteristics, the correlations calculated (1960–2009) among all four parameter chronologies pair-wise between the upland and riparian chronologies yielded coefficients 0.461, 0.442, 0.571, and 0.877, respectively, for ARW, EWW, LWW, and BI (Electronic Supplementary Material, Table A1). Over this period, the EPS exceeded clearly the 0.85 level (Fig. 4). These correlations indicated that growth variability in the upland and riparian habitats was somewhat differentiated. As an additional example, the correlations between the EWW and LWW chronologies within same habitat averaged 0.624, whereas the correlations between the same two types of chronologies from upland versus riparian habitats averaged 0.232 only. Negative correlations were obtained between BI and other chronologies (Electronic Supplementary Material, Table A1).

Dendroclimatic response functions

The riparian ARW chronology showed a positive and statistically significant relationship with the temperature

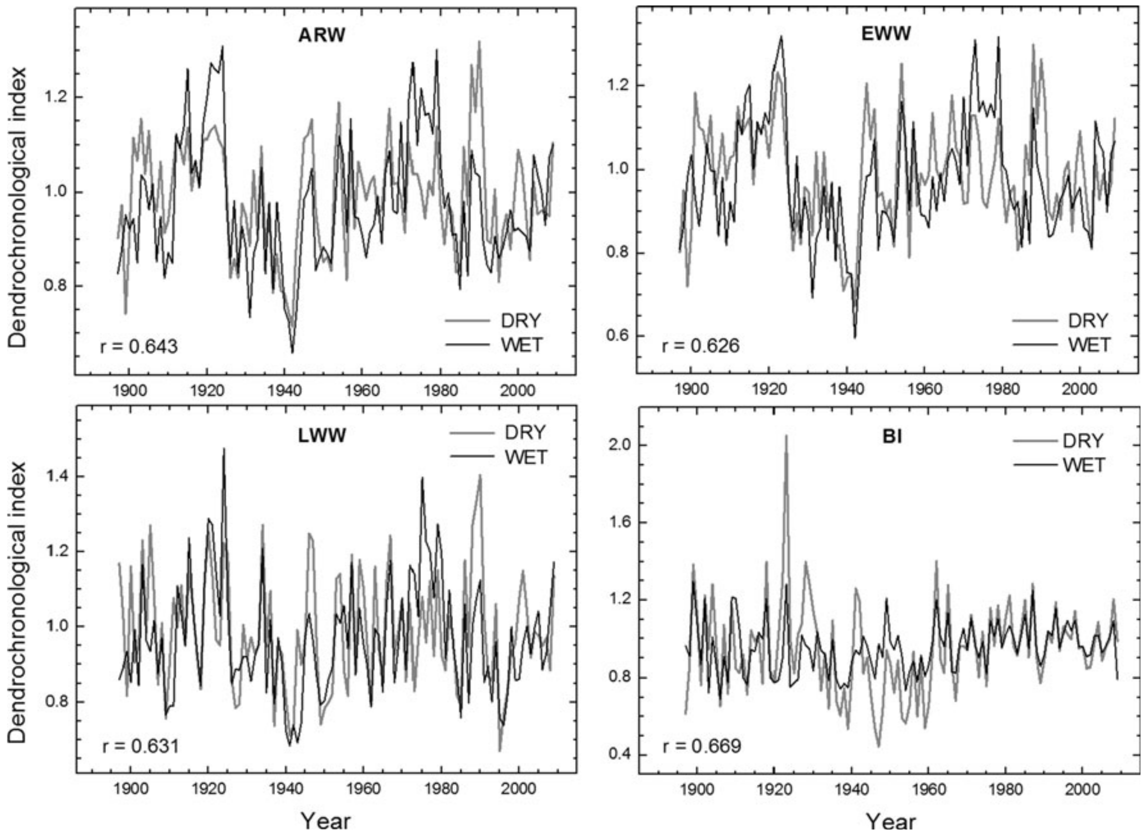


Fig. 2 Chronologies of annual ring width (ARW), earlywood width (EWW), latewood width (LWW) and blue intensity of latewood (BI) from dry (upland) and wet (riparian) habitats. The chronologies are shown since 1897 when the chronologies were covered using at least five pines

