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Research Paper

Can forest water yields be increased with increased precipitation in a Qinghai spruce forest in arid northwestern China?

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A B S T R A C T

Climate-induced changes in regional precipitation are projected to affect forest water yields, although the effects are expected to vary. Few studies, in fact, have examined the response of conifer forests to increases or decreases in precipitation, in arid regions. To answer the question posed above, we investigated the variability of forest canopy transpiration versus precipitation during the 2011–2013 growing seasons, and constructed a complete hydrological budget of an arid montane spruce forest by directly measuring its main component at the stand level, at long-term experimental catchments on Qilianshan Mountain, located in the upper Heihe River Basin, in the arid region of northwest China. It was found that total precipitation during the 2012 and 2013 growing seasons was 12.3% and 36.5% higher, respectively, than during the 2011 growing season, and total stand transpiration during the 2012 and 2013 growing season was 12.5% and 21.7% higher, respectively, than during the 2011 growing season. In the study period, transpiration, soil and moss evaportranspiration, canopy evaporation, and the drainage and change in soil water storage accounted for 71.1%, 19.9%, 5.3%, and 3.8% of the precipitation, respectively. Although the precipitation increased during this study period, the increase was not sufficient to increase the forest water yield. In the future, though, if the precipitation continues to increase in this forest, it may be sufficient to effect such an increase in forest water yield.

1. Introduction

Global warming has become an indisputable fact (IPCC, 2007), and changes in global and regional climate have raised concerns about the potential impact of precipitation and temperature on the water budgets of terrestrial ecosystems (Vitousek, 1994; Hanson and Wullschleger, 2003; Knapp et al., 2001; Weltzin et al., 2003). The spatio-temporal distribution of precipitation and its trends and variability, associated with climate change caused by global warming and human activities, have received much attention, particularly in arid and semi-arid areas where precipitation is an extremely important environmental factor. In these areas, the distribution and variation of precipitation can have a significant impact on the local ecological systems and environment (Lioubimtseva et al., 2005; Lioubimtseva and Henebry, 2009). Increases and decreases in precipitation are expected to alter surface evaporation, transpiration, and soil water content, which, in turn, will have implications for plant function, catchment water yield, and hydrologic budgets across broad spatial scales (Wullschleger and Hanson, 2006).

In arid regions, and especially in northwestern China, water is almost always a strong limiting factor for the continuous existence of biota, even when temperature, radiation, and nutrients are sufficient. In this area, the mountains—including ranges such as the Qilian, the Helan, and the Tianshan, experience higher precipitation than some of the lower-elevation lands in the region, and this precipitation plays an important role in supplying water to those lowlands. Some studies have found that annual precipitation in the arid zone of northwest China has been tending toward moister conditions than normal (Yang et al., 2014; Li et al., 2013; Wang et al., 2013; Lan et al., 2012; Wang et al., 2008; Xu et al., 2008; Zhai et al., 2005). The effects of this increased precipitation on water yield from riparian headwaters are of great concern, given their key role as sources of water supply (National Research Council, 2008). It is not known, however, whether the increased water yield from these headwaters has resulted from an increase in alpine precipitation. One must consider quantifying hydrologic components in the montane forested catchments of this area, as this information is essential for water resource management, especially considering that forest management in the 21st century may need to include provisions for multiple ecosystem services, including maintaining adequate water supplies (Likens and Franklin, 2009).

The Heihe River, which originates in the Qilian Mountains, is one of

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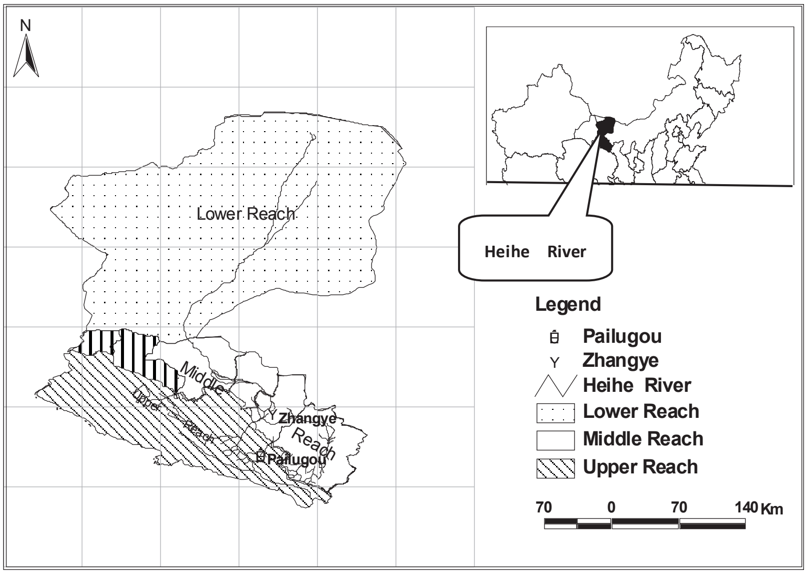

Fig. 1. Map of the Heihe River Basin and its location in the Northern of China.

the largest inland rivers in the arid zone of northwestern China. The forest vegetation of the Qilian Mountains not only serves as a valuable forest resource, but also performs the ecological function of water storage. In fact, this forest is designated as a water conservation forest. These water resources support the oasis ecosystem of the middle and lower reaches of the inland river system, and the adverse processes of deep drainage and runoff are thereby minimized.

