Different responses of radial growth to climate warming of two dominant tree species in each upper limit of Changbai Mountain

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Abstract: We analyzed the influence of climate change to the radial growth of the two wide-distributed major tree species, *Pinus koraiensis* and *Picea jezoensis*, in their own upper limits of Changbai Mountain during the recent 50 years with the method of Dendrochronology. The radial growth of *Pinus koraiensis* shows the same trend with the rising temperature; while *Picea jezoensis* shows the opposite “disturbance problem”, which means radial growth is decreasing with the rising of temperature. The positive response of tree growth to hydrothermal condition is the key reason for the upper limit *Pinus koraiensis* chronology keeping the same pattern with temperature: the increase of temperature and precipitation in growing season is good for *Pinus koraiensis* growth, and the promoting effect of these two factors can strengthen each other. The prolongation of growing season and the rising temperature in growing season can also accelerate the growth of *Pinus koraiensis*. Water stress caused by the increasing temperature is the main reason for the opposite trend of tree ring-width chronology to temperature in the last 50 years. Correlations between *Picea jezoensis* chronology and most temperature index are almost significant negative. As the temperature rising, correlations between ring-width chronology and precipitation, especial spring precipitation, were changing from negative to positive. High temperature in each month and inadequate precipitation in the middle-and-late growing season are the important meteorology conditions for narrow rings, while low temperature in each month and the sufficient precipitation in the late growing season are good for *Picea jezoensis* growth. What’s more, the insignificant extension of growing season may also cause the reduction of temperature sensitivity in tree ring. Based on our research, we conclude that proper temperature rise is good for the upper-limit *Pinus koraiensis* growth at the condition of none less of precipitation, and the upper limit of *Pinus koraiensis* may move upward; while the growth of upper-limit *Picea jezoensis* may be restricted, and the possibility of the up shift of its upper limit is low.

Keywords tree ring, *Pinus koraiensis*, *Picea jezoensis*, climate change, upper limit

Tree ring is the record of responses of tree growth to its own and the outer circumstance[1]. Trees, distributed in high latitude or high elevation, are mainly restricted by temperature, so tree-ring records sampled in the geographical north boundary or the upper limit of high mountain are us[1]ually applied as proxy indicators to construct the history temperature[2, 3]. Lots of studies have found the temperature underestimation of model simulation based on tree ring width since mid-20th century, especially after the remarkable warming period of 1980s [4-10]. This divergence problem known as the anomalous reduction in forest growth indices and temperature sensitivity in tree-ring width and density records has been proven in Northern Hemisphere high latitudes and high altitudes[11, 12]. Because of the complication of climate change and the coupling correlation between environment factors, the reason for divergence is complicated[19]. Nevertheless, there are numbers of chronologies keeping the same trend with the warming temperature in Northern Hemisphere [13-18]. The research, which is focusing on discovering the relationship between tree ring-width chronology and temperature, and analyzing the mechanism for this phenomenon, is of importance for the future paleoclimatic reconstructions based on tree ring width, and for the comprehension of how the climate change influence the forest ecosystem.

In China, Dedrochronology research is usually conducted to reconstruct paleo-climate[20-22] and paleo-hydrology[23, 24], but there is rare mention about divergence problem[25]. Numbers of researches have been conducted to reveal how environmental factors influence tree growth, which were generally concerned on spatial aspects, such as elevation[26], longitude[27], and so on. However, there are few reports on temporal dynamic relationship between tree growth and climate factors.

Tree ring chronology research has been carried out in Changbai Mountain for a long time. There have been a number of achievements in the construction of the historical temperature[25] and precipitation[28]. As heat is one of the most determinant factors for this region’s vegetation, scientists have carried out numbers of researches about the relationship between temperature and ring width. Wang has focused onto the influence of the atmospheric warming to

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the tree ring width in the broad-leaved Korean pine forest; his research shows that temperature rising is good for the growth of this type of forest, and warming may extend the range of the broad-leaved species[29]. Yu analyzed the tree ring width chronology *Betula ermanii*[30] and *Larix olgensis*[26] in timberline area; he concluded that there was a positive correlation between the ring width and annual average minimum temperature, and moisture is one of the determinant factors for the growth of *Betula ermanii* and *Larix olgensis* in timberline area. However, there is rare report about the dynamic relationships between tree ring and meteorology factors, and few research results about the radial growth of *Pinus koraiensis* and *Picea jezoensis* in the timber-line area. As the cosmopolitan species in Changbai Mountain, the response of *Pinus koraiensis* and *Picea jezoensis* to the climate change is vital to the whole ecosystem, so the research about this two species in the upper limit has referential meaning and predictive value.

At the back ground of the climate warming, we focused our research onto the tree-ring-width variation of two maine species *Pinus koraiensis* and *Picea jezoensis* at the upper limit area, and analyzing the possible reasons for this variation. Meanwhile, as the high sensitivity to the environment change of the upper-limit trees[31], our research can provide some predictions for the future distribution of tree species under the future climate change.

1 Materials and methods

1.1 Introduction of study area

Changbai National Nature Reserve (127°55´E—128°08´E，42°04´N—42°23´N) is located in the southeast of Jilin Province, on the border line of China and North Korea. This area is influenced by the East Asian monsoon, and belongs to the temperate continental mountain climate zone. In this area, summer is short, warm and rainy, and winter is long, cold and dry. For the historical reason and the construction of the Nature Reserve, there is the rare primeval forest. The elevation of the peak is 2691m. From the bottom to the top, there are broad-leaved Korean pine forest, dark coniferous and Korean pine forest, dark coniferous forest, alpine *Betula ermanii* forest, and alpine meadow respectively. It is one of the most complete vertical vegetation zones of temperate alpine in Northeast Asia, so it is the desirable area to observe the impact of the climate change to the vegetation.

Pinus koraiensis and *Picea jezoensis* are distributed widely in the Nature Reserve, and the upper limit are 1300m and 1800m respectively. *Pinus koraiensis* is the endemic species of Changbai Mountain and Lesser Khingan Mountains. As the mesophilous tree species, *Pinus koraiensis* is the constructive species of broad-leaved Korean pine forest, spruce-fir and Korean pine forest, two of the zonal vegetation in this area. *Picea jezoensis* is the cosmopolitan species of Northeast China, mainly distributed at the middle and high elevation, especial the cool-and-wet area, and its upper limit is the timber line of the whole Changbai Mountain.

