Characteristics of ring-width chronologies of *Picea crassifolia* and their responses to climate at different elevations in the Anyemaqen Mountains

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Abstract Based on tree-ring samples of *Picea crassifolia* at four different elevations along a north-facing slope in the Anyemaqen Mountains, China, we have reconstructed ring-wise climate variation of this species over the past 100 years. The results showed that both temperature and precipitation are important factors affecting tree growth. At lower elevations, the ring width was significantly correlated with temperatures of the previous year, whereas at higher elevations, precipitation was the main factor. The response of the tree to climate variation shows a significant difference in different altitudinal gradients, and the relationship between climate and tree growth is characterized by elevation. The results provide important evidence that Picea crassifolia has a specific response to climate variation at different altitudes, which may be important for future predictions of climate change and its effect on vegetation.
Anymaqin Mountains
northeastern Tibetan Plateau
we developed four ring-width chronologies. Statistical results showed that characteristics of chronologies are different with the increasing elevation and the correlations of chronologies in the common interval decreased with the increasing elevation. Meanwhile, correlations between the chronologies of different elevation and the two climatic parameters temperature and precipitation exhibited distinct differences. Tree-rings were significantly and positively correlated with the October mean monthly temperature of previous year and also were significantly but negatively correlated with prior August and current May and June mean monthly temperatures respectively. All the correlations were fluctuating with the increasing elevation. Tree-rings were significantly and positively correlated with the September and October precipitation of previous years but were decreasing along the increasing elevation. Tree-rings were also significantly and positively correlated with the May precipitation of current years and the correlations were increasing along the increase of the elevation. Furthermore, tree-rings were also negatively correlated with temperatures of different time interval and the warming index proving that the optimal growing season of *Picea crassifolia* is May-September. The results of response function analyses showed that the influence of temperature and precipitation explained most of the growth variance at the low-elevation site but much less at the high-elevation site. The results were greatly different from previous studies that tree-rings were significantly and positively correlated with temperature at the upper forest limit whereas were significantly correlated with precipitation at the lower forest limit. Principal component analysis was used to indicate regional variations in radial growth patterns. Of the four chronologies, the first PC explains 81.071% of their total variance. According to the response function analyses, the first PC of the four chronologies showed that moisture and temperature of the last stage of prior year growing season and the initial stage of current year growing season are the most important limiting factors of tree growth. This conclusion was further proved by regional model simulation results. Overall, our results indicated the similarities and discrepancies of *Picea crassifolia* ring-width chronologies on the same slope and provided some background information for future dendrochronological studies in this area.

**Key Words** *Picea crassifolia*, elevational gradient, tree-rings, climatic response

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**资料和方法**

### 研究区概况

江群林场位于青海省同德县城西南方向大约50千米处，坐落于阿尼玛卿山地东北部，隶属于黄河上段涵养林区。采样点位于江群林场场部(麦秀镇)西约3千米的加日儿沟南岸，地理坐标为100°19′9.1″E，35°03′48″N。50千米

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大，林相有一定差异，低海拔云杉林中有零星桦树等分布，向上较高海拔为云杉纯林，山顶偶有柏树，灌木也稀少，整个山坡土层较厚，林下稀草分布，都有伐桩。

采样遵循一定的采样策略，样本未受火灾、虫害等干扰，采集树龄长短不同、小生境不同的样本等。按敏感性原则、生态环境原则和复本原则等，每个采样点都在 21 株树以上，每树用生长锥在胸径位置的不同时取芯作为样本，样本树多为树龄较长的健康树。这样，在同一个坡面上按不同的海拔自上而下依次分为 4 个采样带：

