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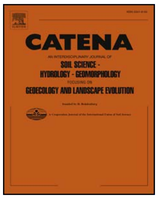

Temporal partitioning of water between plants and hillslope flow in a subtropical climate

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ABSTRACT

Recent work has suggested that ecohydrological separation may exist between the water sources for recharge and plant water uptake. However, the temporal partitioning of plant transpiration and hillslope flow is still poorly understood. In a growing season, the stable isotopes of precipitation, soil water, groundwater, plant water and hillslope flow in a subtropical climate in Southwest China were determined to assess the compartmentalization of vegetation water use and flow generation. The results suggest that the hillslope flow and plant water have different isotopic characteristics in most cases. The lc-excess values of plants significantly differed from those of the hillslope flow. These different isotopic signatures for plants and the hillslope flow were associated with the different proportions of various water sources in each water pool. Precipitation, the hillslope flow and soil water plot approximately along the local meteoric water line (LMWL), and the studied plant xylem waters plot partly below the LMWL, supporting ecohydrological separation. In this subtropical climate with seasonal droughts, the hydrological separation is temporal and does not occur during the wet season due to the increase in hydrological connectivity. On dry days, the various water sources poorly mix in the subsurface. Thus, the ecohydrological separation between the plant water and hillslope flow water sources varies depending on the rooting depth of plant species and moisture conditions. The implications underlying these findings will be helpful for constructing a process-based ecohydrological model and for understanding the mechanisms underlying the hydrologic interactions between plants and subsurface water flow.

1. Introduction

Most watershed hydrology models and coupled ecology-biogeochemical-hydrology models assume complete mixing for subsurface water, and this assumption is called the black box approach (Hewlett and Hibbert, 1967; McDonnell et al., 2007; Alila et al., 2009). This single ecohydrological reservoir paradigm leads to the concept that roots uptake water from the same pool that is moving to streams (Brooks et al., 2010; Evaristo et al., 2015). However, other studies have demonstrated that the mixing process involving precipitation and soil water is not complete in the vadose zone due to preferential flow pathways and the different mobilities of pre-event water, including the mobile and tightly bound fractions of resident soil water (Brooks et al., 2010; Zhao et al., 2013; McDonnell, 2014; Zhao et al., 2016). Good et al. (2015) estimated that hydrological connectivity ranges from 14 to 59% at the global scale, which suggests a pervasive disconnect between water bound in soils and water entering streams, although not a complete separation. Dawson and Ehleringer (1991), Ehleringer and Dawson (1992), Brooks et al. (2010) and Penna et al. (2013) found that the isotopic characteristics of water bodies differed in various climates. In addition, it is important to understand the connections between plant water use and hydrologic flow paths, as well as the associated impact on the streamflow regime, to fully comprehend underground hydrological processes (Asbjornsen et al., 2011; Evaristo et al., 2015). These studies highlight the need for an in-depth deeper mechanistic understanding of the link between plant water uptake and streamflow patterns in different ecosystems and climatic regions. An improved understanding of hydrological connectivity is essential at variety of temporal and spatial scales (Good et al., 2015).

Brooks et al. (2010), Goldsmith et al. (2012) and Evaristo et al. (2015) demonstrated a complete separation between vegetation water, which was strongly enriched by evaporation, and stream-recharged

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water, which was less enriched in Mediterranean and tropical climates due to hydrological separation. However, Geris et al. (2015), Hervé-Fernández et al. (2016) and McCutcheon et al. (2017) found that soil waters with different mobilities could be isotopically similar. They suggested that the isotopic distinction between root-absorbed and draining waters may not be an appropriate indicator of the ecohydrological separation of soil waters. Hervé-Fernández et al. (2016) and McCutcheon et al. (2017) concluded that in a rainy temperate climate, the "two water worlds" hypothesis (an ecohydrological separation of water flowing to streams or recharging groundwater and water used by trees) is temporally variable. In addition, water that contributes to groundwater recharge is not always isolated from water used in plant transpiration (Jasechko et al., 2014; Jasechko and Taylor, 2015). Moreover, most of these studies were based on sampling campaigns of 1 to 2 days (i.e., 10 to 15 xylem samples), so their conclusions may not be representative of all situations. Sprenger et al. (2017) noted that a high sampling frequency over time and at various depths is critical when using stable isotopes as tracers to assess plant water uptake patterns within critical zones. However, few experiments have accounted for the temporal variability of the ecohydrological separation (Hervé-Fernández et al., 2016).

Stream water typically features multiple water sources, including precipitation, soil water, irrigation water, domestic wastewater, and groundwater (Dahl et al., 2007; Tang et al., 2008; Tan et al., 2017). Determining why the source of plant water is different from that of stream water may be hindered by the complexity of the water sources of stream water. Answering the question at the hillslope scale is feasible because this scale represents and determines the streamflow signature, which is ultimately generated with little disturbance (Klaus et al., 2013). The ecohydrological connectivity of plant water use and flow generation is more direct at the hillslope scale than at the catchment scale. However, the literature includes a distinct lack of field work and direct evidence relevant to the complex interactions between plant water uptake and flow generation on hillslopes (Butt et al., 2010).

