Science of the Total Environment 619–620 (2018) 1003–1013

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Meteorological influences on process-based spatial-temporal pattern of throughfall of a xerophytic shrub in arid lands of northern China

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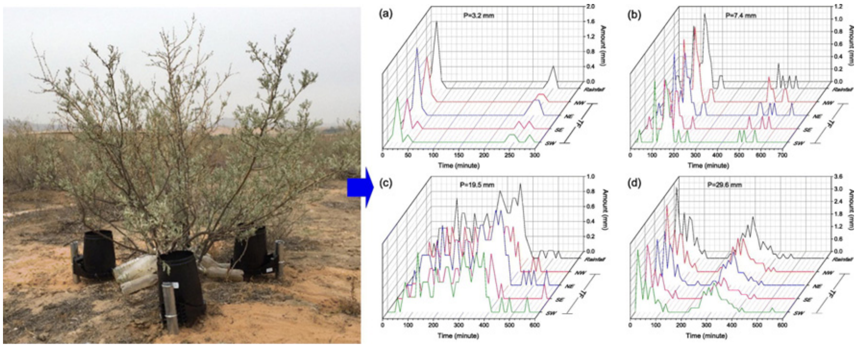
HIGHLIGHTS

- Throughfall were monitored at 10-min intervals at different radial directions beneath shrub canopies.
- Temporal heterogeneity of rainfall clearly affected the timing of throughfall inputs.
- Throughfall differed markedly among different radial directions beneath shrub canopies.
- Principal Components Analysis was performed on meteorological variables.
- Three principal components were introduced into a multiple regression model to predict throughfall.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form 18 November 2017
Accepted 18 November 2017
Available online xxxx

Editor: Ouyang Wei

Keywords:
Throughfall
Spatial-temporal variability
Meteorological variables
Principal components analysis
Caragana korshinskii

ABSTRACT

Numerous field experiments had demonstrated great spatial variability and temporal stability of throughfall under tree canopies within forested ecosystems. Nonetheless, no known studies have investigated the intrastorm spatial-temporal variability of throughfall beneath xerophytic shrub canopies within arid desert ecosystems where water is typically the principal limiting factor determining the structure and dynamics of ecosystems. Here we investigated the spatial-temporal pattern of throughfall at intrastorm scale, and systematically examined the effects of meteorological variables on throughfall based on the principal components analysis (PCA) and a multiple regression model. Throughfall was monitored at 10-min intervals by placing tipping-bucket rain gauges at different radial directions beneath 3 shrubs of *Caragana korshinskii* during the growing season of 2016 within a water-limited arid desert ecosystem of northern China. We found the temporal heterogeneity of rainfall clearly affected the timing of throughfall beneath shrub canopies within discrete rainfall events. Throughfall also differed markedly among different radial directions beneath shrub canopies, which was found to be well associated with wind directions during rainfall events. PCA on meteorological variables indicated that three principal components accounted for 84.2% of the total variance, and we found that the second principal component (loaded strongly on rainfall amount and maximum 10-min rainfall intensity) was the dominant component controlling throughfall and its spatial variability after introducing three principal components into a multiple linear regression model. Our findings highlight the spatial-temporal variability of throughfall at the intrastorm scale, and are expected to be helpful for an improved process-based characterization and modelling of throughfall in vast arid desert ecosystems.

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https://doi.org/10.1016/j.scitotenv.2017.11.207
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1. Introduction

Part of incident precipitation falling on a tree/shrub canopy is intercepted and subsequently evaporated (interception loss), and the remaining reaches the ground in two markedly different ways: (1) the point source inputs as stemflow which funnels down the trunks/stems, and (2) the diffused inputs as throughfall which penetrates the gaps and/or drips from the canopy. Therein, throughfall accounts for approximately four-fifths of incident precipitation, making it a critical component in hydrologic cycle of vegetated ecosystems (Klos et al., 2014; Levia and Frost, 2006). In fact, throughfall has been reported to be linked to a variety of critical ecohydrological variables such as runoff and soil erosion (Vega et al., 2005), percolation (Klos et al., 2014), and soil water variability (Wullaert et al., 2009).

Both canopy architecture and meteorological factors (e.g., Levia and Frost, 2006; Tanaka et al., 2015) affect throughfall, with the former influencing throughfall in a regular and predictable manner and the latter in an irregular way (Levia and Frost, 2006). Generally, the most reported meteorological factors that affect throughfall include rainfall amount and intensity, and throughfall has been shown to increase with them (Carlyle-Moses and Lishman, 2015; Levia and Frost, 2006; Styger et al., 2016; Wullaert et al., 2009; Sadeghi et al., 2016; Zhang et al., 2016). Comparatively, the effects of other meteorological factors such as rainfall duration, intra-event intermittency (no-rain periods during a rainfall event), wind conditions, air temperature, vapor pressure deficit on throughfall were relatively less explored (Tanaka et al., 2015; Van Stan et al., 2016; Zhang et al., 2015). Much less well understood is under what combination of these meteorological conditions a tree/shrub canopy will permit the greatest or least throughfall generation (Van Stan et al., 2016), and few concrete associations have been identified as for the influence of meteorological conditions on throughfall and its spatial variability. Recently, Niemeyer et al. (2016) examined meteorological factors impacting throughfall in western juniper in semi-arid USA, and showed that vapor pressure deficit decreased throughfall and was more important than wind and air temperature. Tanaka et al. (2015) employed boosted regression tree analysis to identify the primary controls on throughfall under a teak plantation in Thailand, and found that throughfall percentage in the leafless phase was most influenced by air temperature, rainfall amount, maximum wind speed, and rainfall intensity, but was dominated by rainfall amount in leafed phenophase. Van Stan et al. (2016) applied multiple correspondence analysis to identify interactive meteorological conditions affecting throughfall, and found that equalling or exceeding rain intensity thresholds (median and median absolute deviation) corresponded with temporal concentration of throughfall percentage across all storms. An accurate characterization of throughfall patterns in relation to interactive meteorological conditions is considered to be critical to an improved understanding of water and solute fluxes among the canopy, understory, and soil (Levia and Frost, 2006; Van Stan et al., 2016).

