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ORIGINAL ARTICLE

Response of stem radial growth of Qinghai spruce (*Picea crassifolia*) to environmental factors in the Qilian Mountains of China

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ABSTRACT

Exploring the response of intra-annual tree growth to environmental factors is critical for the understanding of the effects of climate changes on tree seasonal growth patterns. We monitored stem radial changes of Qinghai spruce (*Picea crassifolia*) over two growing seasons (2014 and 2015) in the Qilian Mountains of China using high-resolution point dendrometers. Our results showed that the onset of the main growth period occurred around 11 May. Soil temperature was a key environmental factor influencing the onset of tree growth. Stem radial growth commenced when soil temperature at 40 cm depth was > 0 °C. The timing of radial growth cessation exhibited greater variability than onset, ranging from late July to early August, and was probably unrelated to climatic conditions. We found close relationships between maximum daily shrinkage (MDS) and air temperature, precipitation, soil water content, and soil temperature. Maximum and mean air temperature, relative air humidity, vapor pressure deficit, and precipitation had significant effects on daily stem radial increment (SRI). Precipitation was one of the most important factors influencing stem radial growth. Moreover, the number of precipitation days was more significant in promoting cumulative seasonal growth of Qinghai spruce than total precipitation. With climate warming, the onset of radial growth may occur earlier than before, and seasonal growth patterns of trees may change.

1. Introduction

Recent climate warming may have considerable effects on tree growth in semi-arid areas (Boisvenue and Running, 2006) because increasing temperatures and changing precipitation regimes may affect seasonal growth patterns. Tree growth responses to environmental factors form the foundation of dendroclimatological studies. Due to the relatively low resolution of dendroclimatology, tree growth responses to environment may be assessed only on inter-annual time scales. However, short time-scale responses of tree growth to environmental factors are needed.

Dendrometer measurements facilitate continuous monitoring of intra-annual stem radial growth at high temporal resolution without invasive sampling (Drew and Downes, 2009; Deslauriers et al., 2011). During the whole growing season, the cumulative stem radial growth curves had an S shape, which could be divided into three periods according to the growth rate (Xiao et al., 2013). The first and third periods were the beginning and ending of the whole growing season, respectively, which mainly related to spring rehydration, tree water status and cell wall thickening. The second period was the main growth period, and the differentiation and growth of cells in the cambium occurred mainly. At a diurnal scale, several variables, such as maximum daily shrinkage and stem radial increment, also could be extracted for the following analysis (Downes et al., 1999). This technique has been extensively used to study the relationships between intra-annual variation in stem radial growth and microclimate for different tree species in a variety of environments (Downes et al., 1999; Zweifel and Häsler, 2000; Deslauriers et al., 2007a; Wang et al., 2012; Xiao et al., 2013, 2014; Zhang et al., 2016). Previous studies found that temperature was the most important factor limiting the initiation of growth (Turcotte et al., 2009; Wang et al., 2014). Belien et al. (2014) showed that rain exclusion repeated for 3 years resulted in a significant reduction in summer stem contraction of mature black spruce, but not in total stem expansion. Jiang et al. (2015) reported that the daily stem radial growth of *Platycladus orientalis*, one of the dominant evergreen tree species in semi-arid areas of northern China, was mainly

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limited by moisture availability.

In the arid northwestern region of China, the Qilian Mountains are one of the most important sources of water, feeding the Shiyanghe, Shulehe, and the Heihe Rivers. Forest vegetation in the area represents not only a valuable forest resource, but also helps to conserve a limited water supply (Xu et al., 2009). Qinghai spruce (*Picea crassifolia*) is an important long-lived dominant evergreen species in the region, growing on shaded or semi-shaded slopes at elevations of 2600–3400 m (Zhao et al., 2006). Due to its recognized sensitivity to climate change, Qinghai spruce has been widely used in dendroclimatological studies (Liang et al., 2006; Liu et al., 2007; Zhang and Wilmking, 2010; Wang et al., 2016). Thus, Qinghai spruce tree-ring width chronology facilitated drought reconstruction for years 1856–2009 for the eastern Qilian Mountains (Deng et al., 2013). Liang et al. (2006) showed that annual radial growth had an opposite response to climatic factors on west- and on east-facing slopes, and a significant positive correlation with winter temperature. However, the responses of intra-annual daily stem radial growth to environmental factors, and the primary growth period of Qinghai spruce remain unclear.

In this study, we measured growth of Qinghai spruce using high-resolution automatic point dendrometers and monitored the environmental factors synchronously over two growing seasons. The main objectives of this study were to (1) determine the main growth period of Qinghai spruce, (2) test the response of daily stem radial increment (SRI) and maximum daily shrinkage (MDS) to environmental factors during the main growth period, and (3) determine which environmental factors control tree growth.

