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Connecting ecohydrology and hydropedology in desert shrubs: stemflow as a source of preferential flow in soils

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Abstract

Ecohydrology and hydropedology are two emerging fields that are interconnected. In this study, we demonstrate stemflow hydrology and preferential water flow along roots in two desert shrubs (*H. scoparium* and *S. psammophila*) in the south fringe of Mu Us sandy land in North China. Stemflow generation and subsequent movement within soil-root system were investigated during the growing seasons from 2006 to 2008. The results indicated that the amount of stemflow in *H. scoparium* averaged 3.4% of incident gross rainfall with a range of 2.3–7.0%, and in *S. psammophila* stemflow averaged 6.3% with a range of 0.2–14.2%. Stemflow was produced from rainfall events more than 1 mm for both shrubs. The average funneling ratio (the ratio of rainfall amount delivered to the base of the tree to the rainfall that would have reached the ground should the tree were not present) was 77.8 and 48.7 for *H. scoparium* and *S. psammophila*, respectively, indicating that branches and stems were fully contributing to stemflow generation and thereby provided considerable amount of water to deep soil layer. Analysis of rhodamine-B dye distribution under the shrubs showed that stemflow entered the soil preferentially along root channels contributing to deep storage and that the depth of stemflow infiltrated increased with increasing incident rainfall amount. Distribution of soil water content under the shrubs with and without stemflow ascertained that stemflow was conducive to concentrate and store water in deep layers in the soil profiles, creating favorable soil water conditions for plant growth under arid conditions. Accordingly there is a clear linkage between aboveground ecohydrology and belowground hydropedology in the desert shrubs, whereby an increase in stemflow would result in an increase in soil hydrological heterogeneity.

1 Introduction

Ecohydrology and hydropedology are two emerging fields that are interconnected within soil-plant-atmosphere continuum in water-limited ecosystems. The integrated interdisciplinary research of hydropedology and ecohydrology would enhance our understanding of the interactions between soil, water and biological factors in the "Critical Zone" (National Research Council, 2001; Lin, 2003; Lin et al., 2005; Newman et al., 2006; Brantley et al., 2006; Young et al., 2007). Vegetation plays an important role affecting ecohydrological and hydropedological processes at local and catchment scales because of the control that vegetation canopies exert on the redistribution of incident rainfall (Carlyle-Moses, 2004; Owens et al., 2006) and plant roots exert on water and nutrient transport in the vadose zone (Devitt and Smith, 2002; Skaggs and Shouse, 2008). Vegetation canopies can affect the vertical and horizontal spatial distribution of water within the plant community (Owens et al., 2006). Canopy interception generally exerts a negative effect on the horizontal distribution of water by retaining small pulses of precipitation in the canopy (Loik et al., 2004, Owens et al., 2006; Llorens and Domingo, 2007) and preventing water from reaching the ground surface. Throughfall affects surface soil layers and stemflow can particularly alter the vertical distribution of water by funneling water to the base of the tree where it can infiltrate rapidly (Devitt and Smith, 2002; Llorens and Domingo, 2007) or be redistributed through diffusion or hydraulic lift (Schwinning and Sala, 2004; Owens et al., 2006). Levia and Frost (2003) reviewed the quantitative and qualitative importance of stemflow in forested and agricultural ecosystems, and pointed out that stemflow was a spatially localized point input of precipitation and solutes at the plant stems and was of hydrological and ecological significance. Stemflow values usually are less than 5% of annual rainfall but can reach 22 to 40% in some cases (Slatyer, 1965; Pressland 1973; Navar and Ryan, 1990; Carlyle-Moses and Price, 2006; Li et al., 2008). Johnson and Lehmann (2006) found that stemflow can vary by more than three orders of magnitude, from 0.07% to 22% of incident rainfall, under a wide range of precipitation regimes (600–7100 mm y^{-1}). Levia and Frost (2003) reported the mean maximum stemflow values of approximately 3.5%, 11.3%, and 19% for tropical, temperate, and semiarid regions, respectively. Stemflow is highly variable between and within types of vegetation, as reviewed by Lorens and Domingo (2007). For example, Lorens and Domingo (2007) found that although stemflow averaged 3% of incident precipitation under Mediterranean conditions, there was an associated coefficient of variation of 111%.

