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Growth characteristics and response to climate change of *Larix* Miller tree-ring in China

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As one of the earliest species used in dendrochronological studies, *Larix* responds sensitively to climate change. In this study, nine larch species and one variety from eleven sites were collected to study the growth characteristics of tree-ring width using dendrochronological methods. Ten residual tree-ring chronologies were developed to analyze their relationships with regional standardized anomaly series by Pearson's correlation analysis. The results suggest that most of the chronologies had significantly positive correlations with the mean temperature and mean maximum temperature in May. The spring temperature evidently limited the radial growth of the larch species without precipitation control. The largest mean tree-ring width was found in Himalayan Larch in Jilong, whereas Master Larch in Si'er reflected the smallest mean value. Both species presented little climate information in this study. Chinese, Potanin, and Tibetan larches are significantly correlated with climate change, implying a huge potential for climate history reconstruction. The elevation of the sampling sites appears to be an important condition for tree-ring growth of larches responding to climate factors.

***Larix* Miller, tree-ring, climate change, mean temperature in May**

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The reconstruction of historical climate change is an important aspect in global climate change research. As a regional climate proxy, tree-ring data have the advantages such as high resolution, widespread distribution, long time series, and precise dating, among others [1, 2]. Tree-ring data play an important role in climate change research [3, 4].

Larches belong to the Gymnospermae phylum, pine family, found in the Temperate, Cold Temperate, and Frigid Zones of the Northern Hemisphere [5]. In China, there are ten larch species and one variety, which are all hardy, photophilous, and dominant timber classes [6] located along the margin of the East Asian Monsoon zone.

Larix Miller is one of the earliest species used in dendroclimatic studies in China. Among the ten species and one variety of larches, Siberian Larch was the first species used in dendrochronological studies. Its chronologies revealed thermic and humid variations for hundreds of years in the Balikun region [7, 8], and in the northern Xinjiang region [9, 10], and significantly positively correlated with the precipi-

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tation in March and June in the far east of Tianshan [11]. Moreover, Peng et al. [12] indicated that there is a difference in corresponding climates between upper and lower forest tree lines, and that the different water-heat patterns during the winter-spring season may control the major radial growth of trees. In the Northeast region, Yu et al. [13] investigated the relationship between the radial growth of Changbai Larch and climate change, and suggested that the temperature is the major factor in tree-ring growth. Wang et al. [14] studied the tree-ring width and density of Dahurian Larch and Mongolian Scotch Pine, and indicated that the maximum density and latewood density of Dahurian Larch tree rings are highly correlated with the mean maximum temperature in July and August, satisfactorily reflecting the temperature fluctuation during the later part of the growing season. In the Northwest and North China regions, Dai et al. [15] reconstructed the temperature index during the last 300 years using Taibai Larch in Taibai Mountain. Liu et al. [16] integrated Pine, Fir, and Hemlock with Taibai Larch to reconstruct the historical variation of the early spring temperature in the Qinling Mountains. In addition, Dai et al. [17] reconstructed the July precipitation in the 20th century using Prince Rupprecht Larch tree-ring width. The abovementioned research demonstrated that larch is a species sensitive to environment variations, exhibiting tremendous potential for usage in dendroclimatology. However, previous studies were mostly focused on single species data at local areas. Studies using multiple larch species to examine zonal climate have not been reported yet. Therefore, it is important to systematically conduct dendrochronological work on the larch species in China.

In this study, tree-ring samples from nine species and one variety of *Larix* Mill. were collected (*Larix speciosa* was not included in the study). These samples were taken from species found in 11 locations (Table 1). Sample collection began at the Great Higgnan Mountains and Changbai Mountain of the Northeastern part of China, crossing over to Wutai and Taibai Mountains towards western Sichuan and northern Yunnan, before finally ending at the Himalayas. In this study, we designed an approach to the tree-ring width chronologies of *Larix* Mill. responding to climate change. Furthermore, we discussed the response patterns influenced by spatial factors, such as latitude and altitude, with multi-species and large-scale regions. This study may provide further information for historical climate change reconstruction in the transition zone between semiarid and arid areas, as well as on the annual fluctuation of the monsoon in these regions.