1.2 Climate data

The climate data is from Songjiang meteorological station (128°15´E，42°32´N), one of the nearest meteorological stations. This station is at the elevation of 591.4m, and the complete calendar year of meteorological observation is from 1958. We choose the temperature and precipitation of different temple scales as the main analysis data. Depending on the research results of the climate influence to the tree growth, we also selected effective accumulated temperature and length of growing season into our analysis to find out their influence to the tree ring growth.

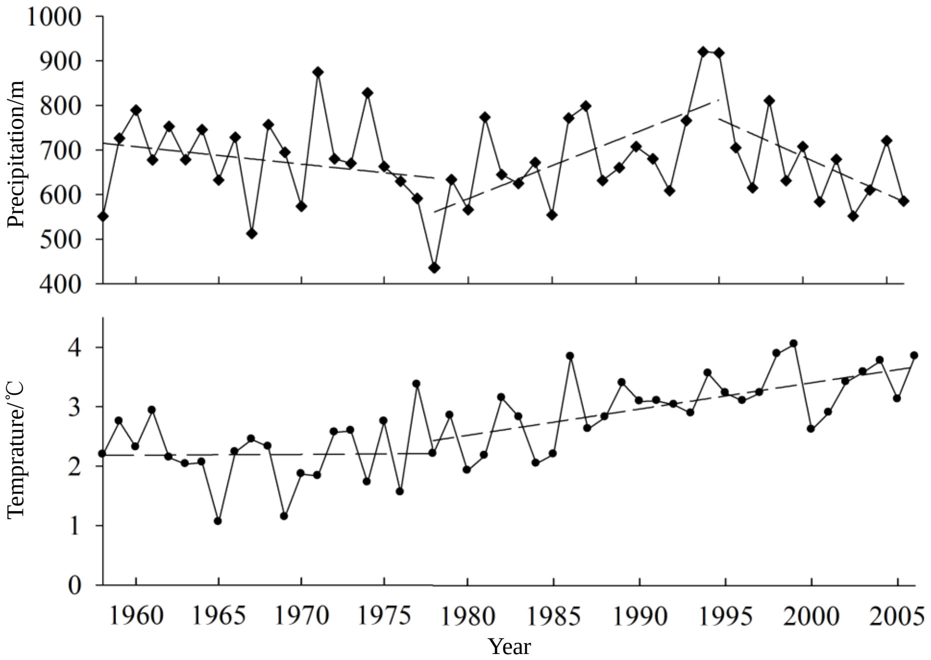

Fig. 1 Annual average temperature and total precipitation of Songjiang meteorological station in 1958-2006: Dash is piecewise fitted linear regression line of the meteorological data.

We divided the temperature into stable period and warmer period by the year of 1978. Since 1978, the annual average temperature has increased from 2.22℃ (1978) to 3.86℃(2006), and the warming speed is about 1.5℃/50a. The lowest and the highest precipitation occurred at 1978 and 1994, and these two points divide the whole range into three periods: dryer—wetter—dryer (Fig.1).

1.3 Construction of Ring-width Chronology

The sampled sites are in the upper-limits of the two species, which are both in the rare man-made interference area. The upper-limit of *Pinus koraiensis* is at the elevation of 1300m with the average slope of 30°. The main storey is mainly occupied by *Pinus koraiensis* and *Picea jezoensis*, and the canopy density is high. The upper-limit of *Picea jezoensis* is at the elevation of 1800m, which is also the timber line of Changbai Mountai. This area is steep (45°), and thinner covered by *Picea jezoensis*, mixed with *Larix olgensis*. Based on the principles of sampling and analysis methods of Dendrochronology[1], we choose these climate-sensitive trees at the steep region, where there is no significant competition with the surrounding trees. At the breast height (H=1.3m), we drilled one core from one tree. Then we finished the following procedures in turn: sticking on board, air dry, polishing, cross-dating[32], measurement, quality verification[33], at last we selected the final ring-width series to construct the chronology. Table1 shows the sample information and the basic statistical characters of the standard chronology of the two species. Both of the two chronologies meet the Dendrochronology research demand.

Table1 Statistical characters of *Pinus koraiensis* and *Picea jezoensis* chronologies in the upper-limit region

	Elevation	N.O.	Period	SSS(0.85)	MS	SD	MC	A1	S/N	EPS	V1
Pinus koraiensis	1300m	39	1805-2006	1852 -2006 (14)	0.11	0.173	0.296	0.687	12.639	0.927	34.33%
Picea jezoensis	1800m	36	1757-2006	1807-2006(13)	0.13	0.281	0.309	0.816	11.192	0.918	36.78%

N.O.-Total number of series, Period-Full chronology interval, SSS-Subsample signal strength, SSS(0.85)-Chronology interval

(SSS >0.85), MS-Mean sensitivity, SD-Standard deviation, MC-Mean correlations Among all radii, A1-First order autocorrelation, S/N-Signal-to-noise ratio, EPS-Express population signal, V1-Variance in first eigenvector.

To maximize the common signal within each chronology, only the most highly inter-correlated radii were retained. So the two chronologies include 39 *Pinus koraiensis* cores, and 36 *Picea jezoensis* ones respectively. Detrending of growth variations associated with age was accomplished using ARSTAN[34] software. Each series was detrended using a negative exponential curve and a linear regression line of negative slope. Finally, we used the bi-weight robust mean of all detrended series to get the standard chronology (fig. 2).

