CLIMATIC SIGNALS IN WOOD PROPERTY VARIABLES OF *PICEA CRASSIFOLIA*

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Abstract. Little attention has been given to climatic signals in wood properties. In this study, ring width (RW), annual average microfibril angle (MFA), annual average tracheid radial diameter (TRD), and annual average density (DEN), as the annual and intra-annual wood property variables, were measured at high resolution by SilviScan-3 on dated *Picea crassifolia* trees. Dendroclimatological methods were used to analyze climatic signals registered in wood property variables. RW, MFA, and TRD negatively correlated with temperature and positively correlated with precipitation in the growing season, whereas the reverse was true for DEN. Climatic signals recorded in the earlywood were similar to those measured for the full width of the annual rings. Climatic signals recorded in latewood were very weak except for latewood MFA. This study showed that wood property variables could be extensive resources for learning more about the influences of climate on tree growth and how trees adapt to ongoing climate change.

Keywords: Wood property, cell characteristics, microfibril angle, wood density, treering, dendroclimatology.

INTRODUCTION

The Tibetan Plateau is the highest and largest plateau in the world with an area of 2.5 Mkm^2 and is known also to have been subjected to large-scale climatic changes in the past (Zhang et al 1996; Thompson et al 2000). *Picea crassifolia* forms pure stands on north-facing slopes in the northeast Tibetan Plateau platform region. *P. crassifolia* forests are well known as a wood resource and for soil and water conservation. A better understanding of the response of *P. crassifolia* to climate variability is needed, especially with respect to ongoing climate change. Several dendroclimatic studies on the ring width (RW) variation of *P. crassifolia* growing at different study sites have been published (Gou et al 2005; Liang et al 2006; Fang et al 2009; Zhang and Wilmking 2010) and have demonstrated that RW was negatively affected by temperature in summer and positively related to spring precipitation.

Tree RW is widely used to reconstruct climate (Schweingruber et al 1993; Splechtna et al 2000) because it can be measured easily by nondestructive increment core measurements (Chen and Evans 2010). In recent years, a growing interest in this area of research has indicated that climatic signals can be found in various properties of wood and that these wood properties can be used to develop climate-sensitive chronologies and proxy climate records (Drew et al 2013). For example, microfibril angle (MFA) is well known in the field of wood science. It is the angle of the cellulose microfibrils in the S_2 layer of the cell wall (the thickest layer) relative to the long axis of the cell. Multiple studies have indicated that for many species, MFA is highly sensitive to short-term cultural changes, such as thinning, irrigation, and fertilizing (Lindström et al 1998; Wimmer et al 2002; Donaldson 2008; Drew et al 2009). However, high-resolution radial variation in MFA has rarely been considered in dendroclimatology research until the use of the SilviScan for nondestructive measurement (Xu et al 2012; Drew et al 2013) allowed this to be executed. Anatomical features of dated tree rings measured at the cellular level have also proven to be of value in dendroclimatology (Fonti et al 2010).

In this study, several wood properties, including annual RW, earlywood width (RWER), latewood width (RWLA), annual average density (DEN), earlywood average density (DENER), latewood average density (DENLA), annual average MFA, earlywood average microfibril angle (MFAER), latewood average microfibril angle (MFALA), and annual average tracheid radial diameter (TRD), were measured using SilviScan-3. To build robust, climate-sensitive chronologies of annual and intra-annual wood properties, climatic signals registered in wood property variables were analyzed using dendroclimatological methods.

MATERIALS AND METHODS

Study Area

The study area of *P. crassifolia* forest lies in the Pailugou River basin of the Xishui Forest Farminin the middle Qilian Mountains at the margin of the Tibetan Plateau. The *P. crassifolia* forest in this area grows from 2600 to 3300 m altitude. The forests grow on sandy loams together with abundant lichens, a few shrubs, and grass. The mean stand density is approximately 300 trees/ha. The site belongs to an alpine semiarid and semihumid mountain forest and grassland climate largely affected by the Qinghai-Tibet Plateau and desert climate. The nearest meteorological station was at Qilian, which provided a continuous record of monthly temperature and precipitation for the period 1957–2009. The distance from the study site to the meteorological station was approximately 30 km. Mean annual temperature and precipitation are 1.5°C and 405 mm, respectively. Monthly rainfall ranges from almost 0 mm in January to 90 mm in July. Precipitation from May to September accounts for 85% of the rain in an average year (Fig 1).