1 Materials and methods

1.1 Study area

China's topography varies greatly and can be described as a staircase descending from west to east. The sampled larches in this paper are distributed naturally on the upper tree line between the first and second steps south of the Qinling and Daba mountains. Larches studied in this paper are also located between the second and third steps from the northern side of these mountains, generally along the cordillera trending towards northeast to southwest. These larch distribution patterns may be characterized as peculiar as larch is the only defoliating conifer thriving in a landform-controlled climate, with temperatures that influence vegetation population locationing [18]. Aside from the abovementioned sampling sites, larch samples were also collected from Burqin in Xinjiang, Keelung in Tibet, and Heihe in Jilin. The brim zone of the East Asia Monsoon-affected region [19] mostly overlaps with the transition region between semiarid and arid areas and our study area (Figure 1, Table 1).

1.2 Tree-ring material

Two cores out of each sampling tree were collected using an increment borer; discs were cut at sites FYG and HNS. Following the dendrochronological laboratory procedure, we prepared the samples through drying, mounting, sanding, and primary cross-dating [20]. The tree-ring widths were measured using DENDROLAB (precision 0.01 mm) on tree-ring cores. The tree-ring discs were cut into 1 mm thin sections with a DENDROCUT twin blade saw (WALESCH ELECTRONIC), then X-rays of the discs were taken and measured on DENDRO2003. The tree-ring series data were cross-dated again using the COFECHA program(version 6.06P, http://www.ltrr.arizona.edu), in which the segments that showed weak correlation with the master series were discarded.

The growth trend of the tree-ring width was detrended using the minus exponential formula of the ARSTAN program (http://www.ldeo.columbia.edu/res/fac/trl) to establish standard and residual chronologies. Given that the residual chronology could preserve more high frequency fluctuations [21], eliminate the abnormal variations on the end of the time series, and appear to have better correlation with climate factors, this chronology was used as the analysis target in this study. The common interval analysis for 1899–1999 was used (except for sites WT and SE) to test the expressed population signal (EPS) and the explained variance of the first principal component analysis.

1.3 Meteorological data

Weather stations close to the sampling sites were chosen for the study. The instrumental data such as the monthly mean temperature, monthly mean maximum and minimum temperatures, and monthly precipitation were used in this study. Missing data at some weather stations were calculated with routine MET (estimating missing meteorology data) in the DPL program (http://www.ltrr.arizona.edu). Around sam-

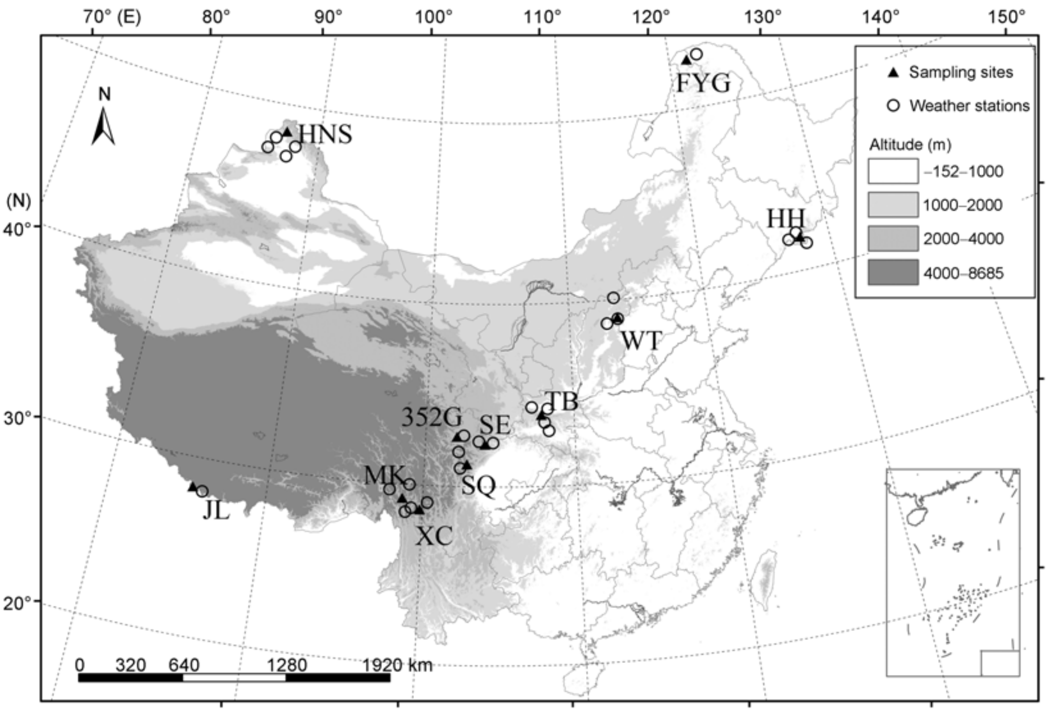

Figure 1 Distribution of tree ring sites and weather stations.