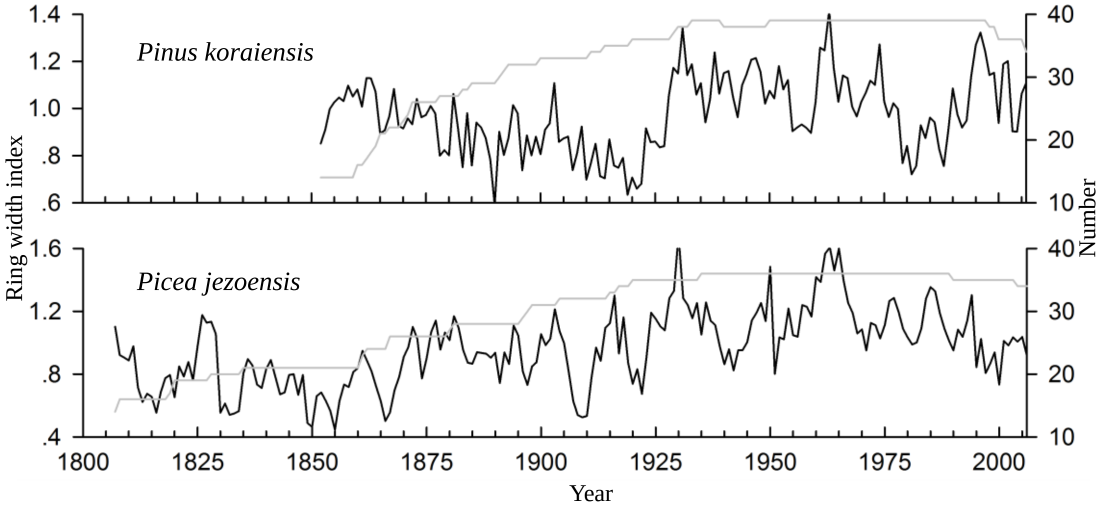

Fig.2 Tree ring-width chronologies of *Pinus koraiensis* and *Picea jezoensis* in the upper- limit region. Solid line is the chronology, and the gray line is the number of the core sampled.

1.4 Method of analyzing the influence of the climate change to the tree radial growth

The change of ring-width can show the influence of the climate change to the tree growth. At the same time, tree ring-width series can provide the lone-term and persistent data to study this influence. By contrasting the trend of the chronology and the temperature series, we found the changing pattern of the tree growth with the rise of temperature. We selected the climate factors that have significant impacts on tree growth, and analyze the correlation between the chronology and the climate data and variations of the correlation. All the analysis are conducted for revealing the mechanism of tree growth variation along with the climate change, which can predict for the tree growth in the future climate circumstances of the two main species, or even for the distribution of species in the large spatial range.

Specifically, we conducted the following analysis.

1) Comparison between the chronology and temperature variation trends: The recent half century is the most significant warming five decades, including the “divergence” period that proved in many places in the world. It is also the most complete record of the meteorological data in these 50 years. We selected 1958~2006’s ring-width chronology and annual average temperature as the analysis objects. The relationship between tree radial growth and temperature at the two species’ upper limit area is concluded by contrasting the variation trends of ring-width chronology and temperature in the last half century.

2) Relationship between ring-width chronology and interannual meteorological factors and its variation character: We conducted the correction between the chronology and interannual meteorological factors to find out the most influential meteorological factors for the tree growth in the upper-limit area. Based on the changing trend of the precipitation, we also analyzed the correction between meteorological factor and chronology in each sub period. To find out the different responses of these two species to the rising temperature and the dynamic responses of the growth to hydrothermal conditions, considering the statistic efficiency and the time span length, 20-year sliding correlation was carried out between chronology and the important annual and seasonal meteorological factors. Because the public region precipitation signal is both included in both the station data and sampling place’s real value, the precipitation of the station is used as the influential factor. The seasonal meteorological data was classified as pre-autumn (Pre Oct – Pre Dec), pre-winter (Jan ~ March), spring (Apr ~ Jun), and summer (Jul~ Sep).

3) Influence of the monthly meteorological factors to tree growth: Monthly meteorological factors are the refinement and supplement of the interannual ones. The response function analyze[1] was conducted to find out the different influence of the monthly meteorological factors to tree growth. We used Pointer Year Analysis[35, 36] to evaluate the course of the wide and narrow rings. Arrange the meteorological factors according to descending order of the corresponding ring-width. Bordering by the upper and lower quartile, the widest 12 years and the narrowest 12 years are the pointer years, and the meteorological factor of the pointer years is calculated. To make the result clearer

and more visually oriented, the standard anomaly value of temperature and precipitation was chosen. The larger the positive value is, the greater the distance above the average is, and vice versa.

4) Other heat factors that influence tree growth: Temperature is only one of the influential heat factors to the tree. Other form of heat can also have a great impact on the tree growth[37], such as the length of the growing season, effective accumulated temperature, the average temperature of the growing season, the average highest and lowest temperature, and so on. In this research, we analyzed the above heat factors to find out the relationships between them and the chronology. Considering the elevation difference between the sampling plot and the meteorological station, we got the plot temperature series based on the station temperature with the theory of the temperature reduction with the rise of elevation. 5℃ is the effective accumulated temperature calculating threshold, and the growing season is counting from the day when the continuous 5 days' average temperatures are all higher then 5℃, and ended with the day when the continuous 5 days' average temperatures are all lower then 5℃. The above heat factors are all calculated for the two species respectively.

2 Results and analysis

2.1 Variation of tree radial growth along with the rising temperature in recent 50 years

The trend comparison between chronology and temperature (Fig.3) shows the relationship between the upper-limit chronologies and annual average temperature. Cubic power function was used to smooth the high-frequency information. The chart shows that the *Pinus koraiensis* chronology has the same rising trend as the temperature series, which means that the warming signal can be presented by *Pinus koraiensis* chronology. But the *Picea jezoensis* chronology shows the opposite trend with the temperature, which is called the “divergence problem”. The *Picea jezoensis* chronology shows that the radial growth of the upper-limit *Picea jezoensis* has been going down in the last 50 years, and the decreasing trend is significant.