Although stemflow may be volumetrically minor compared to throughfall at the stand scale, it has a significant influence on runoff generation, soil erosion, groundwater recharge, soil moisture storage, soil nutrients, and the spatial distribution of understory vegetation and epiphytes (Levia and Frost, 2003; Carlyle-Moses and Price, 2006; Li et al., 2008). Stemflow always results in spatial heterogeneity in soil-water fluxes due to stemflow and root channelization process. In a study in Western Australia, root channels beneath eucalypt forest provided conduits for the penetration of rain water to a depth of 12 m over a period of 20 years, whilst rainwater on wheat lands in the same area had penetrated no deeper than 2.5 m (Allison and Hughes, 1983; Maitre et al., 1999). Nulsen et al. (1986) found that the canopy of mallee vegetation intercepts rainwater and redistributes it into soil via stemflow at depths as great as 28 m. The flow of water through stem-root system often occurs as preferential flow. Devitt and Smith (2002) reported that macropores formed by the root systems of woody shrubs may be an important conduit for downward water movement in desert soils. Stemflow could be an important source of soil moisture in arid and semiarid lands (Tromble, 1987). Mauchamp and Janeau (1993) reported that *Flourensiacernua* was capable of channeling approximately 50% of the incident gross precipitation to the plant stem. Navar and Bryan (1990) calculated that the stemflow inputs to the soil around three semiarid shrub stems in northeastern Mexico represented a water input that was five times that received by other areas below the shrub canopies. Moreover, other arid and semiarid shrubs like *Banksia ornate*, *Xantohorrea australis*, *Haloxylon aphyllum*, *Acacia aneura*, *Diospyrus texana*, *Acacia farnesiana*, *Tamarix ramosissima*, *Caragana korshinskii* and *Reaumuria soongorica* are also adapted to divert rainfall to the base of their stems as stemflow where it subsequently infiltrates the soil and remains available for plant uptake in the deeper soil layers (Pressland, 1976; Nulsen et al., 1986; Navar, 1993; Martinez-Meza and Whitford, 1996; Lorens and Domingo, 2007; Li et al., 2008). This deep infiltrated water is considered as a possible source of available moisture for shrub growth in desert ecosystems even in the absence of accessible water in the upper soil profile (Tromble, 1987). Martinez-Meza and Whitford (1996) hypothesized that the stemflow-root channelization process by shrubs was an adaptive mechanism used to survive seasonal drought, a process referred to as the “nursing effect” by Goodall (1965).

Stemflow hydrology and preferential water flow along roots in the soil are intimately linked. Stemflow hydrology involves stemflow generation and water chemistry change as influenced by meteorological conditions, seasonality, species-specific traits, and canopy structure (Levia and Frost, 2003). In recent decades, stemflow-root channelization process in the soil has received considerable attention (Pressland, 1976; Nulsen et al., 1986; Navar, 1993; Martinez-Meza and Whitford, 1996; Lorens and Domingo, 2007; Segal et al., 2008), however, available data about the interconnection between stemflow and water flow in soil profile remain scarce. For example, stemflow dynamics, velocity, and pathway in relation to rainfall characteristics and vegetation species remain elusive, and the subsequent movement of stemflow water within soil-root system under different canopies and soils is not well understood for plant survival in water-limited ecosystems. Therefore, the objective of this study was to make an attempt to connect ecohydrology and hydropedology through an integrated study of stemflow generation and subsequent water movement in soils. We used a combination of stemflow collection with real-time rainfall monitoring, dye tracing, and soil profile moisture monitoring under two desert shrub species in the south fringe of Mu Us sandy land of North China.

2 Materials and methods

2.1 Study area

The study was conducted at Yulin Experimental Station of Mu Us Sandy Land Ecosystem of Beijing Normal University in Jingbian County, Shaanxi Province, North China

(37°38′ N, 108°50′ E, 1350 m a.s.l.) (Fig. 1). The Mu Us sandy land lies in the transitional zone from typical steppes to deserts. It has a semi-arid continental climate, and is highly susceptible to wind erosion (Runnstrom, 2003). The widespread coating of the Quaternary aeolian sand dunes on the Cretaceous rocks favours shrubs over trees and grasses to such an extent that at least 117 shrub and semi-shrub species have been observed within the Mu Us sandy land (Dong and Zhang, 2001).

The study site lies in the south fringe of Mu Us sandy land. Mean annual precipitation is 395 mm, more than 60% of which occurs between July and September. Mean annual temperature is 7.9°C and annual pan evaporation is 2485 mm. Psammophytic half-shrub communities are the main vegetation, dominant species being *Salix psammophila*, *Artemisia ordosica*, *Hedysarum scoparium*, *Hedysarum laeve*, *Psammochloa villosa* (Chen et al., 2002). We selected *S. psammophila* and *H. scoparium* to investigate the characteristics of stemflow generation and its hydropedological effects. The soil (Typic Ustipsamment) is an aeolian sand with uniform texture throughout the profile (98.48% sand, 1.52% silt, and 0% clay). Average soil organic matter and total N concentration in the 0–100 cm layer are 0.64 and 0.068 g kg^{-1}, respectively (Wang et al., 2006).

2.2 Experimental design

2.2.1 Stemflow characteristics

To investigate stemflow characteristics of *S. psammophila* and *H. scoparium*, we measured stemflow from 14 mature plants representing the two shrub species (7 samples for each species). Stemflow volumes were determined on a rainfall event basis during rainy seasons between June and September from 2006 to 2008. Stemflow drainage was collected using plastic funnels fitted around the main stems and sealed with silicone sealant. The funnels were connected by a collecting bottle where the stemflow was stored via plastic tubes (Fig. 2). We measured stemflow by hand using graduated cylinder after each rainfall event. Stemflow volume of each plant was divided by

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its canopy area to calculate the stemflow depth on a stand basis. Total incident rainfall was measured automatically with a tipping bucket rain gauge (Delta-T, Cambridge, UK) located 20 m away from the study plots in an open area. Canopy variables that were measured on each shrub included shrub height, number of branches, branch angle, canopy height, basal area and canopy area (Table 1) using methods of Martinez-Meza and Whitford (1996). Shrub height was measured at the centre of the canopy, basal area was calculated with collar girth at the base, canopy area was calculated by taking the east-west and north-south diameters through the centre of the fullest part of the canopy.