Sample Processing and Measurement

Two cores from each of 40 dominant *P. crassifolia* trees of similar diameter on the north slope were sampled at 2600 m by removing a 12-mm-diameter, bark-to-pith increment core at breast height. Fifty-two cores (from 26 trees) without cracks and decay were cut to form 2-mm-wide (tangential dimension), 7-mm-high (longitudinal dimension), pith-to-bark (radial) strips, which were treated with heated acetone for 48 h to remove the influence of resin on wood density. One transverse cross-section of each strip was polished to reveal the cell details. The strips were conditioned to a constant moisture content in a controlled-environment room (20°C, 40% RH) for 2 da.

To obtain cell size, automated microscopy and image analysis of SilviScan-3 with 0.025-mm resolution was used (Xu et al 2013). After cell size measurement, the strip samples were analyzed using an automated X-ray scanning densitometry system of SilviScan-3 with a 0.01-mm resolution (Xu et al 2013). Wood density profiles were grouped in 0.010- to 0.025-mm intervals to match the cell diameter profiles. The MFA of the S_2 layer in the secondary wall was measured by X-ray diffraction across 0.2-mm radial intervals after measurement of wood density. To obtain MFA and TRD, the radial strips were measured by SilviScan-3 (Xu et al 2012, 2013).

Annual ring boundaries were recognizable in the cross-section images, attributable to the rapid drop in density from latewood formed at the

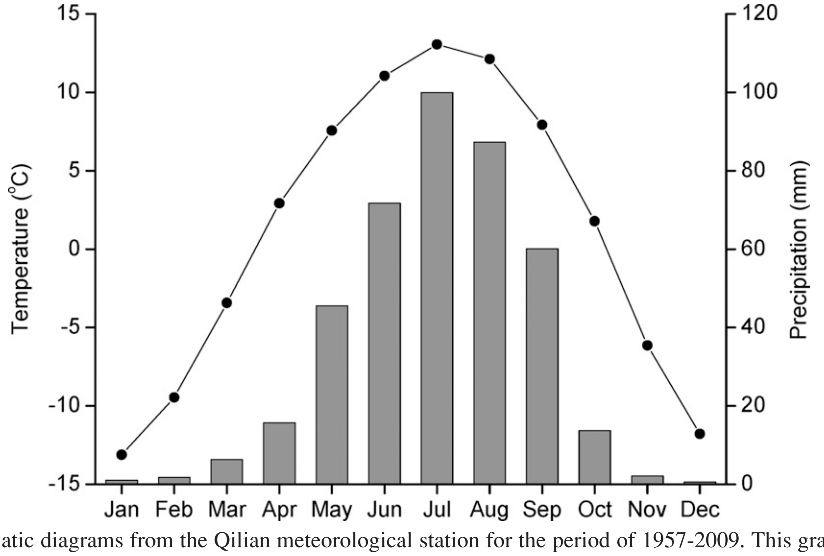

Figure 1. Climatic diagrams from the Qilian meteorological station for the period of 1957-2009. This graph shows mean monthly temperature (line) and precipitation (bars).

end of one growing season to the earlywood of the next growing season. Software developed as part of the SilviScan-3 system allowed annual ring boundaries to be identified based on changes in the density profile and crosschecked against images of the surface cross-section. This process allowed annual RW to be determined and values for RW, DEN, annual average MFA, and average annual TRD to be calculated. Earlywood and latewood boundaries were identified based on the median of maximum and minimum density (Fig 2) (Xiong et al 1998; Pant et al 2000). Values for RWER, DENER, MFAER, RWLA, DENLA, and MFALA were calculated.

Data Analysis

To ensure that the calendar year of wood property variables was correct, RW series obtained from the SilviScan-3 data were cross-dated using the COFECHA program (Holmes 1983). To remove nonclimatic signals in the wood property variables series, each individual series of RW, RWER, RWLA, DEN, DENER, DENLA, MFA, MFAER, MFALA, and TRD was standardized using the ARSTAN program (Cook 1985; Cook and Holmes 1996) by fitting of spline functions with a 50% frequency response of 32 yr. Because all wood property variables were highly autocorrelated (Table 1), the autoregression modeling option of the ARSTAN program was used to remove any remaining autocorrelation pattern from each standardized series of all wood property variables. Then the residual indices of each variable for individual series were averaged by calculating robust biweight means to obtain residual chronologies. The quality of the chronologies was assessed by the standard basic statistics (Briffa and Jones 1990; Fritts 2001): mean sensitivity (MS), mean correlation between trees (R_{bt}), expressed population signal (EPS), signal-to-noise ratio (SNR), and first-order autocorrelation (AC_1).MS is a measure of the variation in RW from one ring to the next. R_{bt} indicates cross-matching between trees. Higher SNR is believed to indicate a strong