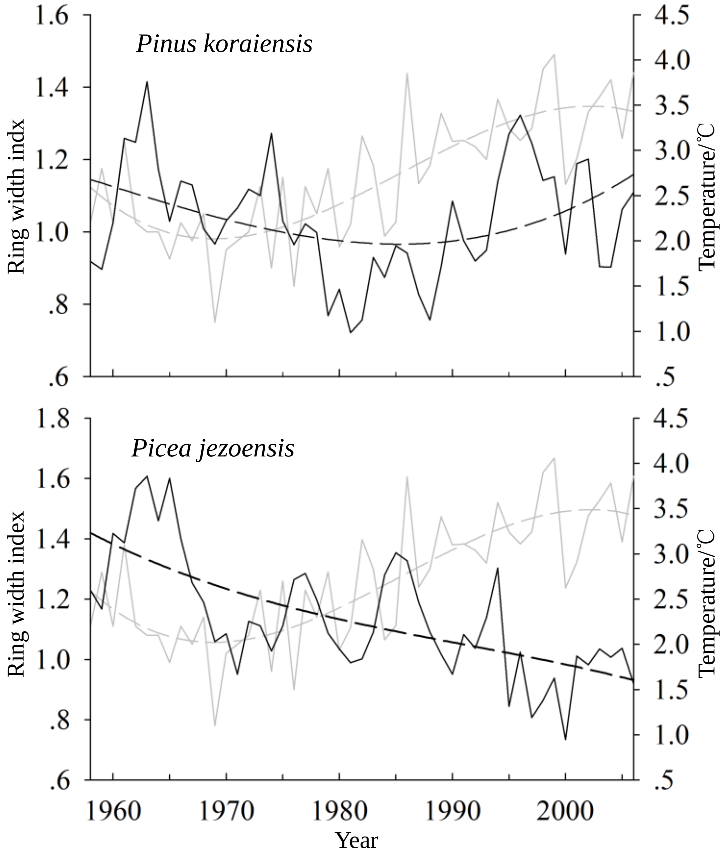

Fig.3 Consistency analyze between ring-width chronologies of two upper- limit tree species and annual average temperature in 1958~2006. Black solid line stands for the ring-width chronology, and the gray solid line for the annual average temperature. Dash line is the trend line of each chronology.

2.2 Interannual meteorological factors that influence tree growth

Biological characters of tree and different environment of the two tree species are the reasons for the different response of the two chronologies to the rising temperature in the recent 50 years. Generally speaking, low temperature in the alpine timber line and the upper-limit area is the main restrict factor for tree growth[31], but the trend analyze of the chronologies shows that the main influential meteorological factors for the two species in the upper-limit area are different.

2.2.1 Correlation between tree ring width and interannual meteorology factors

The correlation between tree ring width and interannual meteorology factors (Fig.2) shows that the summer temperature and precipitation can benefit the growth of the upper-limit *Pinus koraiensis*, and there is a significant negative correlation between *Picea jezoensis* ring width chronology and almost all temperatures.

Tab.2 Correlation between tree-ring-width chronology and interannual meteorology factors of two species in

upper-limit area in 1958~2006

	Temperature							Precipitation				
	Mean	Min	Max	Atu	Win	Spr	Sum	total	Atu	Win	Spr	Sum
Pinus koraiensis	0.05	0.07	0.14	-0.11	0.01	0.09	0.14	0.23	0.05	-0.08	-0.04	0.31*
Picea jezoensis	-0.42**	-0.18	-0.26	-0.22	-0.39**	-0.33*	-0.34*	-0.02	0.03	-0.07	-0.19	0.12

* Correlation is significant at the 0.05 level (2-tailed)，** Correlation is significant at the 0.01 level (2-tailed). The correlation objects are the ring-width chronology and the average temperature and total precipitation of each interval. Season classification is based on pre-autumn: pre Oct ~ pre Dec, pre-winter: Jan ~ Mar, spring: Apr ~ Jun, and summer: Jul ~ Sep.

The chronology of upper-limit *Pinus koraiensis* shows weak positive correlations with all seasonal temperature, especially for the positive correlations with summer average temperature. There is a significant positive correlation between *Pinus koraiensis* chronology and summer or yearly precipitation, and the positive correlation between chronology and summer precipitation has passed the significant level (α =0.05). The positive response of upper-limit *Pinus koraiensis* to the hydrothermal conditions agree with the normal rule of the upper-limit and north-limit trees[31], which means the hydrothermal conditions improving equals to the moving downward or south direction of the vegetation belt in the northern hemisphere, and the change are all good for the tree growth.

Picea jezoensis chronology of upper-limit shows a different correlation result from *Pinus koraiensis*. The correlations between *Picea jezoensis* chronology and interannual temperatures are all significant negative, and the correlations between chronology and yearly or winter average temperatures have both passed the extreme significant level (α =0.01), and the correlations between chronology and spring or summer average temperature have passed the significant level (α =0.05). The correlations between *Picea jezoensis* chronology and precipitation series are all not significant. *Picea jezoensis* mainly showed the negative response to the spring precipitation and positive response to the summer precipitation. There is a remarkable moisture signal in the upper-limit *Picea jezoensis*’s ring-width chronology in accordance with the former research about the upper-limit *Betula ermanii*[30] and *Larix olgensis*[26] chronologies. That may caused by the thin soil in the alpine area, and the low water storage capacity of the soil condition in Chanbai Mountain. As the rise of temperature, moisture gradually becomes the restrictive factor, which also shows the negative effect of warming.

Tab.3 Interval correlation between the upper-limit chronologies of two tree species and meteorological data

	Temperature		Precipitation		
	1958~1977	1978~2006	1958~1977	1978~1993	1994~2006
	Stable	Warmer	Drier	Wetter	Drier
Pinus koraiensis	0.090	0.446*	0.238	-0.180	0.343
Picea jezoensis	0.118	-0.281	-0.119	-0.073	0.182

* Correlation is significant at the 0.05 level (2-tailed)

The interval correlation analysis (Tab.3) further proved the moisture threaten for the upper-limit *Picea jezoensis* caused by the rising temperature, and also showed the positive response of the upper-limit *Pinus koraiensis* to the hydrothermal conditions. For the *Pinus koraiensis*, during the period of lack of moisture (before 1978, and after 1994), the increase of the precipitation can benefit the growth of tree; and when the restriction of the moisture is lessen (after 1978), proper temperature rise is good for tree growth. For the *Picea jezoensis*, the temperature increase showed a negative effect. As the rising of the temperature, the effect of heat to the upper-limit *Picea jezoensis* was changing from positive to negative. At the same time, the rise of temperature can accelerate the evaporation from the soil and plants, which may worsen the moisture stress, so the effect of precipitation to tree growth was changing from negative to positive.

2.2.2 Dynamic relationship between ring width and important interannual meteorological factors

Climate change is a consistence process, so the effect to the tree growth is a long-term and dynamic process. Climate change may cause the reduction of tree-growth sensitivity to some climate factors, or even to the opposite side. The ring-width chronology and the continuous meteorological monitoring data provide the condition for the research about how the climate change influences tree growth.

