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Water source utilization by woody plants growing on dolomite outcrops and nearby soils during dry seasons in karst region of Southwest China

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SUMMARY

In the seasonally dry karst region of Southwest China, woodland vegetation is frequently associated with rocky outcrops. We used stable isotope techniques to determine the water sources of two woody plant species (the semideciduous tree *Rademachera sinica* and the deciduous shrub *Alchornea trewioides*) across three surface types: continuous and isolated dolomite outcrops, as well as adjacent surfaces with soils. Main water sources for *R. sinica* growing on the continuous outcrops shifted from deep water sources (e.g., water in the saturated zone) on March 23, 2009 (the late dry season of 2008–2009) to rainwater stored in rock fissures of the unsaturated zone on November 8, 2009 (the early dry season of 2009–2010). *R. sinica* growing on nearby thin soils exhibited a similar shift of main water sources, from deep water sources in the late dry season to shallow soil water (0–30 cm) in the early dry season. However, they extracted deep water sources from the bottom of nearby outcrops rather than from deeper layers below the soil surface. Main water sources for *R. sinica* growing on the isolated outcrops shifted from previous (one to two months ago) rainwater in the late dry season to the mixture of recent (within the last one month) and previous rainwater in the early dry season, while using little or no deep water sources. In contrast, *A. trewioides* growing on these two kinds of outcrops always relied on recent rainwater, while those growing on soils always relied on shallow soil water. The shift of water sources for tree species (especially those growing on continuous rock outcrops and nearby soils) may allow them to maintain normal transpiration throughout the year, which increases the amount of evapotranspiration in the watershed and further enhances the water storage capacity of the study area.

1. Introduction

Southwest China is home to one of the largest karst regions (here and elsewhere) in the world, with an area of approximately 500,000 km^2 (Yuan, 1994). This area is characterized by rocky desertification with a high ratio of bedrock outcrop to shallow soil and low vegetation cover. The characteristics of rocky desertification together with the "dual" conduit and diffuse flow systems of karst aquifers contribute to the rapid hydrological processes (rapid penetration of rainwater through thin soil layer and connected fissures in bedrock layer to below the rooting zone or groundwater) of the area (Butscher and Huggenberger, 2009), as well as frequent flood/drought events.

Although this area is considered a subtropical region, with total annual precipitation exceeding 1000 mm, plants endure 4–5 months of annual drought. Still, naturally reforested bedrock outcrops tend to thrive. Forest restoration increases the relative contribution of plant transpiration to evapotranspiration, and regulates the karstic hydrological process (Asbjornsen et al., 2011). Therefore, detailed observations of water sources used by rocky habitat plant species, especially during the dry season, can provide data for estimating effects of forest restoration on water balance. Many authors have revealed the type and diversity of plants growing on rock outcrops (Burgman, 1987; Anderson, 1999; Crow and Ware, 2007; Ware, 2010), however few have focused on sources of water used by plants and have examined the hydrological characteristics of these forests.

Plant water sources can be determined through stable isotope analysis of stem water (Dawson et al. 2002), and this technique has been widely used in determining water sources used by plants (Brunel et al., 1995; Meinzer et al., 1999; Schwinning et al., 2003; Querejeta et al., 2006, 2007; Asbjornsen et al., 2007; Hasselquist et al., 2010; Nie et al., 2011). There is no isotopic fractionation during water uptake by terrestrial plants, although examples of plant species that seem to fractionate hydrogen (but not oxygen) during

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water uptake exist (Lin and Sternberg, 1993; Ellsworth and Williams, 2007). Water sources can be pinpointed by comparing the isotope ratios of all potential water sources with water extracted from plant stems (Dawson et al., 2002).

Rose et al. (2003) found that both pine and manzanita growing on thin soil underlain by weathered granitic dolomite predominantly used surface soil water (0–75 cm), and exploited dolomite-derived water when soil water was depleted. McCole and Stern (2007) found that in thin soils over karstified carbonate bedrock, water sources of juniper changed from dominantly deep water during a hot, dry summer to dominantly soil water during a cool, moist winter. Schwinning (2008) found that tree species in karst savannas used water stored in the epikarst zone rather than groundwater. However, little is known about water sources utilized by plants growing on bedrock outcrops, or the difference between species growing on outcrops and nearby soils.

Rooting habit is an important factor affecting water use patterns of plants. Zwieniecki and Newton (1994, 1995) found that in thin soils underlain by thick zones of weathered bedrock, roots of some species were restricted in thin soil layer, while others could exploit water held in bedrock by growing roots into and following joint fractures. Zwieniecki and Newton (1996) verified that two conifer species showed limited ability to utilize water from bedrock even during dry periods. Ericaceous plants, on the other hand, were very efficient in taking water from deep rock layers, using nearly all available water and removing twice as much water as conifers of the same age. Hubbert et al. (2001) and Rose et al. (2003), both suggest that water stored in bedrock was especially important to pine relative to manzanita as active roots of manzanita were restricted to the upper 100 cm.

