Tree growth and its association with climate between individual tree-ring series at three mountain ranges in north central China

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\section*{ABSTRACT}

Individual tree-ring series may show changed growth trends and divergent climate–growth associations even within a site, highlighting the need to examine tree growth and its climate association before building a chronology. We provided a case study for the stratification and temporal variability of tree growth and its climate associations of individual cores for three mountain ranges in north central China. Tree growth is mainly limited by moisture conditions in previous July–September and current June–August. Repeated sampling and field investigations of \textit{Picea wilsonii} at Xinglong Mountain over a growth year of 2004 suggested that the growing season is from about the end of April to the end of September. It appears that the moisture conditions in previous and current growing seasons are crucial for tree growth in this region. However, a decrease in drought limitation was observed for a few tree-ring series. We thereby built the pooled chronology and sub-site chronologies with only drought-sensitive tree rings similar climate–growth relationships from the three mountain slopes. Growth disturbances of tree-ring series are detected by checking the occurrence of successively low values of the biweight series, which are treated by fitting a flexible curve.

\section*{Introduction}

Dendrochronology provides an empirical way to investigate radial tree-growth variability and its interaction with climate change (Fritts, 1974; Cook and Kairiukstis, 1990). Most of such studies have been implemented at the site level for tree-ring chronology averaged from a population of individual tree-ring series (e.g. Fritts, 1974; Cook et al., 2001; Gou et al., 2005; Wang et al., 2005; Büntgen et al., 2006; Andreu et al., 2007; D’Arrigo et al., 2008; Liang et al., 2008; Fang et al., 2009a,b). On the other hand, tree-growth of individual tree-ring cores within a site may show different tree-growth patterns and/or divergent climate–growth associations (e.g. Riitters, 1990a; Tardif et al., 2003; Wilmking et al., 2004, 2005). A study in Alaska has noticed that contrasting climate responses could occur even within a site, highlighting the need for investigation of tree-growth and its climate response of individual trees of a given site prior to building a chronology (Wilmking et al., 2004). Still, only very limited knowledge is available on tree-growth variability and climate–growth responses for individual trees. We herein provide a case study on investigating tree growth and climate–growth relationships in three mountain ranges in north central China.

Common signal strength of tree growth and climate association between chronologies of various sites can vary through time (Büntgen et al., 2006; Andreu et al., 2007; D’Arrigo et al., 2008; Tardif et al., 2003). However, limited studies are available about the temporal stability of shared signal strength of tree growth between individual cores within a given site. Biweight methodology is widely used in dendrochronology to produce robust mean chronology averaged from dimensionless tree-ring indices (Cook, 1985; Riitters, 1990a,b). Temporal change of biweights of a group of trees can be regarded as measure of the stability of tree-growth variability between individual trees (Riitters, 1990a,b). For example, continuously low weights received by some cores of given periods may be an indicator of the occurrence of non-climatic disturbances, because macroclimatic influences normally lead to common growth variability of a site. In this study we explore the possibility of detecting the time-varying common signal strength between individual tree-ring cores by examining the variability of averaged biweights through time and determine the existence of unexpected disturbances.

Tree-ring investigations at the site level have been conducted for our study region in north central China (Fang et al., 2009a,b). In
this paper, we will study the stratification and temporal variability of tree growth and its relevance to climate change for the same sites at the individual tree level. Additionally, tree-ring cores were repeatedly sampled during a growth year in Xinglong Mountain in order to identify the growing season, helping in interpreting the climate–growth relationships. Our objectives of this study are to study the stratification of growth variability and its relevance to climate between individual cores, as well as the temporal variability of common signal strength among tree-ring cores.

