Spatiotemporal Variation in Growth-Climate Relationships of Three Major Hardwood Species in the Northern Zhangguangcai Range Postprint

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Abstract

Comparisons of tree rings at spatiotemporal scales can better reflect the impacts of environmental changes on tree growth and are of great significance for understanding the effects of climate change on forest ecosystems. Dendrochronological methods were employed to analyze the spatiotemporal variation in climate-growth relationships of radial growth for three main broadleaf tree species in broadleaf-Korean pine forests in the northern Zhangguangcai Mountains—Fraxinus mandshurica, Phellodendron amurense, and Juglans mandshurica. The results demonstrated that climatic responses differed significantly among species at the same site; Juglans mandshurica was jointly influenced by precipitation and minimum temperature, whereas Phellodendron amurense and Fraxinus mandshurica were primarily limited by minimum temperature, indicating that tree growth-climate relationships exhibit species-specific characteristics. With alterations in temperature and precipitation patterns, the relationships between tree rings of the three major hardwood species and climate varied across space; Juglans mandshurica at Fangzheng and Xidaquan sample sites exhibited significant positive correlations with minimum temperature from June to August ($P < 0.05$), whereas at the Fenghuangshan site, it showed positive correlations with minimum temperature and precipitation in May and June ($P < 0.05$). The radial growth of Phellodendron amurense and Fraxinus mandshurica displayed gradually weakening correlations with late growing season precipitation as the spatial precipitation pattern changed. After 1980, significant temperature increases occurred in the northern Zhangguangcai Mountains; before warming, the growth trends of the three major hardwood species were relatively consistent, but after warming, the tree-ring widths of Phellodendron amurense and Fraxinus mandshurica showed increasing trends with rising temperature, whereas Juglans mandshurica exhibited a 'divergence phenomenon' of decreasing growth with increasing temperature. If future warming trends

continue or intensify, it can be inferred that Juglans mandshurica in the northern Zhangguangcai Mountains may suffer from intensified drought stress and could experience growth decline, whereas warming may be more favorable for the growth of Phellodendron amurense and Fraxinus mandshurica.

Full Text

Preamble

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Spatio-temporal Variations in Climate-Growth Relationships of Three Hardwood Tree Species Across the North Zhangguangcai Mountains, Northeast China

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Abstract

Comparative analysis of tree rings across spatial and temporal scales can better reflect the impacts of environmental change on tree growth and is critically important for understanding the influence of climate change on forest ecosystems. Using dendrochronological methods, we analyzed the spatio-temporal variations in radial growth-climate relationships for three dominant broadleaved species (*Fraxinus mandshurica*, *Phellodendron amurense*, and *Juglans mandshurica*) in broadleaf-Korean pine forests in the northern Zhangguangcai Mountains. At the same site, interspecific differences in climate response were significant: *Juglans mandshurica* growth was jointly limited by precipitation and minimum temperature, whereas *Phellodendron amurense* and *Fraxinus mandshurica* were primarily limited by minimum temperature, indicating species-specific characteristics in climate-growth relationships. As temperature and precipitation patterns changed, the relationships between tree rings and climate factors varied spatially across the three hardwood species. At the Fangzheng and Xidaquan sites, *Juglans mandshurica* showed significant positive correlations with June minimum temperature, while at the Fenghuangshan site, it correlated positively with both May-June minimum temperature and precipitation. The radial growth of *Phellodendron amurense* and *Fraxinus mandshurica* showed gradually weakening correlations with end-of-growing-season precipitation as the spatial precipitation pattern changed from west to east. Temperatures in the northern Zhangguangcai Mountains have increased significantly since 1980 ($P < 0.05$). Before 1980, the growth trends of the three hardwoods were relatively consistent, but after warming, the ring widths of *Phellodendron amurense* and *Fraxinus mandshurica* increased with rising temperatures, whereas *Juglans mandshurica* showed a growth decline. If future warming continues or intensifies, *Juglans mandshurica* may experience drought stress and growth decline in the northern

Zhangguangcai Mountains, while warming may benefit *Phellodendron amurense* and *Fraxinus mandshurica*.