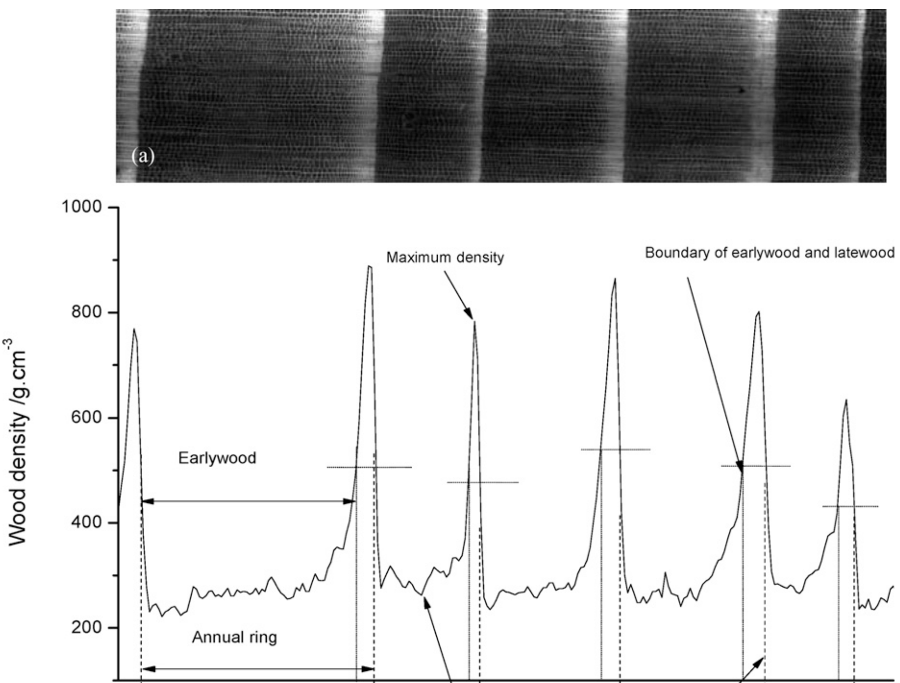

Figure 2. Cross-section (a) and wood density profile (b) of *Picea crassifolia*.

Table 1. Statistics of wood property variable chronologies.[a]

Wood property variables	Mean value (SD)	AC_1[b]	MS	R_{bt}	SNR	EPS
RW	1.72 (0.75)	0.57**	0.31	0.85	81.91	0.99
RWER	1.42 (0.65)	0.55**	0.35	0.59	63.69	0.98
RWLA	0.25 (0.12)	0.49**	0.32	0.41	29.24	0.97
DEN	0.39 (0.05)	0.48**	0.09	0.69	48.54	0.98
DENER	0.33 (0.03)	0.36**	0.08	0.55	43.32	0.98
DENLA	0.67 (0.07)	0.29**	0.10	0.32	19.00	0.95
MFA	15.05 (0.03)	0.69**	0.09	0.4	23.1	0.96
MFAER	16.05 (0.04)	0.74**	0.12	0.29	21.9	0.96
MFALA	12.39 (0.02)	0.46**	0.13	0.14	6.6	0.87
TRD	31.49 (2.54)	0.34*	0.07	0.77	139.3	0.99

[a] SD, standard deviation; AC_1, first-order autocorrelation; MS, mean sensitivity; R_{bt}, mean correlation between trees; SNR, signal-to-noise ratio; EPS, expressed population signal; RW, annual ring width; RWER, earlywood width; RWLA, latewood width; DEN, annual average density; DENER, earlywood average density; DENLA, latewood average density; MFA, annual average microfibril angle; MFAER, earlywood average microfibril angle; MFALA, latewood average microfibril angle; TRD, annual average tracheid radial diameter.

[b] $*p < 0.05$; $**p < 0.01$.

climatic influence on tree growth. AC_1 presents the influence of the condition in the previous year on tree growth in the current year (Cook and Kairiukstis 1990). EPS assesses the sample number size. The threshold of EPS is 0.85 (Wigley et al 1984).

