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Environmental and physiological controls on sap flow in a subhumid mountainous catchment in North China

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ABSTRACT

To accurately quantify tree transpiration and determine related hydrologic and physiological processes, it is important to have reliable information on environmental and physiological controls on sap flow. The objective of this study is to explore the environmental and physiological controls on sap flow in a headwater catchment in the subhumid mountainous region of North China, which has pronounced environmental specificities in hydro-climatic conditions, bedrock properties, and edaphic features. Sap flow in Aspen (*Populus davidiana*) (one of the dominant tree species in the region) and relevant environmental and physiological factors were measured from 2013 to 2014. The results indicate the following: (1) The dominant controlling factor of sap flow switched from a meteorological to a physiological factor when leaf area index (*LAI*) dropped to a low value (approximately <1 $m^2\ m^{-2}$) around early October; (2) *LAI* exhibited a threshold control on possible maximum sap flow with a *LAI* threshold value of 3.5 $m^2\ m^{-2}$, while environmental factors led to fluctuations in sap flow within the upper bound that was determined by the physiological factor *LAI*; (3) Photosynthetically active radiation (*PAR*) was the key environmental factor controlling sap flow as a whole, while at the monthly timescale the controls of environmental factors on sap flow had significant seasonal variability; (4) The diurnal relationships between sap flow and environmental factors revealed evident hysteresis loops, which were markedly influenced by the radiation factor. With the combination of the environmental factor *PAR* and the physiological factor *LAI*, an empirical regression equation ($SFD = 0.7059PAR * LAI + 4.5068$, $R^2 = 0.8862$, $n = 207$) was established for sap flow estimation in the study area. These results shed light on the hydrologic and physiological processes involved in tree transpiration, and contribute to the refinement of tree transpiration models in regions under similar environmental conditions.

1. Introduction

Tree transpiration is an important component of the water balance in forest ecosystems (Small and McConnell, 2008; Sun et al., 2014; Wilson et al., 2001). Accurate estimates of individual tree transpiration are significant for plant physiology, hydrology, and other studies (Chang et al., 2014; Dragoni et al., 2005; Mitchell et al., 2009). Sap flow, an indicator of water movement in the tree trunk, has a strong linear relationship with individual tree transpiration (Dragoni et al., 2005; Kume et al., 2008). A few approaches have been developed to measure sap flow, of which the thermal dissipation method is perhaps the most widely used (Bovard et al., 2005; Chang et al., 2014; Chen, D. et al., 2014; Chen, L. et al., 2011; Clausnitzer et al., 2011; Du et al., 2011; Granier, 1985, 1987; O'Brien et al., 2004; Oren and Pataki, 2001; Small and McConnell, 2008; Wullschleger et al., 2001).

Sap flow is primarily controlled by both environmental and physiological factors. Environmental factors mainly include meteorological factors (air temperature, rainfall, vapor pressure deficit, and radiation), soil moisture content, edaphic features, groundwater table and others. Physiological factors mainly include leaf area index, crown width, and other factors representing the dynamics of tree growth and phenology. To acquire accurate tree transpiration estimates and have a sound understanding of the hydrologic and physiological processes involved in tree transpiration, it is of great importance to conduct in-depth analyses of the environmental and physiological controls on sap flow (Chang et al., 2014; Ford et al., 2005). Many studies have been carried out on this question for

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various tree species under different environmental/hydro-climatic conditions (Arneth et al., 1996; Bovard et al., 2005; Chang et al., 2014; Chen, D. et al., 2014; Chen, L. et al., 2011; Clausnitzer et al., 2011; Du et al., 2011; Liu et al., 2012; O'Brien et al., 2004; Oren and Pataki, 2001; Small and McConnell, 2008; Zeppel et al., 2004). These studies revealed that the major controlling factors of sap flow include, but are not limited to, vapor pressure deficit, radiation, air temperature, soil moisture, and leaf area index, while the environmental and physiological controls on sap flow vary significantly with environmental/hydro-climatic conditions, tree species and time period. Several studies have combined environmental factors with physiological factors to acquire more-accurate estimates of sap flow (Chang et al., 2014; Chen et al., 2014; Liu et al., 2012; Wullschleger et al., 2001; Xu et al., 2011), while the forms of the estimates are quite different from each other.

This study focuses on the environmental and physiological controls on the sap flow in the subhumid earth-rocky mountainous region of North China, which has pronounced environmental specificities in hydro-climatic conditions, bedrock properties and edaphic features (Peng et al., 2016; Sun et al., 2014; Zhao et al., 2015). The rainfall is moderate (~600 mm $year^{-1}$) and concentrated in summer, a typical characteristic of monsoon-influenced climate. The soil layer is quite thin (0–1.5 m). There is a layer of regolith between the soil layer and the bedrock layer under the ground, and the groundwater table is generally shallow (1–10 m). These environmental specificities lead to significant specificities in the environmental and physiological controls on sap flow, which, to the knowledge of the authors, have seldom been analyzed in depth in previous studies. Aspen (*Populus davidiana*), which is widely distributed over China, is one of the dominant tree species in the region (Lee et al., 2011; Li et al., 2004; Zhang et al., 2009). In this study, field experiments were carried out in a headwater catchment (named the Xitaizi Experimental Watershed) that is a typical subhumid earth-rocky mountainous region of North China. The sap flow in Aspen (*Populus davidiana*) was measured using the thermal dissipation method from 2013 to 2014, and relevant environmental and physiological factors were monitored simultaneously.