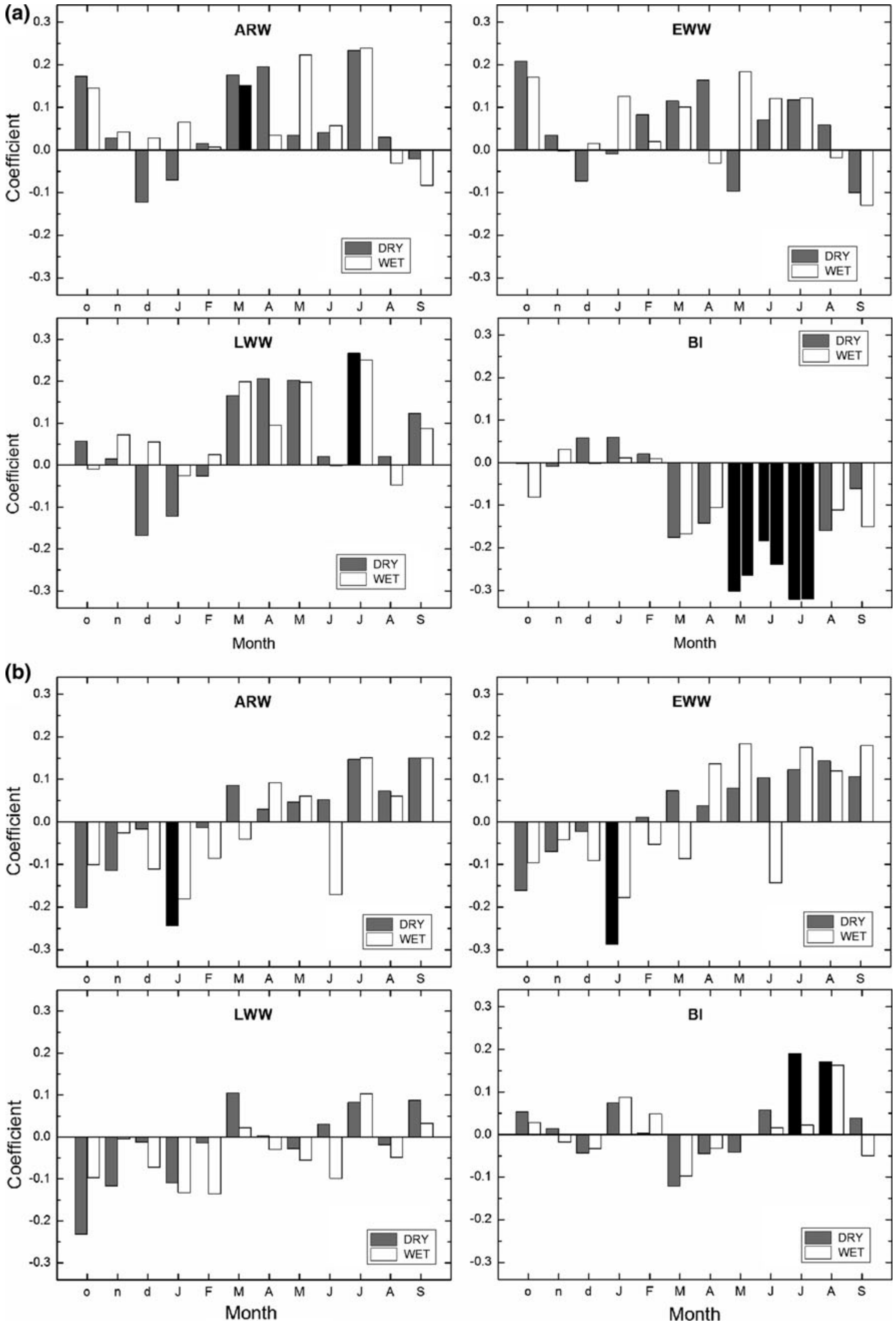
for March, whereas there were no significant temperature associations with EWW chronologies (Fig. 3a). The latewood chronologies, LWW and BI, reacted to summer temperatures. For LWW, the positive summer temperature correlation was found only in upland habitat for July, whereas the BI chronologies exhibited strong negative association with growing season temperatures for the May–July season, independent of habitat. Notably, it was found that the chronologies of the tree-ring width parameters (ARW, EWW, and LWW) did not indicate any climate variable having impacted the growth similarly and statistically significantly in both habitats.

