Prediction of the carbon pool for lacebark pine under future temperature changes

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ABSTRACT

The correlation between tree-ring widths of lacebark pine and climate was investigated. Radial growth was positively correlated with monthly mean temperatures in the previous September and significantly negatively correlated with monthly mean and monthly maximum temperatures in March. There was no significant response to levels of precipitation. Tree-ring variation was reconstructed by a transfer function using STD chronology and monthly mean temperatures. Assuming future temperature increases of 1.4 °C to 4.0 °C according to IPCC (2006), tree-ring widths would increase by 4.7% to 12.8%, and lacebark pine carbon pools would increase observably by 10.9% to 31.1%. Temperature has a positive impact on increasing biomass and hence carbon stored for lacebark pine. The results provide a theoretical reference for forest management and an evaluation of the capacity for forests to sequester carbon under climate change.

Key words: lacebark pine, temperature changes, tree-ring growth, biomass, carbon stock

RÉSUMÉ

Cette étude porte sur la corrélation entre la largeur des anneaux de croissance du pin Napoléon et le climat. La croissance radiale a démontré une corrélation positive avec les températures moyennes du mois de septembre précédent et négative avec les températures moyennes et les températures maximales mensuelles du mois de mars. Le niveau de précipitation ne semblait pas avoir d'effet significatif. La variation dans la largeur des anneaux de croissance a été reproduite au moyen d'une fonction de transfert utilisant une chronologie STD et les températures mensuelles moyennes. Si la température devait augmenter de 1,4 °C à 4,0 °C dans le futur, tel que prévu par le GIEC (2006), la largeur des anneaux de croissance pourrait augmenter de 4,7 % à 12,8 % et la rétention de carbone chez le pin Napoléon afficherait une augmentation notable de 10,9 % à 31,1 %. La température a un effet positif sur l'accroissement de la biomasse et de ce fait sur le carbone séquestré par le pin Napoléon. Les résultats offrent une base théorique pour guider l'aménagement forestier et pour évaluer la capacité des forêts à séquestrer le carbone en réponse aux changements climatiques.

Mots clés : pin Napoléon, changements climatiques, croissance radiale, biomasse, stock de carbone

Introduction

Forests play an important role in carbon exchange between the atmosphere and the terrestrial biosphere (Dixon *et al.* 1994, Wolf *et al.* 2011). A good understanding of the relationship of the changes to forest biomass and carbon pools, growth and climate will help to predict the impact of climate change on forest ecosystems, thus having a vital significance on sustainable forest operations and management, and on the assessment of carbon pool capacities. Tree rings can provide annual proxy climate information, and have been widely used for temperature and precipitation reconstructions over the past several centuries (Cook *et al.* 2004). China's tree-ring eco-climatology research has focused on sites on the Tibetan Plateau and on other areas of northwestern China (Zhu *et al.* 2009, Liu *et al.* 2010, Shi *et al.* 2013). However, there has been

no research on predicting future carbon pools under climate change using the relationship between tree-ring width and climate variability. Lacebark pine (*Pinus bungeana* Zucc. ex Endl.) is a naturally distributed species in the temperate and subtropical regions of China, ranging from 30° 52' to 38° 5' N latitude and from 113° 15' to 104° 15' E longitude (Li *et al.* 2013). Lacebark pine forests occur naturally in mountainous regions and are widely used as an important plantation species in northern and central China due to their adaptation to dry, cold climates. This study used tree-ring data of the species to analyze radial growth response to climate change. The objectives of the study are: 1) to reconstruct the model between tree rings and temperature; and, 2) to predict the carbon pool for lacebark pine under future temperature and precipitation changes.

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Materials and Methods

Study area

The study was carried out at sites on Xiaolongshan Mountain approximately 16 km northeast of Hui county, eastern Gansu Province (Fig. 1). The region has a temperate climate with a 30-year mean annual temperature of 12.5°C. Average annual precipitation is 770 mm, of which 438 mm falls from May to September. The mean annual frost-free period is 209 days and the average growing season is 225 days. These are natural stands with the species composition dominated 93% ~ 98% by lacebark pine mixed with *Pinus tabulaeformis* Carr., *Pinus massoniana* Lamb., *Quercus variabilis* Blume and *Platycladus orientalis* (L.) Franco.