Data and methods

Tree-ring data

Ring-width cores were collected in previous studies (Fang et al., 2009a,b) from Xinglong Mountain, Tulugou and Muoshigou near Lanzhou city (Fig. 1 and Table 1), a transitional region between the Chinese Loess Plateau and Tibetan Plateau. The study area is characterized by a semi-arid continental climate with mean annual temperature 4–7°C and total annual precipitation of 400–600 mm (Fang et al., 2009a), which is regarded as a boundary area influenced by the Asian monsoon (Chen et al., 2008). We herein employed tree-ring samples of *Picea wilsonii* from 5 sites (at elevations of 2270 m, 2370 m, 2460 m, 2570 m, and 2660 m) along a mountain slope of Xinglong Mountain, *Picea crassifolia* from 4 sites (2325 m, 2550 m, 2630 m, and 2690 m) and *Pinus tabuliformis* from 4 sites (2230 m, 2290 m, 2340 m, and 2400 m) from mountain slopes of Tulugou and Muoshigou (Fang et al., 2009a). In the following analyses, we treat tree-ring cores from each mountain slope as a pooled dataset.

Climate data

Climate–growth relationships were investigated by calibrating tree rings with temperature and precipitation data from the Lanzhou meteorological station (36.05° N, 103.89° E). Since tree rings of north central China tend to show a drought-stressed growth pattern (Fang et al., 2010), we also calculated drought-growth correlations with the Palmer Drought Severity Index (PDSI) of the nearest grid (36.25° N, 103.75° E) derived from a 2.5° × 2.5° global dataset (Dai et al., 2004). We selected the climate data since 1951 because the instrumental climate data before the 1950s is less reliable in western China (Fang et al., 2010). Climate–growth correlation analyses were undertaken for a dendroclimatic year from...
previous to current growing seasons (Fritts, 1974; Cook et al., 2001), i.e. from previous May to current October in this study.

**RPCA**

Rotated principal component analysis (RPCA) as determined by the commonly used varimax method is a variant from principal component analysis (PCA), which is used to produce more interpretable loadings (Cook et al., 2001; Fang et al., 2010). In this study the variables in PCA and RPCA refer to tree-ring series or their climate–growth relationships, and the observations are the yearly measurements of ring-width or the monthly climate–growth correlations for each series. Sub-site chronologies are developed from cores that show high loadings over the same PC factor. That is, tree-ring series showing higher loading over the first principal component (PC1) are grouped into what we call “chronology PC1”. Similarly, we probably develop chronologies of “chronology PC2” and “chronology PC3” of a given mountain slope based on the distribution of common growth signal strength. Tree ring series without high loadings over these principal components are not included in further analysis.

**Biweight calculations**

The biweight estimator in dendrochronology is a robust way to calculate a mean chronology, which is insensitive to the outlier but behaves as arithmetic mean for those near median (Cook, 1985; Riitters, 1990a). The calculation for biweight robust mean in this study is based on an iteratively reweighted, least-square algorithm (Cook, 1985; Riitters, 1990a). The empirical biweight robust mean weights assigned to individual trees are dependent on their similarity to the shared signal strength (Cook, 1985; Riitters, 1990b). Therefore the time-varying mean values of biweights among tree-ring series can be used to measure the common signal strength between series (Riitters, 1990b). In the present study, special attention is paid to those periods constantly receiving low weights of individual series, which is probably a consequence of random disturbances.

**Results**

Field investigations on bud activity and wood formation covered one year’s growth cycle in Xinglong Mountain. On April 11th, some terminal leaf bud started to activate while other buds were still in dormancy stage. Some terminal leaf bud started to activate on April 11th, and most of the leaf buds started to activate on May 1st. This indicates that growing season may start at around from the end of April to the start of May. The new leaves and shoots started to form on May 22nd. Clear formation of new woody tissue was observed on cores taken from June 20th. This may indicate that the process for xylogenesis is less intense before the end of June, probably because of the relatively low temperature. The bud activity is easily identified during the onset of a growing season relative to the end of the growing season for this evergreen species. Therefore we considered the start of bud activity as the onset of growing season and the end of wood formation as the end of the growing season. The latewood seemingly completely formed on September 2nd. As indicated above, it should be noted that the determination of the start and end of wood formation is less precise using this method. Taken together, the growing season for *P. crassifolia* in Xinglong Mountain is in from around the end of April to the end of September. According to the Lanzhou meteorological station, this growing season generally corresponds with mean daily temperature above 12°C in 2004. We need to keep in mind that the elevations of the sampling sites (around 2400 m for the middle sites) are around 900 m higher than the Lanzhou station (1508 m), resulting that the sampling sites are around 5°C colder due to a 0.6°C/100 m collapsing rate. This means that the growing season generally corresponds to mean temperature above 6.6°C, which is generally consistent with previous studies on the threshold temperature for tree growth (Körner, 2003; Rossi et al., 2007). It also should be noted that the growing season in 2004 may be different from other years since the temperature may change from year to year.