To determine the extent to which the branches of shrubs spatially concentrate stemflow inputs and operate as a collection of incident gross precipitation, a funneling ratio (F) was calculated as (Herwitz, 1986):

$$F = \frac{V}{B \times P} \tag{1}$$

where V is stemflow volume (L), B is trunk basal area (m^2), and P is the depth equivalent of gross incident precipitation (mm). The product $B \times P$ provides the volume of water that would have been caught by a rain gauge having an opening equal to that of the trunk basal area. Thus, F represents the ratio of the amount of precipitation delivered to the base of the shrub to the rainfall that would have reached the ground if the shrubs were not present. Funneling ratios higher than unity indicate that canopy components other than the trunk are contributing to stemflow (Herwitz, 1986; Carlyle-Moses and Price, 2006).

2.2.2 Dye tracer experiment

To assess redistribution of stemflow into the soil profile for *S. psammophila* and *H. scoparium*, we selected another three plants for each species with similar growth shape to those for stemflow measurements to conduct dye tracer experiments under three rainfall events representing small (4.9 mm), medium (9.1 mm), and large (32 mm) rainfall in the study area. One plant was used for one rainfall event for both *S. psammophila* and *H. scoparium*. The selected plants were a few meters away from those for measuring stemflow. Rhodamine-B dye powder was sprinkled on the surface around the base of the trunk (at the root crown) of the selected shrubs of each species as well as the adjacent bare area without shrubs before rain occurrence (Martinez-Meza and Whitford, 1996). Twenty-four hours after rainfall, pits were dug along the main roots beneath the canopy of the shrubs, and the photographs were taken by a digital camera, and then downloaded and transferred to ArcGIS (ESRI, Redlands, CA) for the dye tracing analysis (Devitt and Smith, 2002). Dye coverage diagrams were made according to the procedure of Janssen and Lennartz (2008). Canopy parameters of plants in this part of the study were obtained by the same methodology as that used in the stemflow measurements.

2.2.3 Soil water content measurements

To explore the effect of stemflow on soil water recharge, soil water contents were measured under two other plants with similar growth for each shrub species, one was the control with stemflow, while the other one was treated as no stemflow using the same stemflow collector (described in Sect. 2.2.1) to prevent the channeling of the stemflow into the soil. Soil water contents were measured using TRIME-FM time domain reflectometry (TDR) (IMKO, Ettlingen, Germany) to a depth of 100 cm with sampling increment of 20 cm after each rainfall event. The TDR access tubes were installed to a depth of 1.2 m around the stem of the shrub. Soil moisture at each depth was obtained by taking three measurements and calculating the average.

3 Results and discussion

3.1 Rainfall and stemflow

During rainy seasons between June and September from 2006 to 2008, a total of 64 rainfall events were recorded with individual rain amount ranging from 1.1 to 33.9 mm. Fifty-three percent of these rainfall events were of less than 5 mm and their contribution to the total rainfall amount during rainy reasons from 2006 to 2008 was less than 17%, while the rains exceeding 10 mm generated 69% of the total rainfall. Analysis of the rainfall intensity (I_{10}, maximum rainfall intensity in 10 min) showed that the records were in the range of 1.2–57.6 mm h^{-1} and 59% were less than 5.0 mm h^{-1}, whereas rainfall intensity over 20 mm h^{-1} accounted for only 16% of rainfall events. The results suggest that most storms were of small size with low intensity, but the total amount of annual rainfall mainly depended on a few of lager size storms.

Stemflow was measurable only for 49 events (76.6%) (Fig. 3), among which the minimum rainfall was 1.1 mm for *S. psammophila* and 1.2 mm for *H. scoparium*, respectively. This suggests that the threshold amount of rainfall for stemflow initiation is slightly over 1 mm for these two shrubs. This threshold value is comparable with the rainfall threshold of 1.5 mm reported by Pressland (1973) for *A. aneura*, 1–2 mm reported by Enright (1987) for *Rhopalostylis sapida*, and 1.3–1.8 mm reported by Martinez-Meza and Whitford (1996) for *Larrea tridentata*, *Prosopis glandulosa* and *Flourensia cernua*.

Individual stemflow was significantly correlated with individual rainfall amount. Stemflow increased with increasing rainfall depth and followed a positive linear function (Fig. 4a). For the same amount of rainfall, *S. psammophila* on average produced 1.85 times higher stemflow than *H. scoparium.* Stemflow amounts in *H. scoparium* averaged 3.4% of incident gross rainfall with a range of 2.3–7.0%, while in *S. psammophila*, stemflow averaged 6.3% with a range of 0.2–14.2% (Fig. 5). Higher stemflow production for *S. psammophila* was likely a result of its larger canopy area, larger basal area, taller shrub height, and smaller branch angel, as compared with *H. scoparium*

(Table 1). Several earlier studies have reported positive correlation between stemflow amount and canopy area (Ford and Deans, 1978; Martinez-Meza and Whitford, 1996; Li et al., 2008).

The relationship between stemflow and rainfall intensity was weak and negative (Fig. 4b). Both shrubs showed an exponential decline in stemflow as rainfall intensity increased from 0.2 mm h^{-1} until about 3.5 mm h^{-1} and then relatively stabilized up to the intensity near 10 mm h^{-1}.

