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ORIGINAL ARTICLE

Increased sensitivity of Dahurian larch radial growth to summer temperature with the rapid warming in Northeast China

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Abstract

Key message Temperature increase would benefit tree radial growth in the high latitude permafrost zone due to the increment of the thaw depth of permafrost.

Abstract Tree rings from temperature-limited regions are highly sensitive to temperature variations. Seven Dahurian larch (*Larix gmelinii* Rupr.) tree-ring width chronologies sampled at the permafrost zone in western Great Xing'an Mountain, Northeast China, were developed to investigate regional larch growth. A regional larch growth record was produced using the first principal component (PC1) of a principal components analysis. PC1 accounted for 65.6 % of the total variance. Regional larch growth was mainly limited by summer temperatures in this region. The temporal variations in the linear trend of average summer temperature were calculated at 30-year intervals. A significant increase trend ($P < 0.05$) was found in average summer temperature after the 1971–2000 period, indicating that temperature started to increase rapidly after the 1971–2000 period; there was no obvious trend before that period. Moreover, the relationship between tree radial growth and temperature intensified since the 1969–1998 period. Thaw depth also started to show significant

influences on the tree radial growth after the 1969–1998 period where rapid warming accelerated the thaw of permafrost and benefited tree radial growth. Tree radial growth was more sensitive to temperature after the rapid warming because of changes in the moisture availability caused by the permafrost thaw. From these results, it appears that an increase in temperature would benefit tree radial growth in the high latitude permafrost zone by increasing the thaw depth of permafrost.

Keywords Tree ring · Temperature increase · Northeast China · Rapid warming · Tree radial growth · *Larix gmelinii* Rupr.

Introduction

Tree radial growth is influenced by conditions within the tree (e.g., genetic factors) and environmental factors (e.g., precipitation, temperature and competition) (Fritts 1976; Cook and Kairiukstis 1990; Zhang and Chen 2015). Among these, climate has been frequently found to be among the most important factors affecting annual tree growth as the result of high annual and multi-annual variation. Climate variation affects a tree's physiological processes, which in turn influence its radial growth (Fritts 1976). The impact of climate change on tree radial growth can be evaluated by analyzing the relationship between climate factors and tree ring chronology in which most of the non-climatic influences on growth are considered to have been removed.

Global temperatures have shown a clear increasing trend since the beginning of the twentieth century (Stocker et al. 2014). While warming accelerates tree growth (Salzer et al. 2009; McMahon et al. 2010), it also causes regional forest

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die-off by exacerbating drought (Breshears et al. 2005; Allen et al. 2010). In high latitude and altitude regions, tree radial growth is primarily positively correlated with temperature (e.g., D'Arrigo et al. 2006; Frank et al. 2007; Youngblut and Luckman 2008; Koprowski 2012). Hence, temperature increases are expected to be beneficial to tree radial growth near a tree's distribution limits (Cullen et al. 2001; Andreu et al. 2007).

A change in the relationships between temperature and tree-ring width indices had been found in high latitude and tree-line areas. A reduction in the sensitivity between tree-ring indices and temperature had detected in tree-ring width records from northern latitude sites since the 1960s (e.g. Jacoby and D'Arrigo 1995; Coppola et al. 2012; Franceschini et al. 2013; Lebourgeois et al. 2012). In these cases, tree-ring indices tracked the rising temperature up to a certain point and then began decreasing as temperatures continued rising. In contrast, an increase in sensitivity to temperature has been found in some tree-ring records (Cullen et al. 2001; Andreu et al. 2007). Thus, opposing effects of rising temperatures have been detected, decreases in growth (Wilson et al. 2007) as well as increases in growth (Andreu et al. 2007).