Pooled or sub-site chronologies were constructed for each site (Table 1). Both PC2 and PC3 of the pooled tree-ring samples from Xinglong Mountain explained relatively considerable variance (Table 1). We therefore built “chronology PC2” and “chronology PC3” for Xinglong Mountain. A drought-stressed pattern was indicated by negative correlations with temperature of previous July–September and current June–August and positive correlations with precipitation of previous July–September and current June–August (Fig. 2). This is confirmed by high, positive correlations with the PDSI in previous July–October and current June–August. Different from Muoshigou, tree-growth patterns at Xinglong Mountain and Tulugou show slightly higher correlation with the PDSI in previous July–October and current June–August. Different from Muoshigou, tree-growth patterns at Xinglong Mountain and Tulugou show slightly higher correlation with previous climate conditions (Fig. 2). Monthly PDSI-growth correlations peak in previous September and in current July in Xinglong Mountain and in Tulugou and in current June at Muoshigou. Climate–growth correlations for “chronology PC1” are consistent with the pooled chronology in each mountain slope. A slightly intensified drought response for “chronology PC1” is evidenced by slightly higher correlations with precipitation and PDSI. On the other hand, “chronology PC2” showed decreased correlations with PDSI and increased correlations with temperature (Fig. 2), indicating that these tree rings are not drought-stressed. Based on the

### Table 1

<table>
<thead>
<tr>
<th>Region</th>
<th>Lat. (N)</th>
<th>Long. (E)</th>
<th>Chronology</th>
<th>No. cores</th>
<th>Explained variancea (%)</th>
<th>Time spanb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xinglong Mountain</td>
<td>35.7</td>
<td>104.07</td>
<td>Pooled</td>
<td>164</td>
<td>67.8</td>
<td>1798–2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PC1</td>
<td>129</td>
<td>14.7</td>
<td>1805–2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PC2</td>
<td>19</td>
<td>6.5</td>
<td>1879–2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PC3</td>
<td>12</td>
<td></td>
<td>1842–2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pooled</td>
<td>144</td>
<td></td>
<td>1883–2002</td>
</tr>
<tr>
<td>Muoshigou</td>
<td>36.7</td>
<td>102.73</td>
<td>PC1</td>
<td>112</td>
<td>76.9</td>
<td>1889–2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PC2</td>
<td>8</td>
<td>4.9</td>
<td>1936–1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pooled</td>
<td>190</td>
<td></td>
<td>1857–2002</td>
</tr>
<tr>
<td>Tulugou</td>
<td>36.69</td>
<td>102.71</td>
<td>PC1</td>
<td>160</td>
<td>67.7</td>
<td>1868–2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PC2</td>
<td>9</td>
<td>9.4</td>
<td>1918–2002</td>
</tr>
</tbody>
</table>

a Based on principal component analysis derived from monthly correlation values between tree-ring series and climate records of temperature and precipitation from previous May to current October.

b Based on the reliable portion of a given chronology with the statistics of subsample signal strength (SSS) greater than 0.8.
above classification, we built the pooled and sub-site chronologies for the three mountain slopes (Fig. 3). The “chronology PC1” shows similar growth variability in certain years, while changed growth pattern for other years at Xinglong Mountain. For example, the pooled chronology and “chronology PC1” almost match during the 1920–1930s, while changed patterns are found during the 1950–1960s. Growth patterns of pooled and sub-site chronologies are most consistent at Muoshigou. At Tulugou, the “chronology PC1” shows similar growth pattern with the pooled chronology, but with a lower variability (Fig. 3).
curves at Xinglong Mountain, as well as (low panel) their biweight time series.

