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Rainfall partitioning into throughfall, stemflow and interception loss by two xerophytic shrubs within a rain-fed re-vegetated desert ecosystem, northwestern China

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SUMMARY

Knowledge of rainfall partitioning into throughfall, stemflow and interception loss by xerophytic shrubs is useful for implementing and evaluating re-vegetation projects, and for hydrologic budget modeling over vast arid desert areas. However, information about rainfall partitioning by xerophytic shrubs and the controlling factors are still under-represented in the literature. This study examined whether morphological features play a significant role in rainfall partitioning, using two xerophytic shrubs that are widely used in re-vegetation in arid areas of China, and evaluated the effects of rainfall characteristics and meteorological variables on rainfall partitioning. *Caragana korshinskii* is a multiple-stemmed shrub with smooth stems and ovate leaves, while *Artemisia ordosica* is a highly branched dwarf-shrub with a rough stem and needled leaves. We hypothesized that rainfall partitioning significantly differs between the two shrubs with a higher stemflow production and lower interception loss for *C. korshinskii* than *A. ordosica*. Gross rainfall, throughfall and stemflow for the two shrubs were measured during 3 growing seasons between 2011 and 2013 within a re-vegetated desert ecosystem of northwestern China. On average, measured throughfall, stemflow and derived interception loss for *C. korshinskii* accounted for 74.31%, 8.99% and 16.70% of incident gross rainfall, respectively. Corresponding values for *A. ordosica* were 74.83%, 2.89% and 22.28%, respectively. Significant differences ($P < 0.05$) in stemflow and interception loss were detected between *C. korshinskii* and *A. ordosica*. Rainfall partitioning (in mm) was significantly positively correlated with individual rainfall depth. Stemflow generally did not occur following rainfall events of less than 1.3 mm for *C. korshinskii* and 2.2 mm for *A. ordosica*. Small amounts of rainfall contributed to a lower percent of net rainfall and higher percent of interception loss. The percentages of stemflow and throughfall showed the increased tendency with increasing rainfall intensity, while a decreased tendency for the percentage of interception loss; and after a threshold value of $\sim$2 mm h^{-1}, they tended to be quasi-constant. Meteorological variables such as air temperature, relative humidity and wind speed had no significant correlations with rainfall partitioning. In general, monitoring of rainfall partitioning supported our hypothesis. Gross rainfall characteristics are considered to be sufficient in estimating stemflow and throughfall; while for a better prediction of interception loss, other meteorological variables are suggested to be included.

1. Introduction

Vegetation canopies, by partitioning precipitation into interception loss, throughfall and stemflow, affect the hydrological and biogeochemical fluxes between vegetation and soil (Dunkerley, 2000; Llorens and Domingo, 2007), which leads to the spatial variability in soil properties and soil moisture conditions under vegetation canopies (McClain et al., 2003; Tobon et al., 2004; Zhang et al., 2013). Interception loss refers to the part of the incident precipitation intercepted by the canopy which evaporates directly back into the atmosphere during and after rainfall. The remaining incident precipitation, i.e., net precipitation, reaches the ground either as throughfall or stemflow. Throughfall reaches the ground directly through canopy gaps without hitting the canopy surfaces as free throughfall and via dripping from leaves, branches and stems as

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released throughfall (Dunkerley, 2000; Xiao et al., 2000). Stemflow reaches the ground by funnelling down the stems or trunks after the incident precipitation is intercepted by leaves, twigs and branches. Throughfall accounts for the majority of gross precipitation; while stemflow, being volumetrically minor in comparison with throughfall, is a spatially localized point input of water and solutes at the base of stems or trunks, which can be transported to deeper soil layers and easily be available for the roots (Levia and Frost, 2003; Swaffer et al., 2014). In general, trees have a higher relative throughfall (the ratio of throughfall to gross rainfall) and a lower relative stemflow than shrubs (Llorens and Domingo, 2007).

In desert ecosystems (often characterized by vegetation patchiness), discrete precipitation pulses are often the sole source of soil water replenishment, and the vegetation growth and ecosystem processes are typically limited by soil water scarcity (Kéfi et al., 2007; Noy-Meir, 1973). An understanding of the hydrologic balance induced by desert vegetation is crucial for assessing the spatial patterns, establishment and permanence of vegetation in vast desert areas (Reynolds et al., 1999; Rietkerk et al., 2004). Shrubs are the dominant vegetation and play an important role in the desert ecosystems by altering the hydrological, physical and biological soil environment induced by their canopies (Li et al., 2013; McKell, 1975). Therein, from a hydrologic point of view, individual shrub canopies exert a significant control by modifying both evaporation and redistribution of incident rainfall (Domingo et al., 1998). A number of studies have quantified rainfall partitioning in forest ecosystems (e.g., Ghimire et al., 2012; Livesley et al., 2013; Macinnis-Ng et al., 2012; Muzylo et al., 2012; Staelens et al., 2008; Zimmermann et al., 2009), but systematic reports dealing with shrubs are very scarce, particularly in arid desert ecosystems. For example, a review of 90 papers dealing with Mediterranean vegetation interception by Llorens and Domingo (2007) concluded that only 11% of published reports referred to shrubs or bushes. Moreover, rainfall partitioning in forest ecosystems has been reported to be a function of incident rainfall characteristics (amount, intensity and duration), meteorological variables (air temperature, relative humidity, wind speed and net radiation), tree species and architecture, and the possible interactions between these factors (Crockford and Richardson, 2000; Llorens and Domingo, 2007; Staelens et al., 2008; Xiao et al., 2000), and event-scale measurements provide better insights of rainfall partitioning than periodic measurements (Llorens et al., 1997; Staelens et al., 2008). However, how these factors affect rainfall partitioning by shrubs in arid desert areas is less understood. Although the importance of rainfall partitioning by desert shrubs is widely acknowledged, there are a scarce number of studies on this topic. Therefore, quantifying rainfall partitioning by shrubs and assessing the controlling factors merits great attention.