Dahurian larch (*Larix gmelinii* Rupr.) mainly grows in the high latitudes of northeast China, where it forms the largest natural coniferous forest of China. Radial growth of Dahurian larch in permafrost regions have a positive relation to summer temperature (Zhang et al. 2011; Chen et al. 2013), while those from non-permafrost regions showed negative correlation with summer temperature (Zhang et al. 2010). The increasing trend of summer temperature in northeast China is most significant in China (Qian and Qing 2006). Drawing from those trends, an important question is, "How does tree growth react to the temperature increases in the high latitude permafrost region of northeast China?" Investigating the relation between tree growth and temperature over time can address this question. It is not yet clear whether accelerated warming in this region would increase or decrease the radial growth of the regional dominant trees. Results from this investigation would give insight as to how the structure and function of conifer forest ecosystems might vary in this region in response to accelerated global change.

In this study, we use a network of Dahurian larch-ring width chronologies from the permafrost region of northeast China to investigate the impacts of rapid warming on tree growth. Accordingly, we (1) determined the relationship between radial growth and climate, and (2) investigated the relationship between radial growth and temperature in correspondence with rapid warming.

## Materials and methods

Study area and sampling sites

The study area is located at western Great Xing'an Mountain in northeast China (Fig. 1). Annual mean temperature is approximately −5 °C, and total annual precipitation is approximately 450 mm. Mean January temperature, the coldest month of the year, is approximately −25 to −28 °C, while mean July temperature, the warmest month of the year, is approximately 16–19 °C. Dahurian larch is the dominant species in a region characterized as being a coniferous forest.

Cores were collected from seven sites located from old-growth Dahurian larch forest in four regions: Mo'erdaoga, Genhe, Jinhe and Hanma (Table 1). Sites were far from residential areas and there was no fire notable history in these regions. Permafrost is widely distributed in these regions (Jin et al. 2000) and all of our sites were located on permafrost settings where deep soil is frozen continually through the year. Water at these sites mainly comes from the thaw of permafrost in summer. Older trees were a priori sampled to minimize the age effect on tree ring growth (Carrer and Urbinati 2004). Two or three samples were cored from each tree at breast height using an increment borer.

Tree-ring width chronology development

After drying and stabilizing all samples, cores were sanded until the rings were clearly visible when using a microscope. All samples were visually cross-dated to avoid missing or false rings and ring widths were measured to the nearest 0.001 mm by the LINTAB 5 measuring system. Time-series of ring widths were checked and verified by through a cross-dating program, COFECHA (Holmes 1983).