The main objectives of this study were: (1) to investigate synergetic mechanisms and processes of environmental and physiological controls on sap flow; (2) to detect key environmental factors controlling sap flow and to analyze the synchrony and hysteresis relations between sap flow and environmental factors; and (3) to establish an empirical equation combining environmental and physiological factors to estimate sap flow.

2. Materials and methods

2.1. Study site

The field experiment was conducted in 2013–2014 in the Xitaizi Experimental Watershed (XEW, located at 40°32′ N and 116°37′ E, see Fig. 1). It is in the headwater area of Miyun Reservoir, the drinking water source for Beijing, the capital city of China. The catchment area is 6.48 km^2, and the elevation ranges from 550 to 1200 m a.s.l.

XEW has a monsoon-influenced subhumid continental climate characterized by a hot/humid summer and cold/dry winter. According to the Miyun meteorological station (40°23′ N, 116°52′ E, 71.8 m a.s.l., 27 km southeast of XEW), the mean annual air temperature, accumulated temperature (>0 °C), sunshine duration, relative humidity, and precipitation values are 11.5 °C, 4565.0 °C, 2334.5 h, 59.1%, and 625.4 mm, respectively. Rainfall mainly occurs from June to September (~80% of the annual total).

XEW is a typical area of the earth-rocky mountainous region of North China. According to the soil map and the field investigations, the main soil types are brown earth and cinnamon soil (in terms of Chinese soil taxonomy) with a depth of 0–1.5 m, depending on topography. The bedrock is mainly granite (approximately 88% of the total), while gneiss and dolomite are also distributed sporadically in XEW. The groundwater table is 1.2–9.4 m below the ground surface according to the water level data of 10 groundwater observation wells (named OW 1 to OW 10; see Fig. 1). By interpreting high-resolution satellite remote sensing data, a land use map of XEW with a spatial resolution of 1 m was acquired. This map shows that the forest covers 98.0% of XEW, of which 54.2% is broad leaved, 2.3% is coniferous, 10.5% is coniferous and broad leaved mixed, and the other 33.0% is shrubbery. The forest of XEW is dominated by Aspen (*Populus davidiana*), according to our field investigations.

A typical hillslope in XEW was chosen as the study hillslope (named SH, see Fig. 1). It is a north-facing hillslope at an elevation of 780–805 m a.s.l. and is covered by a broad leaf forest consisting of pure stands of Aspen (*Populus davidiana*). According to the sample plot investigation, the stand density is 13 trees/100 m^2, the average tree height is 11.6 m, the average crown width is 3.5 m, and the average diameter at breast height (*DBH*) is 14.5 cm.

2.2. Sap flow measurements

Sap flow was measured in 2013–2014 by thermal dissipation probes (TDPs) (Dynamax, Inc., Houston, TX, USA). A probe set consists of two needles, a heated needle above and a reference needle below. Each needle has a copper-constantan thermojunction inserted in a needle-shaped stainless steel tube. The heated needle has a heating element inserted in the tube, while the reference one does not. After two pieces of tree trunk bark (roughly a 5 cm^2 rectangular area) were peeled off, the two needles were inserted into the sapwood approximately 0.15 m apart vertically. The temperature difference between the upper heated needle and the lower reference needle was measured at 1 min intervals, and 10 min averages were recorded on a CR1000 data logger (Campbell Scientific, Inc., Logan, UT, USA). The empirical relationship established by Clearwater et al. (1999) and Granier (1987) was adopted to calculate the sap flux density from the temperature difference between the two needles, i.e.:

$$SFD_i = 0.0119\left(\frac{\Delta T_m - \Delta T}{\Delta T}\right)^{1.231} \quad (1)$$

where SFD_i is the sap flux density of tree i (g cm^{-2} s^{-1}), ΔT is the temperature difference between the two needles (°C), and ΔT_m is the maximum value of ΔT recorded in the non-transpiration period when SFD_i is near zero (°C).

Twelve trees with different *DBH* were selected for sap flow measurements in SH during the growing seasons of 2013 and 2014. The general features of the sample trees are summarized in Table 1. To match the sapwood width of the different trees, three different-sized probes were used (TDP10, TDP30, TDP50, with lengths of 10 mm, 30 mm, and 50 mm, respectively). Because the trees should be preserved from destruction for future studies, only a single probe was installed on the trunk of each sample tree to minimize tree injury (O'Brien et al., 2004). According to Jimenez et al. (2000), considerable variation in sap flow measurements can be induced by probe placement. To avoid such placement variation among different sample trees, all probes were consistently installed on the south side of the corresponding trunks at approximately 1.1 m above the land surface. After installation, the probes were sealed with silicon foam to prevent rain water infiltration and were shielded with aluminum foil to avoid physical damage and insulate them from thermal influences from ambient temperature fluctuations and solar radiation.

The sap flux density of a single tree may have significant variability for a study on the general sap flow characteristics of a typical