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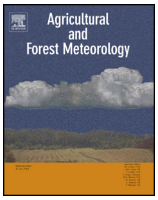

Deep soil water extraction helps to drought avoidance but shallow soil water uptake during dry season controls the inter-annual variation in tree growth in four subtropical plantations

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ABSTRACT

Some essential features of forest hydrologic cycles are based on observations of the soil water balance. However, measurements of soil water dynamics in subtropical forests have mostly been restricted to the upper 100 cm of soil. The relative shallow depth in soil water measurement would bias the understanding how and to what extent soil water contributes to evapotranspiration. We investigated and compared the soil water dynamics down to 200 cm depth over 7 years in four subtropical plantations, including one mixed stand type (*Cunninghamia lanceolata* mixed with *Schima superba*) and three pure stand types (*C. lanceolata*, *Pinus elliottii*, and *Pinus massoniana*). We also examined the variations in fine root distribution and tree basal area increment across stand types. We showed that, in contrast to the *P. elliottii* and *P. massoniana* stands, the *C. lanceolata* stand type extracted deep soil water when the top soil was still wet, depleted soil water over a longer season, but consumed less total soil water during the dry season. Our results revealed that the mixed stand type depleted more soil water during the dry season than the pure *C. lanceolata* stand type. In addition to the species-specific traits of water consumption, the different soil water depletion between stand types seems to be also accounted for by the different slope aspect and rock fragment content. During the entire dry season, the four stand types mainly relied on the soil water in the 100–200 cm soil depth where fine root density was considerably low, however, the inter-annual variation in stem growth depended on the soil water depletion from 0 to 50 cm soil layer. We conclude from these results that deep soil water is likely to make a significant contribution to drought avoidance over the dry period, but the available of shallow soil water to the fine roots during dry season may determine how well trees grow. This study highlights the important to consider the deep soil water extraction when explain the ecosystem evapotranspiration variations.

1. Introduction

Key features of the terrestrial hydrologic cycle have been inferred from observations of the soil water balance of different ecosystems and results of stochastic models of soil moisture dynamics (Guswa et al., 2002; Porporato et al., 2004). Forests cover approximately 30% of the land surface (Bonan, 2008) and emphasize the need to understand how different forests use soil water.

Trees could have dimorphic root systems, which enable them to switch between shallow and deep water sources depending on availability (Burgess et al., 2001). During the wet season, trees extract water primarily from shallow layers where the root density is highest. During the dry season, however, transpiration is sustained by water taken up from progressively greater depths and deep taproots may also act as conduits that transfer soil water from wet deep soil layers to dry topsoil layers via hydraulic redistribution (Burgess et al., 1998). The water extracted from deep soil or even within bedrock is important for tree growth, especially during the dry season (Jackson et al., 2000; Stahl et al., 2013; Deng et al., 2015). Interspecific variation in leaf phenology and rooting patterns

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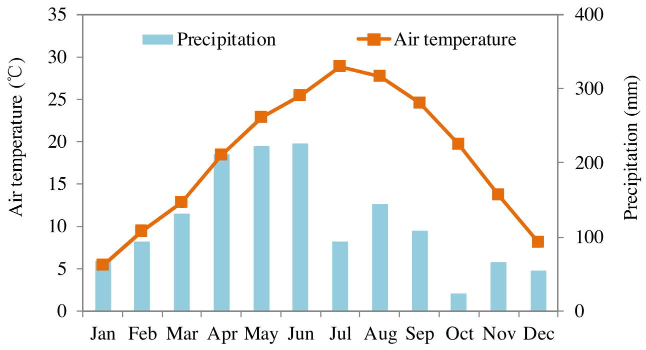

Fig. 1. Multi-year (2004–2010) monthly precipitation (bars) and average monthly air temperature (curve) at the meteorological station in the study site.

contribute to temporal variation in water use and responses to seasonal droughts (Meinzer et al., 1999; Nie et al., 2011). Analyses of the natural abundance of stable isotopes of hydrogen and oxygen in soil and tree xylem water have permitted characterization of the temporal dynamics of reliance on soil water resources at different depths during the dry season in temperate forests (Plamboeck et al., 1999; Hipps et al., 2014) and tropical forests (Jackson et al., 1995; Meinzer et al., 1999; Stratton et al., 2000; Stahl et al., 2013), and for selected months in subtropical forests (Nie et al., 2011; Deng et al., 2015). However, the vertical dynamics of soil water use by vegetation cannot be adequately characterized when the vertical gradients of $\delta^{18}O$ and δD in soil water are weak or irregular (Yang et al., 2015). Alternatively, seasonal dynamics of reliance on soil water resources at different depths can be determined at the stand level from changes in soil water storage over given time periods using traditional techniques for measurement of soil water content such as neutron probes (Chanasyk and Naeth, 1996), time domain reflectometry (Ledieu et al., 1986) and frequency domain reflectometry (Warren et al., 2005).