Table 1 Sampling sites of Chinese Larch[a)]

Code	Sample site	Tree species	Location	Altitude (m)	Eco-geographical region	Sample (tree core)
JL	Jilong, Tibet	*Larix himalaica* Cheng et L. K. Fu	28.37°N, 85.32°E	3000	Southern Tibet high mountain and valley shrub-steppe region	21 (43)
MK	Markam, Tibet	*Larix griffithiana* (Lindl.et Gord) Hort et Carr.	29.25°N 98.68°E	4125	Western Sichuan and Eastern Tibet high mountain and deep valley coniferous forest region	20 (39)
XC	Xiangcheng, Sichuan	*Larix potaninii* Batal var. *macrocarpa* Law	28.67°N 99.83°E	4208	Western Sichuan and Eastern Tibet high mountain and deep valley coniferous forest region	21 (42)
SQ	Xiaojin, Sichuan	*Larix potaninii* Batal.	31.23°N 102.80°E	3864	Western Sichuan and Eastern Tibet high mountain and deep valley coniferous forest region	21 (42)
SE	Pingwu, Sichuan	*Larix mastersiana* Rehd.et Wils.	32.33°N 103.97°E	2062	Western Sichuan and Eastern Tibet high mountain and deep valley coniferous forest region	20 (40)
352G	Hongyuan, Sichuan	*Larix potaninii* Batal.	32.73°N 102.08°E	3780	Western Sichuan and Eastern Tibet high mountain and deep valley coniferous forest region	20 (40)
TB	Taibai Mountain, Shaanxi	*Larix chinensis* Beissn.	33.93°N 107.77°E	3270	Qinling and Bashan Mountains evergreen and deciduous broadleaved forest mixed region	26 (52)
WT	Wutai Mountain, Shanxi	*Larix principis-rupprechtii* Mayr.	39.03°N 113.50°E	2450	North China mountain deciduous broadleaved forest region	21 (41)
HH	Heihe, Jilin	*Larix olgensis* Henry	41.83°N 127.78°E	1020	Hinggan, Changbai mountains broadleaved and coniferous forest region	18 (39)
FYG	Mohe, Heilongjiang	*Larix gmelini* (Rupr.) Rupr.	52.78°N 121.57°E	626	North Great Hinggan Mountains deciduous coniferous forest region	12
HNS	Burqin, Xinjiang	*Larix sibirica* Ledeb.	48.50°N 87.18°E	1570	Altay Mountain steppe, coniferous forest region	20

a) HH is provided by Fang Xiuqi of Beijing Normal University; FYG and HNS are tree disc samples.

pling sites where there were no weather stations, CRU TS2.1 (www.cru.uea.ac.uk) 0.5°×0.5°grid data was used instead (http://www.cru.uea.ac.uk/~timm/grid/CRU_TS_2_1.html). After performing instrumental data homogeneity test (refer to Table 2 for stations and time spans), we found that a number of weather stations did not pass the examination. To eliminate the nonhomogeneous effect, the standardized regional anomaly value was used to treat the in

Table 2 Weather stations and combined instrumental data information for each site[a)]