The residual chronologies for wood property variables were used for the correlation analyses by program DENDROCLIM2002 (Biondi and Waikul 2004). The statistical significance of the coefficients was determined in DENDROCLIM2002 by calculating 95% quantile limits based on 1000 bootstrap resamples of the data. The residual chronology was analyzed against total monthly precipitation and mean monthly temperature for the Qilian meteorological station for the period 1957-2009.

RESULTS AND DISCUSSION

Chronologies

Table 1 lists the general chronology statistics of wood property variables. The AC_1 of all wood property variables ranged from 0.34 to 0.74, indicating that it was necessary to remove the autocorrelation in the processing of chronology development. The mean residual series of wood property variables are shown in Fig 3.

The MS of the RW series was higher than that of the DEN, MFA, and TRD, meaning that RW has higher year-to-year variation. The R_{bt} and SNR for all annual variables were higher than those of earlywood and latewood variables. Higher R_{bt} and SNR are generally believed to indicate greater climatic influence on tree growth (Cook and Kairiukstis 1990; Fritts 2001), which is useful to assist in the selection of the best chronology in the processing of chronology development for a treering variable or to compare the characteristics of the same treering variable from different sites or species. Lebourgeois (2000) investigated the influence of climate on earlywood width and latewood width of *Fagus sylvatica* growing at 15 sites in France. They found the SNR of earlywood width chronologies was higher than that of latewood width, and earlywood width was more sensitive to climate. However, Xiong et al (1998) and Pant et al (2000) show that wood density parameters with lower MS and SNR recorded higher climate signals than RW.

Climate Signals in Annual Wood Property Variables

The correlation coefficients of wood property variable chronologies with mean monthly temperature and monthly total precipitation from October in the previous year to the following September are listed in Table 2. RW, MFA, and TRD were negatively correlated with temperature and positively correlated with precipitation, whereas DEN was positively correlated

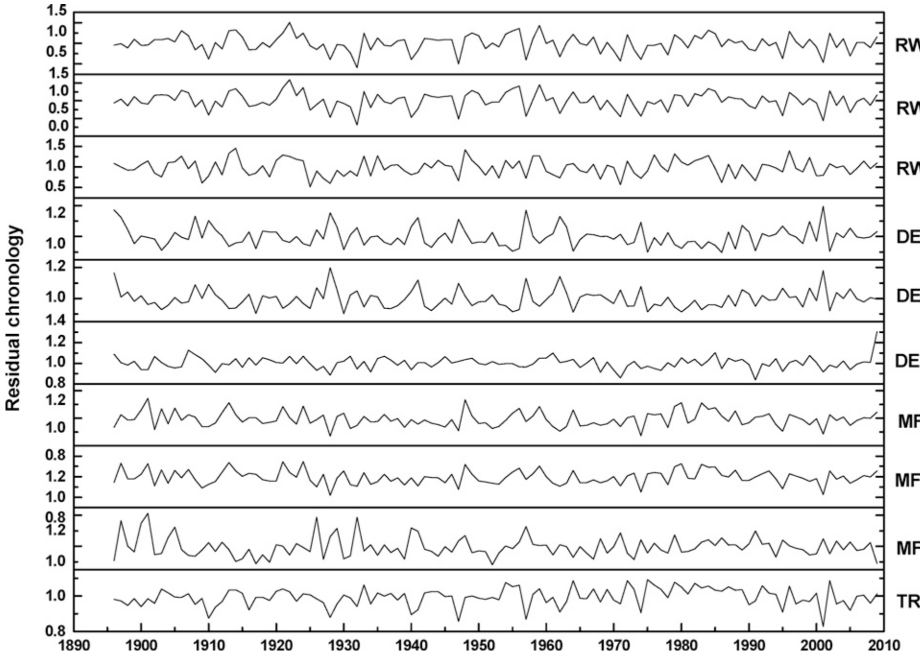

Figure 3. Time series of residual chronologies of wood property variables.

with temperature and negatively correlated with precipitation.

Temperature in the growing season (May to September) had a significant influence on annual wood property variables, but temperature variations in different months had different influences on variables. RW and TRD were significantly correlated with mean monthly temperatures in June and July. MFA correlated closely with mean monthly temperatures in May, June, and July. DEN significantly correlated with mean monthly temperatures in June, July, August, and September. The maximum monthly temperature had a stronger influence on annual wood property variables than that of mean monthly temperatures, whereas minimum monthly temperatures had a weak influence on annual wood property variables (Table 3).