Correlation between chronology and meteorological data has revealed the differences between the responses of the two species to the climate change. It is an important discover for the significant positive correlation between *Pinus koraiensis* chronology and summer precipitation, and the significant negative response of *Picea jezoensis* chronology to the temperature and spring precipitation series. The response function analysis (Fig.5) for the chronology and monthly meteorological data showed the positive response of *Pinus koraiensis* to summer (growing season) hydrothermal condition and the high sensitivity of *Picea jezoensis* to the spring climate factors. So we concluded that the summer climate condition was vital for *Pinus koraiensis*, and the spring climate was important for *Picea jezoensis* in their own upper-limit areas.

Fig.4 is the dynamic of correlation between tree radial growth and annual average temperature and precipitation. The sliding correlation presented the two species' different response to the rise of temperature well. The effect of temperature to *Pinus koraiensis* growth gradually became positive, but that to *Picea jezoensis* was changing from benefiting to limiting. At the changing progress of temperature effect, moisture, which may be caused fluctuating by precipitation and the evaporation of the rising temperature, has played an important role.

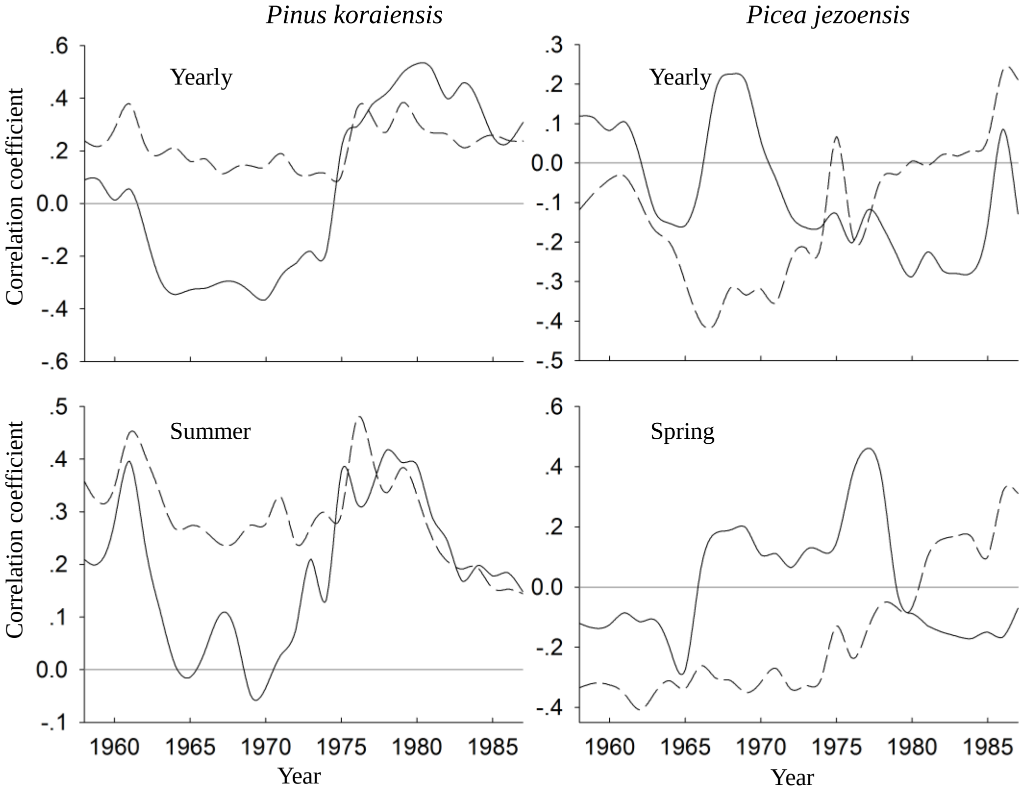

Fig.4 20-year sliding correlation between ring-width chronology of two species and meteorological data Solid line presents the changing of temperature correlation, and the dash line is for that of precipitation.

The positive effects of heat and moisture to *Pinus koraiensis* can promote each other. The benefit of precipitation increase to tree growth also enlarged the positive effect of warming, and when one effect went down, the other’s effect also decreased. The above result is significant in the summer sliding correlation: there is a significant correlation between *Pinus koraiensis* growth and summer precipitation, while the impact of temperature is changing as the change of precipitation. The sliding correlation curve shows a high-low-high trend, which is accordance with the precipitation change (drier-wetter-drier) of Changbai Mountain in recent 50 years. So we think the *Pinus koraiensis* grows better in the better hydrothermal conditions, and we predict that climate warming is good for the upper-limit *Pinus koraiensis* growth and spread in the condition of enough moisture.

The upper limit of *Picea jezoensis* is higher than that of *Pinus koraiensis*. The main result of sliding correlation is that the moisture restriction was getting bigger as the temperature rose. The moisture status for tree growth has been changing from efficient to deficient, which is the main reason for the divergence of *Picea jezoensis* chronology from the rising temperature. As the temperature rises, the evaporation of soil and plant moisture is accelerated. The former water condition, which was sufficient for tree growth, may change into a limiting factor. This phenomenon is obvious in the dry spring. So the correlation between chronology and spring precipitation was rising with the temperature increased. Meanwhile, the curve of *Picea jezoensis* with temperature has the opposite trend with that of *Pinus koraiensis*, that is low-high-low. This is also caused by the precipitation fluctuation. During the moisture sufficient period, warming is good for tree growth, but when moisture is the restrictive factors, the increase of temperature can worsen the water stress, which leads to the significant negative correlation between tree growth and temperature.

In summary, the moisture condition can satisfy the upper-limit *Pinus koraiensis* growth, and the positive effect of rising temperature is influenced by the moisture condition. The effects of heat and moisture to *Pinus koraiensis* growth have the consistency, and its chronology showed the trend of warming. The moisture of upper-limit yulin changed from sufficient to deficient. The rise of temperature induced the increase of the effect of moisture to tree growth. High temperature can aggravate the drought, which lead to the divergence between chronology and temperature.