<table>
<thead>
<tr>
<th>Sampling sites</th>
<th>Elevation</th>
<th>Sample numbers</th>
<th>Time-span</th>
<th>r</th>
<th>M</th>
<th>A. C.</th>
<th>M. S.</th>
<th>Missing rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>TJQH</td>
<td>3370 – 3445</td>
<td>35[29]</td>
<td>1880 – 2002</td>
<td>0.685</td>
<td>2.97</td>
<td>0.817</td>
<td>0.245</td>
<td>0.155</td>
</tr>
<tr>
<td>TJQMH</td>
<td>3300 – 3350</td>
<td>26[20]</td>
<td>1874 – 2002</td>
<td>0.725</td>
<td>2.38</td>
<td>0.759</td>
<td>0.277</td>
<td>0.547</td>
</tr>
<tr>
<td>TJQML</td>
<td>3250 – 3270</td>
<td>31[21]</td>
<td>1821 – 2002</td>
<td>0.701</td>
<td>2.25</td>
<td>0.752</td>
<td>0.274</td>
<td>0.254</td>
</tr>
<tr>
<td>TQJL</td>
<td>3120 – 3160</td>
<td>30[20]</td>
<td>1851 – 2002</td>
<td>0.764</td>
<td>2.39</td>
<td>0.713</td>
<td>0.328</td>
<td>0.113</td>
</tr>
</tbody>
</table>

$r$ 代表样本序列同主序列间的平均相关系数，$M$ 代表平均年轮宽度，$A. C.$ 代表一阶自相关系数，$M. S.$ 代表平均敏感度。

1.2 气候数据的选择

选取距采样点最近的同德县气象站（G2J/& 4 <!B 0/I/ 3 2110）年的器测资料。该站多年平均气温为 1X 4I，多年平均降水量为 422& 1 <<。本研究所选的气候要素为前一年的 H 月份至当年的 01 月份共 0K 个月的 1H2G 生态学报 2H 卷。
月平均气温和月总降水量和有生长意义的不同时段的组合以及生态学指标:温暖指数(\textit{}/0)、寒冷指数(\textit{10})和湿润指数(\textit{20})。温暖指数是采用月平均气温高于78的总和,作为植物生长的热量条件;寒冷指数是采用月平均气温低于78的总和来表示;湿润指数则是年降水量与温暖指数的比值。

研究方法
本文利用相关函数软件\textit{9:99}计算年表间的相关,目的是想通过树木年轮宽度年表之间的关系揭示不同海拔树木之间的生长异同和影响树木生长因子的差异。利用主成分分析可能归纳出各年表包含的树木径向生长的共同区域变化特征,同时也分析不同海拔树木生长过程中影响因子的异同;利用年表的权重或载荷来表达采样点与主成分间的生长特征关系:权重越高关系越密切。利用\textit{4:1@}软件对4个树轮宽度年表在1880 ~ 2002年的共同区间上进行主成分分析。分别选取树木年轮学专业软件\textit{A'.BC)>??>}和\textit{:DE1FG}应用程序对树木年轮宽度指数与气候因子的关系进行简单相关函数和响应函数分析,以寻求不同海拔树木生长的限制因子以及气候因子及其前期生长对树木年轮形成和发展的贡献,都选用了同德气象站前一年6月份到当年3?月的月平均气温和月降水量分别对不同海拔采样点的树木年轮宽度指数进行相关分析和响应分析,显著性检验用\textit{I))"J"C-#}方法随机执行7??次,以分析不同海拔树木年轮中记录的信号差异。

结果与讨论
树木年轮原始序列结果在不同海拔高度上的差异
不同海拔4个高度的青海云杉,它们的树轮宽度序列特征值在海拔梯度上表现出了一定的规律性(表3):平均相关系数\textit{!}在?& =;7 5 ?& 6=4之间,平均敏感度\textit{K& 9&}在?& >47 5 ?& H;之间,都表现出从低到高递减趋势;平均轮宽高海拔(上限)大于低海拔(下限)大于森林中部,表明森林中部相互竞争和相互干扰使树木生长受到抑制,同时也说明上限树木生长的环境条件优越于其它位置;一阶自相关系数\textit{@& 1&}值在?& 63H 5 ?& ;36之间,说明这一地区前一年的树轮生长强烈地影响着下一年的树轮生长,并且海拔越高影响越大。

