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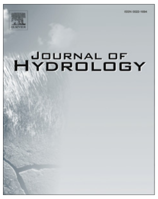

Throughfall and its spatial variability beneath xerophytic shrub canopies within water-limited arid desert ecosystems

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S U M M A R Y

Throughfall is known to be a critical component of the hydrological and biogeochemical cycles of forested ecosystems with inherently temporal and spatial variability. Yet little is understood concerning the throughfall variability of shrubs and the associated controlling factors in arid desert ecosystems. Here we systematically investigated the variability of throughfall of two morphological distinct xerophytic shrubs (*Caragana korshinskii* and *Artemisia ordosica*) within a re-vegetated arid desert ecosystem, and evaluated the effects of shrub structure and rainfall characteristics on throughfall based on heavily gauged throughfall measurements at the event scale. We found that morphological differences were not sufficient to generate significant difference ($P < 0.05$) in throughfall between two studied shrub species under the same rainfall and meteorological conditions in our study area, with a throughfall percentage of 69.7% for *C. korshinskii* and 64.3% for *A. ordosica*. We also observed a highly variable patchy pattern of throughfall beneath individual shrub canopies, but the spatial patterns appeared to be stable among rainfall events based on time stability analysis. Throughfall linearly increased with the increasing distance from the shrub base for both shrubs, and radial direction beneath shrub canopies had a pronounced impact on throughfall. Throughfall variability, expressed as the coefficient of variation (CV) of throughfall, tended to decline with the increase in rainfall amount, intensity and duration, and stabilized passing a certain threshold. Our findings highlight the great variability of throughfall beneath the canopies of xerophytic shrubs and the time stability of throughfall pattern among rainfall events. The spatially heterogeneous and temporally stable throughfall is expected to generate a dynamic patchy distribution of soil moisture beneath shrub canopies within arid desert ecosystems.

1. Introduction

Gross rainfall partitions into interception loss, stemflow and throughfall as it passes through the vegetation canopy, which alters the horizontal and vertical distribution of incident gross rainfall and increases the tempo-spatial variability of soil water (Durocher, 1990; Johnson and Lehmann, 2006). Interception loss is the part of the intercepted incident rainfall that evaporates directly back into the atmosphere during and after rainfall. Stemflow refers to the portion of gross rainfall that delivers to the ground via trunks or stems (Johnson and Lehmann, 2006; Levia and Germer, 2015). Throughfall reaches the ground directly through canopy gaps without hitting the canopy surfaces as free throughfall, or indirectly via dripping from leaves, branches and stems as released throughfall (Dunkerley, 2000; Xiao et al., 2000). Percentage of throughfall to the incident gross rainfall in trees is generally higher (approximately four-fifths) than in shrubs (50%) and less variable (Levia and Frost, 2006; Llorens and Domingo, 2007). As the major component of under-canopy rainfall, throughfall affects a host of critical ecological, hydrological and biogeochemical processes, including the spatial distribution of water and solutes in soil (Navar et al., 2009; Zhang et al., 2013), soil erosion (Vega et al., 2005), root distribution and growth (Li et al., 2013), and the soil microbial community structure (Rosier et al., 2015). Thus, understanding throughfall behavior is of critical importance to improved characterization of hydrologic and biogeochemical cycling in vegetated terrestrial ecosystem.

Numerous studies have documented considerable variability in throughfall over diverse forest types globally (e.g., Gomez et al., 2002; Carlyle-Moses et al., 2004; Levia and Frost, 2006; Zimmermann et al., 2007; Sato et al., 2011; Shen et al., 2012; Dohnal et al., 2014; Klos et al., 2014; Fan et al., 2015). However, the throughfall variability of shrubs in water-limited arid desert ecosystems has been less explored, though the importance of throughfall of shrubs in influencing potential soil water dynamics

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is acknowledged. Throughfall variability has been reported to be influenced by a suite of biotic and abiotic factors, including canopy structure and architecture (Aboal et al., 2000; Van Stan and Pypker, 2015), rainfall amount, intensity and duration (Germer et al., 2006; Dohnal et al., 2014; Tanaka et al., 2014), wind direction and speed (Gomez et al., 2002; Fan et al., 2015), and vapor pressure deficit (Tanaka et al., 2014) in forested ecosystems. Generally, the abiotic factors are found to vary irregularly as a function of rainfall event characteristics, while the biotic factors are more uniform and constant, influencing throughfall variability in a regular and predictable manner (Levia and Frost, 2006). Nevertheless, how these factors affect throughfall variability remains poorly known. Also opposing results can often be found in the existing literature. For example, some studies indicate that throughfall increased with increasing distance from the tree/shrub stem (e.g., Beier et al., 1993; Li et al., 2013), while others reported a decrease (e.g., Robson et al., 1994; Fan et al., 2015). As such, a systematic study of throughfall variability of shrubs and the associated controlling factors merits great attention.