The RCSigFree program (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software) was used to develop the chronologies for every site to alleviate the "trend distortion" problem (Melvin and Briffa 2008). In the RCSigFree program, raw series of ring widths were firstly detrended to produce an initial chronology. Then, the signal-free measurements were indexed by dividing the raw ring measurement by the initial chronology indices. Next, the initial chronology was updated by dividing the raw measurements by the fitted curves derived from signal-free measurements. The above steps are iterated until the signal-free indices showed limited differences. Trend distortion could be seemed to be absent in the signal-free chronologies.
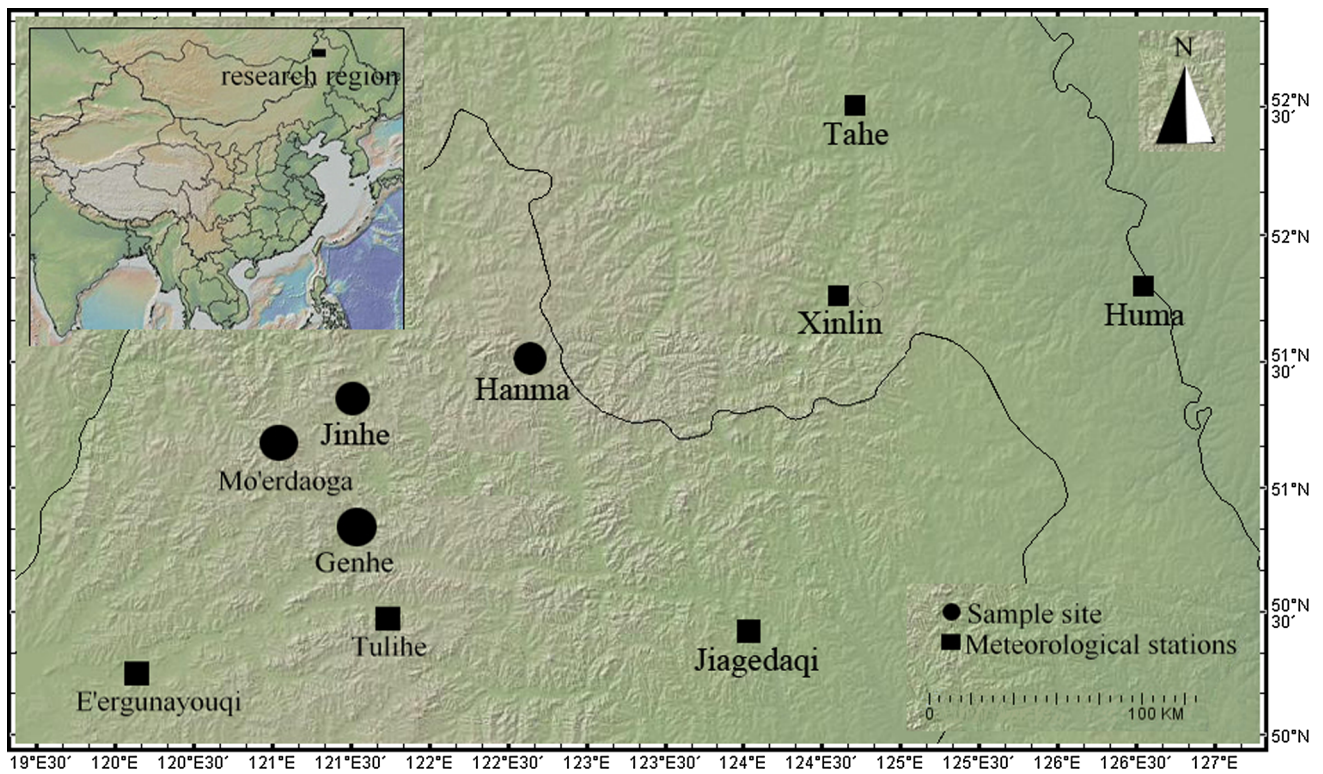
Fig. 1 Locations of the sample sites and climate stations at Great Xing'an Mountain in northeast China

Table 1 Description of tree-ring collections used in this study

Site ID	Latitude	Longitude	Time span	No. trees	No. radii
Hanma1	51°27′N	122°34′E	1827–2013	37	65
Hanma2	51°26′N	122°33′E	1786–2013	9	16
Jinhe1	51°28′N	121°35′E	1825–2013	30	67
Jinhe2	51°22′N	121°18′E	1827–2013	39	74
Mo'erdaoga	51°15′N	120°46′E	1715–2008	21	42
Genhe1	50°50″N	121°30E	1840–2008	26	45
Genhe2	50°52′N	121°35′E	1697–2008	31	62

Table 2 Statistics of the Signal-free chronologies used in this study

	Length (year)	SD	MS	AC1	Skew	Kurtosis	EPS (>0.85)
Hanma1	187 (1827–2013)	0.328	0.194	0.679	1.09	2.29	0.857 (1868)
Hanma2	228 (1786–2013)	0.248	0.179	0.53	0.961	6.897	0.861 (1922)
Jinhe1	289 (1725–2013)	0.27	0.23	0.506	0.60	0.93	0.863 (1760)
Jinhe2	287 (1727–2013)	0.197	0.161	0.507	0.030	3.060	0.873 (1740)
Mo'erdaoga	294 (1715–2008)	0.203	0.150	0.604	0.154	2.815	0.886 (1755)
Genhe1	169 (1840–2008)	0.211	0.183	0.364	0.241	3.256	0.854 (1856)
Genhe2	312 (1697–2008)	0.210	0.162	0.563	0.233	3.017	0.850 (1766)

SD standard deviation, *MS* mean sensitivity, *AC1* first-order autocorrelation, *EPS* expressed population signal

Tree-ring data

Signal-free chronology statistics are listed in Table 2. Mean sensitivity (MS) is a measure indicating the difference between adjacent rings to reflect annual tree growth variability. First-order autocorrelation (AC1) is used to evaluate the influences of the previous year on the growth year. The expressed population signal statistic (EPS, Wigley et al. 1984) is criterion that can be used to evaluate the reliability of a chronology.