Sample site	Weather station	Code	Latitude (N)	Longitude (E)	Altitude (m)	Annual mean temperature (°C)	Annual precipitation (mm)
JL	Nyalam	NLM	28°11′	85°58′	3810	3.627	647.046
MK	Grid1	Grid1	29°15′	98°45′		4.125	725.337
	Batang	BT	30°00′	99°06′	2589.2	12.756	483.671
	Zogong	ZG	29°40′	97°50′	3780	4.589	448.955
	Deqin	DQ	28°43′	99°17′	7422.9	5.334	644.970
XC	Grid2	Grid2	28°15′	99°45′		3.165	754.829
	Daocheng	DC	29°03′	100°18′	8727.7	4.365	643.174
	Deqin	DQ	28°29′	98°55′	3319	5.334	644.970
SQ	Xiaojin	XJ	31°00′	102°21′	2369.2	12.028	622.547
	Maerkang	MEK	31°54′	102°14′	2664.4	8.619	774.553
SE	Pingwu	PW	32°25′	104°31′	893.2	14.712	813.931
	Songpan	SP	32°29′	103°34′	2850.7	5.884	720.482
352G	Maerkang	MEK	31°54′	102°14′	2664.4	8.619	774.553
	Songpan	SP	32°29′	103°34′	2850.7	5.884	720.482
	Hongyuan	HY	32°48′	102°33′	3491.6	1.407	750.139
TB	Baoji	BJ	34°21′	107°08′	612.4	13.093	671.453
	Foping	FP	33°31′	107°59′	827.2	11.735	907.440
	Shiquan	SQ	33°03′	108°16′	484.9	14.609	877.126
	Wugong	WG	34°15′	108°13′	447.8	13.207	605.577
WT	Datong	DT	40°06′	113°20′	1067.2	6.871	376.858
	Yuanping	YP	38°44′	112°43′	828.2	8.938	427.074
	Wutai Mountain	WTS	38°57′	113°31′	2208.3	2.826	792.047
HH	Fusong	FS	42°06′	127°34′	774.2	3.612	812.767
	Changbai	CB	41°25′	128°11′	775.0	2.291	670.362
	Linjiang	LJ	41°48′	126°55′	332.7	5.096	809.350
FYG	Mohe	MH	52°58′	122°31′	433.0	4.467	427.712
HNS	Altay	ALT	47°44′	88°05′	735.3	4.354	196.053
	Fuhai	FH	47°07′	87°28′	500.9	4.012	122.147
	Habahe	HBH	48°03′	86°24′	532.6	4.683	185.325
	Jeminay	JMN	47°26′	85°52′	984.1	4.108	206.363

a) Tree-ring width chronology cannot be developed in JL because of singular values. Grid1 (29°15′N, 98°45′E) and Grid2 (28°15′N, 99°45′E) are extracted from CRU with resolution of 0.5°×0.5° gird. Annual mean temperature and annual precipitation were calculated during the time interval of combined instrumental data for each site. Time interval of combined instrumental data of site HNS is from 1961 to 2000, and the rest are from 1960 to 2002.

strumental data, where the standardized data for each station were first taken, then the standard data anomaly calculated, and finally, the anomaly data for each region around the sampling site averaged [22, 23]. The relationship between regional climate data and tree-ring width chronology was determined using Pearson's correlation. Results are discussed in subsection 2.2.

2 Results

2.1 Establishing and analyzing the residual chronology of tree-ring width

Among the 11 sites (Table 3), Himalayan Larch at JL showed the largest ring width and biggest variation, and the correlation between cores was quite low. Thus, it did not qualify for chronology construction. Master Larch at SE displayed the narrowest ring width and least variance, which appeared indifferent to climate change. Table 4 shows the statistics of residual chronologies for each site and the analysis of common interval of 1899–1999 except for sites WT and SE because the time spans for these locations were too short. Comparing the sensitivity, signal to noise ratio and mean correlation coefficient, FYG and WT showed low signal to noise ratio. Likewise, FYG reflected low average sensitivity as well as low EPS, whereas TB showed the opposite way according to the statistics.

For the residual chronologies, the series at MK reflected abnormal fluctuation during 1950–2000. The samples exhibited extra-high ring-width value in this period, which is an abnormal growth trend (Figure 2). Some years, coincidentally, reflect the same low value such as 1892, reflected in 352G, SE, FYG and HNS; and 1893 in XC, SQ, TB, and HH. Furthermore, there were similar low values for 1807, 1808, 1817, 1882, and so on.