Arid desert ecosystems are typically characterized by vegetation patchiness, where the discrete and unpredictable precipitation pulses are often the major or even the sole source of soil water replenishment, and the vegetation growth and ecosystem processes are typically limited by soil water scarcity (e.g., Noy-Meir, 1973; Aguiar and Sala, 1999; Tongway et al., 2001; Rietkerk and Van de Koppel, 2008). An understanding of the rainfall partitioning by desert vegetation is crucial for assessing vegetative spatial patterns (Navar and Bryan, 1990; Li et al., 2013; Zhang et al., 2013). Shrubs are the dominant vegetation and plays a crucial role in the hydrological and biogeochemical cycles over vast desert areas (McKell, 1975; Schlesinger and Pilmanis, 1998). In terms of throughfall, individual shrubs may play an important role in throughfall spatial distribution. We hypothesized that throughfall shows a patchy distribution beneath individual shrub canopies. If this is the case, how do shrub architecture and rainfall characteristics affect throughfall spatial variability? Further, does the spatial variability of througfall persist among discrete rainfall events? To test our hypothesis and answer our questions, we initiated the following specific objectives: (1) characterize and quantify the spatial pattern associated with throughfall of individual shrubs; (2) quantify the effects of shrub structure and rainfall characteristics on the variability of throughfall; and (3) evaluate the time stability of throughfall spatial patterns. To achieve these tasks, event-based throughfall were volumetrically measured in the field under heavily gauged two morphological distinct xerophytic shrub species (6 for *Caragana korshinskii* and 5 for *Artemisia ordosica*) that are widely used in re-vegetation in northwestern China. Our heavily gauged throughfall study is expected to contribute to a better understanding of the spatial nature of throughfall and its time stability by the xerophytic shrub canopies with respect to canopy architecture and rainfall characteristics.

2. Materials and methods

2.1. Site information

Field measurements were carried out during the growing season (May to October) of 2015 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. 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% (Wang et al., 2005). Most storms are of low amount and intensity, being around 80% of the rainfall intensities $\leqslant 5$ mm h^{-1} (Zhang et al., 2015). The groundwater is deep to 50–80 m, being inaccessible to plant roots. Potential evapotranspiration is approximately 2500 mm during the growing season, 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. Average annual wind speed is 2.9–3.5 m s^{-1} at 2 m height, with the direction being predominantly northwesterly (Wang et al., 2010).

Extensive re-vegetation efforts were made during 1950–1980s to protect the Baotou-Lanzhou railway against encroaching sand dunes in the Shapotou area. A 16-km-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).

Water Balance Experimental Field (WBEF) is a 1-hectare area that was re-vegetated 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. It is shaped like an inverted cone. Stems are smooth, leaves are pinnately compound and opposite or subopposite in arrangement with 6–10 cm long, and each pinna has 5–8 pairs of ovate leaflets (7–8 mm in length and 2–5 mm in width). *A. ordosica* is a highly branched dwarf-shrub with plumose, full split needled leaves (10–30 mm in length and 0.3–1 mm in width). It has only one short rough stem with thick, loose and inclinedly fractured bark. The average height and the average canopy diameter of *C. korshinskii* were 145 and 130 cm, respectively; the corresponding values for *A. ordosica* were 64 and 96 cm, respectively.

2.2. Shrubs selection and measurements

Eleven robust and healthy shrubs (6 for *C. korshinskii* and 5 for *A. ordosica*) were selected for field observation, as a representation of the range of sizes of the two xerophytic shrub species in WBEF. Table 1 quantifies the morphological characteristics of the selected shrubs for *C. korshinskii* and *A. ordosica*. Stem diameter was measured with a vernier caliper at each stem base, stem angle was determined by a protractor, and plant area index (PAI) of individual shrubs was estimated using a LAI-2000 plant canopy analyzer (Li-Cor, Inc., USA) with a 30° view cap at the ground by stem. Shrub height was measured at the center of the canopy. The basal area for each individual shrub is the sum of the cross-sectional area of all its stems at shrub base. Projected canopy area (approximated as an ellipse) was calculated by taking the east-west and north-south diameters through the center of the fullest part of the canopy (MartinezMeza and Whitford, 1996).

2.3. Throughfall and rainfall measurements

Fig. 1 displays the photographs of throughfall collection and the corresponding schematic layouts of throughfall collector location distribution. A throughfall collector consists of a polyethylene funnel (13 cm in diameter) with sharp-edged vertical rim and a slope of 45° with a container under the funnel. The funnel openings were 15 cm above the ground to avoid splash entering funnel. Due to a larger canopy of *C. korshinskii* relative to *A. ordosica*, throughfall collectors for *C. korshinskii* were installed at six radial directions (0°, 60°, 120°, 180°, 240° and 300°, clockwise, referencing 0° as North) beneath each shrub canopy; in each direction, four collectors were placed with a distance of 35 cm between two neighboring collectors. For *A. ordosica*, throughfall collectors were placed radiating out in the four cardinal directions (northern: N; eastern: E; southern: S; western: W) beneath each shrub canopy, three col-