Throughfall has been observed on an intrastorm scale, rainfall event scale, weekly scale, monthly scale, or even larger time scale due to varying objectives and the expense and logistics involved in monitoring throughfall (Levia and Frost, 2006). Some studies from mostly forested areas that have monitored intrastrom throughfall dynamics suggest that intrastorm scale, e.g., with a frequency of 5 min (Durocher, 1990; Reid and Lewis, 2009; Van Stan et al., 2016), or 10-min (Massman, 1983; Sun et al., 2017), or 15-min (Dolman, 1987; Dohnal et al., 2014), or 30-min (Link et al., 2004) or even 1 h (Iida et al., 2017; Owens et al., 2006), allows us to evaluate the throughfall dynamics in response to changing meteorological conditions during individual storms, and helps to interpret some eco-hydrological processes as recent work had shown that many eco-hydrological processes occurred under fine-scale temporal “hot moments” (McClain et al., 2003; Vidon et al., 2010). This is of critical importance to an improved characterization of hydrologic and biogeochemical cycling in vegetated terrestrial ecosystems. Surprisingly to date no known studies have investigated the intrastorm variability of throughfall beneath xerophytic shrubs in arid desert areas, though the importance of temporal-spatial variability of throughfall of shrubs in influencing potential soil water dynamics and vegetation spatial distribution is acknowledged (Li et al., 2013).

Numerous field experiments have demonstrated great spatial variability and temporal stability of throughfall under tree canopies within a wide variety of ecosystems (e.g., Carlyle-Moses and Lishman, 2015; Fan et al., 2015; Fang et al., 2016; Fathizadeh et al., 2014; Gaitán et al., 2016; Keim et al., 2005; Sato et al., 2011; Wullaert et al., 2009; Zimmermann et al., 2009). Nevertheless, studies on spatial-temporal variability of throughfall remain limited for xerophytic shrubs within water-limited arid ecosystems (Li et al., 2013; Zhang et al., 2016) where shrubs are the dominant vegetation and discrete water is the principal limiting factor for their survival and growth (Kéfi et al., 2007; Noy-Meir, 1973). Detailed process-based knowledge of the heterogeneity of throughfall from individual shrubs within discrete rainfall events is crucial for a better understanding of the water partitioning and the hydrologic cycle in arid areas and its relevance to runoff, vegetation growth and afforestation initiatives, etc., and thus merits great attention.

It is clear that there is a lack of understanding on how meteorological factors and/or their interactions affect throughfall and the variability of throughfall of xerophytic shrubs. To enhance our knowledge-base on the above issues, the present study was initiated with the following objectives: (1) characterize and quantify the intrastorm spatial-temporal patterns of throughfall beneath shrub canopies, and (2) evaluate the influence of meteorological factors on throughfall. To achieve these tasks, throughfall was monitored at 10-min intervals by placing tipping-bucket rain gauges at different radial directions beneath 3 shrubs of *Caragana korshinskii* during the growing season of 2016 within a water-limited arid desert ecosystem of northern China. This study is among the first to use the high-resolution tipping-bucket rain gauge to characterize the intrastorm spatial-temporal pattern of throughfall beneath xerophytic shrub canopies within arid desert ecosystems. Therefore, our process-based study on throughfall is also expected to contribute to a better characterization and modelling of rainfall redistribution within vast arid desert ecosystems.

2. Material and methods

2.1. Site information

Field measurements were carried out during July to October of 2016 at the Water Balance Experimental Field (WBEF) of 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 which falling between July and September with a coefficient of variation of 45.7%. Most storms are of low amount and intensity, with around 80% of the rainfall events having an intensity ≤ 5 mm h^{-1} and only around 2% of the rainfall events having an intensity >10 mm h^{-1} (Wang et al., 2016). 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

Table 1
Descriptive statistics (mean ± standard error) of canopy morphology of *C. korshinskii*

Shrub ID	NS	SD (cm)	SA (°)	SH (cm)	CA (m^2)	BA (cm^2)	PAI
S1	11	2.4 ± 0.3	58 ± 7	186	5.1	57.3	0.93
S2	13	1.6 ± 0.1	59 ± 4	162	2.1	25.2	1.19
S3	11	1.8 ± 0.1	52 ± 5	156	3.7	30.4	0.99

NS: number of stems; SD: stem diameter; SA: stem angle; SH: shrub height; CA: canopy area; BA: basal area; PAI: plant area index.