EFFECTS OF CLIMATE ON THE RADIAL GROWTH OF *LARIX GMELINII* UNDER DIFFERENT COMPETITION INTENSITIES IN THE GREATER KHINGAN MOUNTAINS

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Abstract. In this study, the effects of climatic factors on the radial growth of trees in the Greater Khingan Mountains, under different competition intensities, were studied using dendrochronology and a competition index. The results showed that under different competition intensities, the radial growth of the trees was affected by climatic factors, under different circumstances. Under low competition intensities, the tree-ring width index was negatively correlated with the monthly average maximum temperature in March and positively correlated with the precipitation in April of the current year. Under moderate competition intensities, the tree-ring width index was negatively correlated with the monthly average temperature and monthly average maximum temperature in March and positively correlated with the precipitation in April and the monthly average minimum temperature in May of the current year. Under high competition intensities, the monthly average minimum temperature in May of the current year was significant. A multiple-stepwise regression method was used to simulate the relationship between the tree-ring width index and climate factors; a model was established to predict whether the radial growth of *Larix gmelinii* would be inhibited by increasing the annual average temperature.
Keywords: *competition intensity, tree-ring, Larix gmelinii, regression analysis, climate warming, Northeast China*

Introduction

The boreal forest has some of the greatest potential to affect global carbon levels, and the effects of climate change on the radial growth of its dominant species, *Larix gmelinii*, has a significant impact on the global carbon balance. As an important part of forest ecosystems, tree growth is influenced by both genetic and environmental factors (Kawata, 1997). Changes in climate factors, such as temperature and precipitation, are not entirely consistent over time (IPCC, 2013). As external environmental factors, they affect the photosynthesis, respiration, and transpiration of trees, and their effects are uncertain due to climate change and the different forest types (Linderholm et al., 2004; Carrer et al., 2007; Yu et al., 2013). Different tree species (He et al., 2005) as well as the altitudes (Bai et al., 2016) and latitudes (Jiang et al., 2016) of the study sites contribute to these effects. Sun et al. (2019) studied Larix Xingan in the northern Greater Khingan Mountains and found that the environmental water content affected the plant's response to future climate warming. Chang et al. (2017) discovered that if the temperatures continued to rise in the future, the radial growth of larch in the Greater Khingan Mountains would decrease in the southern and central regions and increase in

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the northern regions. Zhang et al. (2017) found that the main limiting factor affecting the radial growth of P. sylvestris in the Greater Khingan Mountains was the monthly average temperature from April to August of the current year.

In addition to this, the relationship between tree radial growth and climate is regulated by competition (Liu et al., 2007). Competition in the forest ecosystem is mainly manifested by the competition between the aboveground parts of adjacent trees for light resources and the underground parts for soil organic matter; the trees compete for limited resources during the growth process (Wang et al., 2000; Kang et al., 2020). The competitive ability of individual trees in a stand has an important influence on the growth of the trees, provided that the tree species and site conditions are similar in the same stand. Kang et al. (2019) discovered during their study of red pines in the Lesser Khingan Mountains that competition will, to some extent, intensify the response between the radial growth of the red pine and June precipitation. Kwon et al. (2019) found that the growth of *Pinus sylvesteris* in Hulunbuir Sandy Land was affected by competition and that trees with different competitiveness had different responses to climatic factors.

As an important ecological forest protection area and ecological green barrier in northern China, the Greater Khingan Mountains forest area is highly sensitive to climate change, especially global warming (Gao et al., 2019). However, there are relatively few studies on the effects of radial growth and climatic factors on *Larix gmelinii* (Xu et al., 1998), under different competition intensities in this area. In this study, *Larix gmelinii* was the dominant tree species in the Greater Khingan Mountains. The relationship of trees between their radial growth and the climate under different competition intensities was analyzed. This study will provide a scientific basis for forest resource management under abnormal climate changes in the future.

The objectives of this study were to: (1) identify the dominant climatic factors that inhibit or promote the radial growth of trees; and (2) construct a linear regression model between the climatic factors and tree-ring width index, under different competition intensities. (3) predict the radial growth trend in *Larix gmelinii*, in the context of climate change.

Materials and Methods

Study Area

The sampling site was situated in the Chaocha Forest Farm, Genhe Forestry Bureau, Greater Khingan Mountains, Inner Mongolia, northern China (50°56′N,121°29′E), approximately 800–1000 m above sea level (*Fig. 1*). It has a cold temperate continental monsoon climate with hot rains at the same time. Precipitation is mainly concentrated from June to August and accounts for more than 70% of the total annual precipitation. The winter is cold and long, the summer is short and humid, and the temperature difference between day and night is large. The average annual temperature in the study area is -3 °C, and annual precipitation is approximately 440 mm. The soil is mainly brown coniferous forest soil, with a large area of marsh wetland and continuous permafrost (Wang et al., 2016). The dominant tree species is *Larix gmelinii*, followed by *Betula platyphylla* and *Populus davidiana* (Wang et al., 2021). Understory vegetation includes *Rhododendroni*, *Ledum palustre, Betula fruticosa, Vaccinium uliginosum*, *Maianthemum bifolium*, *Pyrola incarnata*, etc. (Li et al., 2015). Because of the differences in site conditions and altitudes, the *Larix gmelinii* forest showed

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different forest types. The widely distributed and representative forests include *Rhododendron-Larix gmelinii*, *Ledum palustre-Larix gmelinii*, and *grass-Larix gmelinii*.