Keywords: tree rings; broadleaf-Korean pine mixed forest; drought stress; global warming; radial growth

Introduction

Global climate is undergoing significant changes characterized by warming, with the most pronounced effects in the mid-to-high latitudes of the Northern Hemisphere, particularly in inland ecosystems [1-4]. Increasing data indicate that northeast China has experienced significant warming since the 1980s, entering a warm-drying trend. This warming affects forest ecosystems at various scales. Previous studies have shown both declining forest productivity after climate warming [5-7] and changes in forest tree growth trends, phenology, and distribution [9]. In the broadleaf-Korean pine forests of northern Zhangguangcai Mountains, *Phellodendron amurense*, *Fraxinus mandshurica*, and *Juglans mandshurica* are important companion species to Korean pine (*Pinus koraiensis*), playing crucial roles in forest regeneration and the structural and functional dynamics of these ecosystems. Due to physiological limitations of broadleaved species, tree-ring studies on them are more challenging than on conifers, and their rings may contain different information [10-11]. However, broadleaved species constitute an important component of the ecosystem response to climate change in these forests.

Dendrochronology provides reliable information on spatio-temporal variations in tree radial growth [12]. Previous studies on broadleaved species' climate responses have reported spatial variations. For example, Huang et al. [13] found that *Populus tremuloides* in Canada was mainly affected by summer humidity in the south and temperature in the north. Pierre et al. [14-16] showed that elevation and latitude variations affected oak growth in Central Europe and western France. In China, Zhang Hansong et al. [17] reconstructed past precipitation in Changbai Mountains using *Fraxinus mandshurica* chronologies, while Wang Weiwei et al. [18] reconstructed autumn temperatures, finding *Fraxinus mandshurica* was more sensitive to temperature signals. Li Mu et al. [19] reconstructed growing-season minimum temperatures in Dunhua using Korean pine and the three hardwoods. However, studies in the Qinghai-Tibet Plateau and Northeast China have shown unstable climate-growth responses, with obvious shifts after climate warming [20-22], a phenomenon known as growth divergence [23]. Under global warming, how will the spatio-temporal patterns of growth divergence change for the three hardwoods in the northern Zhangguangcai Mountains? This study addresses this question by examining the spatial patterns of climate responses and temporal stability of the relationships after warming, aiming to reveal differential responses of the three hardwoods to climate change and understand future impacts on forest ecosystems.

1. Sampling Site Description

We selected three minimally disturbed sites along a longitudinal gradient in the northern Zhangguangcai Mountains of Heilongjiang Province: Shuangzishan National Forest Park in Fangzheng County, Xidaquan Forest Park in Boli County, and Fenghuangshan National Nature Reserve in Jidong County. The region belongs to the Changbai Mountain system and features a temperate continental climate with distinct seasons. Soils are primarily dark brown forest soils. The vegetation is dominated by temperate species, with annual precipitation of 400-600 mm and a growing season of 100-160 days. The complex topography supports various forest types including mixed conifer-broadleaf forests, broadleaf-Korean pine forests, and *Quercus mongolica* deciduous broadleaf forests. Dominant tree species include Korean pine, *Phellodendron amurense*, *Fraxinus mandshurica*, *Juglans mandshurica*, *Tilia amurensis*, and *Quercus mongolica*. The three hardwood species are widely distributed in the Zhangguangcai Mountains, and the sampling sites with minimal human disturbance provide ideal conditions for dendroclimatic research.