In the context of hydroclimatic influence (Fig. 3b), both the ARW and EWW chronologies showed a negative and statistically significant influence to mid-winter (January) precipitation in the upland habitat. This indicated that the accumulated snow during this month may have decreased growth of the pines in this habitat. Precipitation did not influence the growth as indicated by the LWW chronologies, whereas there appeared a positive relationship between the upland BI chronologies and summer (June–July) precipitation.

The ring-width growth of riparian pines (ARW and EWW, and LWW) reacted negatively to increased rainfall in June, whereas the upland pines showed a positive response. The dissociation was strongest for EWW chronologies. Calculating the difference between the riparian and upland EWW indices for each calendar year, and correlating this series with the record of June precipitation (1960–2009), reveals a negative and statistically significant Pearson correlation −0.317 ($p < 0.05$) (Electronic Supplementary Material, Fig. A2). It therefore becomes more evident that the riparian pine growth was decreased in relation to growth of upland pines in years of increased June precipitation.

Connections with snow conditions

In order to explore the possible snow associations behind the relationships judged as statistically significant by the response functions (Fig. 3), we correlated the series of March temperatures and January precipitation with the records of snow depth during the winter season (Electronic Supplementary Material, Fig. A3). It was found that the mid-winter precipitation actually has prolonged influence on the snow depth through the winter months. Positive and statistically significant correlations between mid-winter precipitation and snow depth can be obtained throughout the season until mid-April. Moreover, negative and statistically significant


(a)
ARW
EWW
LWW
BI
(b)
ARW
EWW
LWW
BI
Coefficient
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
DRY
WET
o n d J F M A M J J A S
Month

◀ **Fig. 3** Bootstrapped response analysis showing the relationships between tree-ring parameters and monthly mean temperatures (**a**) and precipitation sums (**b**) (1960–2009) by response coefficients as multivariate estimates from a principal component regression model. Chronologies of annual ring width (ARW), earlywood width (EWW), latewood width (LWW), and blue intensity of latewood (BI) from dry (upland) and wet (riparian) habitats were compared separately to weather variables of the previous (*small letters*) and concurrent year (*capital letters*). Statistically significant relationships (0.05 level) are indicated as *black histograms*

correlations between March temperature and snowpack at the end of the same month indicate that cooler (milder) conditions result in deeper (thinner) snowpack at the beginning of the months March to April.

Summer temperature response

The BI chronologies correlated most strongly with warm-season temperatures (Fig. 3). Over the recent period (1959–2009), the upland BI chronology explained around 34–52 % of the temperature variance, depending on the season chosen (Electronic Supplementary Material, Fig. A4). The range of explained variance in the case of riparian BI chronology was 39–51 %. Over this period, the highest correlations were found for the March–August season for both the upland and riparian chronologies. Performing the analyses over an earlier period revealed weaker coherence with the upland and riparian BI chronologies explaining 17–45 and 12–43 % of the temperature variance, respectively. The drop in correlations could be viewed in the context of declining EPS values over the early period (Fig. 4). Over this period, both chronologies showed highest correlations for the May–August season. No clear difference in warm-season temperature correlativity could be revealed in terms of the upland and riparian habitats.