不同海拔树木年轮年表序列结果的对比
表明显可以看出,各采样点标准年表样本间和树与树间的相关系数(\textit{!}3,\textit{!}>\)、信噪比(\textit{9GD})、样本量的总体解释信号(\textit{E:9})和第一主分量(\textit{:1@3})在不同海拔都有较高的数值,表明各海拔生长的树木都含有较多的环境信息;但反映环境变化的树轮年表平均敏感度(\textit{K& 9&})和标准差(\textit{9& A&})则随海拔升高呈降低升高降低的波状趋势。这与祁连山青海云杉的叶长、干重和气孔密度随海拔变化的趋势基本一致\textit{>7},显然这是青海云杉对不同海拔气候适应的结果;高海拔树木生长对气候变化的敏感性虽然在一定程度上降低,但由于坡面长度和海拔高差较小的缘故,使敏感性的变化不像祁连山中部\textit{;}那么突出。
不同海拔树木年轮标准年表之间表现出很高的一致性,最低的相关也达到0.637（超过445相关检验）。

主成分分析结果发现第一主成分的贡献率占67.0375,表明同一坡面不同海拔影响树木生长的主导因子是一致的;其它的主成分贡献率都低于70.5,说明单个小生境因子的影响相对较小(表2)。但从不同主成分的载荷(特征向量)来看,第二、三、四主成分的差别很大,表明不同海拔影响树木生长的小生境要素比较复杂。从载荷的变化规律来看,第三主成分的载荷表现出的变化规律与海拔高度的变化有一定的联系。

表3

<table>
<thead>
<tr>
<th>Principal components</th>
<th>Eigenvalue</th>
<th>Variance</th>
<th>Cumulative</th>
<th>Eigenvectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TJQH</td>
</tr>
<tr>
<td>PC1</td>
<td>3.2428</td>
<td>81.071</td>
<td>81.071</td>
<td>0.493</td>
</tr>
<tr>
<td>PC2</td>
<td>0.3698</td>
<td>9.245</td>
<td>90.316</td>
<td>-0.582</td>
</tr>
<tr>
<td>PC3</td>
<td>0.2116</td>
<td>5.289</td>
<td>95.605</td>
<td>0.619</td>
</tr>
<tr>
<td>PC4</td>
<td>0.1758</td>
<td>4.395</td>
<td>100.000</td>
<td>0.189</td>
</tr>
</tbody>
</table>

青海云杉的生长与不同时段的温度和温暖指数都成负相关,尤其春、夏季均温和温暖指数特别显著,说明生性喜温凉的云杉,在气温高、太阳辐射强和空气相对湿度低的条件下,树木失水较多,气孔生理学报卷932010年6月22日。
图

第一主分量与月均温和月降水量的简单相关分析结果

部分关闭引起光合作用能力下降，在生理上起到生长抑制作用。当然春末夏初的高温往往会造成地面水
分蒸发旺盛，使树木生长初期出现生理缺水现象，从而形成窄轮。温暖指数实际上是一种简化了的有效积
温，树轮宽度与温暖指数和月份均温的相关数值基本相同，从而也证明了月份就是本研究点青
海云杉的活跃生长季即树木的高生长期，这与同德县志上注明的江群一带的农作物生长季一般始于
月，月终于，日基本对应。青海云杉生长的海拔高度比作物高，生长季自然要比作物生长季开始晚
些，但生长季的结束也比作物晚些，这一点可用康兴成
“高海拔地区柏树的生长季主要在夏秋季”来解释。

<table>
<thead>
<tr>
<th></th>
<th>Mean month temperature</th>
<th>Total month precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TJQH</td>
<td>TJQMH</td>
<td>TJQML</td>
</tr>
<tr>
<td>JUL</td>
<td>-0.151</td>
<td>-0.205</td>
</tr>
<tr>
<td>AUG</td>
<td>-0.246</td>
<td>-0.227</td>
</tr>
<tr>
<td>SEP</td>
<td>0.033</td>
<td>-0.040</td>
</tr>
<tr>
<td>OCT</td>
<td>0.277</td>
<td>0.294</td>
</tr>
<tr>
<td>May</td>
<td>-0.337</td>
<td>-0.399</td>
</tr>
<tr>
<td>Jun</td>
<td>-0.450</td>
<td>-0.467</td>
</tr>
<tr>
<td>Jul</td>
<td>-0.040</td>
<td>-0.204</td>
</tr>
<tr>
<td>Aug</td>
<td>-0.197</td>
<td>-0.299</td>
</tr>
<tr>
<td>Sep</td>
<td>0.016</td>
<td>0.004</td>
</tr>
<tr>
<td>Oct</td>
<td>0.011</td>
<td>-0.025</td>
</tr>
<tr>
<td>Spring</td>
<td>-0.301</td>
<td>-0.339</td>
</tr>
<tr>
<td>Summer</td>
<td>-0.297</td>
<td>-0.417</td>
</tr>
<tr>
<td>May-Sep</td>
<td>-0.280</td>
<td>-0.422</td>
</tr>
<tr>
<td>WI/PI</td>
<td>-0.285</td>
<td>-0.423</td>
</tr>
</tbody>
</table>