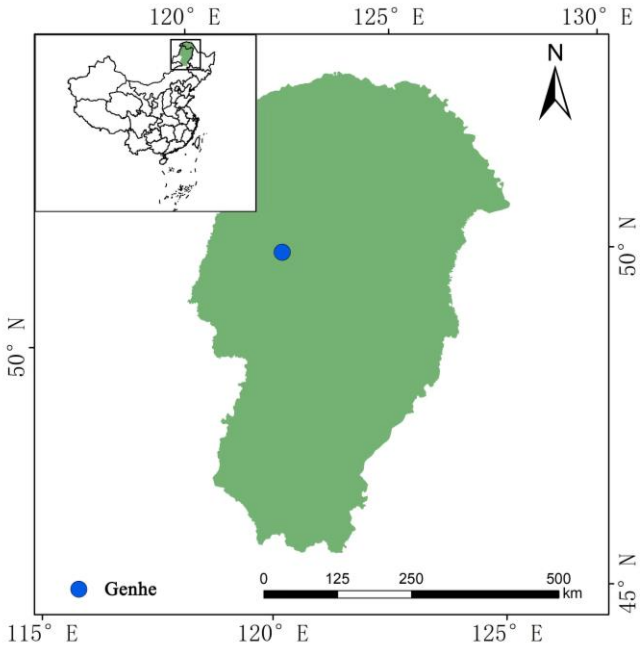

Figure 1. *Chaocha Forest Farm, Genhe Forestry Bureau, Greater Khingan Mountains location (50°56'N,121°29'E)*

Tree-Ring Sampling and Chronology Development

The field survey sampling was conducted in September 2021. A 100 × 50 m standard plot of *Ledum palustre-Larix gmelinii* forest was established on a flat or gentle slope area that had little human disturbance. Each tree was investigated, and tree cores were collected. The survey of each tree included the index of species, plant number, height of tree, range of tree-crown, and the latitude and longitude of the plot. *Larix gmelinii*, which displayed good growth and a large DBH (diameter at breast height) in the sample plot was selected as the target tree species, and the nearest four trees around the target tree were selected as competing trees. The DBH of the target trees, the DBH of the competing trees and the distance between competing trees and the target trees were measured and recorded, and the tree-ring samples of the target trees in the sample plot were collected. Using a growth cone with an inner diameter of 5.15 mm, the sampling cores were drilled at the height of a chest (1.3 m) of a well-grown larch with no scars on the trunk, one on each side of the parallel and vertical slopes (*Fig. 2*). The sample cores were sealed in a plastic hose and numbered individually.

The tree core samples were taken back to the lab, according to the international standard of tree-ring protocol (Fritts et al., 1972). First, the sample core was fixed on a grooved wooden strip with white latex and wound using a string. After natural drying, 240, 360, 600, and 800 mesh sandpapers were used to grind the surface of the sample core from coarse to fine, step by step, until it was smooth, and the ring boundary was clear under the microscope. Skeleton cross-dating was then carried out on the polished sample core. LINTAB 6.0, a tree-ring width analyzer with a measurement accuracy of 0.001 mm was used for the measurements. The wheel-width sequence dating results

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were detected using the COFECHA program (Holmes et al., 1983), and any cores that were seriously inconsistent with the main sequence were eliminated. A total of 90 tree cores were retained for this experiment. The chronology was established after detrending, by the ARSTAN program (Cook et al., 1986). To reduce the loss of low-frequency signals, a conservative negative exponential function or linear function fitting method was used for detrending. Finally, three types of detrended chronologies were obtained: standard chronology (STD), residual chronology (RES), and ARSTAN chronology (ARS).

Figure 2. *The standard plot setting, and the tree sampling cores collection*

Climatic Data

Meteorological data from 1969 to 2020 were obtained from the China Meteorological Data Network (http://data.cma.cn/). Data such as the monthly average temperature (Tm), monthly average maximum temperature (Tmax), monthly average minimum temperature (Tmin), and monthly precipitation (P) of the meteorological station in Genhe City, closest to the sampling point, were selected (*Fig. 3*). The climatological data were obtained from the World Climate Database (www.worldclim.org) and the climatic data of the average annual temperature and annual precipitation in the 2050s and 2090s for Genhe City in Northeast China was extracted using the ArcGIS software (*Table 1*). Three scenarios of Shared Socioeconomic Pathways (SSPs) were selected: sustainable development (SSP126), moderate development (SSP245), and conventional development dominated by fossil fuels (SSP585) (Hernandez et al., 2006; Yang et al., 2021). Considering the "lag effect" of the previous year's climatic factors on the radial growth of the trees in the current year (Wu et al., 1990; Yu et al., 2005; Fan et al., 2009), the period of the meteorological data used in this study was from June of the previous year to August of the current year, that is, from the beginning of the previous year's growing season to the end of the current year’s growing season. To assess the relationship between seasonal climate and tree growth, the study was conducted across multiple seasons which were defined as follows: previous growing season (PG): June to August of the previous year; previous autumn (PA): September to October of the previous year; previous winter season (PW): previous November to current March; pre-current growing season (BG): April to May of the current year; and current growing season (CG): June to August of the current year.

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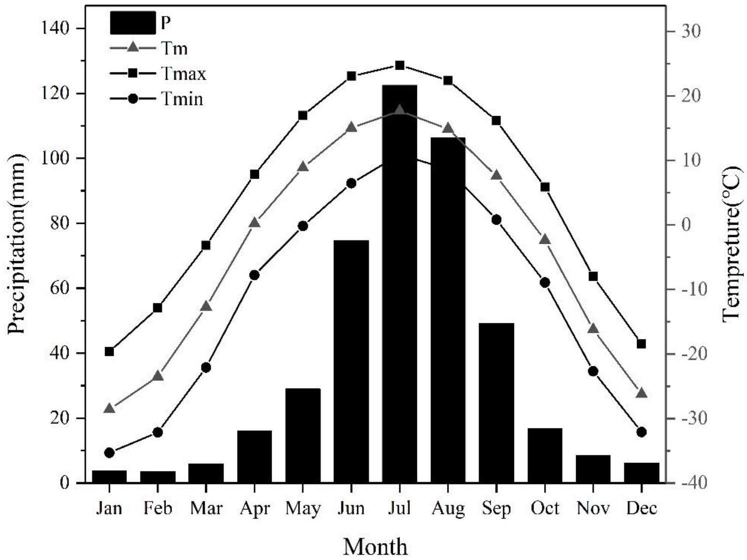

***Figure 3.** Changes in the annual precipitation (P), annual average temperature (Tm), annual average maximum temperature (Tmax), and annual mean minimum temperature (Tmin) in Genhe, from 1969 to 2020*

***Table 1.** Climatic data of the annual average temperature and annual precipitation in Genhe in the 2050s and 2090s*

Factor	Current	2050s			2090s		
		SSP126	SSP245	SSP585	SSP126	SSP245	SSP585
Annual T_m / °C	-3.78	-2.98	-2.32	-1.30	-2.48	-0.97	1.81
Annual P/ mm	440	523	517	532	504	536	579

Data Treating

For calculating the competition index of a single wood, the distance-related Hegyi competition index formula was adopted (Kang et al., 2019):

$$CI = \sum_{j=1}^{n} \frac{D_i}{D_j} \times \frac{1}{L_{ij}} \quad \text{(Eq.1)}$$

where CI is the competition index, Di is the DBH of the i'th competing tree (cm), Dj is the DBH of the j'th target tree (cm), and Lij is the distance (m) between the i'th competing tree and j'th target tree.