2.3 Monthly meteorological factors that influence tree growth

2.3.1 Response function analysis between ring width and monthly meteorological factors

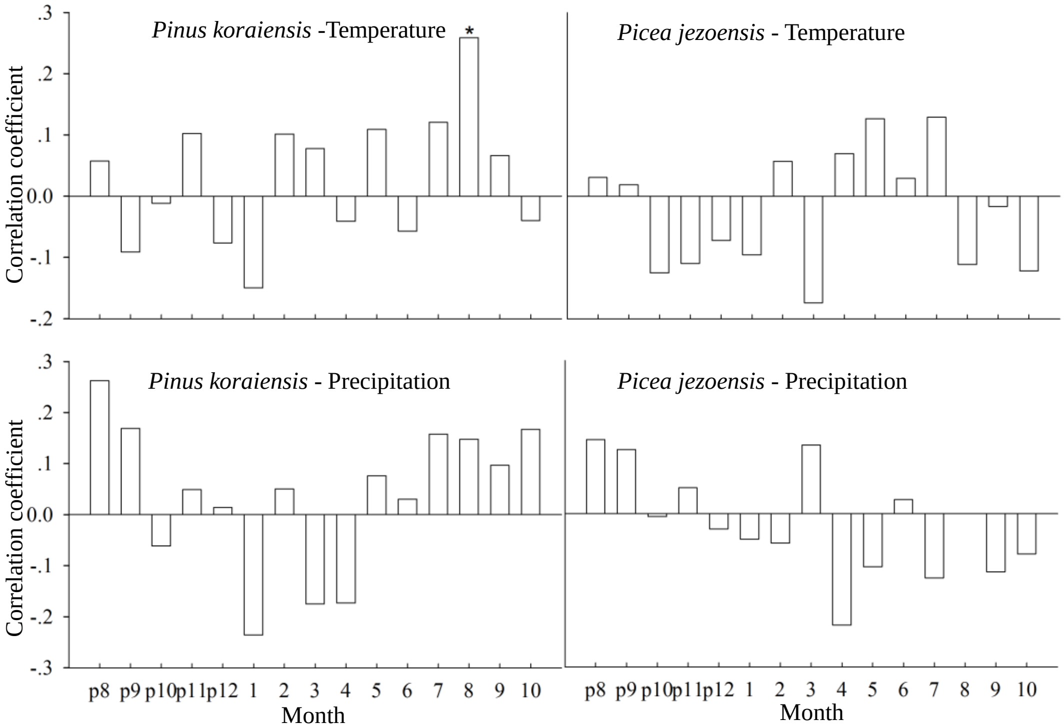

Fig.5 Response function analysis between ring-width chronology and monthly meteorological data. * Correlation is significant at the 0.05 level (2-tailed). p stands for the previous year. For instance, p8 means previous August.

Pinus koraiensis ring width has a remarkable positive response to the temperature and precipitation of the growing season, especially the significant positive correlation with August temperature. The response function results agree with the interannual data correlation results, that is to say, the improvement of hydrothermal condition is good for *Pinus koraiensis* growth. There is a significant positive correlation between *Pinus koraiensis* chronology and previous August-and-September's precipitation, which shows the hysteretic effect of precipitation. The sufficient moisture condition in the growing season is not only good for this year's growth; the accumulated nutrition can also benefit the next year's growth.

The upper-limit of *Picea jezoensis* is almost the timberline of Changbai Mountain. Low temperature is the main characteristic of this region's climate. The sooner the tree gets into growing season, the longer the growing season will lasts, which means it would benefit tree growth. Response function analysis proved the above deduction. The result shows that the temperature of early period of growing season (April ~ July) has an important impact on *Picea jezoensis* growth. The negative correlation between chronology and precipitation further proved the low temperature caused by the precipitation is not good for tree growth.

2.3.2 Meteorological reasons for wide or narrow rings

Tree ring has recorded rich climate information, especially for the narrowest and the widest rings. We extracted the climate signals from the narrowest and the widest rings (Fig.6) to further analyze how the climate change influence tree growth, and to provide the prediction basis for the future tree growth and vegetation distribution.