Precipitation in the growing season also had a significant influence on annual wood property variables. RW was significantly correlated with total monthly precipitation in March, May, June, and September. DEN was significantly correlated with total monthly precipitation in March. MFA was significantly correlated with total monthly precipitation in May, June, and September. TRD was significantly correlated with total monthly precipitation in May and June.

The significant correlation of annual wood property variables with temperature and precipitation (Tables 2 and 3) showed that precipitation in the growing season had a strong influence on RW. This indicated that precipitation in the growing season was the main factor that restricted radial growth of the *P. crassifolia* trunk. Rainfall was helpful to radial growth of the trunk because sufficient rainfall in the growing season can accelerate the rate of cell division and extend the duration of the cell volume expansion stage. Pedini (1992) found higher MFA in faster-growing trees of *P. sitchensis*. In our previous study (Xu et al 2012), MFA and RW significantly and positively correlated with each other and they responded to climate change in similar ways. In general, the upper limit of tree growth in forests is mainly affected by temperature and the lower limit by precipitation (Fritts 1976). The sampling site of this study area, located at the lower limit of *P. crassifolia* forests in the Qilian

Table 2. Correlation coefficients of wood property variable chronologies with mean monthly temperature and monthly total precipitation.[a]

	RW	RWER	RWLA	DEN	DENER	DENLA	MFA	MFAER	MFALA	TRD
POct T	0.07	−0.07	0.05	0.07	0.06	−0.19	0.05	0.04	0.14	−0.11
PNov T	0.15	0.14	0.1	−0.04	−0.09	0.06	0.10	0.07	−0.02	0.07
PDec T	0.11	0.09	0.09	0.05	0.03	0.1	0.08	0.06	0.03	0.05
Jan T	0.06	0.07	−0.04	−0.03	0.01	−0.07	−0.01	−0.04	−0.10	0.03
Feb T	−0.08	−0.08	0.05	0.17	0.09	−0.04	−0.07	−0.05	0.10	−0.13
Mar T	0.05	0.05	−0.01	0.05	0.09	0.04	−0.01	−0.04	−0.21	−0.03
Apr T	0.11	0.13	−0.01	0.06	0.04	0.16	−0.04	−0.03	**−0.25***	0.01
May T	−0.12	−0.13	−0.07	0.15	0.12	−0.02	**−0.23***	**−0.23***	−0.12	−0.17
Jun T	**−0.35***	**−0.35***	**−0.32***	**0.32***	**0.34***	−0.16	**−0.41***	**−0.43***	0.06	**−0.45***
Jul T	**−0.31***	**−0.31***	**−0.31***	**0.35***	**0.37***	−0.12	**−0.34***	**−0.35***	−0.11	**−0.45***
Aug T	−0.03	−0.04	−0.12	**0.24***	**0.24***	0.13	−0.22	−0.22	**−0.39***	−0.17
Sep T	−0.19	−0.2	−0.07	**0.38***	**0.34***	−0.02	−0.20	−0.23	−0.23	−0.26
POct P	−0.03	−0.03	−0.05	0.23	0.2	0.14	−0.20	−0.20	−0.06	−0.11
PNov P	−0.09	−0.08	−0.06	0.18	0.21	0.01	−0.12	−0.11	−0.09	−0.22
PDec P	−0.1	−0.1	−0.07	−0.05	−0.04	0.05	−0.08	−0.05	0.09	0.13
Jan P	0.17	0.14	0.23	−0.09	−0.17	−0.11	0.13	0.13	−0.02	0.09
Feb P	−0.02	−0.01	−0.15	−0.05	−0.02	0.14	0.01	0.02	−0.16	0.01
Mar P	**0.25***	**0.27***	−0.02	**−0.28***	−0.22	0.15	0.10	0.12	−0.13	0.15
Apr P	−0.03	−0.04	−0.02	0.1	0.13	−0.08	−0.11	−0.13	−0.06	−0.11
May P	**0.36***	**0.40***	0.06	−0.26	−0.17	0.22	**0.29***	0.27	**−0.25***	**0.29***
Jun P	**0.25***	**0.26***	0.19	−0.26	**−0.33***	0.21	**0.33***	**0.35***	0.00	**0.32***
Jul P	0.06	0.03	0.16	0.12	0.07	0.09	−0.08	−0.06	0.05	−0.11
Aug P	−0.01	−0.02	0.14	−0.07	−0.11	−0.1	0.21	0.20	**0.27***	0.07
Sep P	**−0.33***	**−0.33***	−0.19	0.15	0.11	−0.26	**−0.31***	**−0.32***	0.06	−0.21