Tree ring and climate data

Forty-six core samples and 15 disks from 45 trees were collected and after air drying, surfaces were smoothed to ensure an accurate ring count. The image analysis system (WinDENDRO™ Density 2009, Regent Instruments Canada Inc.) with the precision of 0.001 mm was used to measure tree-ring

width. Quality control of cross-dating used the COFECHA program (Holmes 1983); samples with ambiguities were eliminated. After cross-dating, individual sequences of tree-ring widths were detrended and standardized using the ARSTAN program (Cook and Kairiukstis 1990). All individual index sequences were combined into a single chronology by calculating the bi-weight robust mean. Standard chronology (STD) and residual chronology (RES) were established (Table 1). The mean sensitivities of STD and RES remain between 0.15 and 0.17, both being at an acceptable level (Kerhoulas and Jeffrey 2011). The STD chronologies are obviously better than those of RES; therefore lacebark pine STD in the study area can better reflect the impact of climatic change on tree-ring growth.

Monthly mean temperatures (T mean), monthly mean maximum temperatures (T max), monthly mean minimum temperatures (T min) and monthly precipitation (P mean) were obtained for Baoji Weather Station (34°21'N, 107°08'E) from the China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn>). The records cover the years 1958 to 2009.

Fig. 1. Location of the study area

Table 1. Chronology characteristics and common analysis of STD and RES chronology of Lacebark pine (n=55).

Basic statistics	Standard chronology	Residual chronology
Mean tree-ring width	0.942	1.001
Mean sensitivity	0.171	0.159
Standard deviation	0.125	0.175
Mean correlation between trees	0.664	-0.261
Common interval time span	1959–2009	
Mean correlation between trees	0.347	0.293
Signal to noise ratio	13.692	10.890
Expressing population signal	0.913	0.896
Variance in first eigenvector	37.5	33.1

Growth-climate response analysis

To explore the statistical associations between different monthly-mean climate factors and ring-width indices from 1959 to 2009, the period of tree growth encompassing the previous July to the current October (16 months) for the current tree-ring was selected as the “potential effective climatic window”. Individual monthly climate–growth relationships were analyzed using the software DENDROCLIM 2002 (Biondi and Waikul 2004). Based on the results, the optimum monthly assemblies were selected for the growth-climate response analysis.

Fig. 2. Correlation between tree-ring width, temperature and precipitation

Fig. 3. Comparison of predicted and observed tree-ring width indexes

Results and Discussion

Tree-ring climatic response

Tree-ring width index of lacebark pine was positively correlated with monthly mean temperatures in September, and significantly negatively correlated with mean temperatures and mean maximum temperatures in March (Fig. 2, $p < 0.05$); however, there was no significant response to precipitation. The development of forests is directly related to climate, and tree species are shifting their ranges in altitude and latitude as a response to changing regional climates (Walther *et al.* 2002). The growth of different tree species shows certain characteristics in response to climatic factors (Davi *et al.* 2006). Our results reflect the response pattern of tree-ring growth for lacebark pine to temperature changes and indicate that

increasing temperatures in the previous September will lead to wider tree rings, but narrower rings in the current March. This is because monthly mean maximum temperatures in September extend the growing period and significantly increase tree-ring widths. This finding is in agreement with prior findings for *Pinus uncinata* Ramond ex DC. (Gutiérrez 1991). In spring, high temperatures accelerate evaporation and evapotranspiration, which can result in significant moisture stress for tree growth (Oberhuber *et al.* 1998). Precipitation in this region is 770 mm and it is not a limiting factor in the growth of lacebark pine, thus there was no significant response between tree-ring width and precipitation.

Regression model and reconstruction

The transfer function is established by linear regression using STD chronology using monthly mean temperatures in previous Septembers and monthly mean maximum temperatures in current Marches from 1958 to 2009. The transfer function is as follows:

$$[1] \text{ RWI}_i = 0.017 - 0.034 \times \text{Tmax}_{\text{C3i}} + 0.076 \times \text{Tmean}_{\text{p9i}} \quad (R^2 = 0.51, N = 51, p < 0.001)$$

In the equation, RWI_i stands for the tree-ring width in year i ; Tmax_{C3i} for the mean maximum temperature of the current March and $\text{Tmean}_{\text{p9i}}$ for the mean temperature of the previous September in year i .

The correlation coefficient of eq. 1 is 0.5 for the period of 1959 to 2009. Comparison of actual and estimated tree-ring widths during the period (Fig. 3) reveals that change trends are homologous and estimated values agree well with actual values. These findings demonstrate that the reconstruction function is credible. The statistical fidelity of our reconstruction model was evaluated using split-sample calibration-verification and leave-one-out cross-validation methods (Michaelsen 1987; Table 2). The positive values of reduction error (RE) and coefficient of efficiency (CE) demonstrate that the model yields accurate estimates (Fritts 1976, Cook *et al.* 1999). CE is more rigorous than RE, and values of CE lower than those of RE indicate good regression model ability (Cook *et al.* 1999).