A principal component analysis (PCA) based on the covariance matrix was calculated for the signal-free chronologies for the 1957–2008 period common to the meteorological record (below). The first principal component (PC1) of the seven chronologies explained 65.6 % of the total variance (Fig. 2).

Meteorological data and regional climate definition

Monthly mean temperature, total precipitation and relative humidity data were obtained from the Chinese Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/) for the longest and most continuous climate records from six nearby stations (Table 3). Records from these stations were selected to model the regional climate signals in the tree rings from 1957 to 2008. Averaging meteorological records from different stations decreases small-scale noise or stochastic components and improves statistical relationships between tree rings and meteorological data (Blasing et al. 1981; Pederson et al. 2001). Thus, regional mean meteorological data were produced by averaging the monthly records of the six nearby stations over their common interval from 1957 to 2008.

Palmer Drought Severity Index (PDSI) is a soil moisture index based on temperature and precipitation (Dai et al. 2004). Regional PDSI (50°–52°N, 120°–126°E) from 1901 to 2014 was downloaded from KNMI Climate Explorer (http://www.knmi.nl). Thaw depth, which indicates the soil water condition in the permafrost zone, and thaw depth (Zhang et al. 2006) was retrieved from the website http://nsidc.org/data/docs/fgdc/ggd651_frzthw_depth_efact/ for the 50°–52°N, 120°–126°E region.

Growth–climate relationship

The relationship between climate variables (monthly mean temperature, monthly total precipitation and PDSI) and the PC1 of seven signal-free chronologies was detected by performing correlation analyses to quantify the climate–growth relationship from the previous May to the current September.

Mean state of climate is generally regarded as 30-year averages of meteorological conditions such as temperature and rainfall (WMO 1989). The 30-year period is

Table 3 Information of climate stations near the sample sites of this study

Station	Latitude	Longitude	Elevation (m)	Time span
Tulihe	50.48	121.68	732.6	1957–2013
E'ergunayouqi	50.25	120.18	581.4	1957–2013
Tahe	52.35	124.72	361.9	1972–2013
Xinlin	51.70	124.33	494.6	1972–2013
Huma	51.72	126.65	177.4	1957–2013
Jiagedaqi	50.40	124.12	371.7	1967–2013

Fig. 2 Seven signal-free chronologies and their first principal component (PC1) from 1957 to 2008
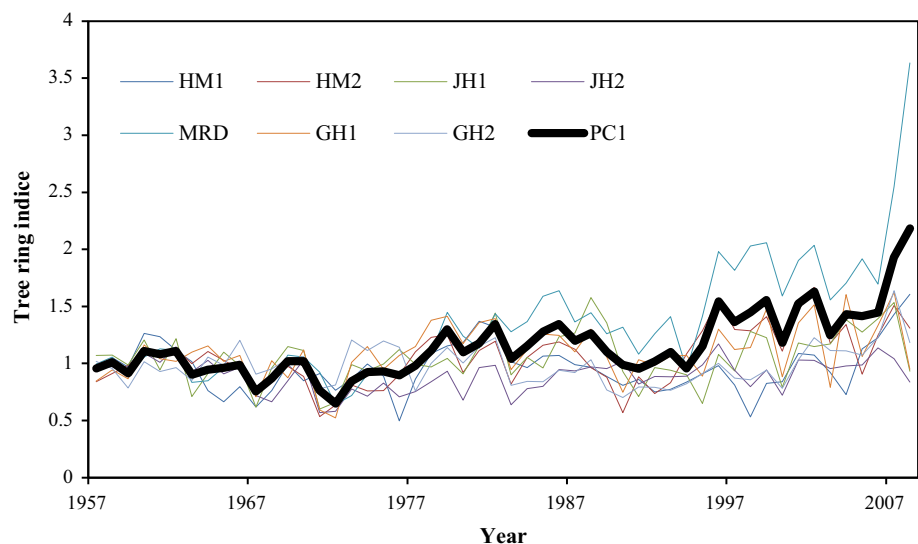
sufficiently long to figure out the trend of climate change. Thus, linear trends were fitted to the 30-year time series of JJA temperature by increasing the initial and finial years by one for each iteration beginning with 1957–1986 and ending 1979–2008. The coefficients of determination (R^2) were calculated for the linear trend to detect whether the increasing trend was significant or not. The variation of bootstrapped correlation coefficients between climate factors and the PC1 was assessed using evolutionary and moving interval response analysis, through the software program Dendroclim2002, to detect the changes in tree growth–climate relationship throughout the study period. A base length of 30 years was chosen as a fixed interval, changing the initial and final years of the analysis series (Biondi 1997; Biondi and Waikul 2004). Whether or not the temporal shifts in climate–growth interactions related to the effect of stochastic processes was verified by Gershunov test (Gershunov et al. 2001).