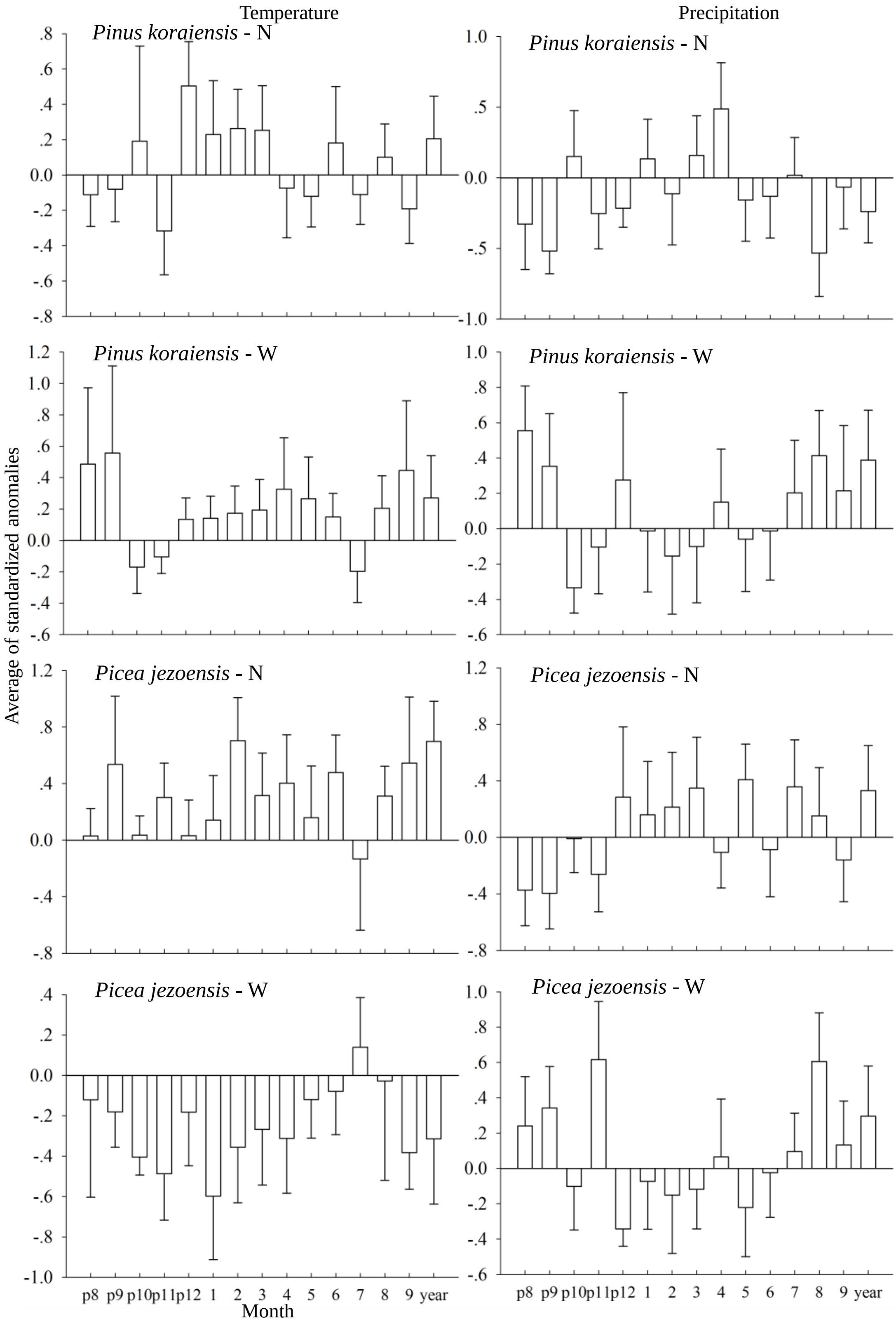

Fig.6 Pointer year analysis for the pointer years' climate information The object of pointer year is the average of standardized anomalies of the pointer years. N stands for the years of narrowest 12 rings, and W is the years of widest 12 rings. In the x-coordinate, number is the month, and year is the annual average temperature or the annual precipitation. The y-coordinate is the average of standardized anomalies. Err bar is the standard error for the pointer years' anomalies.

The climate condition in the growing season is the main factor affecting *Pinus koraiensis* ring width. The sufficient heat during the before-growing (April and May) and the late period of growing season (August and September) and plentiful precipitation during growing season can benefit *Pinus koraiensis* growth, which are the main climate reason for the widest ring. The climate condition for the narrowest rings is the low temperature and drought in the growing season. The temperature and precipitation in April, which happens before the growing season, is also important for tree growth. April is the dormancy breaking time for *Pinus koraiensis*. During this period, the proper high temperature can promote plants into growing season, but over precipitation may cause the drop in temperature, which may shorten the growing season of the year. So the low temperature and over precipitation is one of the reasons for the narrowest rings, and the opposite climate condition is good for the wide rings. What's more, sufficient hydrothermal condition of the former year is not only good for the former year's tree growth; it can also benefit the next year's tree growth for the accumulated nutrients last year, which is also a reason for wide rings. And if the last year's hydrothermal condition is inadequate, the next ring may be narrow.

For the upper-limit *Picea jezoensis*, the conditions for narrow and wide rings are almost totally opposite. High temperature can form narrow rings, and low temperature is for the wide rings. The negative correlation between tree growth and temperature is significant, which is accordance with the interannual analysis. Sufficient precipitation in the growing season and the last year's growing season is an important condition for the wide rings, and if the moisture is not enough, the narrow rings may appear. This result proved our former guess that the water stress caused by warming leads the reduction of growth. What's more, high precipitation in the winter time, which is corresponding with low temperature, can usually form the next year's narrow ring. That shows the restriction of low temperature in the alpine area.

2.4 Other heat index influence tree growth

Lots of research shows that pure temperature can not represent the whole heat system for tree growth. Growing season length, effective accumulated temperature, average temperature, and average maximum and minimum temperature are all main factors for the upper-limit tree growth[37]. The minimum temperature in winter is also a vital restriction for the upper-limit tree growth.

2.4.1 Effect of length of growing season and effective accumulated temperature to tree growth

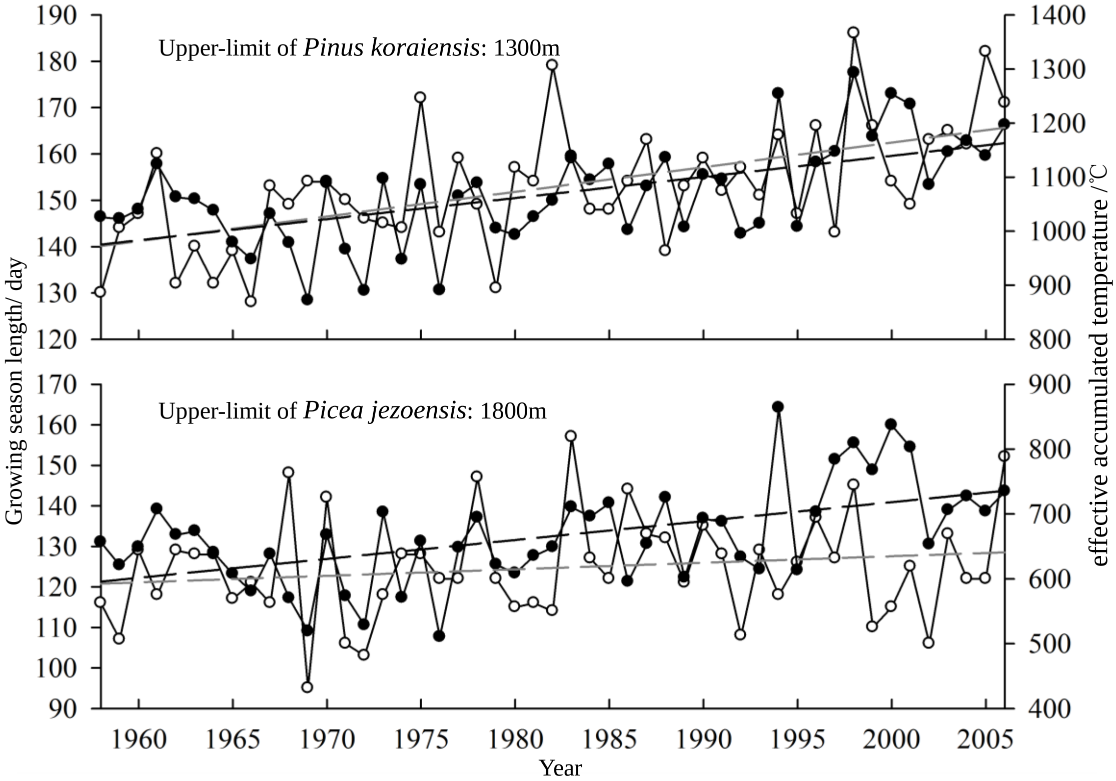

Fig.7 Variation of effective accumulated temperature and growing season length in the upper-limit of two tree species in 1958~2006　Solid dot and line is the accumulated temperature, and hollow dot and line is the growing season length. Black dash is the linear fit for the accumulated temperature, and the gray one is the fit for growing season.