The biweight time series is shown in Fig. 4, where constantly low weights (with three weights lower than 0.90 within five years) are found over periods of 1823–1828, 1876–1881, 1887–1892, 1923–1929, 1932–1936 and 1950–1955. Constantly low weights may result from systematic deviations from the common growth pattern, the chronology indices, which might be related to non-climatic disturbances. We identified 19 series with constantly low weights for certain periods, which show clear non-climatic disturbances. Four of the nineteen series with low biweights and divergent growth trends were shown from the sampling sites of lowest (2270 m) and highest (2660 m) elevations at Xinglong Mountain as an example (Fig. 4). We fitted the 19 tree-tree-ring series with strong disturbances by a relatively flexible curve, Friedman smoother with alpha 5, and built a modified “chronology PC1” in Fig. 5. In general, the variability of tree-ring chronology increases towards recent decades, while the variability of the biweight time series decreases. Biweights of the modified “chronology PC1” slightly increase at those periods where successive low weights are observed for the original “chronology PC1”. At the same time, there are also some years where biweights of the modified “chronology PC1” are lower than the original chronology (Fig. 5). Tree-ring series constantly receiving low weights were also found showing strong disturbances at Muoshigou and Tulugou (detailed results are not shown).

**Discussion**

**Climate–growth relationships**

It is readily understood that tree growth shows high correlations with moisture conditions during the growing season from the end of April to the end of September, particularly for the period from June to September (Fig. 2) when the wood formation is intense and obviously identified. Three factors may account for the correlations between tree growth and climate in previous growing season. First, photosynthesis of the 1-year-old needles developed in previous year may be crucial bud break and shoots growth of current year, thus influencing current wood formation (Hansen and Beck, 1994). For example, less old needles due to drought of previous year may lead to reduced photosynthesis of current year. Second, food storage may directly contribute to current tree growth by favoring new bud break and shoots growth (von Felten et al., 2007). Third, moisture condition of previous growing season is related to the current soil moisture conditions (Fritts, 1974). It should be noted that high correlations between ring width and PDSI are found at nongrowing seasons, for example, from previous November to current April, while it is not the case for correlations with temperature and precipitation (Fig. 2). This may be because of the precondition nature of PDSI data that show higher autocorrelation between monthly variables relative to precipitation and temperature (Dai et al., 2004). That is, high correlation between tree growth and PDSI in non-growing season may actually be reflection of the drought response of the previous growing season.

Climate–growth relationships for spruce trees (P. crassifolia and P. wilsonii) at Xinglong Mountain and Tulugou are more similar compared to the pine trees (P. tabulaeformis) at Muoshigou. This probably suggests the important role of species-related physiological and ecological features in determining climate–growth relationships (Fang et al., 2009a), since P. crassifolia and P. wilsonii belong to the same genus. Species determinism on climate–growth associations were also detected in other studies (Cook et al., 2001), which may occur at regions where the environmental gradients are smaller than the species-related physiological and ecological gradients. One difference between climate–growth relationships of spruces and pines is that spruces shows higher correlation with previous climate conditions, while the latter one shows higher correlations with climate of current year. This suggests that P. tabulaeformis trees at Muoshigou are less influenced by climate of previous year.

**Divergent temperature responses**

Temperature–growth correlations changed from negative to positive between tree-ring series of “chronology PC1” and “chronology PC2” for three mountain ranges. These tree-ring series of “chronology PC2” are probably at shaded locations without strong sunlight where the temperature-induced evaporation is less intense. Therefore the temperature-induced moisture loss for these locations is not a limiting factor to tree growth. It is common for arid northwestern China that strong sunlight would cause increase in

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**Fig. 4.** Plot showing (upper panel) biweight series of “chronology PC1” for Xinglong Mountain and (lower panel) some tree-ring indices with growth disturbances as identified by the occurrence of constantly low weights, as well as a comparison with (dark heavy line) the chronology indices.