Average funneling ratio was 77.8 and 48.7 for *H. scoparium* and *S. psammophila*, respectively, indicating that branches and stem were fully contributing to stemflow generation and thereby provided greater amount of water to deep soil layer. The lower funneling ratio of *S. psammophila* as compared to *H. scoparium* was due to *S. psammophila*'s larger basal area (Table 1). From Eq. (1), in fact, 1.6 lower F for *S. psammophila* is expected because *S. psammophila* has 1.85 higher stemflow for the same amount of incident rainfall and 2.8 larger basal area. Figure 6 showed the relationship between F and rainfall depth for the *H. scoparium* and *S. psammophila*. Both shrubs indicated a general pattern of F first being increased with daily rainfall amount and then declined after reaching a maximum value. Similar trend appeared to exist for the relationship between F and rainfall intensity (Fig. 7). Carlyle-Moses and Price (2006) explained that, with increasing rainfall input, a greater proportion of a tree becomes saturated and thus the area contributing to stemflow increases until a threshold rainfall input is reached that saturates all tree areas capable of producing stemflow. Once this threshold rainfall is exceeded, F-value begins to decrease. Li et al. (2008) also found such pattern between F and incident rainfall for *C. korshinskii*, *R. soongorica* and *T. ramosissima*. The *H. scoparium* had high variability in F, and the largest F-value was 194.5 during a 8.8-mm rainfall event. In contrast, *S. psammophila* exhibited small variability in F with the largest values of 147.2 during a 10.8-mm rainfall event.

3.2 Dye coverage

As observed in the photos of Fig. 8, the dye stained area was significantly influenced by the presence of a shrub or not. In the bare area, the dye coverage was higher but only confined to the upper part of the vertical sectional areas with a rather uniform distribution (Fig. 8g, h, i), and the maximum dye stained depth was 8, 10 and 14 cm for the rainfall of 4.9, 9.1 and 32 mm, respectively (Fig. 9). However, in the area with the shrub presented, dye movement was localized along main roots where the dye had penetrated farther into the vertical profiles (Figs. 8a–f and 10). The maximum depth of dye stain ranged from 18 to 20 cm for *H. scoparium* and from 20 to 26 cm for *S. psammophila*, respectively, under the three rainfall events (Fig. 9). The maximum dye depth increased with increasing rainfall for both shrubs. Also, the larger rain produced more uniform flow in the upper soil profile while the smaller rain produced a higher degree of preferential flow pattern (Fig. 8). These show that stemflow enters the soil preferentially along root channels to deep storage, and that the depth of stemflow infiltrated varies as a function of rainfall characteristics and root distribution. This is consistent with the findings of Martinez-Meza and Whitford (1996) and Devitt and Smith (2002), who used artificial application of water of higher amount (40–300 mm). In our experiment, we traced stemflow in the soil profile under natural rainfall conditions. Stemflow penetrated as deep as 18 cm under a rainfall of 4.9 mm, suggesting that stemflow from small rainfall events can also recharge deeper soil in the sandy desert area.

As for the horizontal dye distribution from the top to the bottom of the soil profile under the rainfall of 4.9 mm, two high concentrated dyed layers could be observed in *H. scoparium* in the depth ranged from 0 to 2 cm and 8 to 14 cm, of which more than 40% was covered (Fig. 9). While under the rainfall of 9.1 mm, two high concentrated dye stained layers presented in *S. psammophil* in the depth ranged from 2 to 6 cm (with a dye coverage of >80%) and 12 to 18 cm (with a dye coverage of >20). In contrast, under the rainfall of 32 mm, a distinct area characterized by a high dye coverage in a certain depth could be observed (more than 80% of the area was covered), and the dye coverage abruptly decreased underneath (Fig. 9). In *H. scoparium*, this high concentrated dyed layer presented in the depth from 2 to 10 cm, while in *S. psammophila* it was in the depth from 6 to 12 cm. High concentrated dye layers presented in different depths for different shrubs under different rainfall conditions highlighted the root systems of desert shrubs provide preferential flow paths of stemflow to deeper sandy soil depths (Figs. 8, 9 and 10). Kung (1990) reported that preferential flow paths constitute dominant flow pattern in a sandy vadose zone, and that water flowing through the root zone was funneled into concentrated flow paths that occupied only a small portion of the soil matrix in the vadose zone and yet accounted for most of the transport. The different patterns of high concentrated dye stained layers presented in the soil under different rainfalls could be attributed to different root networks of desert shrubs and rainfall characteristics. Pressland (1976) found that the stemflow effect would be masked by large rainfall events.

3.3 Soil water content

Soil water content with soil depth directly reflected the influence of stemflow-root system on water movement. Wetter soil and deeper penetration of the water can be clearly noted when there was stemflow (Fig. 11). During the three rainfall events characterized by small (4.3 mm), medium (14 mm) and large (32.5 mm) amounts, as much as 10–60% increase in soil water content could be found in *S. psammophila* and 10–140% increase in *H. scoparium* as compared to that without stemflow. This confirms that stemflow is conducive to concentrate and store water in deep layers in the soil profile, suggesting that stemflow creates favorable soil water conditions for plant growth under arid conditions (Pressland, 1976; Martinez-Meza and Whitford, 1996). This suggests that stemflow would be considered as an essential property of desert shrubs that contributes to the stability of shrub communities in harsh environments (Martinez-Meza and Whitford, 1996). For the deciduous forests, Liang et al. (2007) also reported that maximal soil water storage was more than 100 to 200% of the cumulative open-area rainfall at the points downslope from a tall *stewartia* stem on a hillslope. They attributed this to concentrated stemflow rapidly flowing into soil layers along the pathways of roots as bypass flow.