Table 3 The statistics of tree-ring width

	Mean	Median	Minimum	Maximum	Std. Dev.	Variance	Partial variance	Kurtosis	Amount
JL	2.046	1.740	0.110	13.690	1.397	1.950	0.683	156.361	2812
MK	1.007	0.709	0.023	6.702	0.842	0.709	0.837	−199.466	6489
XC	0.768	0.502	0.011	6.082	0.670	0.449	0.873	−3240.498	11497
SQ	0.811	0.687	0.032	4.226	0.556	0.309	0.686	642.693	7130
SE	0.409	0.348	0.038	3.706	0.267	0.071	0.653	2435.155	3730
352G	1.253	1.120	0.080	5.820	0.674	0.454	0.538	3528.923	11017
TB	0.660	0.573	0.014	3.505	0.428	0.183	0.648	631.683	7825
WT	1.350	1.320	0.040	3.730	0.585	0.342	0.433	−12.143	2338
HH	1.031	0.930	0.050	4.370	0.534	0.286	0.518	426.734	6039
FYG	1.148	0.920	0.050	5.110	0.763	0.582	0.665	−17.728	2691
HNS	0.799	0.670	0.030	3.430	0.497	0.247	0.622	−114.470	4386

Table 4 Residual chronology statistics and common interval analysis[a)]

	Tree-ring width residual chronology				Common interval analysis				
	Time span	Sample (tree/core)	Mean sensitivity	Standard deviation	Sample (tree/core)	$\overline{r}$	Signal-to-noise ratio	Expressed population signal	Explained variance of first principal component (%)
XC	1592–2005	21/42	0.247	0.211	19/35	0.430	26.412	0.964	47.2
MK	1775–2005	20/38	0.245	0.250	19/32	0.461	27.344	0.965	48.9
SQ	1798–2005	19/37	0.189	0.180	19/37	0.372	21.894	0.956	39.6
SE	1877–2005	18/35	0.214	0.171	18/35	0.382	21.663	0.956	41.0
352G	1614–2006	19/37	0.195	0.202	19/35	0.454	29.060	0.967	48.4
TB	1786–2004	27/50	0.327	0.283	21/40	0.595	58.855	0.983	60.7
WT	1930–2004	21/41	0.294	0.254	6/8	0.559	10.122	0.910	62.7
HH	1710–2003	14/27	0.178	0.147	15/25	0.359	13.999	0.933	39.0
HNS	1757–2000	19/19	0.206	0.185	18/18	0.418	12.932	0.928	45.6
FYG	1749–2000	10/19	0.188	0.164	4/7	0.388	4.442	0.816	48.4

a) Time span of common period analyses of SE is 1929–1999. Time span of common period analyses of SE is 1934–2004.

2.2 Correlation analysis between tree-ring chronologies and climate data

To study the tree-ring growth corresponding to climate factors, we used Pearson correlation analysis to determine the relationship between tree-ring width residual chronologies and standardized regional anomaly series of the climate instrument data. The time span studied was 1961–2002 except for HNS (1962–2000). The results are shown in Figure 3.

The correlation between the chronologies and climate factors varied depending on site and species; however, most of the series had significantly positive correlation with the monthly mean temperature and monthly mean maximum temperature in May (Figure 3). Master Larch in SE did not reflect any significant correlation with climate factors. There was a significantly positive correlation with the monthly mean temperature and monthly mean minimum temperature in August for Dahurian Larch at FYG, and with monthly mean minimum temperature in July for Sibirian Larch at HNS.

3 Discussion

The natural distribution of larch species in China, aside from Dahurian Larch and Sibirian Larch, nearly overlaps with the brim of the East Asian Monsoon [6], a marginal region of ecosystem and transitional climate zone. The climate factors at the brim of this zone affected vegetation more strongly compared with the other regions, and the vegetation in this area is more sensitive [24]. Previous studies regarding the vegetation of the monsoon margin zone indicate that the spring temperature is the major controlling factor in plant growth, despite the water supply is also very important during this period [24]. The eight sampling sites used in this study are located in the brim of the East Asian Monsoon zone, in which the chronologies of seven sites showed positive correlation with the monthly mean temperature and monthly mean maximum temperature in May (Figure 3), indicating the remarkable influence of the spring temperature to larch species radial growth. In the physiological analysis, the annual radial growth of tree-ring tracheid, including tracheid development and photosynthetic