The Pearson correlation analysis from the SPSS software was used to calculate the correlation coefficients between the chronology of standardized tree-ring width and climatic factors under different competition intensities.

The "relaimpo" package from the R (Kwon et al., 2019) software was used to construct the multiple regression model (2) between the tree-ring width index and climate factors, and the unitary regression model (3) between the climate factors and annual average temperature or annual precipitation of *Larix gmelinii*. First, the climatic factors such as monthly precipitation, monthly average temperature, monthly average maximum temperature, and monthly average minimum temperature, in this region, from

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June of the previous year to August of the current year, were selected as variables and entered into the regression *Equation (2)*:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + b \tag{Eq.2}$$

where y represents the standardized tree-ring width index, x_1 and x_2 represent the climatic factors in the significant months, β_0 is the intercept, β_1 and β_2 are the regression coefficients of the climatic factors in the significant months, and b is the random error. When a variable had no significant influence on the tree-ring width index, it was eliminated. After screening the climatic factors with significant influences, the regression equation was tested.

Thereafter, we selected the climatic factors retained in the multiple regression model and brought them into the univariate regression model (3) one by one:

$$y = ax + b \tag{Eq.3}$$

where y represents the annual average temperature or precipitation, x represents the climatic factor, b is the intercept, and a is the regression coefficient of the climatic factor. When the climatic factors were the monthly average temperature, monthly average maximum temperature, and monthly average minimum temperature, y was the annual average temperature. When the climatic factor was monthly precipitation, y was the annual precipitation.

EXCEL was used for data calculation, and the ORIGIN software was used for plot analysis.

Results

Characteristics of the Single Wood Competition of Larix gmelinii

The average competition index of *Larix gmelinii* was 1.13, which was between 0.22 and 4.64. Taking the upper (1/4) and lower (3/4) quantiles of the single wood competition index of *Larix gmelinii* as the cut-off point (Carnwath et al., 2016), the *Larix gmelinii* trees were divided into three competition grades: low competition index group (low), medium competition index group (medium), and high competition index group (high). The low competition index group included 24 sample cores and 12 trees, and the average DBH of the trees was 33.26 cm. The medium competition index group included 48 sample cores and 24 trees, and the average DBH of the trees was 29.67 cm. The high competition index group included 24 sample cores and 12 trees, and the average DBH of the trees was 24.29 cm. Therefore, with an increase in the competition index of *Larix gmelinii*, the competition intensity gradually increased; DBH decreased accordingly.

Characteristics of the Tree-Ring Width Chronologies

Table 2 presents the statistical characteristic values of the standard and different chronologies of *Larix gmelinii* under different competition intensities. The results showed that the expressed population signal (EPS) of each chronology reached 0.9 and indicated that the tree-ring samples collected in this study can represent the overall growth trend of the forest, at the sampling site. The variance in the first eigenvector

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(PC1) reflects the synchrony of the sample sequence in the chronology. The PC1 of the residual chronology was over 40%, indicating that the tree-ring widths of the sampling points had strong sequence consistency. The mean sensitivity (MS) reflects the sensitivity of *Larix gmelinii* to the regional climate at the sampling site; the mean sensitivity values of the standard chronology and residual chronology are similar. First-order autocorrelation (AC1) reflects the lagged effect of the previous year's climate factors on tree growth in the current year. The smaller the coefficient, the higher the chronology quality. The AC1 of the residual chronology under each competition intensity was lower than that of the standard chronology. The chronological signal-to-noise ratio (SNR) size reflected the amount of climate information it contains. The SNR of the residual chronology was higher than that of the standard chronology, indicating that the residual chronology contained more climate information; that is, the environmental information used for analysis was relatively large. The residual chronology of *Larix gmelinii* showed great advantages in the EPS, PC1, SNR, etc., via comprehensive comparative analysis; therefore, the residual chronology was selected for the correlation analysis in this study (Wang et al., 2007).

Table 2. *Basic statistics of the Larix gmelinii tree-ring width chronology, under different competitive intensities*

Site code	Cores/trees	Mean length of series	EPS	MS	PC1 %	SNR	SD	AC1
Low	24/15	118.54 years	0.91 0.94	0.19 0.21	35.83 44.36	10.30 15.06	0.22 0.19	0.43 0.09
Medium	42/30	111.55 years	0.95 0.96	0.17 0.20	38.17 42.08	19.56 24.00	0.19 0.18	0.43 0.06
High	24/15	112.54 years	0.90 0.92	0.17 0.17	37.99 42.93	8.62 11.10	0.15 0.15	0.49 0.08

The following conclusions can be found by comparing the tree-ring width index of the chronology of different values of *Larix gmelinii* under different competition intensities (*Fig. 4*). The reliability interval of the larch ring width chronology under low competition intensity was 1865–2020, the reliability interval of the larch ring width chronology under medium competition intensity was 1861–2020, and the reliability interval of the larch ring width chronology under high competition intensity was 1865-2020. The length of each chronology was essentially the same.

