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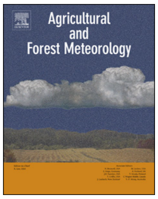

Increased growth of Qinghai spruce in northwestern China during the recent warming hiatus

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ABSTRACT

The effect of warming-induced drought stress on tree growth has been frequently discussed, and a decline in the growth of forest and increased mortality has been reported for many areas of the world. A hiatus in the global warming trend began around the year 2000, but how tree growth has responded to this warming slowdown remains unclear. Here we present a study of the recent impacts of climate change on Qinghai spruce (*Picea crassifolia*) growth using 38 tree-ring records collected from the Qilian Mountains in northwestern China. Results indicate that there was a clear increase in Qinghai spruce growth during the recent warming hiatus. Similarly, regional vegetation growth also improved as indicated by NDVI variations, which is closely associated with regional climate changes. The mean air temperature increased dramatically during the period 1980–2001, whereas precipitation decreased slightly. This combination of warmer temperatures and reduced precipitation created drought conditions that limited the growth of Qinghai spruce during this period. Since 2001, the warming trend has slowed, whereas precipitation has clearly increased, creating moist conditions as reflected by the higher drought index (SPEI). A decline in drought pressure, coupled with an increasingly long growing season, might be the main reason for the recent improvement in the growth of Qinghai spruce in the Qilian Mountains. Our results suggest that the growth of Qinghai spruce is very sensitive to climate change. A better understanding of future climate changes and their likely impact on tree growth should be of significant interest to forest managers.

1. Introduction

Climate change has important implications for forest productivity, carbon stocks, and forest community structure and species compositions because it directly influences tree growth, phenology, vulnerability to disturbance, and so on (Bonan, 2008; Seidl et al., 2017). Many studies have suggested that a warming climate has aggravated the effects of drought stress on forest growth, and drought-induced tree decline and mortality have been reported all over the world (Allen et al., 2010; Worrall et al., 2013; Liu et al., 2013; Hogg et al., 2017; Chen et al., 2017). However, the warming climate has also been shown to lengthen the growing season, accelerating tree growth rates and increasing forest biomass at some sites (Salzer et al., 2009; McMahon et al., 2010; Pretzsch et al., 2014). Thus, climate warming might affect tree growth in diverse ways for different area and tree species.

At the same time, there is debate about the temporal stability of the tree growth response to climate change. At several circumpolar northern latitude sites, a reduction in the sensitivity of tree-ring records to temperature since the mid-20th century has been found to be related to global warming (Briffa et al., 1998; D'Arrigo et al., 2008). The recent global warming hiatus, which began around the year 2000 and has persisted for nearly 15 years (Kosaka and Xie, 2013; Guan et al., 2015), is likely to have had a significant influence on tree growth. However, the effects of this warming slowdown on tree growth remain unclear. A comprehensive study of tree growth response to this hiatus using a large number of tree samples would help shed light on this question, especially in the vulnerably arid and semi-arid regions.

The Qilian Mountains are located in the arid and semi-arid transition regions of northwestern China and at the northeastern edge of the Tibetan Plateau. They stretch from east to west for about 800 km. Climate change, glacier melting and vegetation variations in the Qilian Mountains will significantly influence the oasis farming in the down-river Hexi corridor, which is an important region for China's 'Belt and Road' plan. Qinghai Spruce (*Picea crassifolia*) is an endemic tree species in northwestern China; in the Qilian Mountains, Qinghai spruce as one of the dominant coniferous species, occupying about 20.5% of the forest area and playing an important role in climate regulation, water conservation and the prevention of desertification (Zhang and Zhou, 2003).

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Several climate projections indicate increasing drought intensity, frequency and duration (IPCC, 2013), and accelerated dryland expansion in the arid and semi-arid regions in the coming future (Huang et al., 2016). Therefore, understand how the Qinghai spruce growth respond to the climate change in the Qilian Mountains is critical for ecological and social development in this region.

Several previous studies in the Qilian Mountains have analyzed the spatial variability of Qinghai spruce growth along a latitudinal transect (Liang et al., 2010) and the elevation gradients (Gao et al., 2013; Zhang et al., 2017a). These studies suggest that moisture availability is a dominant limiting factor for tree growth in this area. In the central Qilian Mountains, a decline in Qinghai spruce tree growth and an increasing in tree mortality has been reported for several high elevation sites (Liang et al., 2016). At the same time, an increase in the growth of Qinghai spruce has been attributed to warming temperatures and a reduction in the frequency of frost during the growing season at a high elevation site in the eastern Qilian Mountains (Waring and Gao, 2016). In addition, some previous studies indicate that the decline of Qinghai spruce growth since the 1980 s is due to accelerated warming (Li et al., 2015). However, because global warming paused after 2000 for almost 15 years (Guan et al., 2015), we hypothesize that the growth of Qinghai spruce should show signs of recovery in response to the warming hiatus and reduction in drought stress.

In this study, we investigated the impacts of climate change on Qinghai spruce growth using tree-ring data collected from 38 plots in the Qilian Mountains. We aim to 1) assess the tree growth patterns and responses to the climatic shift from warming to a warming hiatus, as well as to precipitation and drought variations; 2) analyze the climate-growth relationships of Qinghai spruce with climate change; 3) evaluate the regional vegetation variation tendency and provide some insights for future forest management.