**Fig. 5.** Comparisons between (upper panel) indices of “chronology PC1” and modified “chronology PC1” averaged from a set of tree-ring indices treated by flexible curves at Xinglong Mountain, as well as (low panel) their biweight time series.
soil temperature and thus limit tree growth. For example, trees are mainly found at the north facing slopes with weaker sunlight in our study region. On the other hand, correlations between tree growth and precipitation are relatively consistent among individual tree-ring series. We therefore summarize that moisture availability is crucial for most trees of this arid area, while tree growth at a few locations (e.g. shaded locations) may be less limited by moisture availability. Since divergent growth trends are possibly related to micro-environmental conditions of different trees, these highlight the necessity to record the micro-environmental conditions of each tree.

It would be expected that a tree-ring chronology built from only drought-sensitive tree rings could retain more "pure" drought signal. As shown in Fig. 2, PDSI-growth correlations for "chronology PC1" are clearly higher than the pooled chronology. Indices of "chronology PC3" at Xinglong Mountain appear to have more extremely high and low values than the pooled chronology, which may indicate that "chronology PC3" is more sensitive to extreme climate conditions. More divergent growth pattern is seen for "chronology PC2" with different temperature responses (Fig. 3). At Xinglong Mountain divergent growth trends between "chronology PC2" and the pooled chronology are found, for example, at the 1870s, 1900s and 1960–1970s, which may be related to the changed temperature–growth interactions. Chronology indices better match each other at Muoshigou, except for the period towards recent. This seems consistent with previous results that trees of this mountain show higher common signal strength as indicated by the explained variance (76.5%) of PC1. At Tulugou, "chronology PC2" shows clearly lower variability relative to the others of this area, possibly suggesting a decrease in climate sensitivity for this chronology. This may be a consequence of a decrease in PDSI limitation, as shown in Fig. 2, that the correlations between indices of "chronology PC2" and PDSI approach zero.

Time-varying biweights series

The increase in the common signal strength of tree growth often corresponds to stressed climate conditions such as drought (Fritts, 1974; Tardif et al., 2003). However, it is not significant that the successive low weights coincide with extreme climate conditions (Figs. 4 and 5). One cause is that the biweight calculation is based on the distribution of ring widths of a single year, without considering the growth trends of a few years (Cook, 1985; Riitters, 1990a,b). We therefore focus on the periods with continuously low biweight of a given chronology, because successive deviations from the mean growth pattern may indicate the occurrence of non-climatic disturbances. We found that the tree-ring series with successively low weights often show systematic deviations from common growth trends (Fig. 4). We noticed that systematic deviations of individual tree-ring signals tend to be found close to the pith. This may be because the young trees in closed forests with low tree height tend to suffer from disturbances from other trees. A decrease in variability towards recent decades is seen for the biweight series of "chronology PC1" at Xinglong Mountain (Figs. 4 and 5). This is because the tree-ring signals are more stable with more replication towards recent. It seems that biweight variability could be regarded as an indicator for measure of common signal strength in some sense. This is consistent with the generally accepted view that biweight scheme is more efficient and active for low sample size (Cook, 1985). On the contrary, variability of the chronology indices becomes more variable towards recent. This appears to be an indicator of the increase in drought variability of this area (Fang et al., 2009b). Meanwhile, tree-ring variability at the early portion of a chronology with low replication might be dampened during the averaging process, while the more stable and consistent growth signals towards recent are relatively well preserved.

Conclusions

We provided a case study on investigations of the spatiotemporal features of tree growth and its associations with climate for individual tree-ring series within sites in three mountain ranges in northern China. Most tree rings show positive correlations with moisture of previous and current growing seasons with negative correlations with temperature and positive correlations with precipitation. However, a few tree-ring series are less drought-stressed with positive correlations with temperature, suggesting the temperature-induced evaporation is less intense in this semi-arid region. This suggests the necessity to examine the growth variability and its associations with climate for individual tree-ring series within a given site, in order to exclude tree rings with changed climate–growth relationships. It is also suggested to examine the homogeneity of individual tree-ring series through time prior to the establishment of a chronology. Continuous low weights of individual tree-ring series calculated from a biweight scheme were indicators of the existence of non-climate disturbances, which should be fitted by data-adaptive curves (e.g. spline).

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