The southeastern fringe of the Tengger Desert has experienced a long term re-vegetation by planting xerophytic shrubs, mainly *Caragana korshinskii* and *Artemisia ordosica* that are widely used in re-vegetation in northwestern China. The successful re-vegetation efforts has turned the former landscape with bare and homogeneous moving sand dunes into a landscape characterized by a mosaic of the sparse shrubs and herbs and the interspaces covered by biological soil crusts (Li et al., 2006; Li, 2012). *C. korshinskii* is a multiple-stemmed shrub species with smooth stems and ovate leaves, while *A. ordosica* is a highly branched dwarf-shrub species with a rough stem and needled leaves. This raises a question: do morphological differences of shrubs affect rainfall partitioning into stemflow, throughfall and interception loss? To address this question, we hypothesized that rainfall partitioning significantly differs between the two species due to their distinct morphological characteristics, with a higher stemflow production and lower interception loss for *C. korshinskii* than *A. ordosica*. Moreover, the annual average precipitation of this area is <200 mm, with more than 90% of rain falling in the growing season, and the pulsed rainfall is regarded as the chief limiting factor for vegetation growth (Wang et al., 2005; Li et al., 2014). Then, what are the effects of rainfall characteristics and other meteorological variables on rainfall partitioning? In the present study, event-based measurements of gross rainfall, throughfall and stemflow at individual shrub scale were made during 3 rainy seasons of 2011–2013 within a rain-fed re-vegetated desert ecosystem for the two co-occurring, whereas morphologically distinct xerophytic shrubs, i.e., *C. korshinskii* and *A. ordosica*, at the southeastern fringe of the Tengger Desert. To test our hypothesis, we define two objectives: (1) quantify the partitioning of rainfall into throughfall, stemflow, and interception loss by two xerophytic shrubs at the individual rainfall event scale; and (2) evaluate the influences of rainfall characteristics and meteorological variables on rainfall partitioning. Our systematic study on rainfall partitioning by xerophytic shrubs is also expected to be of use in implementing (e.g., choosing the right shrubs) and evaluating re-vegetation projects, and in hydrologic budget modeling in arid desert areas.

2. Materials and methods

2.1. Site information

Field measurements were carried out during 3 growing seasons of 2011–2013 at the Shapotou Desert Research and Experiment Station (SDRES) of Chinese Academy of Sciences (37°32′N, 105°02′E, an elevation of 1300 m a.s.l.), southeastern fringe of the Tengger Desert in northwestern China. The area is surrounded by relatively plain interdunes and free from any disturbances of grazing, fire, and wood chopping. The dune sand mainly consists of fine *Typic Psammaquents* sand (0.05–0.25 mm) with a clay content of approximately 0.2% (Berndtsson et al., 1996; Zhang et al., 2014). Mean annual precipitation is 191 mm (1955–2005, SDRES) with 80% of rain falling between July and September with a coefficient of variation of 45.7%. Most storms are of low amount and intensity, being around 70% of the rainfall intensities $\leqslant 5\ \mathrm{mm\ h^{-1}}$ (Wang et al., 2005). The groundwater is deep to 50–80 m, being inaccessible to plant roots. Dew condensation on soil surface contributes to a very minor water source (Liu et al., 2006; Pan et al., 2010). All plants, thus, rely on precipitation for their growth. Potential evapotranspiration is approximately 2500 mm during the growing season (April–October), resulting in a large annual moisture deficit. Mean maximum and minimum air temperature are 24.7 °C in July and −6.1 °C in January. Annual mean wind velocity is approximately $2.8\ \mathrm{m\ s^{-1}}$.

Extensive re-vegetation efforts were made during 1950–80s to protect the Baotou-Lanzhou railway against encroaching sand dunes in the Shapotou area. A 16,000-m-long artificial protection system was established along the railway with 500 m widths to the north and 200 m to the south. Straw barriers were set up following a checkerboard pattern in the mobile sand dunes at both sides of railway, and subsequently within which xerophytic shrubs (mainly *C. korshinskii*, *H. scoparium* and *A. ordosica*) were planted. A detailed description of the re-vegetation procedure can be found in Li et al. (2006).

The 1-hectare Water Balance Experimental Field (WBEF) is one of the re-vegetated enclosures here. It was established in 1989 by planting two morphologically different shrubs, i.e., *C. korshinskii* and *A. ordosica*. *C. korshinskii* is a multiple-stemmed deciduous perennial leguminous shrub with inverted cone shape. Stems are smooth, leaves are pinnately compound and opposite or subopposite in arrangement with 6–10 cm long, and each pinna has 5 to 8 pairs of ovate leaflets (7–8 mm in length and 2–5 mm in width). *A.*