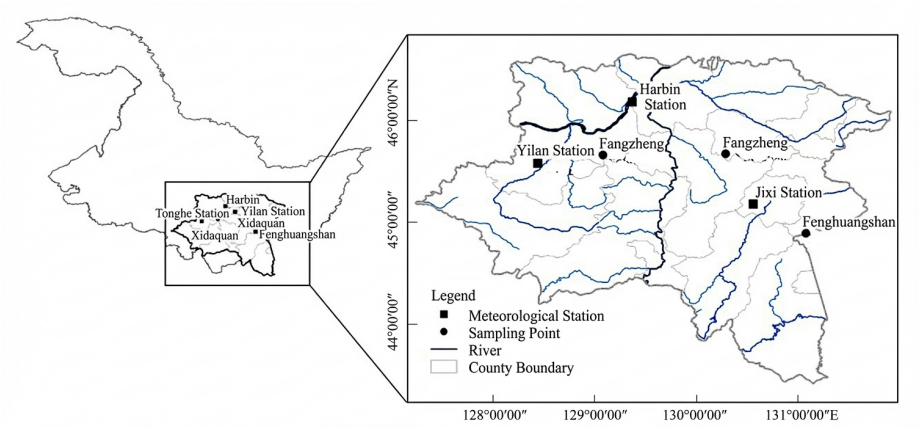

Figure 1: Figure 1

Map of sampled sites for three hardwood tree rings and weather stations near sampled sites

Tree-ring sampling information for different sites and tree species in north Zhangguangcai Mountains

2. Sample Collection and Chronology Development

In May 2014, we collected tree-ring samples from the lower slopes of north-facing aspects at three sites: Fangzheng (FZ), Xidaquan (XDQ), and Fenghuangshan (FHS). Healthy trees were selected and cored at breast height (1.3 m) using increment borers. Two cores per tree were taken from 20-30 trees per species, with

habitat conditions recorded for each tree. Samples were placed in plastic straws and transported to the laboratory for mounting, sanding, and cross-dating. Ring widths were measured using a Velmex measuring system with 0.001 mm precision. The COFECHA program [25] was used to verify cross-dating and measurement accuracy. After cross-dating, the ARSTAN program [26] was used for detrending and standardization. Negative exponential or linear functions were applied to remove age-related growth trends, followed by double averaging to produce standard chronologies for *Juglans mandshurica* and *Fraxinus mandshurica*. The *Phellodendron amurense* samples from one site were insufficient for chronology development.

[FIGURE:2] Monthly mean temperature and total precipitation variation at study area meteorological stations

3. Statistical Analysis

Meteorological data were obtained from China Meteorological Data Sharing Service Network (http://cdc.cma.gov.cn/). For Fangzheng (FZ) and Fenghuangshan (FHS), we used data from nearby Tonghe and Jixi stations, respectively. For Xidaquan (XDQ), we averaged data from Yilan and Jixi stations, which are equidistant from the site. Climate variables included monthly mean minimum temperature (Tmin), maximum temperature (Tmax), mean temperature, total precipitation, and relative humidity (RH). Since previous-year climate can affect current-year growth [24], we analyzed correlations between 18 months of climate data and the standard chronologies. Based on physiological ecology, seasons were defined as: winter (previous December-February), spring (March-May), summer (June-August), and autumn (September-November). Principal component analysis (PCA) was performed on chronologies from the same site and different sites to analyze minimum temperature effects. Statistical analyses were conducted using SPSS 19.0, and figures were prepared using SigmaPlot 12.5.

General information of meteorological stations at each sampled site

Results

1. Chronology Characteristics

Among the nine standard chronologies, tree ages varied significantly among sites. The oldest was *Fraxinus mandshurica* at Fangzheng (208 years), while the youngest was *Juglans mandshurica* at Fenghuangshan (64 years). Mean sensitivity, reflecting responsiveness to climate variability, was generally higher for *Juglans mandshurica* than for *Phellodendron amurense* and *Fraxinus mandshurica*, indicating greater climate sensitivity. First-order autocorrelation was high for all species, showing strong carryover effects of previous-year climate. All chronologies had expressed population signal values above 0.85, indicating

good representation of population-level patterns and suitability for dendroclimatic analysis.