Results

Climate–growth relationships

Correlation analysis between the PC1 and climate variables showed that temperature had positive effects on radial growth (Fig. 3), particularly for February, April ($p < 0.05$), and June to August ($p < 0.01$). The precipitation and PDSI showed insignificant correlation with PC1. Seasonally averaged climatic variables can be more representative of climatic conditions than single months and have greater influences on tree growth (Cook et al. 1999). Thus, different combinations of seasonal months were tested. February–April mean temperature was correlated significantly with the PC1 ($r = 0.37$, $p < 0.01$), while the best relationship was found between the PC1 and June–July–

August (JJA) mean temperature ($r = 0.61$, $p < 0.01$). Consequently, JJA temperature was the strongest factor influencing the variation of the radial growth trend in this region.
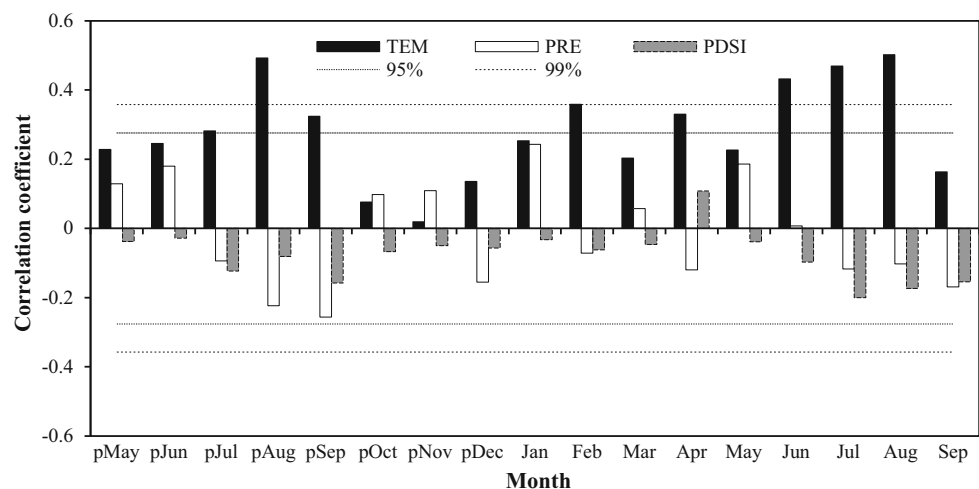
Regional climate change trend

JJA temperature had a significant increasing trend during the past 52 years (1957–2008). However, 30-year JJA temperature did not always show a significant increasing trend at every interval. The coefficients of determination of the linear models that simulated the trends of 30-year JJA temperature showed that the JJA temperature had non-significant increasing trends before the period 1971–2000, but significant increasing trends after the period 1971–2000 at 30-year interval ($p > 0.05$; Fig. 4). Thus, the rapid warming in the climate started after the period 1971–2000.