Figure 12 shows the differences in soil water contents at various depths for *H. scoparium* and *S. psammophila* between the treatments with and without stemflow under different rainfall conditions. The results indicated that the increase of soil water content due to stemflow tended to increase with increasing rainfall amount for both shrubs. This is consistent with the above results in Sect. 3.1 that stemflow amount increases with increasing rainfall. Increases of soil water content changes were observed at all depths from 20 to 100 cm. In particular, increase at 60-cm depth was much greater than that in the upper layers (20-cm) and deep layers (100-cm). This suggests that stemflow mostly reached 60-cm soil layers and only small portion reached 100-cm soil layers in the study area. Liang et al. (2008) reported that, in the stemflow infiltration process, water flowed rapidly through a deep layer, causing irregular changes in vertical soil water content. This process is very different from the vertical rainfall infiltration process, in which the wetting front expands slowly from the upper layer to the deeper layer. Johnson and Lehmann (2006) found that stemflow has a double contribution to uneven water input and preferential rainwater infiltration that enlarges the heterogeneity of soil water dynamics in forested stands. Therefore, stemflow not only serves as a point source of rainwater on the floor, but also has a high potential to infiltrate multiple soil layers as bypass flow (Liang et al., 2007). The *S. psammophila* had more soil water increase and exhibited significant response to stemflow as compared to the *H. scoparium*, because *S. psammophila* generated more stemflow during rainfall events.

4 Conclusions

Shrubs redistribute hydrologic fluxes to the root zone through a double-funneling process: Shrubs first partition rainfall into throughfall and stemflow, resulting in a spatial redistribution of water fluxes reaching the soil; stemflow delivered to the soil at the base of trees is then further funneled by tree roots through belowground preferential flow pathways. The results of this study demonstrate that stemflow from intercepted rainfall can greatly influence the downward movement of water through the soil profiles. Deeper penetration of water can clearly be noted when stemflow occurred, and the depth of stemflow infiltrated varies as a function of rainfall characteristics and root distribution. There is a clear connection between aboveground and belowground shrub effects on ecohydrology and hydropedology, whereby an increase in stemflow relative to bulk precipitation would contribute to an increase in soil hydrological heterogeneity. Deep infiltration of stemflow through preferential flow pathways augments the quantity of available water in the rhizosphere and aids shrubs in withstanding droughts. This study reveals the importance of integrating ecohydrology and hydropedology in understanding the hydrologic cycle in desert shrubs.

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Table 1. Mean values (±standard deviation) of morphological parameters of the two dessert shrub species studied (n=12).

	H. scoparium	*S. psammophila*
Shrub height (m)	1.7±0.3	2.1±0.2
Branch angle (°)	70.5±10.0	61.8±6.5
Basal area (cm^2)	3.9±1.8	10.9±8.3
Number of branches	13±9	6±2
Canopy area (m^2)	2.7±0.6	3.6±3.1

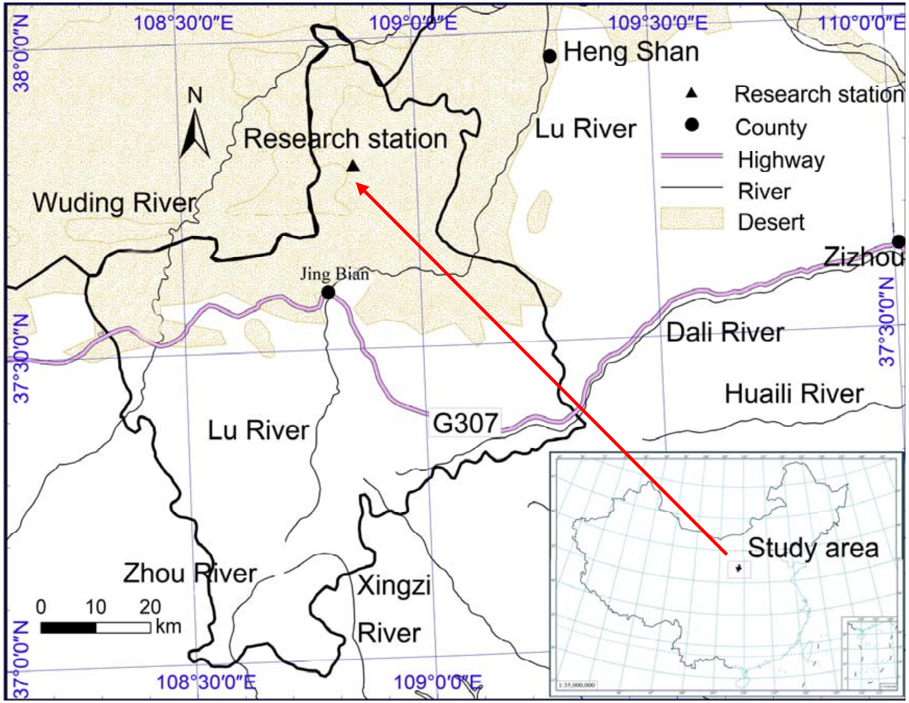

Fig. 1. Location of the study area.