Major characteristics of STD chronologies for three hardwood species

Inter-chronology correlations showed overall consistency but with local differences. The highest correlation was between *Juglans mandshurica* and *Phellodendron amurense* at Fenghuangshan ($r = 0.64$), while the lowest correlations occurred between *Fraxinus mandshurica* at Fenghuangshan and *Juglans mandshurica* or *Fraxinus mandshurica* at Fangzheng. These differences suggest that species-specific physiological traits influence climate responses.

Correlation coefficients of standard chronologies for different sites and tree species (common period 1949-2013)

2. Spatial Variation in Climate-Growth Relationships

Correlation analysis revealed species- and site-specific climate responses. *Juglans mandshurica* at Fangzheng showed significant positive correlations with growing-season precipitation and minimum temperature, particularly in June, July, and September. At Fenghuangshan, *Juglans mandshurica* correlated positively with pre-growing-season minimum temperature and May-June precipitation, but negatively with September precipitation. The correlation strength was significantly higher at Fenghuangshan than at Xidaquan and Fangzheng.

In contrast, *Phellodendron amurense* and *Fraxinus mandshurica* showed weak correlations with precipitation across all sites but strong positive correlations with minimum temperature, particularly at Fenghuangshan. The correlation with precipitation weakened from west to east across sites, consistent with the precipitation gradient.

[FIGURE:4] Correlation coefficients between standard tree-ring chronologies and monthly climate variables (monthly mean minimum temperatures and monthly total precipitation) for different sites and tree species

Seasonal analysis showed that *Juglans mandshurica* growth was positively associated with seasonal minimum temperatures and precipitation, with summer minimum temperature and precipitation having highly significant effects. *Phellodendron amurense* and *Fraxinus mandshurica* showed highly significant positive correlations with annual minimum temperature ($P < 0.01$), confirming minimum temperature as their primary limiting factor. The weakening precipitation correlation from west to east for these species reflects increasing moisture availability.

Correlation coefficients between standard chronologies and seasonal climate data

3. Temporal Variation in Climate-Growth Relationships

Temperature data from 1950-2013 show significant warming since around 1980, with minimum temperature increasing at 0.03°C per year. Precipitation showed no clear trend. Before 1980, the three hardwoods showed consistent growth patterns. After 1980, *Phellodendron amurense* and *Fraxinus mandshurica* maintained stable growth trends, while *Juglans mandshurica* growth rates declined at all three sites.

[FIGURE:5] Correlation coefficients between standard chronologies and monthly climate variables (monthly mean maximum temperature, mean temperature, and monthly mean relative humidity) for three hardwoods at different sites

[FIGURE:6] Variation of annual mean minimum temperature and total precipitation in the study region from 1950 to 2013

[FIGURE:7] Changes of tree-ring index for three hardwoods with minimum temperature before and after rapid warming (1980) at different sites

Principal component analysis of chronologies from the same site and different sites confirmed these patterns. The first principal components showed that after 1980 warming, *Phellodendron amurense* and *Fraxinus mandshurica* growth increased with temperature, while *Juglans mandshurica* showed the opposite trend.

[FIGURE:8] Changes of the first components of chronologies for the same tree species and sites with annual mean minimum temperature before and after rapid warming (1980)

Discussion

1. Effects of Climate Factors and Spatial Environmental Variation on Radial Growth

The radial growth of the three hardwoods is primarily limited by temperature and precipitation. Minimum temperature is the main limiting factor for *Phellodendron amurense* and *Fraxinus mandshurica*, while *Juglans mandshurica* is co-limited by both minimum temperature and precipitation, consistent with findings from Dunhua [19]. These interspecific differences likely reflect genetic characteristics. *Fraxinus mandshurica* is shade-tolerant, prefers moist environments, and has the highest photosynthetic rate [27-28]. Temperature directly affects photosynthesis, making *Fraxinus mandshurica* most sensitive to minimum temperature. *Juglans mandshurica* has higher water consumption and wilting coefficients than the other two species [28-29] and cannot grow under drought stress [30-31], making it more water-limited.