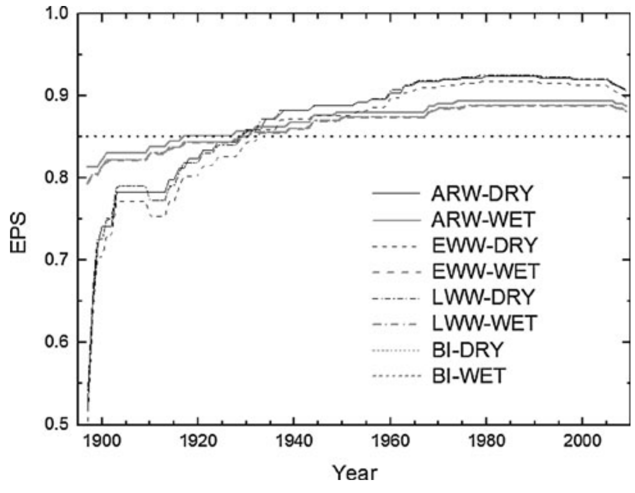


Fig. 4 Expressed population signal (EPS) of annual ring width (ARW), earlywood width (EWW), latewood width (LWW), and blue intensity of latewood (BI) from dry (upland) and wet (riparian) chronologies. The *horizontal line* represents the 0.85 level of an acceptable level for chronology confidence

Discussion

Riparian and upland habitats

Growing habitats of riparian and upland pines differed in several ways. First, the habitat of riparian pines is wetter and their roots may in fact reach the lake water itself, whereas the upland pines growing on well-drained soils are depending on ground as moisture source. Second, the upland pines grow in forest interior conditions where the effects of shading can be more considerable, while the riparian pines have no competitors on the side of the lake. These effects are theorized to cause the differences we observed in the radial growth variations between the two habitats. In fact, the mean correlation coefficient between the upland and riparian chronologies (~0.6) indicates that upland and riparian chronologies share only ca. 35 % of common variance. The response functions (Fig. 3) identified growth/climate relationships that could explain a notable portion of the obvious differences in riparian and upland pine growth.

Winter and hydroclimate signals

The upland pines showed negative association with precipitation in January (Fig. 3b), while the riparian pines reacted positively to the March temperatures (Fig. 3a). In boreal forests, the dendroclimatic signals to winter climate variables can be associated with varying snow conditions (Helama et al. 2013). The influence of snow is generally twofold. First, if the snowpack is adequately deep, it provides the thermoinsulation effect of snow (e.g., Helama et al. 2011) on the pine roots. Thermoinsulation is essential for the frost survival of Scots pine roots (Sutinen et al. 1999). Moreover, a lack of snow during winter months is known to cause premature yellowing of pine needles (Jalkanen 1993). If the snowmelt, on the other hand, becomes delayed because of deeper snowpack, the springtime soil warming may become postponed with considerable effects on the start of the growing period. This is realized as the persistent snow cover may cool the soil due to the effects of albedo and latent heat (Zhang et al. 2001; Zhang 2005). Previous studies have shown that northern conifers exhibit delayed cambial activity when the melting of snow was delayed in the beginning of the growing reason (Vaganov et al. 1999; Kirdyanov et al. 2003). In the riparian habitat, anomalously deep snowpack could also translate into more severe spring flooding at the time of snowmelt.

Actually, the mid-winter precipitation controls the snow depth through the remaining winter as observed in the study region (Electronic Supplementary Material, Fig. A3) and over larger areas in Finland (Helama et al.

2013). That the growth of upland pines responded negatively to January precipitation could indicate that these pines likely benefited more from earlier snowmelt in comparison to thermoinsulation by snowpack. Likely, the snowmelt in the forest interior can be slower owing to the more considerable shading in that habitat, leading to delayed snowmelt (Musselman et al. 2008). This process consequently strengthened the dendroclimatic signal of winter precipitation in that habitat. That riparian pines did not react comparably could implicate the relative importance of thermoinsulation in that habitat. As the thicker snowpack leads to a higher springtime lake level, the lack of comparable response could also indicate that the riparian pines are not drastically suffering from this effect. This finding was similar to that observed previously for riparian environments where the pine growth was not decreased following the flooding during the earliest part of the growing season (Tuononen et al. 1981).

