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Patterns and dynamics of tree-line response to climate change in the eastern Qilian Mountains, northwestern China

Xiaohua Gou[a,*], Fen Zhang[a], Yang Deng[a], Gregory J. Ettl[b], Meixue Yang[c], Linlin Gao[a], Keyan Fang[a]

[a] *Research School of Arid Environment and Climate Change, Key Laboratory of West China's Environmental System, Ministry of Education, Lanzhou University, Lanzhou 730000, PR China*
[b] *Center for Sustainable Forestry at Pack Forest, School of Forest Resources, University of Washington, Box 352100, Seattle, WA 98195, USA*
[c] *State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, PR China*

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ABSTRACT

Tree-line ecotones are strongly climatically limited and serve as potential monitors of climate change. We employed annual growth increment from tree-rings, and tree density and age structure data derived from two *Juniperus przewalskii* tree-line sites in the eastern part of the Qilian Mountains, northeastern Tibetan Plateau, to detect the responses of tree growth and population dynamics to climate change. High temperature favors tree growth and is associated with increased tree density at tree-line, and an advance in tree-line position. Significantly positive correlations were found between ring-width and mean monthly air temperatures in current and previous June, July and August. Tree recruitment began to increase rapidly at the two sites after the Little Ice Age, but then decreased starting in the 1970s. The number of trees established coincides with temperature changes. The warming trend after the Little Ice Age favors increases of tree density and an advance of tree-line. The majority of trees established during the period of 1931–1970, which coincides well with the rapid radial growth of the trees.

Introduction

Global climate change and its impact on the environment are of serious concern, and it is thought that the dynamics of the tree-line are very sensitive to a change in climate (Holtmeier, 2009). In this paper, "tree-line" is applied to the transition zone extending from closed subalpine forests, to the uppermost stunted and usually scattered, individuals, regardless of their height (Holtmeier, 1981, 2003). Several studies show that tree-line changes with latitude on global and regional scales. Jobbagy and Jackson (2000) demonstrated the importance of warm season temperature in limiting the position of alpine tree-line, and Malyshev (1993) the importance of July temperature in the position of the arctic–boreal ecotone. Tree-line ecotones are sensitive to climate change with increases in temperature being associated with an increase in tree density and tree-line position (Camarero and Gutiérrez, 2004; Fang et al., 2009a). Numerous studies have demonstrated climate-induced community level responses in tree-line dynamics using climate–growth relationships and changes in stand structure and density at high-elevation tree-line ecotones (Harcombe, 1987; Liang et al., 2001; Wang et al., 2006; Pederson et al., 2008; Fang et al., 2009a). Tree-line advances to higher elevations in mountain areas in recent decades have been widely reported (Bradley and Jones, 1993; MacDonald et al., 1998; Camarero and Gutiérrez, 2004). In addition, many dendroecological studies have revealed that stand density also increases (Szeicz and Macdonald, 1995; MacDonald et al., 1998; Camarero and Gutiérrez, 2004) with increased recruitment in response to recent warming at tree-line (Kullman, 1986, 1990; Lavoie and Payette, 1994). However, the responses of tree-line to climatic change are likely complex and other studies have not found significant tree-line advances in response to recent warming trend (Lloyd et al., 2002; Dalen and Hofgaard, 2005; Goldblum and Rigg, 2005; Pfeifer et al., 2005; Wang et al., 2006).

Tree-line responses to recent climate warming are based mainly on the study of tree growth and recruitment within these ecological boundaries using retrospective approaches that take advantage of information stored in tree rings (Tranquillini, 1979; Payette and Filion, 1985; Slatyer and Noble, 1992; Lescop-Sinclair and Payette, 1995; Paulsen et al., 2000). Since the 1990s, many tree-ring studies have been conducted in north central China (Liu et al., 2005; Gou et al., 2007, 2008a,b; Fang et al., 2009b; Shao et al., 2009) including tree-line studies in western China. Previous work has focused on the *Taibai* Mountains (Liu et al., 2003a), *Wutai* Mountains (Liu et al., 2003b), and *Tianshan* Mountains (Wang et al., 2006). To date, few studies have investigated tree-line responses to climate change in

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* Corresponding author. Tel.: +86 0931 8915309; fax: +86 0931 8912330.
E-mail address: xhgou@lzu.edu.cn (X. Gou).

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the Qilian Mountains (Fang et al., 2009a); however this area is an important climatic transition representing the northern boundary of the Tibet Plateau. Our study region located in the Qilian Mountains is little influenced by Asian monsoons and vegetation of this area is sensitive to changes in temperature and precipitation. In this study, we focus on the tree-line ecotone of *Juniperus przewalskii* forest to examine the spatial and temporal dynamics of the tree-line response to climate change by evaluating climate–growth relationships using tree rings, and tree age structure and tree density at tree-line.

Materials and methods

Study areas

The Qilian Mountains (93.52–103.00°E, 36.50–39.50°N; Fig. 1) are located in the marginal areas of Asian monsoon, where the Chinese Loess Plateau meets the Tibetan Plateau. This mountain system is about 850 km long and 200–300 km wide with peaks over 4000 m a.s.l. The precipitation decreases from east to west and mainly occurs in the summer. The mean temperature is 0–5 °C within the elevation of 2000–3000 m a.s.l. The dominant tree species in this region are Qilian juniper (*J. przewalskii* Kom.), Qinghai spruce (*Picea crassifolia* Kom.), aspen (*Populus davidiana* Dode), and birch (*Betula platyphylla* Suk.). Qilian juniper grows in open stands on dry, exposed slopes at elevations ranging from 2700 to 3400 m a.s.l. Forest soils are typically montane, brownish grey, and subjected to serious erosion where not protected by vegetation cover (Liu et al., 2005).