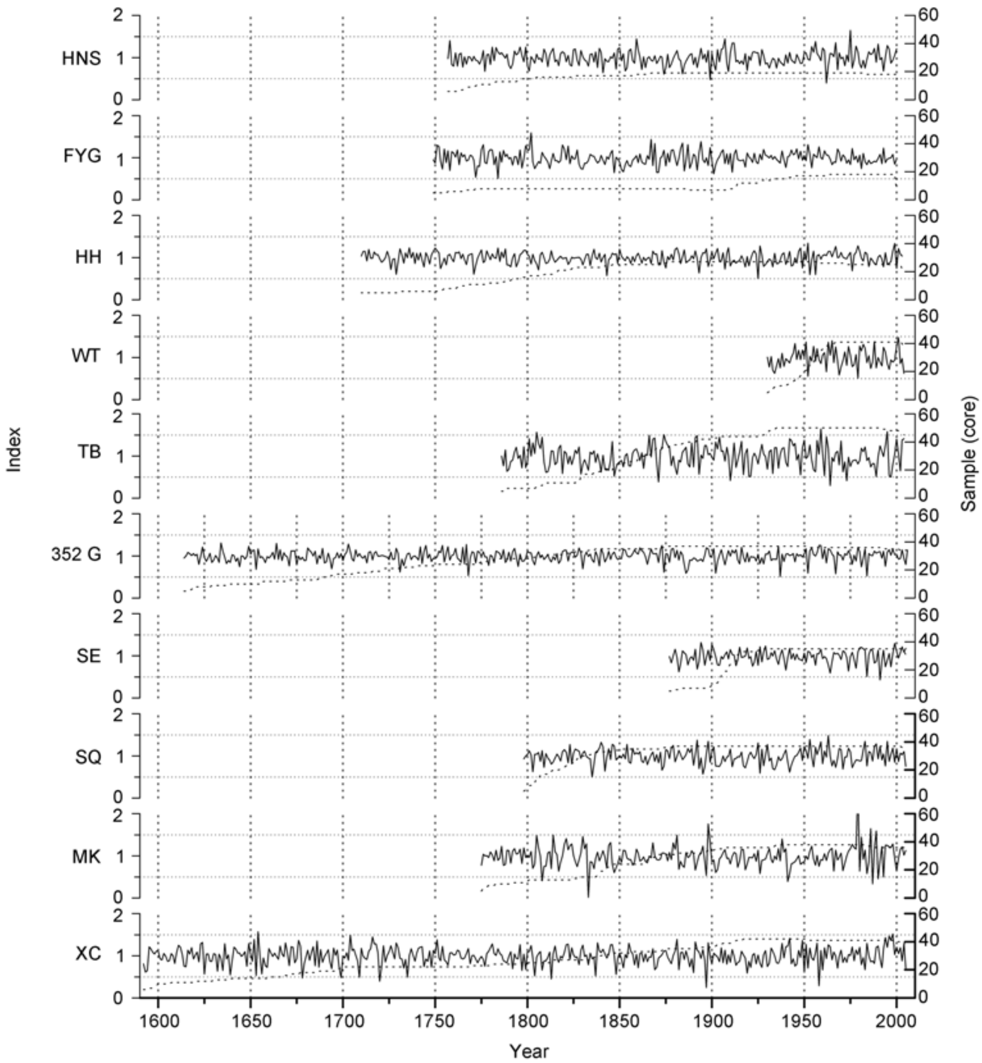

Figure 2 Tree-ring width residual chronologies of ten sites and sample depths.

accumulation, took place during the growing season. During the early part of the growing season, cambium differentiation and cell enlargement processes occurred rapidly, resulting in increments of tree-ring width [14, 25, 26]. Larches develop new needles in May, while the xylem cambium begins to differentiate new tracheid in the stem [18], making the temperature in May very important to Larch ring-width formation.

The precipitation present in the East Asian Monsoon mainly occurs in the summer season, with some periods of high temperature [6]. Due to the abundant rainfall along with monsoon activities, the water supply cannot be the controlling factor of larch growth. Therefore, there is no corresponding relationship between precipitation and tree-ring width in the correlation analysis. Cai et al. [27] studied *Pinus tabulaeformis* and suggested that there is no significantly positive correlation between tree-ring width and precipitation in the rainy summer region. With sufficient water supply, the mean temperature of the growing season is the major limiting factor to tree growth, which corresponds to the results in our study. Although chronologies of seven sites have significantly positive correlation with monthly mean temperature in May, the response to monthly maximum/minimum temperature does not appear consistent. In some months, the results are even on the contrary, but the reason remains unclear.