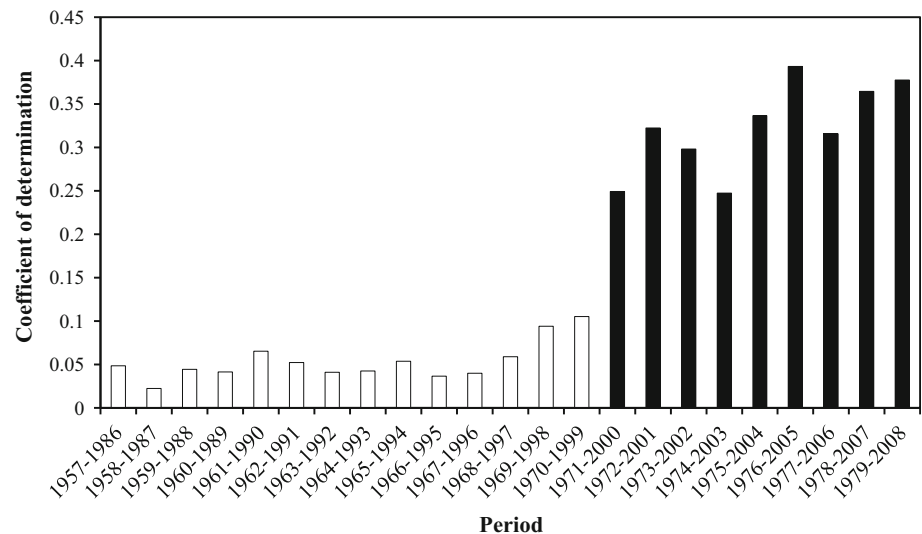### Response of radial growth to rapid warming

Correlation coefficients of PC1 to summer monthly and seasonal temperatures varied over time (Fig. 5). Before the 1969–1998 period, these relationships were non-significant. Significant correlations started after the 1969–1998 period. The Gershunov test showed that the temporal change in climate–growth relationships since the period 1969–1998 could not be explained by an effect of stochastic processes. Radial growth and JJA temperature became more closely correlated after the period 1971–2000.

Additionally, the correlation between the PC1 and thaw depth of permafrost varied with the upward shift of temperature: PC1 had a non-significant correlation with thaw depth before the 1969–1998 period, but a significant negative correlation between PC1 and thaw depth thereafter (Fig. 5). When checked with the Gershunov test, the
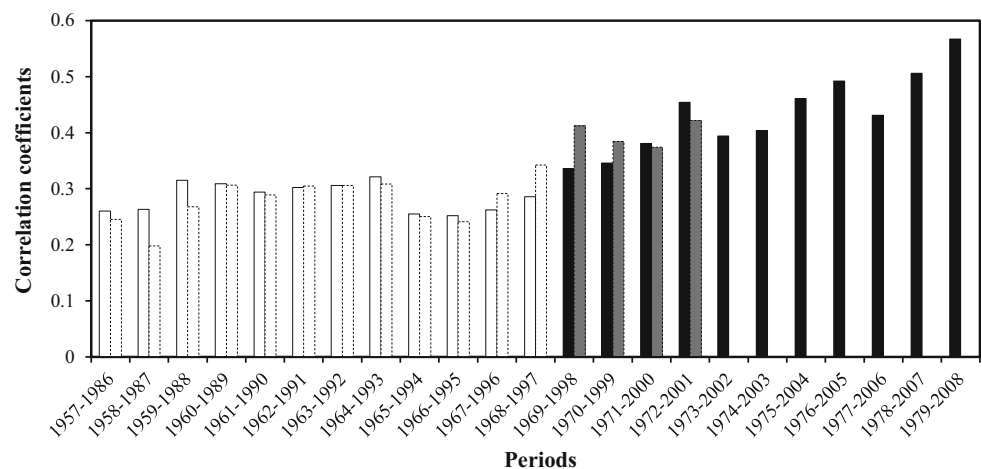

Fig. 3 Correlation coefficients between the PC1 and climate variables [temperature (TEM), precipitation (PRE) and PDSI] from the previous May to the current September during 1958–2008

temporal change in the relationship between thaw depth and growth since the period 1971–2000 could not be explained by an effect of stochastic processes.