Sampling strategy and dendrochronological methods

Field measurements and sampling were carried out in August 2008 in the Shiyang river basin, the eastern part of the Qilian Mountains. The tree-ring samples were collected at sites *JinDongGou* (JDGs: JDG01, 101°37′17″E, 37°43′52″N, 3558–3680 m a.s.l.; JDG02, 101°37′18″E, 37°43′52″N, 3592–3700 m a.s.l.) from living *J. przewalskii* trees generally growing on steep south-facing slopes (Fig. 1). Two rectangular plots (35 m × 160 m at JDG01 site; 30 m × 120 m at JDG02 site) were established at each site in topographically uniform parts of the tree-line ecotones. The two rectangular plots had their longer side (120 or 160 m), *y* axis, parallel to maximum slope and included current tree-line, and the *x* (short) axis (30 or 35 m) follows the altitudinal gradient upslope. Tree locations (*x* and *y* coordinates) and size (diameter at cored height as close to the ground as possible) were recorded in the field for individual *J. przewalskii* trees within the plot. Individuals with heights less than or equal to 0.5 m were regarded as seedlings and were not sampled. One to two tree cores were extracted from trees over 0.5 m in each plot. At site JDG01, 160 cores (from 80 trees) were collected and the position of 167 trees was recorded within the plot. At site JDG02, 77 cores (from 37 trees) were collected and the position of 50 trees was recorded.

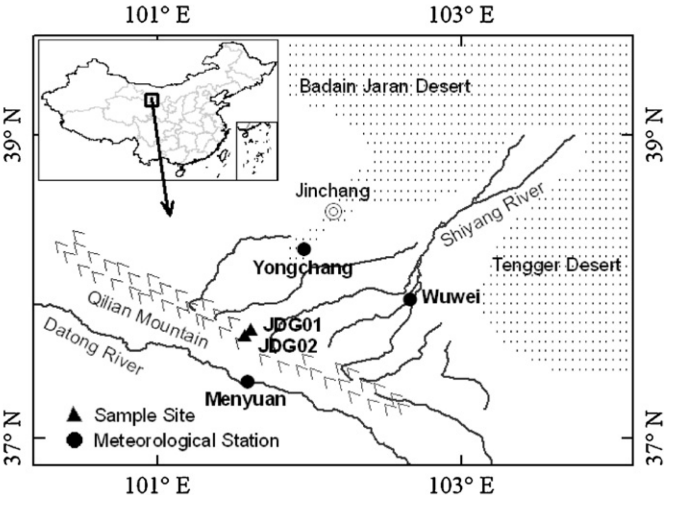

Fig. 1. Locations of the sampling sites (JDG01, JDG02) and meteorological stations along the Qilian Mountains.

All cores were mounted, air dried, sanded and cross-dated using standard dendrochronological methodology (Stokes and Smiley, 1968). The rings were counted, and visually cross-dated; the ring widths were then measured to 0.001 mm precision using Velmex TBA. Cross-dated series were verified using the cross-dating program COFECHA (Holmes, 1983). In this study, we only included trees older than 100 years to develop a chronology. Age-related trend in growth was removed conservatively from raw series by fitting either a straight line or a negative exponential curve with the program ARSTAN (Cook and Holmes, 1986). For some tree-ring series, this conservative approach left substantial decadal variation in growth which was removed by fitting a conservative cubic spline equal to 67% of the series length spline functions. Thirty-four detrended cores representing 19 trees were used to produce mean standard chronologies (STD) using a bi-weight mean calculation (Cook and Holmes, 1986).

Increment cores sometimes failed to reach the pith of the tree because of incorrect borer alignment, eccentric growth rings or rotten tree centers. We adopted the Initial Radial Growth model of Rozas (2003) in order to extrapolate the ages for the missing portion of tree cores. The model is based on the assumption that the growth of individuals of the same species from a region is similar. Finally, a linear multiple regression function was used to predict the number of rings in the missing radius from the length of missing radius and the mean growing rate of rings adjacent to the pith as predictors. In addition, we adopted Duncan's geometrical model to estimate the length of the missing radius (Duncan, 1989).

We established the age–diameter relationships at the cored height to estimate the *J. przewalskii* ages. A regression of tree diameter at the cored height and age was developed from 79 cores to estimate the ages of all trees which were too young to be sampled in the plots (Fig. 2). Cores were then sorted into age groups of 10-year intervals (Fig. 4a and b).

Results and discussion

Radial growth and its climate associations

Meteorological data from Wuwei meteorological station, which is about 100 km away from the sampling sites, was used in analyses (Fig. 1). Correlation coefficients were calculated to quantify relationships between tree-ring chronologies and monthly mean air temperature and monthly precipitation from 1961 to 2004. Tree growth can be influenced by climate conditions in previous and current years (Fritts, 1976), and therefore correlation analysis was performed from June of the previous year to September of the current year.

Climate–growth correlations indicate growth was mainly limited by monthly mean air temperature with positive temperature–growth correlations for all months (Fig. 3). The mean air temperature in the summer season (June–August) was significantly positively correlated with ring-width indices, especially for current June ($r = 0.543$, $p < 0.01$). No significant correlations were found