In our study, the tree-ring width in SE showed the lowest variance among all sampled sites. Its chronology was not correlated with climate factors and seemed indifferent to climate change. The reason may be because SE is located in the middle of the forest, and has not approached the upper tree line. Moreover, the narrowest tree-ring width was observed in SE, which may be caused by poor soil conditions. The latitudes of sites FYG and HNS are much higher than those of others; thus, the monsoon activity barely influences these locations. The climate patterns in these regions are also quite different from other sampling sites. This could be the main reason behind the alternate results in the correla-

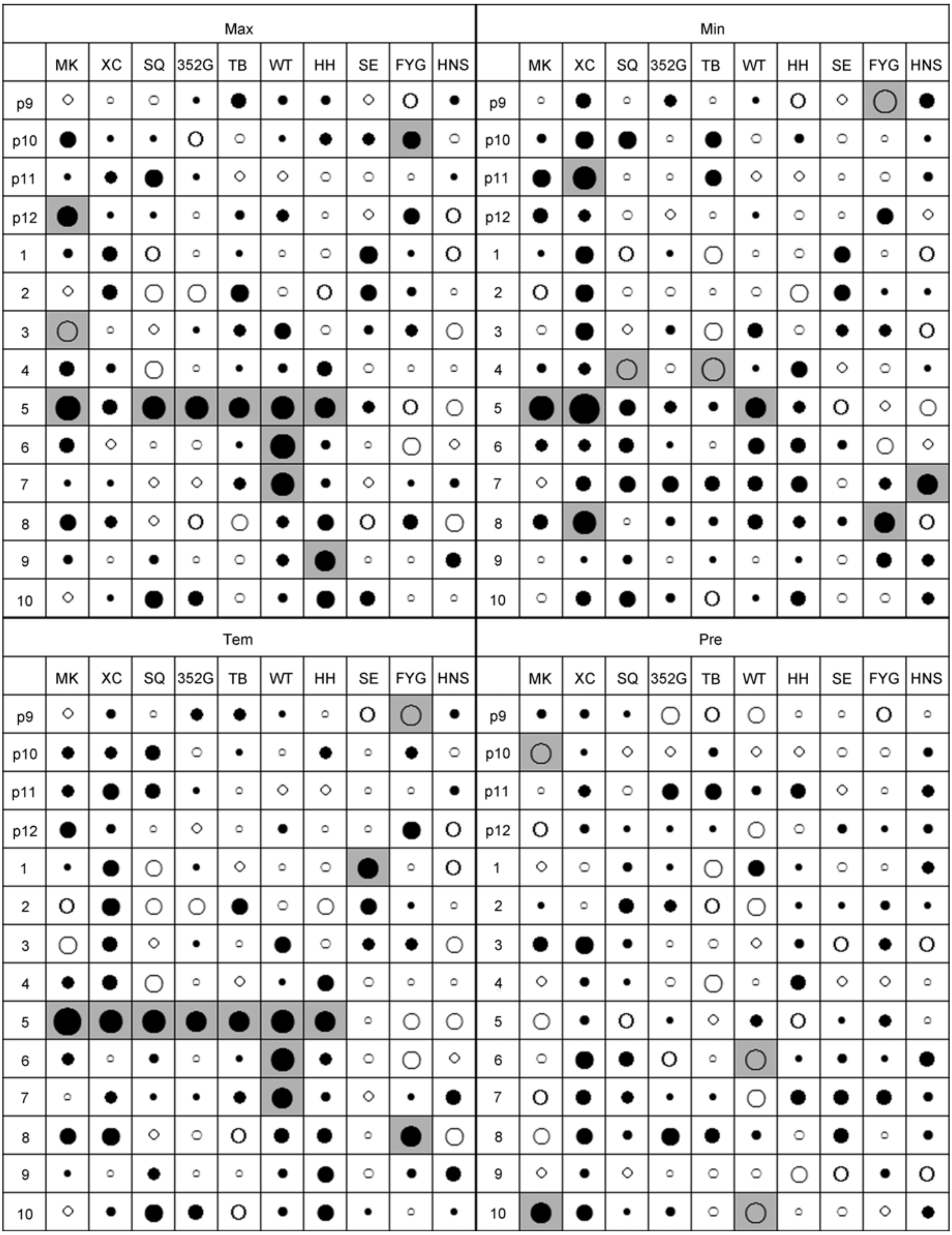

Figure 3 Schematic diagrams of correlation coefficients between tree-ring width series and climate data. Max is the average of maximum temperature; Min is the average of minimum temperature, Tem is mean temperature, Pre is precipitation. ● means positive correlation, ○ means negative correlation. The bigger circle means larger correlation coefficient. The shadow square means that the correlation is significant at the 0.05 level.

tion analysis.