2. Data and methods

2.1. Study sites

On the north side of the Qilian Mountains, 38 studied plots were selected along a northwest-southeast transect, with an average distance from one plot to the next of about 20 km (Fig. 1a). The elevation of the Qilian Mountains increases gradually from southeast to northwest, with a maximum elevation of 5808 m in the northwest of the range. For the period 1961–2015, the mean annual temperature in the study sites ranged from −7.1 °C to 7.6 °C, which is strongly related to elevation (Fig. 1b). The total annual precipitation varied from 109 mm to 588 mm, with the central-eastern part of the mountains receiving the most moisture (Fig. 1c). The majority (79%–91%) of the annual precipitation occurred between May-September, which is also the warmest period of the year. Qinghai spruce is a cold- and shade-tolerant species that is usually found on north facing slopes. This species is mainly distributed at elevations ranging from 2500 to 3500 m a.s.l (Zhao et al., 2008). Pure Qinghai spruce forests are very common in this area, with high canopy closure and few understory shrubs.

2.2. Tree-ring data

We conducted the tree-ring sampling work in the autumn of 2016. 38 pure Qinghai spruce forest stands were carefully selected in areas with light human activity. The elevations of these sampling plots ranged from 2655 m to 3140 m a.s.l. (see details in Supplementary Table S1). For each stand, a 20 m × 20 m sampling plot (or 25 m × 25 m for some stands with sporadic and large trees) was deployed, and 25–39 trees were randomly selected and sampled. Two cores were extracted from different directions for each tree at a height of about 50 cm above the ground. In a few cases (27 trees), the extracted cores run through the transversal surface of the tree. We measured the two sides of these cores to help with cross-dating and to get more useful tree-ring series. In total, 2349 tree-ring cores from 1161 Qinghai spruce trees were collected for this study.

All of the tree cores were taken to the laboratory and processed according to the standard techniques of dendrochronology (Stokes and Smiley, 1968). After being air-dried and mounted, tree cores were polished with sandpaper until all rings were clearly visible under the microscope. We then dated every ring and measured ring-widths using the Velmex measuring system with a precision of 0.001 mm. The COFECHA and TSAP programs were applied to check the quality of cross-dating (Holmes, 1983; Rinn, 2003). The computer program ARSTAN was used for detrending and for calculating the tree-ring chronologies (Cook et al., 2013). Conventional straight lines and negative exponential curves were used to detrend most of the tree-ring series, but a cubic smoothing spline with a 50% frequency response cutoff equal to 67% of the series length was used in a few cases if the previous two curves did not provide a good fit. Finally, 38 standard chronologies were developed for the subsequent analysis. To verify the growth trend of Qinghai spruce indicating by the tree-ring chronologies, we also calculated the basal area increment (BAI) from the ring widths using the Dendrochronology Program Library in R (dplR, Bunn, 2008).

2.3. Climate data

Several kinds of climate data were used to explore the climate variations and the climate-growth relationships, including precipitation (monthly), temperature (monthly and daily), and the Standardized Precipitation Evapotranspiration Index (SPEI;Vicenteserrano et al., 2010). Because publicly available weather stations are sparse and generally far from the sampling sites in this region, gridded climate data with a spatial resolution of 0.5° × 0.5° was used in this study. The precipitation and temperature datasets were downloaded from the China Meteorological Data Service Center (CMDC; http://data.cma.cn/). These datasets were developed from quality- controlled observational data from 2472 gauges located throughout mainland of China and in operation since 1961. The data were interpreted to a 0.5° × 0.5° grid with the ANUSPLIN software using the thin plate smooth spline method. Because there were some missing values for the years 2015 and 2016, we used monthly data from 1961 to 2015 and daily data from 1961 to 2014. The daily mean temperature was used to compute the number of days with a daily temperature higher than 5°C, which was referenced as the length of the growing season. This is because Qinghai spruce growth usually begins in May (Tian et al., 2017), when temperatures are about 5°C on average. The SPEI data utilized in this study were obtained from the SPEI base version 2.5 (Beguería et al., 2010; available at http://sac.csic.es/spei/database.html), which was calculated from the CRU TS 3.24.01 dataset. For this study, we used the SPEI at the 12-month scale for the period 1961–2015.

2.4. NDVI data

To investigate variations in the satellite-derived regional vegetation greenness over the last several decades, the biweekly Normalized Difference Vegetation Index (NDVI; obtained from the GIMMS team; https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/; Pinzon and Tucker, 2014) was used in this study. This updated NDVI dataset has a spatial resolution of 1/12° and spans the period from 1981 to 2015. However, as the records for 1981 are incomplete, we used just the data from 1982 to 2015 for this analysis. The maximum value at each grid point for each year was used, and only the grid points with a mean annual NDVI larger than 0.1 were applied in the analysis to exclude no or sparsely vegetated grid points. Differences in the NDVI between the 1990 s and the 1980 s were calculated, as were the differences between the 2000 s and the 1990 s, and the 2010 s and the 2000 s.