Correlation Analysis of the Climatic Factors

By comparing the results of the correlation analysis between the annual ring width index and climatic factors under different competition intensities (*Fig. 5*), it was found that the radial growth of *Larix gmelinii* was not only related to monthly climatic factors, but also closely related to seasonal climatic factors. Under low competition intensities, the tree-ring width index of *Larix gmelinii* had a low correlation with all the climatic factors; it only had a significant negative correlation with the monthly average maximum temperature in March and a significant positive correlation with the precipitation in April of the current year. Under medium competition intensities, the tree-ring width index of *Larix gmelinii* was negatively correlated with the monthly average temperature and monthly average maximum temperature in March and positively correlated with the precipitation in April and the monthly average minimum

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temperature in May of the current year. Under high competition intensities, the tree-ring width index of *Larix gmelinii* was positively correlated with the monthly average minimum temperature in January and May, precipitation in April and May, and the monthly average temperature in August of the current year. The monthly average minimum temperature in May of the current year was highly significant. Under the monthly combination conditions, the tree-ring width index under medium competition intensities and high competition intensities showed a significant positive correlation with the average minimum temperature in the previous autumn and precipitation in the previous winter. In addition to this, the width of the tree rings under high competition intensities was positively correlated with the pre-current growing season precipitation, average temperature, and average maximum temperature in the current growing season.

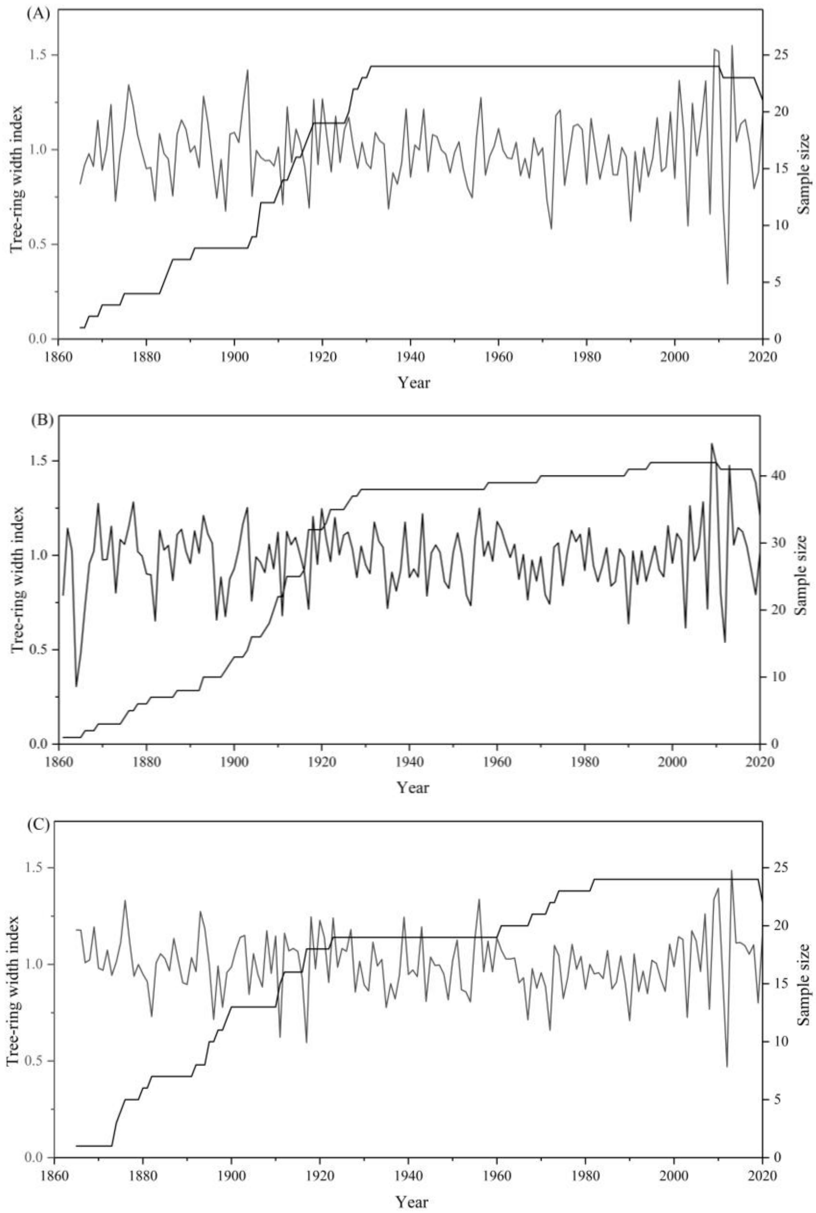

Figure 4. *Tree-ring width index and sample size of Larix gmelinii under low, medium, and high competition intensities. A: The low competition index group; B: The medium competition index group; C: The high competition index group*

