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Seasonal variations in depth of water uptake for a subtropical coniferous plantation subjected to drought in an East Asian monsoon region

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ABSTRACT

Seasonal drought will become more intense and frequent in some regions due to global climate change, which may lead to significant changes in the competitive interactions and uptake depths of plant water sources. Based on δ^{18}O and δD in xylem and soil water, we investigated the impacts of seasonal drought on plant water sources from July 2011 to October 2013 for a subtropical coniferous plantation in southeastern China. Our results indicated that the studied tree species of *Pinus massoniana*, *Pinus elliottii* and *Cunninghamia lanceolata* appeared to have inter-specific competition for water resources from similar depths. There was a switch of the major water source from shallow soil during the non-drought periods (July to October) to deep soil during the drought periods (November–June). Similar seasonal trend of water uptake was estimated by δ^{18}O and δD. However, relative to the results of δD, water sources predicted by δ^{18}O showed that trees seemed to derive more deep soil water during the drought periods and more shallow soil water during the non-drought periods. The differences of plant water source partitioning based on δ^{18}O and δD were significant during both the drought and non-drought periods, which probably resulted from the artifacts of the cryogenic vacuum distillation and spectral contamination correction. These findings will have important implications for further studies when just one of the dual stable isotopes of δ^{18}O and δD is applied.

1. Introduction

Forests play an important role in terrestrial ecosystem hydrological cycles, and the distribution and abundance of which are mainly constrained by water resources (Dodd et al., 1998; Drake and Franks, 2003; Liu et al., 2010a,b). As anthropogenic influence has led to significant changes in climate, the occurrence of drought will become more intense and frequent in the future (IPCC, 2013). During the drought periods, coexisting plants usually adopt contrasting water use strategies, such as temporal and spatial partitioning of resource utilization, to maximize species diversity (Dodd et al., 1998; Liu et al., 2010a,b; Moreno-Gutiérrez et al., 2012). It also has been suggested that species with dimorphic root morphology could tap distinct zones of soil water, and change source water utilization seasonally (Ehleringer and Dawson, 1992; Meinzer et al., 1999; Nie et al., 2011). The hydrogen and oxygen stable isotopes (δ^{18}O and δD) provide us a powerful tool for determining plant water sources in a number of environmental conditions (Dawson and Ehleringer, 1991; Eggemeyer et al., 2009; Brooks et al., 2010; West et al., 2012).

Plant species with contrasting water use strategies are shown to coexist in different ecosystems (Eggemeyer et al., 2009; Liu et al., 2010a,b; Moreno-Gutiérrez et al., 2012). For example, mixed woody–herbaceous systems are able to exist, mainly because trees and shrubs tend to utilize deeper soil water than grasses (Le Roux et al., 1995; Asbjornsen et al., 2008; Eggemeyer et al., 2009). Studies of comparing depths of water uptake by co-occurring woody species show that some species only tap water from deep or shallow soil, while others use both layers (Dodd et al., 1998; West et al., 2007; Eggemeyer et al., 2009). The different water use strategies of coexisting species can be considered as a hydrological niche partitioning, which plays a positive role in minimizing competition and improving adaptability in water-limited ecosystems (Moreno-Gutiérrez et al., 2012).

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Plants capable of absorbing deeper soil water should be more competitive than those of solely depending on surface soil water, due to the severe water deficit of surface soil during drought periods (Ehleringer and Dawson, 1992). As rainfall is plentiful in tropical and subtropical forests, plants are normally shallow rooted and extract water from surface soil layers (Schenk and Jackson, 2005). In water limited regions, where surface soil water tends to be unavailable, plants are generally deep rooted and primarily tap deep soil water (Nie et al., 2011). But in fact, many plant species in arid and semiarid ecosystems, as well as in seasonal dry areas, possess a dimorphic root system: a zone of lateral roots predominantly acquires water from surface soil layers in wet season, and a second zone of penetrating taproots derives water from deep soil layers in dry season (Ehleringer and Dawson, 1992; Dawson and Pate, 1996; Liu et al., 2010a,b).

A number of previous studies have been conducted in arid and semiarid regions; however, plant water sources in tropical and subtropical areas are little known (Liu et al., 2010a,b; Goldsmith et al., 2011; Nie et al., 2011). This is mainly because the premise of identifying plant water sources by stable isotopes is that there must be clear vertical gradients of δ^{18}O and δD in soil stratum (Ehleringer and Dawson, 1992). But the δ^{18}O and δD in precipitation often exhibit little seasonal variations in tropical and subtropical regions compared to that in temperate areas, which leads to the similar signatures of δ^{18}O and δD in soil stratum (Querejeta et al., 2007). Moreover, most of previous studies utilize just one of the dual stables isotopes of δ^{18}O (McCole and Stern, 2007; Querejeta et al., 2007; Liu et al., 2010a,b; Nie et al., 2011) or δD (Jackson et al., 1995; Filella and Peñuelas, 2003; West et al., 2012). Although δ^{18}O and δD are both used in some studies (Cramer et al., 1999; Li et al., 2007; West et al., 2007; Eggemeyer et al., 2009; Wang et al., 2010; Rossatto et al., 2012; Orlowski et al., 2013; Meißner et al., 2014), whether there are differences between δ^{18}O and δD predictions of water source are still unclear.