Subtropical forests have experienced the highest rates of change in forest cover during the last decade because of the extensive forestry practiced within native forests (Hansen et al., 2013), and are likely to experience major reductions in rainfall during the next century (Bard, 2013). Understanding how subtropical forests use soil water is thus crucial to establishing and quantifying how the terrestrial hydrologic cycle adapting to the forestry practices and regional climate anomalies in this region. Based on an estimate of 700 cm for the maximum rooting depth of trees globally (Canadell et al., 1996) and that the rooting depth of trees in karst regions with shallow soils exceeded 100 cm (Nie et al., 2014), it is reasonable to expect that the rooting depth of the dominant trees in subtropical forests could exceed 100 cm. If this is the case, then the contribution of soil water depletion below 100 cm depth to total soil water use and ecosystem evapotranspiration during dry seasons cannot be neglected. However, measurements of soil water dynamics and depletion in subtropical forests have been mostly carried out within shallow soil horizons of 50 cm depth (Yu et al., 2008; Ritter et al., 2009; Tang et al., 2014; Xu et al., 2014) with only a few soil moisture datasets encompassing relatively deep soil profiles (e.g., 150 cm deep, Fujieda et al., 1997; 100 cm deep, Yang et al., 2015). The relatively shallow depth of soil water content measurements would bias understanding of how and to what extent deep soil water contributes to evapotranspiration.

In the present study, we measured soil moisture to 200 cm depth with neutron probes in four subtropical plantations (including one mixed stand type and three pure stand types) in southeast China over 7 years. Due to its continental monsoon climate, subtropical China is characterized by abundant water resources. However, temperature and precipitation are usually out of phase in summer, and thus subtropical plantations always suffer from seasonal drought (Sun et al., 2006; Wen et al., 2010). Our main objectives were: (1) to quantify the seasonal dynamics of contributions of soil water extraction from different depths to soil water depletion and investigate the impact of planting different tree species and changes in tree species composition on these patterns, and (2) to examine the effects of deep soil water extraction on inter-annual variation in stem growth. This study provides insight into the underlying mechanisms of how soil water availability regulates ecosystem evapotranspiration and tree growth in the subtropical forests.

2. Materials and methods

2.1. Study site

This study was conducted at the Qianyanzhou Ecological Station (26°44′39″N, 115°03′33″E, 102 m a.s.l.) in the Jiangxi Province in southeastern China. The station occupies approximately 204 ha, and has a typical subtropical climate. The mean annual temperature is 17.9 °C, with a mean daily minimum temperature of 6.4 °C in January and a maximum of 28.8 °C in July. The mean annual precipitation is 1489 mm, mostly occurring between March and June. Fig. 1 shows the multi-year (2004–2010) mean temperature and precipitation. The precipitation during the first half year is higher than that during the second half of the year. The research station is characterized by undulating hillslopes, resulting in a gradient of xeric (upslope), subxeric (midslope), and mesic habitats (downslope). The zonal vegetation at the station, a subtropical evergreen broadleaf forest, had almost disappeared prior to the 1980s due to deforestation, and the dominant vegetation had become grassland and scattered shrubland, and severe soil degradation had occurred. Widespread reforestation was implemented in 1983 to revert the soil degradation. The reforested stand types were mainly one mixed stand type (*Cunninghamia lanceolata* mixed with *Schima superba* with the ratio of 2:3) and three pure stand types (*C. lanceolata*, *Pinus elliottii*, and *Pinus massoniana*). *C. lanceolata* and *P. massoniana* are dominant native species, while *P. elliottii* was introduced from southeastern United States. *P. massoniana* and *S. superba* grow well in poor site conditions (Xiang et al., 2011). *C. lanceolata* requires deep, fertile, moist but well-drained soil (Li and Ritchie, 1999). The four stand types were designed to distribute differentially along the hillslopes. The mixed stand type and pure *C. lanceolata* were distributed at the down slope. However, *P. elliottii* and *P. massoniana* were typically associated with mid slope and up slope, respectively.

2.2. Sampling and measurement

2.2.1. Soil moisture measurement and changes of soil water storage estimation

Within each stand type, one edaphically and vegetationally representative plot (30 × 30 m) was established. The soil texture of the four stand types along the soil profile is uniform and classified as silt sandy loam according to the USDA classification. Geographic information about these plots, together with soil properties and stand structure are shown in Table 1. Estimation of soil properties, shrub and herb covers were based on nine locations sampled in August 2014. Stem density, basal area, and DBH were determined for every tree in each plot. Understory cover was estimated visually (Kent and Coker, 1992). Three 2 × 2 m subplots were delimited near the soil water monitoring locations within each plot for the surveys of shrub layer. One 1 × 1 m quadrat was delimited within the 2 × 2 m subplot to estimate the cover of herb and fern. The rock fragment fraction varied considerably among plots with the soil profile in the mixed stand type containing a higher rock fragment fraction than in the pure stands. The soil from the pure *C. lanceolata* stand was more fertile than in the other three stands as indicated