The distinct thermal difference between the upper-limits of the two species is the variation trend of growing season length (Fig.7).　Growing season length of upper-limit *Pinus koraiensis* has increased a lot, while that of *Picea jezoensis* didn’t change much.　The accumulated temperature (>5℃) of two upper-limit rose a lot.　Generally speaking, the prolongation of growing season is good for tree growth, which is the situation of *Pinus koraiensis*.　Under the condition of none significant change in growing season, the rise of accumulated temperature could accelerate both the photosynthesis and the respiration at the same time.　Stronger evaporation of plant and soil moisture could worsen water stress, which may lead the reduction of growth.　So growing season length didn’t extend with the rise of accumulated temperature may be one of the reasons for the reduction of *Picea jezoensis* growth.

2.4.2 Effect of extreme temperature variation to tree growth

Extreme temperature is usually the restriction for tree growth and distribution of alpine area.　The Dendrochronology research about *Larix olgensis*[26] and *Betula ermanii*[30] in the timberline area both mentioned the significant positive correlation between ring-width chronology and annual average minimum temperature or monthly average minimum temperature. But in our research, we found that the ring-width of upper-limit *Picea jezoensis* negatively response to almost all temperature index. The positive correlation was found in the upper limit *Pinus koraiensis* between chronology and temperature in growing season.

We analyze the average maximum and minimum temperature of the growing season (June ~ September) and the average minimum temperature of the coldest months (December ~ February). Result shows that there is a significant rising trend in the minimum temperature of growing season and coldest months, especially in the growing season. But the rising trend of average maximum temperature in growing season is not significant, which means the last 50 years' warming is mainly caused by the night warming. Wang put the night warming as the explanation of the growth increase in the low-elevation broad-leaved Korean pine forest[29].We also found the positive correlation (0.13) between chronology of upper-limit *Pinus koraiensis* and minimum temperature in growing season. But for *Picea jezoensis*, the correlation between chronology and night temperature is significant positive (-0.41). The effect of climate warming or night warming to tree growth is complicated: there is the promotion situation mentioned above, and also the reduction of forest NPP. The NPP reduction caused by the rising temperature and the high-temperature-induced drought has happened in the tropical rain forest[38] and European forest[39]. Based on the strong moisture signal contained in the *Picea jezoensis* chronology, the high-temperature-induced drought may be the main reason for the reduction of *Picea jezoensis* growth.

3 Conclusion and discussion

The responses of the two species' radial growth to the recent half decades' climate warming are different. There is a rising trend in the upper-limit *Pinus koraiensis* chronology as the increase of temperature, and the reduction, known as divergence, happened in the upper-limit *Picea jezoensis*.

The increase of temperature and precipitation is good for tree growth in the upper-limit *Pinus koraiensis*. The promotion of the rising temperature and precipitation in the growing season to tree growth is huge in upper-limit *Pinus koraiensis* area, and the effects of heat and moisture mutually empowered each other. That means the benefit of warming is reinforced by the increase of precipitation, and lessened by the decrease of precipitation. Sufficient hydrothermal condition before growing season and the middle-and-late period of growing season is important for the forming of wide rings, while low temperature and drought in the growing season may cause narrow ring. The increase of growing season length and the improvement of low temperature are the important reasons for the rise of upper-limit *Pinus koraiensis* growth.

The correlations between tree growth and all temperatures are almost negative for upper-limit *Picea jezoensis*. The growth of upper-limit *Picea jezoensis* decreased as the rise of temperature. Effect of temperature rising to tree growth gradually changed into restriction. At the same time, the positive correlation between ring width and moisture condition, especially in growing season, has risen. The sensitivity reduction to temperature of chronology in the cold area has been found in North America[40-42], Europe[43], and Siberia[44]. There is also the discover about the reversal effect of temperature and precipitation to tree growth[45]. That is to say, the moisture signal has been strengthened in the upper-limit *Picea jezoensis* chronology by the rising temperature, which is accordance with the research result of *Larix olgensis*[26] and *Betula ermanii*[30] in the timberline area. Lower-than-average temperature and sufficient precipitation in the growing season are the vital conditions for wide rings for the upper-limit *Picea jezoensis*, and high temperature and little precipitation in the growing season may bring narrow rings. Though the average annual temperature and accumulated temperature are all rising, the growing season length in the upper-limit of *Picea jezoensis* didn’t change a lot. That may be one reason for the reduction of tree growth.

Based on the above research results, we conclude that proper temperature rise is good for the upper-limit *Pinus koraiensis* growth at the condition of none less of precipitation, and the upper limit of *Pinus koraiensis* may move upward. This is accordance with the model predictions of Hao[46], Leng[47], and Zhu[48]. In the upper limit of *Picea jezoensis*, temperature rise cause the restriction of moisture enlarged. Climate warming is not good for *Picea jezoensis* growth in the upper-limit area. The possibility of upward moving of *Picea jezoensis* is low. This result has been mentioned by the model prediction[47].

The divergence mechanism has been studied in international, such as moisture restriction induced by temperature rise[40, 41], atmospheric pollution[49], tail effect of detrend at the process of constructing chronology[50], and different responses of tree growth to the minimum and maximum temperature[10]. We adopted the meteorological station record to analyze the influence of climate warming to the two tree species in their own upper limit, and made some initial progress. There is lots of potential in the physiological mechanism research about how tree growth response to the environment change.

The mechanism of how environmental factors, such as temperature and precipitation, influence tree growth is the basis of Dendrochronology, and is also one of the important ways to discover the impact of climate change to community or even ecosystem. Tree rings can provide long-term and consistent data to study the influence of climate change to tree growth, which is very important in revealing the response of tree to variations of environmental factors, and a necessary supplement for the general plot survey. Ecotone has the amplification effect and prediction value for the influence of environmental change. Study in ecotone can provide basis for predicting the future change of ecosystem under the future climate change circumstances. So Dendrochronology, conducted in sensitive areas, is not only an independent way of studying and predicting the effect of environmental change to ecosystem, but also an efficient supplement for long-term monitoring, remote sensing, model simulation and so on.

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