Simple linear mixing (SLM) models have been widely used in partitioning source contributions to plant water based on stable isotope methods (Liu et al., 2015; Zhao et al., 2016; Rothfuss and Javaux, 2017). Traditional SLM models have been used to estimate two or three water sources (e.g., Thorburn and Walker, 1993; Brunel et al., 1995), and relatively recent SLM models can address multiple sources via an iterative mass balance approach (e.g., IsoSource by Phillips and Gregg, 2003). However, such methods do not consider the effects of standard deviations. When employed in a Bayesian inverse modeling framework based on a Markov Chain Monte Carlo (MCMC) calculation, SLM models have been used to correct the isotopic enrichment coefficient (e.g., MixSIR by Moore and Semmens, 2008; SIAR by Parnell et al., 2010). However, few plant source water partitioning studies have used SLM models in Bayesian frameworks (e.g., Leng et al., 2013; Barbeta et al., 2015). Parnell et al. (2010) and Evaristo et al. (2016) proved that this approach is useful for partitioning the contributions of various sources of plant water. Rothfuss and Javaux (2017) performed a comparison of the "direct inference" method, the two-end member mixing model and multisource mixing models. The inter-comparison underlined the satisfactory performance of the Bayesian approach of Parnell et al. (2010), which uses a rigorous statistical framework.

Determining the various sources of vegetation water and hillslope flow is helpful for vegetation restoration, river discharge predication, and ecosystem protection in ecologically fragile regions. Clarifying the water sources of vegetation water use and hillslope flow generation is also important for understanding the underground ecohydrological processes in various hydroclimate environments. Consequently, the objectives of this study were as follows: 1) to explore the water sources, as well as the temporal variation in these sources, of hillslope flow and plant water, including water uptake by cypress, vitex and maize, for a shallow soil hillslope in a subtropical climate region and 2) to determine whether hydrological separation exists between the water sources of plant transpiration and hillslope flow. The findings of this study improve the general understanding of soil-vegetation interactions and plant water uptake patterns.

2. Material and methods

2.1. Study site description

This research was conducted in a hilly headwater catchment (0.35 km^2) in Yanting County, SW China (31°16′N, 105°28′E) (Fig. 1a). Sloping farmland accounted for 50% of this catchment, and the other portions of the catchment consisted of forestland and residential areas. The dominant landscape unit was sloping farmland. The stream was a transient tributary of the Mi River. This study area was characterized by a moderate subtropical monsoon climate with an annual mean temperature of 17.3 °C and a mean annual precipitation of 826 mm/year from 1981 to 2006. The annual precipitation was mainly concentrated in the summer and autumn, with 85.2% of precipitation occurring during the above period.

The studied Regosol according to World Reference Base (IUSS Working Group WRB, 2006) was a loamy soil composed of 27.1% sand, 51.6% silt and 22.3% clay according to the USDA classification of soil texture. The soil had a pH of approximately 8.3, an average bulk density of 1.33 $g·cm^{-3}$, an average organic matter content of 8.75 $g·kg^{-1}$, and a saturated hydraulic conductivity of 10^{-2} to 10^{-1} $mm·min^{-1}$ (Zhao et al., 2013).

The studied hillslope was used for farming and had a slope of approximately 6°. There were no observable differences in soil type across the studied hillslope. The soil depth on the hillslope averaged 0.5 m. A 30-m long trench was located 50 m upslope from a pond. The main type of tree, shrub and crop on the study slope was cypress (*Platycladus orientalis* (L.) Franco), vitex (*Vitex negundo* L.) and Maize (*Zea mays* L.), respectively. The upslope and downslope were both covered by *Platycladus orientalis* (L.) Francoes and *Vitex negundo* L. The maize was planted on the middle of the slope.

2.2. Climate and hydrological measurements

The climatic data were collected at a standard meteorological station near the study hillslope. Rainfall quantities were measured using an automatic tipping bucket with an error of 0.1 mm (HOBO event data logger, USA). Three collection grooves were constructed on the surface of the topsoil, the surface of the mother rock and the top of the sandrock (Fig. 1c). The depth of mudstone was 2.1 m. The depths of the troughs for surface flow, interflow and underflow were 2.6 m, 1.8 m and 1.5 m, respectively. The depth of the groundwater table was approximately 2.7 m. The flow amounts were measured using a tipping bucket with a HOBO event recorder located in the troughs. The overland flow and interflow were transient, but the underflow was continuous in the study period.

2.3. Sampling of different compartments

Samples of plant water, soil water (in this case, soil water is bulk soil water), hillslope flow and groundwater were collected from the hillslope either on a daily basis during a rainfall event or otherwise on a monthly basis for isotopic analysis. Precipitation was sampled with a 20-cm-diameter glass funnel connected to a 1-L high-density polyethylene bottle. A table tennis ball was placed in the funnel to reduce evaporation. Overland flow, interflow and underflow (groundwater flow in the deep zone) were collected from a trench. Water samples were taken at 8:00 each day during rainfall events from a collective