[a] POct T, monthly mean temperature in previous October; POct P, total precipitation in previous October; Jan T, monthly mean temperature in January; Jan P, total precipitation in January; RW, annual ring width; RWER, earlywood width; RWLA, latewood width; DEN, annual average density; DENER, earlywood average density; DENLA, latewood average density; MFA, annual average microfibril angle; MFAER, earlywood average microfibril angle; MFALA, latewood average microfibril angle; TRD, annual average tracheid radial diameter; * $p < 0.05$. Significant values are highlited with bold and underline.

Mountains, conformed to this rule. The average annual precipitation at the sampling site is less than 400 mm, and without artificial fertilization and watering, precipitation is the only water source for tree growth, suggesting that it is in a typical semiarid region. The amount of precipitation directly affects the rate of tree growth.

Temperature in the growing season was the main factor that restricted wood density of the *P. crassifolia* trunk. The onset, duration, and cessation of cell wall formation is important for the carbon balance of a tree because wood formation represents a large carbon sink. During cell maturation, trees allocate more photosynthate to the production of cellulose microfibrils that contribute to the building of secondary cell walls (Hansen et al 1997). The average annual temperature in this region is only 0.5°C, and only from June to September is the mean monthly temperature greater than 8°C (Fig 1). Photosynthesis decreases dramatically when the temperature is less than 8°C (Zhang 1999). Therefore, the mass of cell wall formation was influenced largely by the temperature from June to September.

Climatic Signals in Intra-Annual Wood Property Variables

Climatic signals recorded in earlywood width, density, and MFA were similar to those in annual width, density, and MFA (Tables 2 and 3). This demonstrated that earlywood cell formation in *P. crassifolia* had a decisive function in the formation of rings because the earlywood ratio of *P. crassifolia* was about 85% (Xu et al 2014). Climatic signals recorded in latewood width and density were very weak, revealing that earlywood was more sensitive to changes in climate than latewood. Our results were similar to those of Pant et al (2000), who found that the

Table 3. Correlation coefficients of wood property variable chronologies with monthly maximum and minimum temperatures.[a]

	RW	RWER	RWLA	DEN	DDENER	DENLA	MFA	MFAER	MFALA	TRD
POctMaT	−0.02	−0.01	−0.04	−0.20	−0.19	−0.18	0.18	0.16	0.01	−0.05
PNovMaT	0.01	0.00	0.04	0.06	0.01	0.00	−0.06	−0.06	−0.01	−0.03
PDecMa T	0.04	0.02	0.05	0.11	0.10	0.09	0.02	0.01	0.01	−0.02
Jan MaT	−0.05	−0.03	−0.13	0.06	0.14	−0.09	−0.13	−0.15	−0.07	−0.01
Feb MaT	−0.09	−0.09	0.07	0.21	0.14	0.02	−0.09	−0.07	0.01	−0.14
Mar MaT	0.00	−0.01	−0.03	0.07	0.12	−0.04	−0.07	−0.10	−0.19	−0.06
Apr MaT	−0.01	0.01	−0.07	0.10	0.10	0.09	−0.08	−0.08	−0.21	−0.07
May MaT	−0.23	−0.24	−0.12	0.15	0.11	−0.07	**−0.28***	**−0.27***	−0.09	**−0.24***
Jun MaT	**−0.45***	**−0.45***	**−0.39***	**0.42***	**0.46***	−0.23	**−0.49***	**−0.51***	0.12	**−0.60***
Jul MaT	**−0.30***	**−0.30***	**−0.35***	**0.31***	**0.33***	−0.05	**−0.33***	**−0.34***	−0.15	**−0.43***
Aug MaT	−0.06	−0.04	**−0.28***	0.18	0.23	0.21	**−0.25***	−0.24	**−0.46***	−0.15
Sep MaT	−0.03	−0.05	0.04	**0.29***	**0.28***	0.08	−0.06	−0.05	−0.15	−0.19
POctMiT	−0.06	−0.06	0.09	**0.23***	**0.23***	−0.09	−0.07	−0.07	0.09	−0.08
PNovMiT	0.23	0.22	0.18	−0.07	−0.12	0.10	0.16	0.14	−0.06	0.12
PDecMiT	0.15	0.13	0.12	0.04	0.02	0.13	0.10	0.08	0.04	0.08
Jan MiT	0.13	0.14	0.05	−0.04	−0.04	−0.03	0.08	0.05	−0.11	0.07
Feb MiT	−0.04	−0.03	0.07	0.11	0.03	−0.02	−0.03	−0.03	0.10	−0.06
Mar MiT	0.14	0.14	0.05	0.01	0.01	0.13	0.06	0.04	−0.21	0.06
Apr MiT	0.24	0.24	0.14	0.04	0.02	0.17	0.01	0.01	**−0.25***	0.09
May MiT	0.17	0.17	0.05	0.00	0.04	0.12	0.03	0.00	−0.12	0.04
Jun MiT	−0.07	−0.05	−0.13	−0.01	−0.03	0.06	−0.07	−0.05	−0.06	−0.04
Jul MiT	−0.23	−0.25	−0.16	**0.33***	**0.35***	−0.18	**−0.28***	**−0.28***	−0.05	**−0.32***
AugMiT	0.05	0.03	0.11	0.16	0.11	0.05	−0.04	−0.05	−0.14	−0.08
Sep MiT	−0.25	−0.25	−0.14	**0.30***	0.26	−0.15	−0.24	**−0.27***	−0.18	−0.21