Spatial environmental variation across the three sites also influences growth responses. Fangzheng, located in the westernmost and more humid area, shows synchronous positive responses of *Juglans mandshurica* to temperature and precipitation, promoting rapid growth. Xidaquan shows weaker correlations be-

tween *Juglans mandshurica* and both minimum temperature and precipitation, possibly because September precipitation (late growing season) hinders nutrient accumulation and lignification. Fenghuangshan, located further east, shows significant positive correlations in May-June, when higher temperatures accelerate snowmelt and soil warming, favoring early-season growth.

The weakening precipitation correlation from west to east for *Phellodendron amurense* and *Fraxinus mandshurica* reflects the semi-humid climate of the region, where high temperatures increase transpiration and soil evaporation, exacerbating water stress. When precipitation falls below a threshold, tree growth shows negative correlations, with the effect intensifying as precipitation decreases [33].

2. Impacts of Climate Warming on Tree-Ring Growth

The 1980s warming in northeast China was significant, with minimum temperatures increasing more than maximum temperatures [34-37]. While some studies show that rising minimum temperatures promote growth [38-40], others suggest inhibitory effects [7]. Our results demonstrate clear interspecific differences: before 1980, the three species showed consistent growth trends, but after 1980, *Phellodendron amurense* and *Fraxinus mandshurica* growth increased with temperature, while *Juglans mandshurica* declined.

This divergence phenomenon is widespread in mid-to-high latitudes [20-21, 41]. For *Juglans mandshurica*, which is co-limited by precipitation and minimum temperature, warming likely enhances transpiration and soil evaporation, creating drought stress that inhibits growth. The weakening divergence gradient from west to east (with increasing precipitation) supports this conclusion. In contrast, *Phellodendron amurense* and *Fraxinus mandshurica*, primarily temperature-limited, may not have exceeded their temperature thresholds, and warming may have enhanced their drought resistance without causing divergence.

Conclusion

The broadleaf-Korean pine forest in northern Zhangguangcai Mountains is a region of significant climate change. Our analysis of climate-growth relationships for *Fraxinus mandshurica*, *Phellodendron amurense*, and *Juglans mandshurica* reveals:

1. **Spatial patterns:** At Fangzheng, synchronous water-heat conditions promote *Juglans mandshurica* growth. At Xidaquan, weak positive correlations with temperature and precipitation occur. At Fenghuangshan, significant positive correlations appear in May-June. *Phellodendron amurense* and *Fraxinus mandshurica* show weakening precipitation correlations from west to east, consistent with the precipitation gradient.

2. **Temporal patterns:** After significant warming since 1980, *Phellodendron amurense* and *Fraxinus mandshurica* show stable growth trends, while *Juglans mandshurica* shows declining growth, indicating species-specific divergence.

3. **Future implications:** Continued warming may cause growth decline in *Juglans mandshurica* due to drought stress, while having minimal impact on *Phellodendron amurense* and *Fraxinus mandshurica*. The mechanisms underlying these spatio-temporal variations require further investigation through tree-ring anatomical and physiological studies.

References

[1] Serreze MC, Walsh JE, Chapin III FS, Osterkamp T, Dyurgerov M, Romanovsky V, Oechel WC, Morrison J, Zhang T, Barry RG. Observational evidence of recent change in the northern high-latitude environment. Climatic Change, 2000, 46(1/2): 159-207.

[2] Andreu L, Gutiérrez E, Macias M, Ribas M, Bosch O, Camarero JJ. Climate increases regional tree-growth variability in Iberian pine forests. Global Change Biology, 2007, 13(4): 804-815.

[3] Diego Galván J, Büntgen U, Ginzler C, Grudd H, Gutiérrez E, Labuhn I, Camarero JJ. Drought-induced weakening of growth-temperature associations in high-elevation Iberian pines. Global and Planetary Change, 2015, 124: 95-106.

[4] IPCC. Summary for policymakers of climate change 2013: the physical science basis // Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2014.