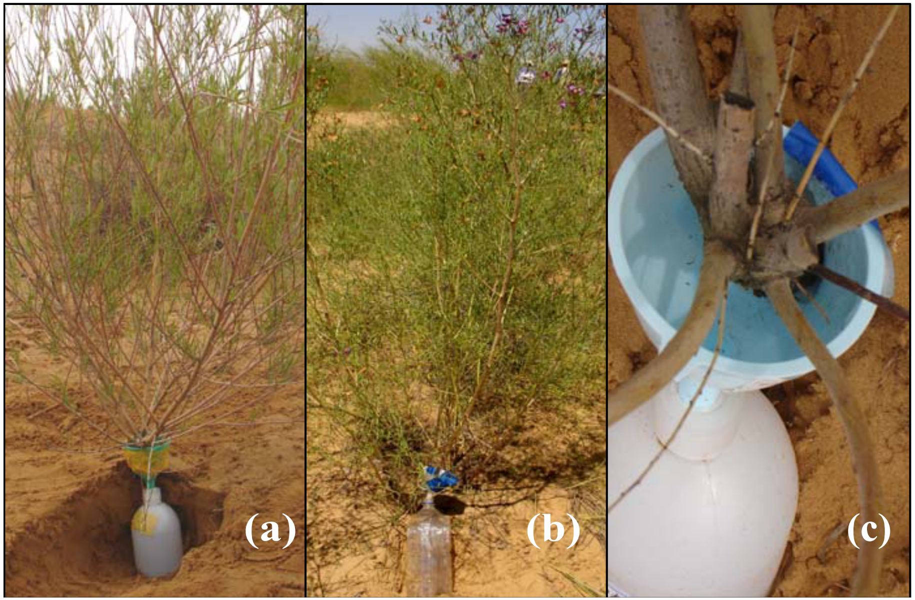

Fig. 2. Photographs showing shrubs of *S. psammophila* **(a)** and *H. scoparium* **(b)** and stemflow collector consisting of plastic funnel and a collection bottle **(c)**.

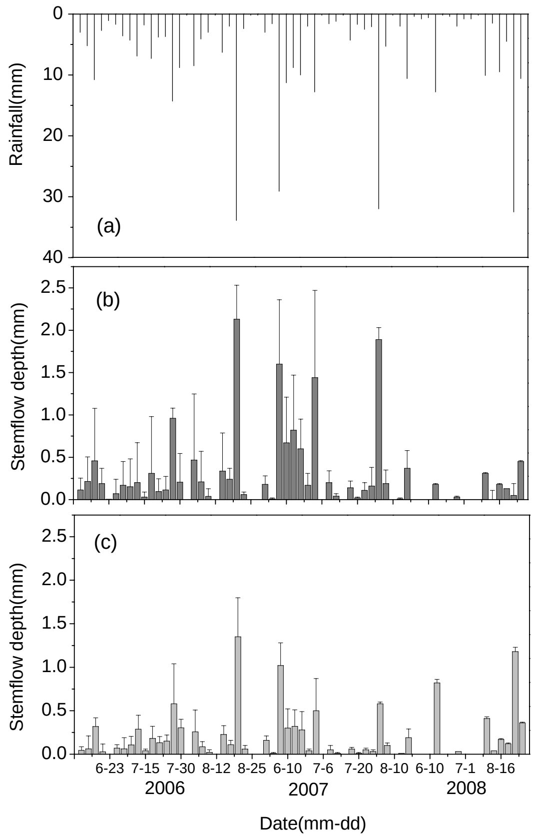

Fig. 3. Daily rainfall distribution **(a)** together with the stemflow depth (mm) for *S. psammophila* **(b)** and *H. scoparium* **(c)** during growing seasons from 2006 to 2008 at the experimental site (bars indicated standard deviation of the seven replicates for each species).

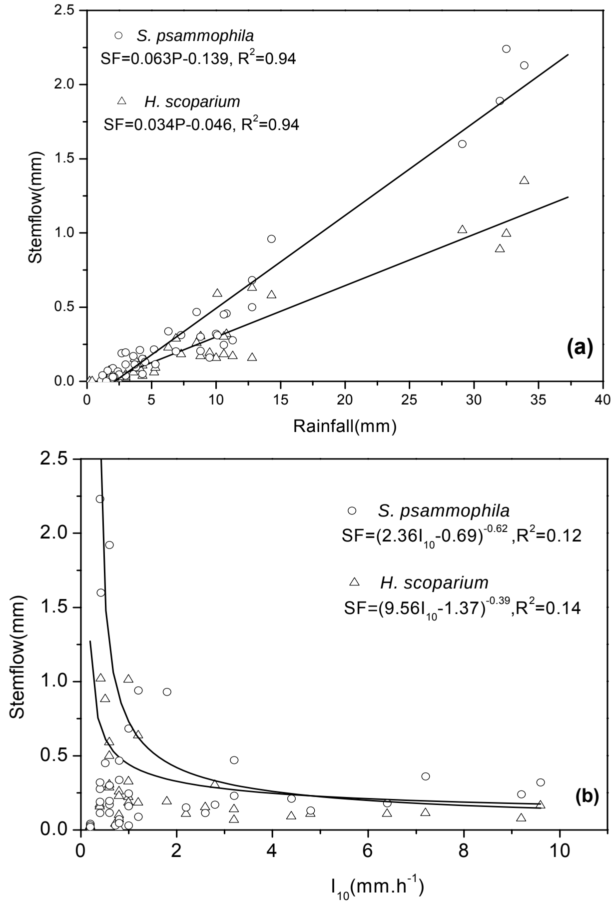

Fig. 4. The relationship between stemflow and daily rainfall amount **(a)** and I_{10} (maximum rainfall Intensity in 10 min) **(b)** for *H. scoparium* and *S. psammophila*.