According to the 7th National Forest Resource Inventory Report, plantations occupy about 31.6% of the total forest area in China, ranking 1st in the world (CAF, 2010). Furthermore, 54.3% of the plantations are distributed in the subtropical region (Sun et al., 2006). This region is characterized by the subtropical Eastern-Asian monsoon with abundant water and energy, however, seasonal drought always occurs resulting from the inconsistent distributions of temperature and precipitation in summer (Wen et al., 2006, 2010; Tang et al., 2014a,b). Previous studies mainly focused on the effects of seasonal drought on carbon and water exchange processes for the coniferous plantation at Qianyanzhou site in ChinaFLUX (Wen et al., 2006, 2010; Saigusa et al., 2010; Tang et al., 2014a,b). The objectives of this study are to (i) investigate the competitive interactions of water sources for tree species of Masson pine (*Pinus massoniana* Lamb.), Slash pine (*Pinus elliottii* Englem.) and Chinese fir (*Cunninghamia lanceolata* Hook.), (ii) analyze the impacts of seasonal drought on water uptake depth for trees, (iii) identify whether there are differences between δ^{18}O and δD predictions of water source.

2. Materials and methods

2.1. Study site

Qianyanzhou site, a member of ChinaFLUX, is located in Qianyanzhou ecological station of the Chinese Ecosystem Research Network (CERN) (26°44′52″N, 115°03′47″E, and elevation 102 m). This area is strongly influenced by the subtropical Eastern-Asian monsoon climate. Annual precipitation and mean air temperature are 1377.4 mm and 17.1 °C (1985–2013), according to meteorological records of CERN. The soil is mainly red earth, which is weathered from red sandstone and mud stone (Wang et al., 2011). Soil texture is divided into the following particle grades: 2.0–0.05 mm (17%), 0.05–0.002 mm (68%) and <0.002 mm (15%). Bulk density of the surface soil (0–40 cm) is 1.57 g cm^{-3}. The coniferous plantation was planted around 1985, and the prevailing tree species were *P. massoniana* Lamb., *P. elliottii* Englem. and *Cunninghamia lanceolata* Hook., with sparsely scattered woody species of *Schima superba* Gardn. et Champ. According to the survey conducted in 2008, mean heights of *P. massoniana*, *P. elliottii* and *C. lanceolata* were 11.2, 14.3 and 11.8 m, mean diameters at breast height were 13.6, 18.2 and 13.8 cm, and the stem densities were 700, 545 and 93 stems ha^{-1}, respectively. Further details about the site are provided in Wen et al. (2006, 2010) and Tang et al. (2014a,b).

2.2. Meteorological measurements

Supporting measurement consisted of a suite of micrometeorological sensors installed above the canopy and in the soil. They provided half-hourly measurement of net radiation (Model CNR-1, Kipp & Zonen Inc.), air temperature (Model HMP45C, Vaisala Inc.), soil water content (Model CS615-L, Campbell Scientific Inc.), soil heat flux (Model HFT-3, Campbell Scientific Inc.), and precipitation (Model 52203, RM Young Inc.).

Budyko's aridity index (AI) is calculated by the ratio of precipitation amount to potential evapotranspiration (P_{ET}). AI < 1 indicates periods of drought stress (Budyko, 1974). P_{ET} was calculated as 1.26 × the equilibrium evapotranspiration (ET_{eq}) (Priestley and Taylor, 1972), which was calculated as

$$ET_{\mathrm{eq}} = \frac{((R_n - G) \times s)}{(s + \gamma)} \quad (1)$$

where R_n is the net radiation (W m^{-2}), G is the soil heat flux, s is the slope of a function relating saturation vapor pressure to temperature (kPa K^{-1}), γ is the psychrometric constant (kPa K^{-1}).

2.3. Water sampling and isotopic analyses

Tree stems and soils were sampled over a twenty-eight month period from July 2011 to October 2013 for determining their δ^{18}O and δD. Stems were sampled from the south side of one mature tree per species (*P. massoniana*, *P. elliottii* and *C. lanceolata*) every 2–4 days per week (at midday). These trees were randomly selected around a bamboo building (~12 m height), which was used to facilitate the sampling of tree twigs. Stems samples for *C. lanceolata* were sampled only once per week since April 2012, because the continuous sampling was more destructive to this tree species. For each sample, phloem tissue was removed to avoid contamination by isotopically enriched water (Querejeta et al., 2007). Then, the stems were immediately cut into small segments, placed in vials and sealed with parafilm.

One soil core of 0–100 cm (increased to 3 soil cores since January 2013) was sampled monthly by a hand auger around the sampling trees. The soil core was collected every 5 cm depth in the 0–20 cm, every 10 cm in the 20–60 cm and every 20 cm in 60–100 cm layers. The three tree species were planted together and mixed well, therefore, we assumed the δ^{18}O and δD in soil water around the sampling trees were consistent.

A funnel and a polyethylene bottle were connected together as a rain collector. A ping-pang ball was put in the funnel to prevent evaporation (Liu et al., 2010a,b). Precipitation samples were collected after each rain event.

All the samples for isotopic analyses were kept frozen in a refrigerator (−15 to −20 °C) prior to water extraction. Water in xylems and soil samples were extracted using a cryogenic vacuum distillation system (West et al., 2006). Generally, 0.5–1.5 h would be required depending on the water content of samples. The extracting