On the other hand, the pine growth was positively related to the March temperatures in both habitats but particularly the riparian pines exhibited this response with statistical significance (Fig. 3a). In northern Norway, a similar dendroclimatic association between pine tree-rings and March temperatures was found and related to the aspect of the stand. That is, the pines growing on south-facing slopes correlated positively with March temperatures (Kirchhefer 2000). However, our pines did not originate from a south-facing slope and therefore some other factor could explain the relationship. It is notable that this temperature parameter is particularly associated with the depth of snowpack in late winter (Electronic Supplementary Material, Fig. A3). In the riparian habitat, the earlier start of the snow-melt season may be advantageous as it may influence a possibly lower maximum lake level in the beginning of the growing season and with an earlier recharge of floodwater. Similarly, the high water levels towards the summer may be seen deleterious for riparian pines (Tuononen et al. 1981). Taking these observations into account, the growth of upland pines may have ameliorated while the growth of riparian pines deteriorated during the years with increased June precipitation and vice versa (Fig. 3b, see also Electronic Supplementary Material, Fig. A2). Similarly, the pines growing on relatively dry soils have been seen to be disadvantaged from droughts in different regions in adjacent areas (Henttonen 1984; Helama et al. 2012b). The negative correlation with riparian pine growth indicates that the trees cannot tolerate extended water saturation of the soils that will more likely occur in that habitat, in comparison to upland conditions, with extended early summer rains.

Summer temperature signals

Mid-summer temperatures influenced the latewood width positively in both habitats but even more significantly in the case of the upland pines. This response was comparable with earlier findings in the region where the widths of annual ring and latewood of Scots pine has been shown to benefit from the warmth of the July–August season (Miina 2000). Moreover, a regional tree-ring width chronology of North Karelia (collected around the province) was seen to correlate positively with July temperatures (Helama et al. 2005). A markedly stronger summer temperature signal was, however, obtained for the BI chronologies (Fig. 3a), these chronologies explaining more than half of the warm-season temperature variance (Electronic Supplementary Material, Fig. A4). These higher correlations are not surprising as BI is known to provide a reasonable surrogate for latewood density, where the BI chronologies correlate highly negatively with the actual densitometric tree-ring chronologies (McCarroll et al. 2002; Campbell et al. 2007). The maximum density of pinewood, in turn, is founded on the increased cell wall thickness and the cell wall proportion, whereas radial tracheid size is known to decrease the density (Helama et al. 2010c). Thus, the dendroclimatic association between the BI chronologies and warm-season temperatures provide evidence that warmer summers result in thicker latewood cell walls and smaller tracheids, leading to higher cell wall proportion.

The summer temperature signals in BI chronologies are similar, or even stronger, in comparison to dendroclimatic reconstructions from high-latitude and high-altitude tree-ring width chronologies, that have utilized ring-width data only (Grudd et al. 2002; Linderholm and Gunnarson 2005; Helama et al. 2010a, b). Moreover, the temperature correlations from BI chronologies were stronger than those derived from dendroisotopic δ^{13}C chronologies as previously constructed for North Karelia, and explaining 29–38 % of the July–August temperature variance (Hilasvuori et al. 2009). Our results were also similar with those obtained previously using microdensitometry-based latewood densities of Scots pine tree-rings from southern boreal forests, explaining around 40 % of the April-September temperature variance (Helama et al. 2012a). In the northern environments, the relatively strong dendroclimatic relationships (explaining around 55–70 % of the temperature variance) have been used to reconstruct past summer temperatures (Schweingruber et al. 1988; Briffa et al. 1992; Esper et al. 2012; Melvin et al. 2013). Our results show an encouraging paleoclimatic potential of warm-season temperature reconstructions using middle/south boreal pine tree-ring archives (Helama et al. 2005, 2008b) for the purpose of climate change research. Such reconstructions will help maximize the spatial picture of the past climate variability in northwestern Europe, especially in the regions south of the timberline areas which have been conventionally used for collecting dendroclimatic proxy materials for temperature reconstructions.

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