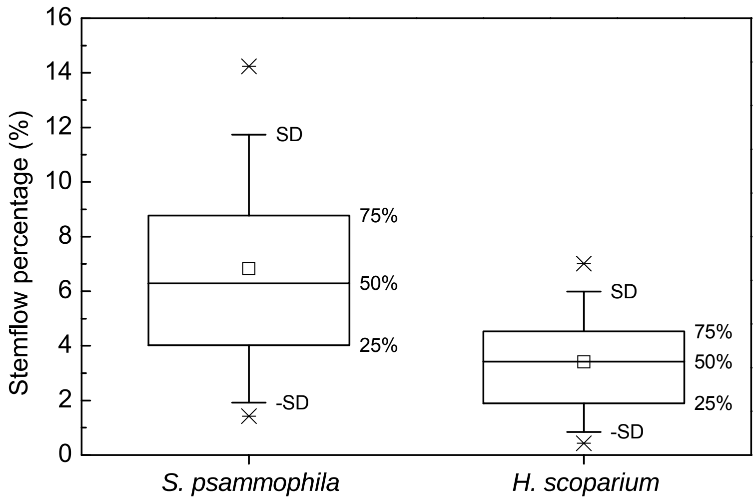

Fig. 5. Box-and-whisker diagrams showing the median, 25th, 50th, 75th percentiles and standard deviation for individual stemflow percentage for *S. psammophila* and *H. scoparium*. (□) Represents mean value, (⋆) maximum and minimum value.

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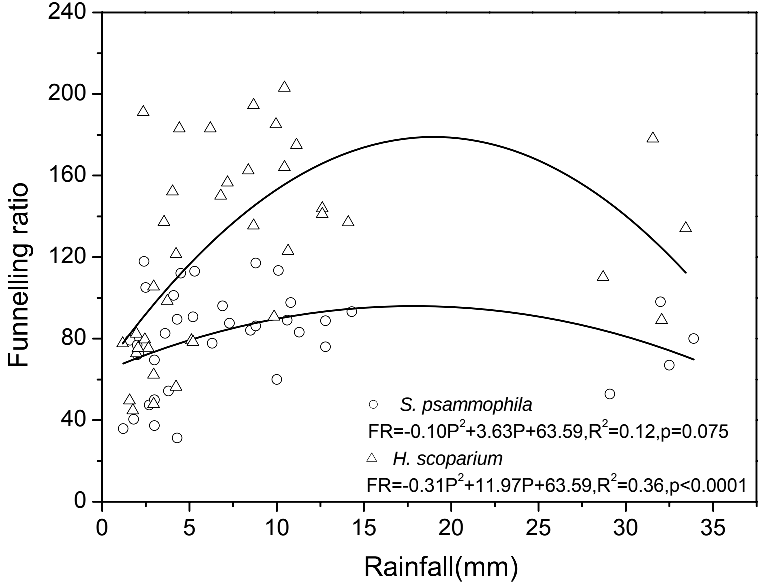

Fig. 6. Relationship between funneling ratio and daily rainfall amount for *H. scoparium* and *S. psammophila*.

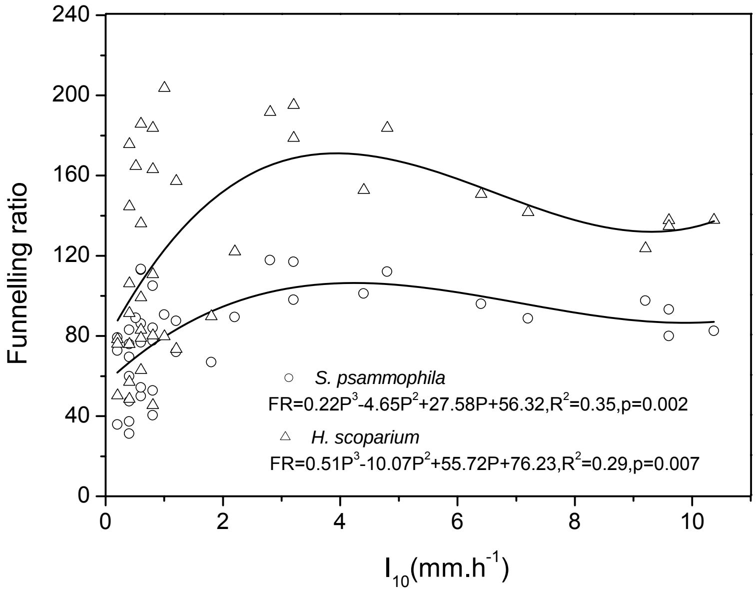

Fig. 7. Relationship between funneling ratio and I_{10} (maximum rainfall Intensity in 10 min) for *H. scoparium* and *S. psammophila*.