Table 2. Regression model statistics for different calibration and verification.

	Calibration (1959–1984)	Calibration (1985–2009)	Full calibration (1959–2009)
R	0.726	0.691	0.714
R ²	0.527	0.477	0.510
RE	0.614	0.573	0.424
CE	0.475	0.362	–

R-correlation coefficient; R²-variance explained by the regression model; RE-reduction of error statistic; CE-coefficient of efficiency.

Fig. 4. Change of tree-ring width index with increasing temperatures

Table 3. Prediction of biomass (kg) and carbon storage (kg C) from increasing of temperature for lacebark pine.

Temperature increasing ΔT(°C)	DBH (cm)	Predicting DBH (cm)	Biomass (kg)	Carbon storage (kg C)
0	10.0	10.0	40.97	20.32
	20.0	20.0	194.49	96.47
	30.0	30.0	483.70	239.92
	40.0	40.0	923.24	457.93
	50.0	50.0	1524.31	756.06
1.4	10.0	10.5	45.43	22.53
	20.0	20.9	215.64	106.96
	30.0	31.4	536.29	266.00
	40.0	41.9	1023.62	507.71
	50.0	52.4	1690.03	838.25
2.7	10.0	10.9	49.62	24.61
	20.0	21.8	235.56	116.84
	30.0	32.7	585.84	290.58
	40.0	43.6	1118.20	554.63
	50.0	54.5	1846.19	915.71
4.0	10.0	11.3	53.71	26.64
	20.0	22.6	254.94	126.45
	30.0	33.8	634.04	314.48
	40.0	45.1	1210.19	600.26
	50.0	56.4	1998.08	991.05

Prediction of carbon storage by lacebark pine

IPCC (2006) suggested that global mean temperatures might rise by 1.4 °C to 4.0 °C by 2100. Supposing that in the three circumstances in 2100 in which global mean temperatures may increase by 1.4 °C, 2.7 °C or 4.0 °C, the increase in annual mean temperatures is caused by the rise of monthly temperatures. Based on the mean values and temperature increments (ΔT = 1.4 °C, 2.7 °C, 4.0 °C) and Eq. 1, the predicted RWI and diameters at breast height (DBHs) of lacebark pine will increase by 4.7%, 8.9% and 12.8% respectively (Fig. 4). According to the biomass equation $Y = 0.232 \times \text{DBH}^{2.247}$ for lacebark pine (Li *et al.* 2014) and carbon concentrations with a mean value of 0.5 (Li *et al.* 2013), biomass and carbon storage at different DBHs (10.0 cm, 20.0 cm, 30.0 cm, 40.0 cm and 50.0 cm) may be predicted. As temperatures rise, biomass and carbon storage significantly increase (Table 3). If temperatures increase by 1.4 °C, carbon storage may increase by 2.2 ~ 82.2 kg C; percentage increases are 10.9%. If temperatures rise by 2.7 °C, carbon storage will increase by 4.3 ~ 159.7 kg C; percentage increases are 21.1%. And if temperatures rise by 4.0 °C, carbon storage will increase by 6.3 ~ 235.0 kg C; percentages increases are 31.1%. Biomass and carbon storage increased as temperatures rose; older trees had larger increases than younger ones. This is in agreement with previous reports that total below-ground biomass increased steadily with age for lacebark pine (Li *et al.* 2013). The percentage increase for carbon storage remains a constant independent of DBH for temperatures.

Generally, there is a positive correlation between the net primary productivity of forests and temperature (Beuker 1994). When forests are well supplied with water, tree species of most temperate and boreal forests respond to increased temperatures by growing faster and increasing production (Morikawa 1993). Average annual precipitation in the Xiaolongshan Mountain region is 770 mm and precipitation is not a limiting factor for lacebark pine growth.

In summary, this study notes that temperature has a positive impact on tree-ring widths of lacebark pine in this region. Assuming future temperatures increase up to 4.0°C, tree-ring widths would increase by up to 12.8%; biomass and carbon pools would increase by percentages of up to 31%. The percentage increase for carbon storage remains a constant independent of DBH for a temperature increment. These findings are important in predicting growth and evaluation of forest biomass and carbon storage of lacebark in future climate change, which are expected to contribute to improved forest management.

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