Discussion

Summer temperature (JJA) was found to be the dominant factor limiting the radial growth of Dahurian larch in this region. In northeast China, low temperatures during the growing season had a great limitation on tree-ring formation (Zhang et al. 2011; Chen et al. 2013). Like other studies in northeastern China, the Dahurian larch tree rings were positively correlated with summer temperature (Shao and Wu 1997; Wang et al. 2005; Chen et al. 2008), indicating a regional homogeneity of the trees' response to climate. Tree growth was also influenced by February–April mean temperature, which was coincident with the

research conducted in Changbai mountain (Zhu et al. 2009).

An upward trend was detected in the JJA temperature in this region—a feature that has been captured in other studies in northeast China (Qian and Qin 2006; Li et al. 2010). Warming accelerated after the 1971–2000 period, and the relationship between JJA temperature and radial growth started to be significantly related around that period. Variability in radial growth was most likely related to the variability of climate (Oberhuber 2004) as has been found in other studies (Clark and Clark 1994; Tardif et al. 2003; Oberhuber 2004; Carrer and Urbinati. 2006; Martín-Benito et al. 2008). Increasing variability of the climate (Andreu et al. 2007) and higher frequency of extreme climate (Oberhuber 2004) in recent years are possible reasons. In northeast China, not only the warming trend significant (Qian and Qin 2006), but also the frequency of extreme temperature and precipitation events (Ma et al.

2004; Zhai et al. 2005) is accompanied by climate warming. These variations in climate could have a great impact on tree growth, increasing the variation in annual tree ring growth under warming climate conditions.

The relationship between tree growth and summer temperature intensified after the rapid warming. Synchronous increasing trends of tree radial growth (PC1 scores) and JJA temperatures after 1969–1998 indicated that the temperature increase was beneficial to tree radial growth. Increased radial growth in relation to climatic warming has been found in Iberian pine forests, Spain (Andreu et al. 2007), tree lines in New Zealand (Cullen et al. 2001), and the eastern Italian Alps (Carrer and Urbinati 2006). Generally, the intensified relationship between tree growth and climate variation is more detectable when tree growth responds significantly to temperature variation in a positive way (D'Arrigo et al. 2008). Thaw depth of permafrost is an important factor to influence tree radial growth. The correlation between thaw depth and PC1 became significant after the period 1969–1998, indicating that the increased thaw depth of permafrost was beneficial to the radial growth. The depth to frozen soil and the root depth of Dahurian larch were shallow, restricting the roots of tree to obtain sufficient water for physiological processes. We hypothesize that this is the reason why the tree growth was correlated insignificantly to the thaw depth in the earlier period. Trees were limited by both temperature and water in the earlier period (lower correlations were showed between them). With the increasing thaw depth, more water became available and temperature became the only limiting factor (stronger growth–temperature correlations recently). Hence, the increasing growth–temperature correlations implied that tree growth was both less cool-temperature limited and less water stressed, which likely explains the increasing growth trend. Radial growth was significantly correlated with the thaw depth when the soil water from the thaw of permafrost started to affect the tree radial growth. Consequently, radial growth was enhanced after rapid warming.

Dahurian larch forest accounts for approximately half of the area of the total forest in the region. Based on the findings in this study, rapid warming was beneficial to Dahurian larch forest ecosystem in the permafrost zone. This is different from results suggesting that the Dahurian larch forest would be replaced by other species (e.g. Leng et al. 2008). Specifically, the biomass of the forest here is expected to increase as climate conditions improved, and the carbon fixation will be enhanced with the increase in tree radial growth.

Author contribution statement ZJ Chen and XL Zhang conceived the idea; XP Bai, YX Chang, XL Zhang and ZJ Chen sampled the tree cores and measured the tree-ring width; XL Zhang conducted the analysis and wrote the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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