表4  Correlation analysis between standard chronologies and mean monthly temperature and total monthly precipitation of Tongde weather station along elevational gradient in Jiangqun area

http://www.ecologica.cn
上都呈显著正相关，其表现因海拔而异：春季降水的相关随海拔升高呈增强趋势，而湿润指数则呈波状递减。

春季的降水有利于促进树木的萌芽及前期生长，树木年轮的结构中树木早期生长形成的早材占年轮宽度的比重很大，所以春季丰富的降水往往促使树木形成宽轮。

图 0/月均温和月降水量对不同海拔树轮径向生长的响应分析

响应函数分析的结果(图 0)表明：随海拔升高月均温和月降水量综合或单因子对树木径向生长的解释量都是逐渐递减，前期生长的解释量都较大且呈上升趋势，表明该林带的上限受气温和降水的限制作用均低于下限，显然与通常认为的森林上限受气温限制下限受降水的限制不一致。这也表明前人在森林上下限的研究结果与生长在同一坡面的森林上下限结果是有一定差异的，这可能是因为前人的研究往往是针对区域森林分布的上下限，其研究中森林的分布有足够大的垂直空间，但小地形和小气候的干扰也比较大。因此，对于生长在同一坡面上的云杉来说，其影响因子存在着一定的差异，采样时对采样点的布控一定要考虑高差因子，但一般情况下一个坡面生长的云杉林作为一个采样点还是可行的。

2.5 系年表间第一主分量与环境因子关系的模拟

由于同一坡面上不同海拔生长的树木与环境因子之间存在一定的差异，本研究尝试利用多元回归模型来描述年表间第一主分量与影响显著的环境因子间的关系。最优方程为：

$$ R^2 = 49.5\% \quad R_{adj} = 39.1\% \quad F = 4.762 \quad p = 0.01 $$

$ R^2 $ 表示模型总解释量的百分比，$ R_{adj} $ 表示调整后的 $ R^2 $ 以修正了模型中自由度的大小，$ F $ 表示方差分析的 $ F $ 值，$ p $ 表示在给定的显著性水平下，模型显著性的概率。
木年轮生长的重要限制因子。树轮宽度与不同时段的降水的响应结果虽因海拔高度而不同,但其共性显然高于差异性,今后进行树木年轮学研究时可以作为一个采样点来考虑。

比降水的显著正相关在高海拔稍大一些。模拟的结果分析发现,月均温和月降水量对树木年轮指数的方差解释量都是低海拔最高,高海拔最低,随海拔升高呈递减趋势,而前期生长的滞后影响则相反,表明同一坡面低海拔生长的青海云杉受温度和降水的影响都比较大,显然与通常研究的“森林上限受气温限制下限受降水限制”不一致,与天山东部西伯利亚落叶松（同一沟谷的上下限）的生长特征也不相似。

通过不同海拔树轮宽度年表与气候因子的响应分析发现,月均温和月降水量对树木年轮指数的方差解释量都是低海拔最高,高海拔最低,随海拔升高呈递减趋势,而前期生长的滞后影响则相反,表明同一坡面低海拔生长的青海云杉受温度和降水的影响都比较大,显然与通常研究的“森林上限受气温限制下限受降水限制”不一致,与天山东部西伯利亚落叶松（同一沟谷的上下限）的生长特征也不相似。


Fig. 4  The first principal component value of four standard chronologies in different elevations and simulation value of main limiting factors in research area

References

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