Qinghai spruce (*Picea crassifolia*) is the dominant tree species in the Qilian Mountains. The upper Heihe River Basin comprises 43.16×10^4 hm^2 of forest area, with Qinghai spruce forests occupying about 25% of the total forest area and 78% of the arbor forests (Chang et al., 2001). Because of this species' critical role in maintaining favorable hydrological processes, it is important to understand its physiological processes and its contributions to maintaining the water balance. To gain a clearer understanding of the water budget of this forest, it is essential to develop a modeling framework for predicting the effects of possible land use and climate changes on water resources in the region, especially rainfall change, because alterations in the quantity, intensity, and frequency of precipitation, and the resulting changes in soil water availability, could have important implications for Qinghai spruce forest ecosystems. However, hydrological knowledge of this system remains poor. Therefore, a detailed estimate of all the components comprising this integrated flux is needed, in order to understand the controls over ecosystem responses to changes in precipitation and climate, namely, Qinghai spruce forests' transpiration (E_C), soil and moss evaportranspiration(E_s), and evaporation originating from precipitation intercepted by the canopy (E_I). This study aimed to fulfill this knowledge gap.

Transpiration by Qinghai spruce forests can be a substantial component of the total water budget of montane systems in the upper Heihe River Basin. Under the complex terrain and spatial heterogeneity of the forest environment, there are a considerable uncertainty in the estimates of transpiration in these systems. Because complex terrain and spatial heterogeneity do not limit its applicability, a sap-flow technique is most effective. This technique has proved to be a useful methodology for investigating forest water use at both temporal and spatial scales (Granier, 1985; Smith and Allen, 1996; Wilson et al., 2001; Green et al., 2003; Kumagai et al., 2007; Ford et al., 2007). Common methods for studying sap flow include heat pulse (Swanson and Whitfield, 1981; Edwards and Warwick, 1984; Edwards et al., 1996; Vertessy et al., 1997; Chang et al., 2006; Chang et al., 2014a, 2014b), stem segment heat balance (Čermák et al., 1998; Cienciala et al., 1992; Jiménez et al., 1996; Čermák et al., 2004), heat dissipation (Granier, 1985; Loustau et al., 1998; Meinzer et al., 2001; Bush et al., 2010), and heat field deformation (Čermák et al., 1998; Meiresonne et al., 1999; Čermák and Nadezhdina, 2000).

In the present study, the heat-pulse velocity method was used to characterize the temporal variability of transpiration from a Qinghai spruce forest in the upper Heihe River Basin of arid northwestern China, as the method can obtain reliable estimates of long-term forest stand transpiration. Estimates of whole-tree transpiration tend to differ by less than 15% between the heat-pulse velocity method sensors and cut-tree (potometer) measurements (Olbrich, 1991; Smith, 1991; Barret et al., 1995; Hatton et al., 1995).

The objectives of this study were to: (a) improve the understanding of the interannual variation of transpiration from Qinghai spruce canopies; (b) partition the water balance of the forest by determining all of its components at the stand level; and (c) provide greater insight into the links between precipitation variability and forest water yields in montane forested catchments of the arid zone of northwestern China.

2. Materials and methods

2.1. Experimental site

This study was carried out on Qilianshan Mountain, located in the upper Heihe River Basin, in pure stands of Qinghai spruce (*Picea crassifolia*) located on a bench within a north-facing slope at 2800 m elevation in the Pailougou watershed (100°17′E, 38°24′N) (Fig. 1), 50 km south of Zhangye, Gansu province, during the 2011–2013 growing seasons. From 1994 to 2010, the mean annual air temperature was 0.5 °C, and the mean maximum and minimum temperatures were 28.0 °C and −36.0 °C, respectively. Annual precipitation was between 290.2 and 467.8 mm, and the pan evaporation was 1051.7 mm. The frost-free period was about 165 days per year.

The forest in the north slope of watershed, 50% coverage of the forest canopy, consists mainly of Qinghai spruce ranging from 80 to 120 years old. The leaf area index (LAI) of the selected stand was 1.84 (measured with a Digital Plant Canopy Imager (CI – 110, CID, Inc., Washington, U.S.A.)). The stand density was 1100 trees ha^{-1} and the frequency distribution of tree diameters at breast height (D_{BH}, mm) is shown in Fig. 2. Tree height ranged from 5.0 m to 16.5 m; the average was 11.8 ± 2.8 m. Diameter at breast height ranged from 80 mm to 330 m; the average was 18.2 ± 6.5 cm. Moss (*Abietinella abietina*) covered the forest floor. The moss was 10 cm to 20 cm thick and at about 95% coverage. There were no Qinghai spruce seedlings or