[5] Climate change and forest ecosystem vulnerability and adaptation. Journal of Natural Resources, 2001, 16(1): 71-78.

[6] Impacts of global climate change on forest ecosystems. Journal of Natural Resources, 2007, 43(11): 138-145.

[7] Clark DA, Piper SC, Keeling CD, Clark DB. Tropical rain forest tree growth and atmospheric carbon dynamics linked to interannual temperature variation during 1984-2000. Proceedings of the National Academy of Sciences of the United States of America, 2003, 100(10): 5852-5857.

[8] D' Arrigo RD, Kaufmann RK, Davi N, Jacoby GC, Laskowski C, Myneni RB, Cherubini P. Thresholds for warming-induced growth decline at elevational tree line in the Yukon Territory, Canada. Global Biogeochemical Cycles, 2004, 18(3): GB3021, doi:10.1029/2004GB002249.

[9] Mérian P, Bontemps JD, Bergès L, Lebourgeois F. Spatial variation and temporal instability in climate-growth relationships of sessile oak (*Quercus petraea* [Matt.] Liebl.) under temperate conditions. Plant Ecology, 2011, 212(11): 1855-1871.

[10] Radial growth responses of coexisting tree species to climate change in broadleaf-Korean pine forest of Changbai Mountains. Journal of Beijing Forestry University, 2013, 35(3): 24-31.

[11] Takahashi K, Okuhara I. Comparison of climatic effects on radial growth of evergreen broad-leaved trees at their northern distribution limit and co-dominating deciduous broad-leaved trees and evergreen conifers. Ecological Research, 2012, 27(1): 125-132.

[12] Tardif J, Camarero JJ, Ribas M, Gutiérrez E. Spatiotemporal variability in tree growth in the Central Pyrenees: climatic and site influences. Ecological Monographs, 2003, 73(2): 241-257.

[13] Huang JG, Tardif JC, Bergeron Y, Denneler B, Berniger F, Girardin MP. Radial growth response of four dominant boreal tree species to climate along a latitudinal gradient in the eastern Canadian boreal forest. Global Change Biology, 2010, 16(2): 711-731.

[14] Lara A, Villalba R, Wolodarsky-Franke A, Aravena JC, Luckman BH, Cuq E. Spatial and temporal variation in *Nothofagus pumilio* growth at tree line along its latitudinal range (35°40 -55°S) in the Chilean Andes. Journal of Biogeography, 2005, 32(5): 879-893.

[15] Friedrichs DA, Trouet V, Büntgen U, Frank DC, Esper J, Neuwirth B, Löffler J. Species-specific climate sensitivity of tree growth in Central-West Germany. Trees, 2009, 23(4): 729-739.

[16] Łupikasza EB, Hänsel S, Matschullat J. Regional and seasonal variability of extreme precipitation trends in southern Poland and central-eastern Germany 1951-2006. International Journal of Climatology, 2011, 31(15): 2249-2271.

[17] Reconstructing precipitation changes in Changbai Mountains over past years using tree-ring width data. Chinese Journal of Ecology, 2007, 26(12): 1924-1929.

[18] Reconstructing past autumn temperature changes in Changbai Mountains region using tree-ring width data. Chinese Journal of Ecology, 2012, 31(4): 787-793.

[19] Climate relationships of three hardwoods in Dunhua and reconstruction of growing-season minimum temperature. Journal of Nanjing Forestry University (Natural Sciences Edition), 2013, 37(3): 29-34.

[20] Zhang YX, Wilmking M. Divergent growth responses and increasing temperature limitation of Qinghai spruce growth along an elevation gradient at

the northeast Tibet Plateau. Forest Ecology and Management, 2010, 260(6): 1076-1082.

[21] Zhang YX, Wilmking M, Gou XH. Changing relationships between tree growth and climate in Northwest China. Plant Ecology, 2009, 201(1): 39-50.