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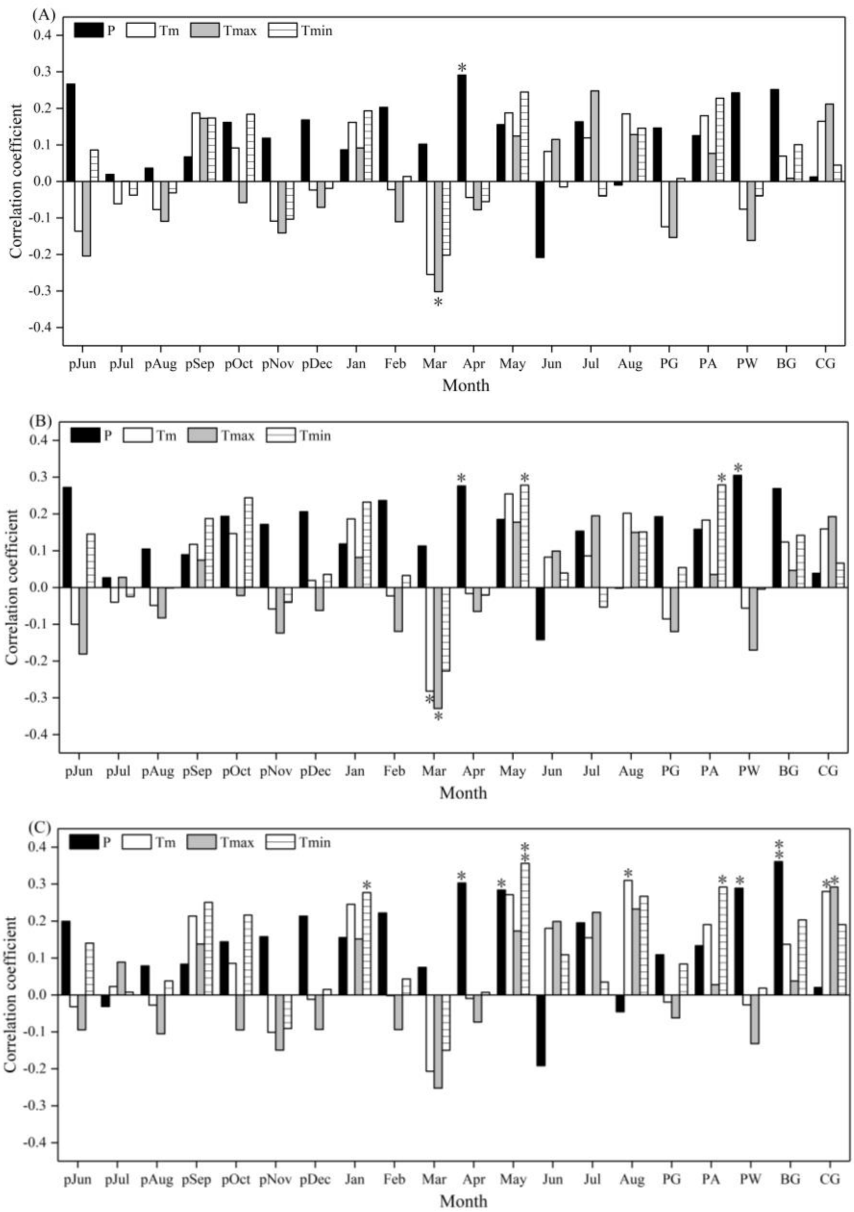

Figure 5. *Correlation coefficients of the Larix gmelinii tree-ring width chronology with the climatic factors, under different competitive intensities. P: Previous year; * represents P <0.05, A: The low competition index group; B: The medium competition index group; C: The high competition index group*

Regression Analysis of the Tree-ring Width Index and Climatic Factors

The relationship between radial growth and climatic factors can be further described by establishing multiple regression models. The monthly and seasonal climatic factors with a strong significance under each competition intensity were selected for the multiple stepwise regression analysis from 1969-2010, and the insignificant variables were retained: average minimum temperature in May and average maximum temperature in March of the same year. The results are presented in *Table 3*.

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Table 3. *Multiple regression statistics of the climatic factors and tree-ring width index*

Competitive intensity	Climatic factor	P	Slope	Absolute contribution rate	DW	R^2
Low	Tmin_5	0.001	0.071	0.14	2.002	0.36
	Tmax_3	0.000	-0.042	0.22		
Medium	Tmin_5	0.000	0.063	0.15	1.945	0.38
	Tmax_3	0.000	-0.037	0.23		
High	Tmin_5	0.000	0.058	0.20	1.940	0.43
	Tmax_3	0.000	-0.030	0.23		

P: significance level; DW: Durbin Watson; R^2: goodness of fit

The climatic factors retained after the multiple stepwise regression analysis (*Table 3*) were selected to construct the optimal equation of the tree-ring width index and significant climatic factors under different competition intensities:

$$Y_1=0.071X_1-0.042X_2+0.885\ (R^2adj=0.33,\ P=1.5\times10^{-4}) \quad \text{(Eq.4)}$$

$$Y_2=0.063X_1-0.037X_2+0.892\ (R^2adj=0.35,\ P=9.4\times10^{-5}) \quad \text{(Eq.5)}$$

$$Y_3=0.058X_1-0.030X_2+0.902\ (R^2adj=0.40,\ P=1.7\times10^{-5}) \quad \text{(Eq.6)}$$

Y_1 is the tree-ring width index under a low competition intensity, Y_2 is the tree-ring width index under a medium competition intensity, Y_3 is the tree-ring width index under a high competition intensity, X_1 is the monthly average minimum temperature in May, and X_2 is the monthly average maximum temperature in March of the current year.

Under different competition intensities, the simulated values curve of the tree-ring width index of *Larix gmelinii* followed the measured values curve closely (*Fig. 6*). The paired t-test showed that there was no significant difference between the observed values and simulation values of the tree-ring width index and that the correlation between them was 0.49, 0.47, and 0.38 (P=0.03; 0.04; 0.1), for the low, medium, and high competitive intensities, respectively. The results obtained demonstrated that the three simulation equations fitted the relationship between the growth tree-ring width index and climate factors; therefore, these equations can be used to predict the tree-ring width growth of *Larix gmelinii* under climate change.

Prediction of Future Tree-ring Width Indices

The climatic factors retained after the multiple stepwise regression analysis were selected to construct a unitary regression equation of the average annual temperature and single significant climatic factors.

$$Y = 0.42904X_1 - 3.70668\ (R^2 = 0.38, P = 9.9 \times 10^{-7}) \quad \text{(Eq.7)}$$

$$Y = 0.23372X_2 - 3.05685\ (R^2 = 0.38, P = 7.6 \times 10^{-7}) \quad \text{(Eq.8)}$$

where Y is the average annual temperature, X_1 is the monthly average minimum temperature in May, and X_2 is the monthly average maximum temperature in March.