[a] POctMaT, monthly maximum temperature in previous October; POctMiT, monthly minimum temperature in previous October; Jan MaT, monthly maximum temperature in January; Jan MiT, monthly minimum temperature in January; RW, annual ring width; RWER, earlywood width; RWLA, latewood width; DEN, annual average density; DENER, earlywood average density; DENLA, latewood average density; MFA, annual average microfibril angle; MFAER, earlywood average microfibril angle; MFALA, latewood average microfibril angle; TRD, annual average tracheid radial diameter; * $p < 0.05$. Significant values are highlited with bold and underline.

response of earlywood width to temperature and precipitation was stronger than that of latewood width of *Cedrusdeodara*. Xiong et al (1998) also arrived at a similar conclusion after studying *Halocarpusbiformis* in New Zealand. However, latewood width in European and North American trees is more sensitive to changes in climate than earlywood (Vagannov et al 1994; Yasue et al 2000). To explore if the difference in sensitivity of earlywood and latewood to climate is correlated with tree age, Vieira et al (2009) carried out research on young (younger than 65 yr) and old (older than 115 yr) *P. pinaster* trees in southeastern Europe. They found that earlywood width of young trees responded vigorously to climate change as did latewood width of old trees but to a somewhat lesser extent. The reason is that the time for active growth in the cambium of young trees started early and hence it was longer than that for old trees and more sensitive in response to changes in climate. The investigation of Cleaveland (1986) on *Pseudotsugamenziesii* and *Pinus ponderosa* revealed that there was a significant correlation between climatic information recorded for earlywood and latewood and tree species as well as the geographic location of trees. However, in this study, climatic signals registered in latewood MFA were different from those in annual and earlywood MFA, indicating that perhaps different wood property variables have different climate signals. These results reveal that wood property variables could be useful and extensive resources to learn more about the influence of climate on tree growth and about how trees adapt to ongoing climate change.

CONCLUSIONS

Temperature and precipitation in the growing season (May to September) had significant influences on annual wood property variables, but temperatures in different months had different influences on those variables. RW, MFA, and TRD negatively correlated with temperature and positively correlated with precipitation, whereas DEN positively correlated with temperature and negatively correlated with precipitation. Precipitation in the growing season was a restricting factor for RW, MFA, and TRD of the *P. crassifolia* trunk. Cold temperatures in the growing season restricted wood density. Climatic signals recorded in earlywood width, density, and MFA were similar to those in annual width, density, and MFA, whereas climate signals recorded in latewood width and density were very weak except for latewood MFA. This is because earlywood cell formation in *P. crassifolia* had a decisive function in the formation of rings. This study showed that MFA and TRD might be useful climate proxies alongside tree RW and wood density. Their application across a broader range of sites and species should provide new insights into climate variation and tree responses to changing climate. The various wood property variables could be useful and extensive resources to learn more about the influence of climate on tree growth and how trees adapt to ongoing climate change.

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