In karst regions, plant root distribution is strongly influenced by soil depth and epikarst structure (Schwinning, 2008). The epikarst (also known as the subcutaneous zone) is highly weathered carbonate bedrock that is either exposed or immediately beneath the surface (Williams, 2008). In some areas of Southwest China where bedrock is dominantly dolomite, soil is thin and the depth of the epikarst is usually restricted to a few meters, which hampers root growth (Cao and Yuan, 2005). However, when dolomite is exposed (usually manifested by ubiquitous cracks and crevices), it adds to the thickness of the epikarst. Thus, the same species growing in soils and on dolomite outcrops may have different water sources. Two kinds of outcrops are commonly encountered in dolomite-dominated areas of Southwest China, continuous and isolated. It is well known that water storage capacity of epikarst depends upon its thickness and continuity. Although there might be no difference of thickness between the epikarst of continuous and isolated outcrops, they could be separated from each other according to the continuity of their epikarst. Continuous outcrop could be regarded as a combination of dozens (if not hundreds) of isolated ones, water could transmit between adjacent ones through connected fissures under the influence of gravity and/or pore water pressure. The widely distributed lateral flow of water in continuous outcrop, contrary to the dominated vertical flow in isolated outcrop, extend the residence time of water in epikarst (which is equal to relatively high water storage capacity) and saturated zone is more likely to be formed in there. Thus, the same species on continuous and isolated outcrops may have different water sources. Roots of some species may penetrate through joint fractures and exploit water held there, while others may not. Species of different root systems in the same habitat may have different water sources, too. To test these theories, we conducted an isotopic study during Southwest China's dry seasons to determine the sources of water used by plants in different habitats. Two commonly encountered woody species, *Radermachera sinica* (a semideciduous tree that lose part of its foliage in the dry season) and *Alchornea trewioides* (a deciduous shrub but can leaf out at the end of dry season if there is rain) were chosen. We hypothesized that the tree exhibits deeper root system than the shrub.

2. Materials and methods

2.1. Study area

The study area is a small watershed (area = 146.1 hm^2) located at the Huanjiang Observation and Research Station for Karst Ecosystems under the Chinese Academy of Sciences in Huanjiang County, Northwest Guangxi, China (24°43′58.9″–24°44′48.8″N, 108°18′56.9″–108°19′58.4″E). The watershed is a typical karstic peak-cluster depression area with a flat depression (area = 22.1 hm^2) surrounded by mountain ranges on three sides and the mouth of the watershed in the northeast. Elevation ranges from 272.0 m to 647.2 m (Fig. 1a). A small stream flows from the southwest out of the watershed into a reservoir in the northeast. The soils are often saturated in a depression located in the southwest with a fluctuating groundwater table that is often below 1–3 m depth in the depression. Seepage springs sometimes appear at the bottom of hillslopes during the rainy season or after rains in the drought season. Hillslopes are characterized by steep slopes (62% > 25°), shallow soils (10–30 cm deep except at the foot of hillslopes and in the depression), and high dolomite outcrop ratio (~30%). Shallow and discontinuous soils have been developed from dolomite and contain significant amounts of rock fragments. Soils are well-drained, gravelly and calcareous, and have a clay to clay loam texture (25–50% silt and 30–60% clay). The steady-state infiltration rate measured with a disc permeameter is 0.7–2.1 mm min^{-1} on the hillslopes (Chen and Wang, 2008). Organic matter content is relatively high ranging from 2.2% to 10.1% while PH varies between 7.1 and 8.0 (Chen et al., 2011). A subtropical mountainous monsoon climate dominates with annual rainfall of 1389.1 mm and annual air temperature of 18.5 °C. The wet season occurs between the end of April and early September. Plants usually experiences a pronounced 4–6 month dry season in winter/spring during which only 20–30% of the total annual rainfall is received.

This area experienced severe deforestation from 1958 to the mid-1980s, and has been under natural restoration for almost 25 years. Currently, the vegetation can be classified into three secondary communities: tussock, shrub, and secondary forest. Almost 70% of hillslopes are dominated by tussocks and shrubs. Most trees are found on dolomite outcrops and nearby soils, or in the deep soils (>100 cm) at the foot of hillslopes. Dolomite outcrops in this area can be divided into two types: continuous and isolated (Chen et al., 2011). Both continuous and large isolated outcrops are severely weathered and characterized by a network of soil-filled (may be litter or humus) cracks, crevices, and channels, with no soil in any place other than the network (Nie et al., 2011). Plant species growing on outcrops usually emerge from cracks or crevices (Fig. 1f), or grow on protuberant rocks with their roots ultimately penetrating into cracks.

2.2. Sampling sites characteristics

According to the distribution of these two types of outcrops, one continuous outcrop (Sampling site 1, SS1) was chosen at an upper slope position of a Northwest-facing hillslope, and one isolated outcrop (Sampling site 2, SS2) was chosen at a lower slope position of the opposite hillslope (Fig. 1a). There are continuous outcrops present at both the upper and lower positions of the Northwest-facing hillslope. The upper outcrop starts at the top of the hill and is about 80 m in length along the slope (Fig. 1c). The average height from the top of the outcrop to nearby soil is 7 m, and