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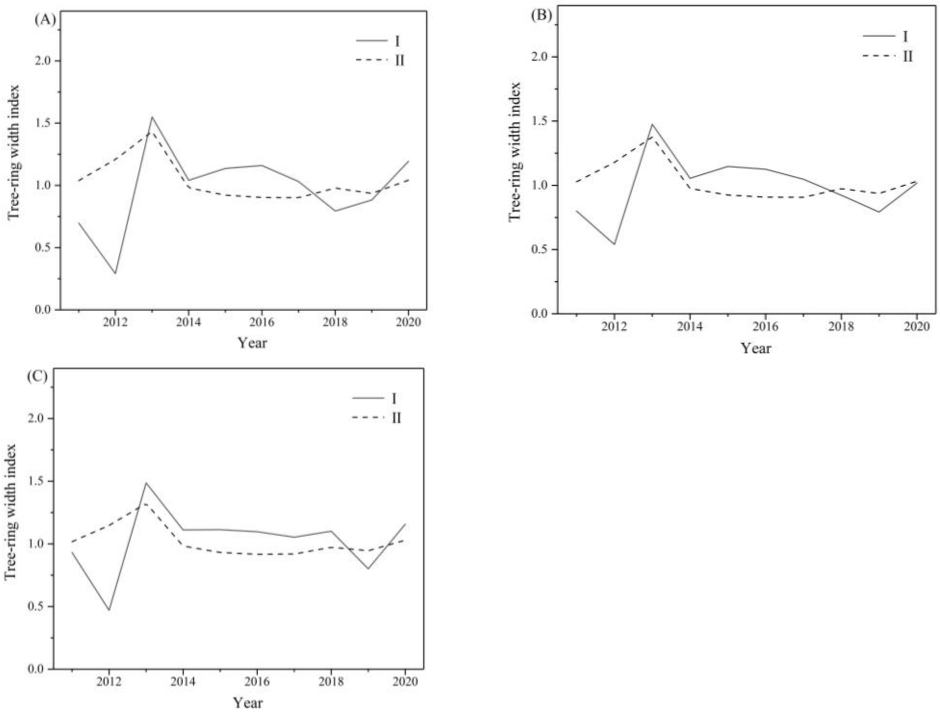

Figure 6. *Time series analysis of the tree-ring width index of Larix gmelinii under different competitive intensities. I: Observed values; II: Simulation values. A: The low competition index group; B: The medium competition index group; C: The high competition index group*

The average annual temperatures in the 2050s and the 2090s, under the three scenarios, were entered into *Equations (7) and (8)*, and the monthly average minimum temperature in May and monthly average maximum temperature in March were obtained (*Table 4*). By substituting them into *Equations (4), (5), and (6)*, the radial growth of *Larix gmelinii* under different competition intensities could be predicted (*Table 5*).

Table 4. *The monthly average minimum temperature in May and the monthly average maximum temperature in March, in the 2050s and 2090s*

Climatic factor	**2050s**			**2090s**		
	SSP126	SSP245	SSP585	SSP126	SSP245	SSP585
Tmin_5	1.69	3.24	5.61	2.85	6.39	12.85
Tmax_3	0.31	3.17	7.52	2.45	8.94	20.82

Table 5. *Tree-ring width index and amplitude of variation of Larix gmelinii under different competition intensities, in the 2050s and 2090s*

Competitive intensity	**2050s**			**2090s**		
	SSP126	SSP245	SSP585	SSP126	SSP245	SSP585
Low	0.986 (-0.174)	0.977 (-0.181)	0.963 (-0.193)	0.979 (-0.179)	0.958 (-0.197)	0.918 (-0.231)
Medium	0.987 (-0.031)	0.979 (-0.038)	0.967 (-0.050)	0.979 (-0.038)	0.965 (-0.052)	0.941 (-0.076)
High	0.990 (-0.144)	0.994 (-0.141)	1.002 (-0.134)	0.994 (-0.141)	1.004 (-0.132)	1.023 (-0.116)

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Discussion

Under different competition intensities, from 1969 to 2020, the *Larix gmelinii* tree-ring width index of the growing season began with the previous year's growing season and ended with the current year's growing season of monthly precipitation, monthly average temperature, monthly average maximum temperature, and monthly average minimum temperature of four climate factor correlation analyses. We found that under different competition intensities, the radial growth of the trees was affected by the climate factors, in different situations.

Under the medium and low competition intensities, the tree-ring width index of *Larix gmelinii* was negatively correlated with the monthly average maximum temperature in March of the current year. In March, trees are in the dormant period (Fu et al., 2018), when they cannot perform photosynthesis, but their respiration continues. If the temperature is too high, the consumption of nutrients will directly increase (Wang et al., 2019), and the physiological drought phenomena will occur (Zhang et al., 2017), resulting in the formation of narrow annual rings. However, an increased maximum temperature in March may also lead to the snow melting earlier during the previous winter, which will result in early spring (Liu et al., 2003) and a rapid increase in soil moisture. In turn, a large amount of the available water needed in the growing season will be lost, which is not conducive to tree growth (Han et al., 2021).

At high competition intensities, the tree-ring width index was positively correlated with the average temperature in the current growing season. Trees under high competition intensity are mostly small-path trees, and it is difficult for their roots to absorb water from the soil to meet the needs of their life activities (Holmes et al., 1983). The growing season is critical for the growth of trees. If the temperature is too low, root activity is limited and the amount of water available to the trees from the soil is reduced (Liang et al., 2006). Moreover, low temperatures limit the division and expansion of the xylems' tracheids (Deslauriers et al., 2003; Guo et al., 2021), which is not conducive to the growth of the trees.

The radial growth of trees was positively correlated with the precipitation in April of the current year, under all three competition intensities. Higher precipitation in the summer can alleviate the drought stress caused by the high temperatures (Wang et al., 2013), thus contributing to the growth of *Larix gmelinii*.

The growth law of *Larix gmelinii* can be understood by establishing a radial growth prediction model over a long timescale. Based on the tree-ring width index data from the 51a climate records, the simulation equations of the tree-ring width index and climate factors were established to quantitatively predict the radial growth of *Larix gmelinii* under three climate scenarios of the future shared socioeconomic path. The results showed that if the temperature continues to increase, the radial growth of *Larix gmelinii* will decrease. Under medium and low competition intensities, the radial growth of trees in the 2050s and 2090s was SSP126>SSP245>SSP585; the radial growth of the trees in the 2090s was decreased compared to in the 2050s. This indicates that the higher the temperature, the stronger the inhibitory effect on the radial growth of the trees. However, the opposite result was found under high competition intensities, which may be related to differences in the physiological function (Zhao et al., 2019) and physiological activity ability of trees with different diameter classes and ages. By comparing the growth of *Larix gmelinii* under different competition intensities in the 2050s and the 2090s, we found that high competition intensities > medium competition intensities > low competition intensities, under the three climate scenarios. This is

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closely related to the fact that trees under a high competition intensity are mostly small-diameter class trees, that is, they are young and in a period of rapid growth (Liu et al., 2018).