Based on the analysis above, we compared the relationships between the mean temperature in May and ring-width chronology of all of the study sites along with altitude and latitude (Figure 4). As shown in Figure 4, the higher the altitude, the higher the correlation, revealing that tree growth is controlled mainly by temperature at the upper tree line of the high elevation region [20, 28]. However, the

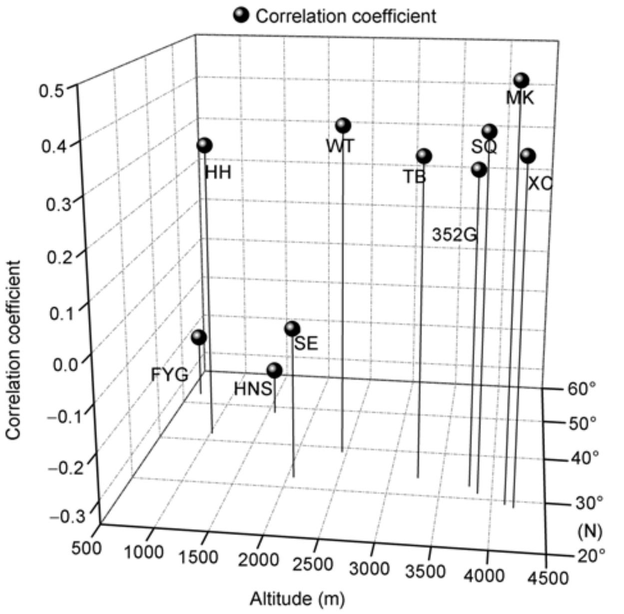

Figure 4 The correlation coefficients (*Z* axis) between tree-ring width residual chronologies and mean temperature in May along with Altitude (*X* axis) and Latitude (*Y* axis).

same result is not reflected at the sites with high latitude. Although the similarity in high latitude to high altitude in connection with the limiting factor to tree growth has been previously reported [29], the northernmost latitude in China is far from the Arctic region [30]. Additional samples have already been collected in high latitude regions in China to determine the characteristics of tree-ring growth and its response to climate change.

According to our results, larch data from sites XC, TB, SQ, and 352G could be used to reconstruct climate history. Sites HNS, HH, and FYG show huge potential if more samples could be collected. Tibetan Larch at MK reflected abnormal fluctuation after 1950, a data component that should be removed before investigating the corresponding climate from the chronology. Only 74 years were reflected in the ring width series of Prince Rupprecht Larch at WT, which is not sufficient for reconstruction even if the significant correlation between ring width chronology and temperature in the growing season is present. There was little climate information observed at site SE, and JL was too little to establish available chronology. The larch species distributed in the high altitude regions proved to be applicable for studying past climate variations. These species were the first group to respond to climate change and altitude (Figure 4), which offered better understanding of past climate tendency by dendrochronological study.

4 Conclusions

(1) Among the nine larch species and one larch variety, Himalayan Larch at Jilong showed the largest tree-ring width; the narrowest was found in Masters Larch at Sier. Both contained little climate information.

(2) The larches at sites MK, XC, SQ, 352G, TB, WT, and HH located at the brim of the monsoon zone showed significantly positive correlation with the mean temperature in May, indicating that the spring temperature obviously affected larch radial growth in the margin of the monsoon region. The precipitation did not appear to limit tree-ring growth.

(3) The larches at sites XC, SQ, and TB may provide historical climate information by reconstruction from tree-ring width chronology. Climate information may also be provided by the larches at sites FYG, HH, and HNS if additional samples could be obtained. In our study, the altitude level was the major factor in larch tree-ring width and for climate change responses.

Due to the sampling limitations, only the preliminary analysis for the dendrochronological information of larch species in China was presented. With collection of supplementary samples, further research work could be undertaken, covering areas such as improving the quality of ring-width chronology and the analysis of tree-ring density to more efficiently discover the relationship between tree-ring properties and climate change. There is also a need to further explore the reconstruction of climatic tendency in longer durations and larger areas.

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