[22] Yu DP, Liu JQ, Benard JL, Zhou L, Zhou WM, Fang XM, Wei YW, Jiang SW, Dai LM. Spatial variation and temporal instability in the climate-growth relationship of Korean pine in the Changbai Mountain region of Northeast China. Forest Ecology and Management, 2013, 300: 96-105.

[23] Briffa KR, Schweingruber FH, Jones PD, Osborn TJ, Shiyatov SG, Vaganov EA. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. Nature, 1998, 391(6668): 678-682.

[24] Fritts HC. Relationships of ring widths in arid-site conifers to variations in monthly temperature and precipitation. Ecological Monographs, 1974, 44(4): 411-440.

[25] Holmes RL. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bulletin, 1983, 43: 69-78.

[26] Cook E, Holmes RL. User Manual for Program ARSTAN, Laboratory of Tree-Ring Research. Tucson: University of Arizona, 1986.

[27] Comparative study on suitable site conditions for *Phellodendron amurense* and *Tilia amurensis*. Forest Resource Management, 1996, (4): 52-56.

[28] Comparative study on photosynthesis, water consumption, and wilting coefficients of *Fraxinus mandshurica* and other species. Journal of Northeast Forestry University, 2010, 35(3): 10-13.

[29] Study on stem sap flow of main tree species in eastern mountainous areas of Northeast China. Journal of Northeast Forestry University, 2005, 41(3): 36-42.

[30] Effects of slope position on growth of *Fraxinus mandshurica* and *Juglans mandshurica*. Journal of Northeast Forestry University, 2005, 33(3): 18-19.

[31] Effects of water stress on growth and biomass allocation of main tree species in broadleaf-Korean pine forest of Changbai Mountains. Chinese Journal of Ecology, 2004, 23(5): 93-97.

[32] Tree-ring climate records of *Picea schrenkiana* and *Larix sibirica* in Tianshan Mountains. Journal of Glaciology and Geocryology, 2005, 14(4): 460-465.

[33] Response of *Picea schrenkiana* tree-ring width to gradient moisture factors in Tianshan Mountains. Chinese Journal of Ecology, 2005, 24(9): 1246-1253.

[34] Analysis of temperature change characteristics in Heilongjiang Province, Northeast China and the whole country over the past 50 years. Journal of Natural Disasters, 2013, 22(2): 124-129.

[35] China' s climate warming. Chinese Science Bulletin, 2007, 52(19): 2292-2298.

[36] Response of *Quercus mongolica* radial growth to climate change in southern Northeast China: A case study in Qianshan. Chinese Journal of Applied Ecology, 2014, 25(7): 1841-1848.

[37] Spatio-temporal variation characteristics and comparative analysis of average minimum temperature in Northeast China. Journal of Applied Ecology, 2006, 26(2): 157-163.

[38] Relationship between larch ring chronologies and climate change on the north slope of Changbai Mountains. Chinese Journal of Applied Ecology, 2005, 16(1): 14-20.

[39] Different responses of radial growth to climate warming for *Pinus koraiensis* and *Picea jezoensis* at their distribution limits in Changbai Mountains. Chinese Journal of Plant Ecology, 2011, 35(5): 500-511.

[40] Effects of atmospheric warming on diameter growth of forest trees in Changbai Mountains. Chinese Journal of Applied Ecology, 1995, 6(2): 128-132.

[41] Driscoll WW, Wiles GC, D' Arrigo RD, Wilmking M. Divergent tree growth response to recent climatic warming, Lake Clark National Park and Preserve, Alaska. Geophysical Research Letters, 2005, 32(20): L20703, doi:10.1029/2005GL024258.

[42] Li Zongshan et al. Temporal stability assessment of tree growth responses to climate in Wolong National Nature Reserve, western Sichuan. Plant Ecology, 2010, 34(9): 1045-1057.

[43] Response of tree-ring width to climate warming on the southern slopes of the Altai Mountains. Journal of Glaciology and Geocryology, 2010, 30(9): 2246-2253.