2. Materials and methods

2.1. Study area

The study was conducted in a pure Qinghai spruce forest, located on a north-facing slope at 2800 m elevation in the Pailugou watershed in the central Qilian Mountains (100°17′13.3″ E, 38°33′11.5″ N). The area is the heartland of a mountainous environment with little human influence except for a few herdsmen occasionally tending to their livestock. The main soil type is gray-cinnamon soil with a calcareous rock parent material, coarse texture, and an average soil depth of 70 cm (Chang et al., 2014a; He et al., 2014). The mean annual air temperature between 1994 and 2015 was 0.5 °C, and the mean maximum and minimum annual air temperatures were 28.0 and −36.0 °C, respectively. The mean annual precipitation at an elevation of 2700 m was 375.5 mm, of which 70% fell from May to September.

Qinghai spruce is the dominant tree species in the watershed, at ages ranging from 80 to 120 years old, and stand density of 1100 trees/ha (Chang et al., 2014a, b). Average tree height is 11.8 ± 2.8 m, and average diameter at breast height is 18.2 ± 6.5 cm (Table 1). For our measurements, we selected four Qinghai spruce trees at an elevation of 2800 m, which represents the middle elevation of Qinghai spruce distribution in the Qilian Mountains.

2.2. Dendrometer records

From late April to late October of 2014 and 2015, high-resolution automatic point dendrometers (EcoMatik, Germany; type DR, accuracy ± 2 µm, temperature coefficient < 0.1 µm/K) were used to measure stem radial changes in four Qinghai spruce trees. Dendrometers were installed on trees at breast height. Parts of the bark were removed without wounding of the cambial zone to reduce the influence of expansion and shrinkage of the bark. Changes in stem radial growth were recorded every 30 min using a data logger (EcoMatik, Germany), and hourly averages were calculated for subsequent analyses.

Due to instrumental problems, measurements from one tree were not available. Therefore, data for only three trees were used for further analyses (Table 1).

Table 1
The basic information of three measured trees.

Trees	Diameter at breast height (cm)	Height(m)	Age(year)	History of damage
Tree1	15.0	10	92	None
Tree2	23.6	13	102	None
Tree3	13.7	9	85	None

2.3. Environmental records

During the seasonal growth period in 2014 and 2015, a weather station was installed in an exposed space near the monitored trees to record precipitation (P, mm), air temperature (T, °C), and relative air humidity (RH, %). The vapor pressure deficit (VPD, kPa) was calculated from the values of T and RH. In addition, an EM50 (Decagon, Inc. Decagon, USA) was installed close to the monitored trees to synchronously and continuously monitor soil moisture content and soil temperature. A soil moisture and a temperature sensor was placed at depths of 5, 10, 20, 40, and 60 cm. Because up to 95% of roots of Qinghai spruce are found up to 45 cm of soil depth, soil moisture and temperature at 20 and 40 cm (SWC20 and SWC40, $m^3\,m^{-3}$; T20 and T40, °C) were selected for analyses. Environmental data were recorded every 30 min synchronously with the dendrometer measurements.

2.4. Measurements of stem radial changes

Stem radial changes, representing a combination of reversible shrinkage and expansion, and irreversible radial growth, were measured continuously. Several variables can be extracted from such raw data to comprise the basis of climate-growth analyses. Based on the stem cycle approach, the circadian cycle can be divided into three distinct phases over approximately 24 h (Downes et al., 1999): (a) contraction phase, period between the morning maximum and daily minimum; (b) recovery phase, the radial increase to the point observed at that morning's maximum; (c) stem radial increment phase, the stem radial growth increase until the commencement of the shrinkage phase in the next diurnal cycle. According to these definitions, stem radial increment (SRI) and maximum daily shrinkage (MDS) were obtained from each tree (Fig. 1). Then, daily averaged SRI and MDS for the study trees were calculated for subsequent analyses (Fig. 2a, b). SRI was considered equal to zero when negative value occurred.

2.5. Estimation of the main growing season

The Gompertz function is one of the most commonly applied models

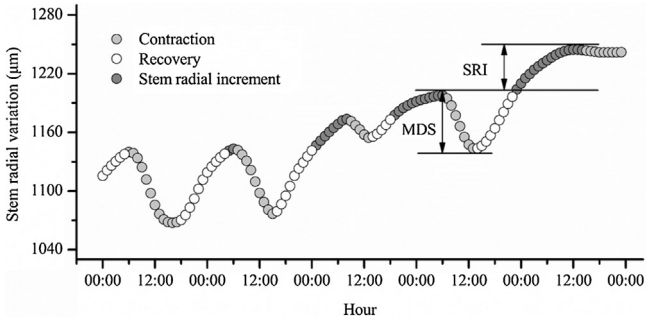

Fig. 1. Circadian cycle of a tree stem divided into three distinct phases: contraction, recovery, and stem radial increment. The SRI and MDS represent daily stem radial increment and maximum daily shrinkage, respectively. The cycles are an example of data recorded for one tree between the day of year (DOY) 184–189 (3–8 July), 2014.