Conclusions

In this study, we modeled future radial tree growth based on measured plot surveys, combining current meteorological data, and three future climate scenarios with shared socioeconomic paths. The study accurately revealed the dominant environmental variables driving the current and future growth of *Larix gmelinii* in the Genhe region of the Greater Hinggan Mountains and predicted the future growth trends of the *Larix gmelinii* species. According to the prediction results of the model, the radial growth of *Larix gmelinii* will decrease with an increase in temperature, in the future period. The results of this study provide a theoretical basis for the development of more scientific and effective strategies that will help with the adaption to climate change, formulate scientific and effective management strategies for *Larix gmelinii* forests, and realize sustainable forest development in Northeast China.

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REFERENCES

[1] Bai, X. P., Chang, Y. X., Zhang, X. L., Ma, Y. J., Wu, T., Li, J. X., Chen, Z. J. (2016): Impacts of rapid warming on radial growth of *Larix gmelinii* on two typical micro-topographies in the recent 30 years. – Ying Yong Sheng Tai Xue Bao 27: 3853-3861. DOI:10.13287/j.1001-9332.201612.036.

[2] Carnwath, G. C., Nelson, C. R. (2016): The effect of competition on responses to drought and interannual climate variability of a dominant conifer tree of western North America. – J. Ecol. 104: 1421-1431. DOI:10.1111/1365-2745.12604.

[3] Carrer, M., Nola, P., Eduard, J. L., Motta, R., Urbinati, C. (2007): Regional variability of climate–growth relationships in Pinus cembra high elevation forests in the Alps. – J. Ecol. 95: 1072-1083. DOI:10.1111/j.1365-2745.2007.01281.x.

[4] Chang, Y. X., Chen, Z. J., Zhang, X. L., Bai, X. P., Zhao, X. P., Li, J. X., Lu, X. (2017): Responses of radial growth to temperature in *Larix gmelinii* of the Da Hinggan Ling under climate warming. – Chin. J. Plant Ecol. 41: 279-289. DOI:10.17521/cjpe.2016.0222.

[5] Cook, E. R., Holmes, R. L. (1986): User's Manual for ARSTAN. – Laboratory of Tree-Ring Research: Tucson; University of Arizona, USA.

[6] Deslauriers, A., Morin, H., Begin, Y. (2003): Cellular phenology of annual ring formation of Abies balsamea in the Quebec boreal forest (Canada). – Can. J. Forest Res. 33: 190-200. DOI:10.1139/x02-178.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_20752089

[7] Fan, Z. X., Bräuning, A., Cao, K. F., Zhu, S. (2009): Growth-climate responses of high-elevation conifers in the central Hengduan Mountains, southwestern China. – Forest Ecol. Manag. 258: 306-313. DOI:10.1016/j.foreco.2009.04.017.

[8] Fritts, H. C. (1972): Tree Rings and Climate. – Sci. Am. 226: 92-100. DOI:10.1038/scientificamerican0572-92.

[9] Fu, Y., He, H., Zhao, J., Larsen, D., Zhang, H., Sunde, M., Duan, S. (2018): Climate and spring phenology effects on autumn phenology in the Greater Khingan Mountains, Northeastern China. – Remote Sens. 10: 1-22. DOI:10.3390/rs10030449.

[10] Gao, W., Yao, Y., Liang, H., Song, L., Sheng, H., Cai, T., Gao, D. (2019): Emissions of nitrous oxide from continuous permafrost region in the Daxing'an Mountains, Northeast China. – Atmos. Environ. 198: 34-45. DOI:10.1016/j.atmosenv.2018.10.045.

[11] Guo, X. M., Wang, Z. P., Zhang, N., Zhang, D. Y. (2021): Responses of radial growth of Pinus sylvestris var. mongolica and *Larix gmelinii* to climate change. – Ying Yong Sheng Tai Xue Bao 32: 3405-3414. DOI:10.13287/j.1001-9332.202110.042.

[12] Han, Y. G., Gai, X. R., Qiu, S. Y., Zhang, Y., Wang, S. L., Zhou, L., Yu, D. P. (2021): Spatial and temporal variations of the responses of radial growth of *Larix gmelinii* to climate in the Daxing'anling Mountains of Northeast China. – Ying Yong Sheng Tai Xue Bao 32: 3397-3404. DOI:10.13287/j.1001-9332.202110.021.

[13] He, J., Zhang, Q., Bazzaz, F. A. (2005): Differential drought responses between saplings and adult trees in four co-occurring species of New England. – Trees 19: 442-450. DOI:10.1007/s00468-004-0403-2.

[14] Hernandez, P. A., Graham, C. H., Master, L. L., Albert, D. L. (2006): The effect of sample size and species characteristics on performance of different species distribution modeling methods. – Ecography 29: 773-785. DOI:10.1111/j.0906-7590.2006.04700.x.

[15] Holmes, R. L. (1983): Computer-assisted quality control in tree-ring dating and measurement. – Tree Ring Bull. 43: 69-75.

[16] IPCC. (2013): Climate change: The physical science basis. – Contrib. Working. 43: 866-871.

[17] Jiang, Y., Zhang, J., Han, S., Chen, Z., Setälä, H., Yu, J., Zheng, X., Guo, Y., Gu, Y. (2016): Radial growth response of *Larix gmelinii* to climate along a latitudinal gradient in the Greater Khingan Mountains, Northeastern China. – Forests. 7: 295. DOI:10.3390/f7120295.

[18] Kang, Y. C., Liu, B. H., Ren, J. Y. et al. (2019): Effect of competition on tree-ring growth and climate factors of *Pinus koraiensis*. – J. Northeast For. Univ. 47: 6-10, 22.

[19] Kang, J., Liang, H. X., Jiang, S. W., Zhu, H., Zhou, P., Huang, J. (2020): Effects of competition and climate on tree radial growth of *Pinus sibirica* in Altai Mountains, Xinjiang, China. – Chin. J. Plant Ecol. 44: 1195-1202. DOI:10.17521/cjpe.2020.0224.

[20] Kawata, M. (1997): Exploitative competition and ecological effective abundance. – Ecol. Modell. 94: 125-137. DOI:10.1016/S0304-3800(96)00008-7.

[21] Kwon, S. M., Pan, L. L., Shi, Z. J., Yang, X. H., Zhang, X., Liu, Y. S., Zhang, K. B. (2019): Radial growth of Mongolian pine and its response to climate at different competition intensities. – Chin. J. Ecol. 38: 1962-1972.

[22] Li, X. M., Zhang, Q. L. (2015): Impact of climate factors on CO_2 flux characteristics in a *Larix gmelinii* forest ecosystem. – J. Beijing For. Univ. 37(08): 31-39.

[23] Liang, E. Y., Shao, X. M., Eckstein, D., Huang, L., Liu, X. (2006): Topography- and species-dependent growth responses of *Sabina przewalskii* and *Picea crassifolia* to climate on the northeast Tibetan Plateau. – Forest Ecol. Manag. 236: 268-277. DOI:10.1016/j.foreco.2006.09.016.

[24] Linderholm, H. W., Linderholm, K. (2004): Age-dependent climate sensitivity of Pinus sylvestris L. in the central Scandinavian Mountains. – Boreal Environ. Res. 9: 307-317.

[25] Liu, H. B., Shao, X. M. (2003): Reconstruction of early-spring temperature of Qinling Mountains using tree-ring chronologies. – Acta Geogr. Sin. 06: 879-884.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2103_20752089

[26] Liu, T., Li, Y. L., Zhou, Z. Q., Hu, H. Q. (2007): Intraspecific and interspecific competition of Japanese yew (*Taxus cuspidata*). – Acta Ecol. Sin. 03: 924-929.
[27] Liu, M., Mao, Z. J., Li, Y. (2018): Response of radial growth to climate change in *Pinus koraiensis* with different diameter classes. – Chin. J. Appl. Ecol. 29: 3530-3540. DOI:10.13287/j.1001-9332.201811.010.
[28] Sun, Z. J., Zhao, H. Y., Zhu, L. J., Zhang, Y. D., Wang, X. C. (2019): Differences in response of *Larix gmelinii* growth to rising temperature under different precipitation gradients in northern Daxing'an Mountains of northeastern China. – J. Beijing For. Univ. 41: 1-14.
[29] Wang, Z., Wu, G., Wang, J. (2000): Application of competition index in assessing intraspecific and interspecific spatial relations between Manchurian ash and Dahurian larch. – Ying Yong Sheng Tai Xue Bao 11: 641-645.
[30] Wang, Y. X., Lu, Z. H., Su, H. X., et al. (2007): Response analysis between tree-ring widths and climatic factors along different regions in Tianshan Mountains Northwestern China. – J. China Univ. Min. Technol. 02: 251-256.
[31] Wang, X. M., Zhao, X. H., Gao, L. S., Jiang, Q. B. (2013): Climatic response of climatic response of *Betula ermanii* tree-ring growth along an altitudinal gradient on the northern slope of the Changbai Mountains. – Chin. J. Appl. Environ. 19: 929-934.
[32] Wang, F., Ye, D. M., Liu, H. P. (2016): Understory Vegetation Biomass Allocation Features of *Larix gmelinii* in Different Growth Stages. – Journal of Northwest Forestry University 31(06): 30-33.
[33] Wang, S. L., Wang, X. Y., Gai, X. R., Dai, L. M., Zhou, W. M., Zhou, L., Yu, D. P. (2019): Interspecific difference of relationship between radial growth and climate factor for *Larix olgensis* and Picea jezoensis var. komarovii in Changbai Mountain, Northeast China. – Ying Yong Sheng Tai Xue Bao 30: 1529-1535. DOI:10.13287/j.1001-9332.201905.028.
[34] Wang, B., Zhang, P. J., Zhang, Q. L. (2021): Soil Physicochemical Characteristics of *Larix gmelinii* Forest with Different Forest Types. – Journal of Northwest Forestry University 36(06): 65-71.
[35] Wu, X. D. (1990): Tree-Ring and Climate Change. – Meteorology Press: Beijing (in Chinese).
[36] Xu, H. (1998): The Daxing’an Mountains Forest in China. – Science Press: Beijing, China.
[37] Yang, Q. J., Li, R. (2021): Predicting the potential suitable habitats of Alsophila spinulosa and their changes. – Ying Yong Sheng Tai Xue Bao 32: 538-548. DOI:10.13287/j.1001-9332.202102.015.
[38] Yu, D. P., Wang, S. Z., Tang, L. N., Dai, L., Wang, Q., Wang, S. (2005): Relationship between tree-ring chronology of *Larix olgensis* in Changbai Mountains and the climate change. – Ying Yong Sheng Tai Xue Bao 16: 14-20.
[39] Yu, D., Liu, J., Benard, J., Zhou, L., Zhou, W., Fang, X., Wei, Y., Jiang, S., Dai, L. (2013): Spatial variation and temporal instability in the climate–growth relationship of *Korean pine* in the Changbai Mountain region of Northeast China. – For. Ecol. Manag. 300: 96-105. DOI:10.1016/j.foreco.2012.06.032.
[40] Zhang, X. L., He, X. Y., Chen, Z. J., Cui, M. X., Li, N. (2011): Responses of *Pinus sylvestris* var. mongolica radial growth to climate warming in Great Xing’ an Mountains: A case study in Mangui. – Ying Yong Sheng Tai Xue Bao 22: 3101-3108.
[41] Zhang, X. W., Yang, L., Liu, X. H., Zhang, Q. L., Wang, W. Z., Zeng, X. M., Wu, G. J. (2017): Study of the difference in climate response of Dahurian Larch and Pinus sylvestris growth in the north Great Higgnan Mountains of permafrost regions, Northeast China. – J. Glaciol. Geocryol. 39: 165-174.
[42] Zhao, Z. J., Guo, W. X., Kang, D. W., Cui, L., Zhao, L. J., Li, J. Q. (2019): Response of Radial Growth of Abies faxoniana and Picea purpurea to Climatic Factors in subalpine of Western Sichuan. – Sci. Silvae Sin. 55: 1-16.