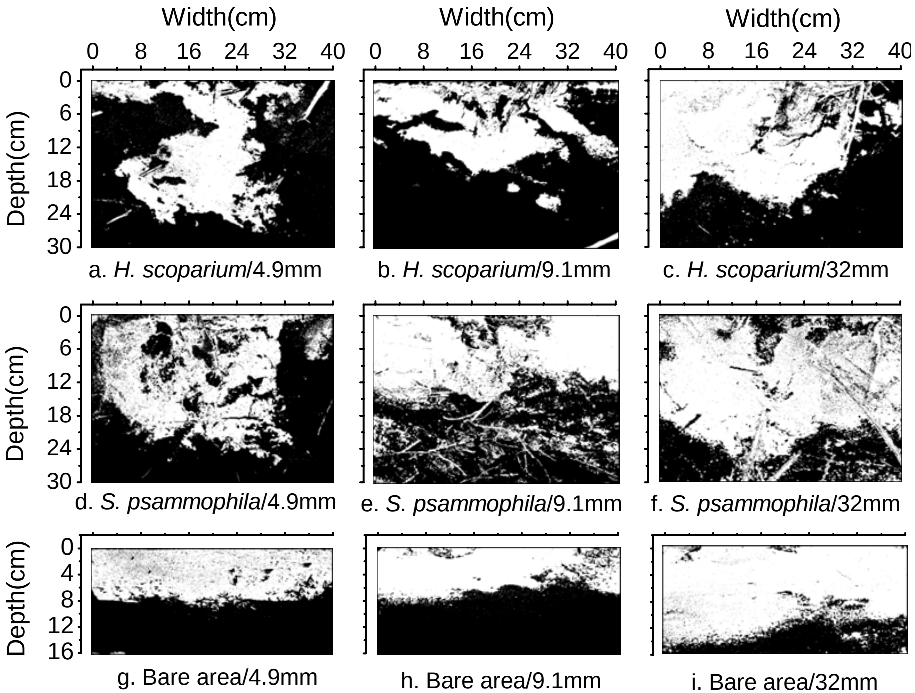

Fig. 8. Computer-enhanced photos of the dye stained area in the vertical soil profile around the base of the trunk beneath the canopy of *H. scoparium*, *S. psammophila* and the bare area, respectively, under three rainfall events with amount of 4.9, 9.1 and 32 mm. White shading indicates dye stained areas, black shading represents unstained conditions, See Fig. 9 for quantitative dye-stained area as a function of soil depth.

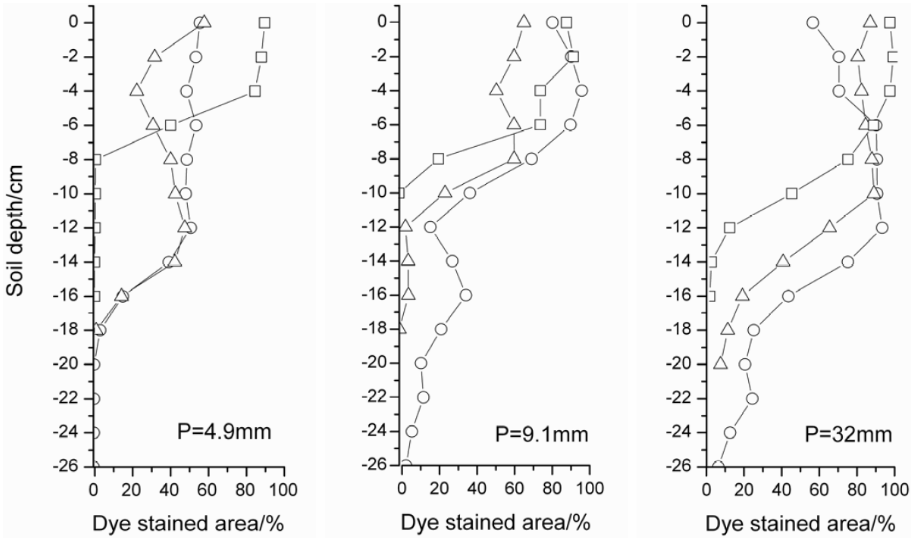

Fig. 9. The percentage of dye stained area with depth for *H. scoparium* (△), *S. psammophila* (o) and the bare area (☐) respectively, under three rainfall events with amount of 4.9, 9.1 and 32 mm.

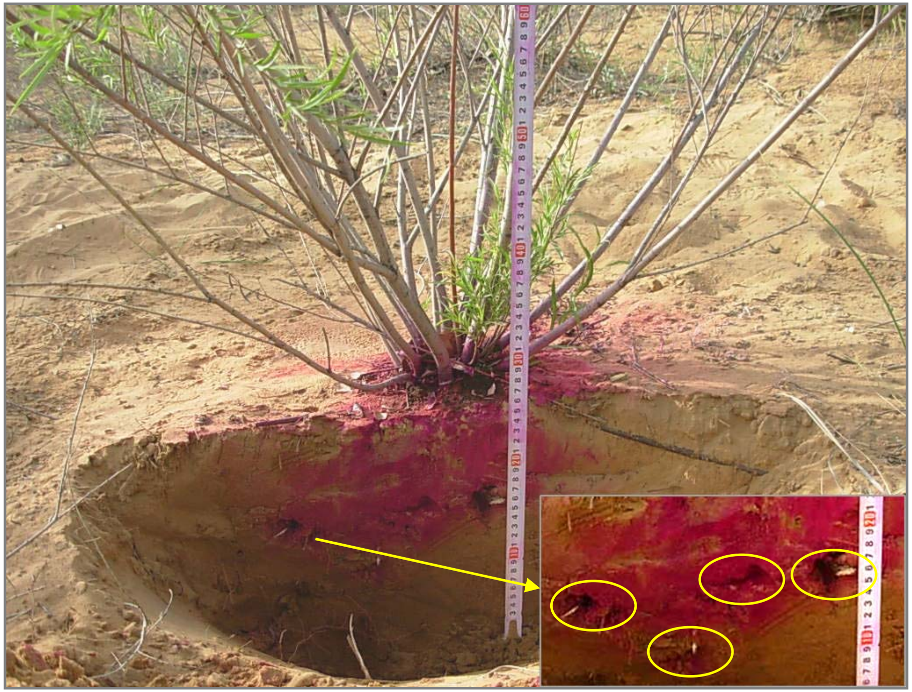

Fig. 10. Colour photograph showing vertical profiles of dye stained area under *S. psammophila* with the position of the root channel macropores (marked by the yellow elliptic frames).

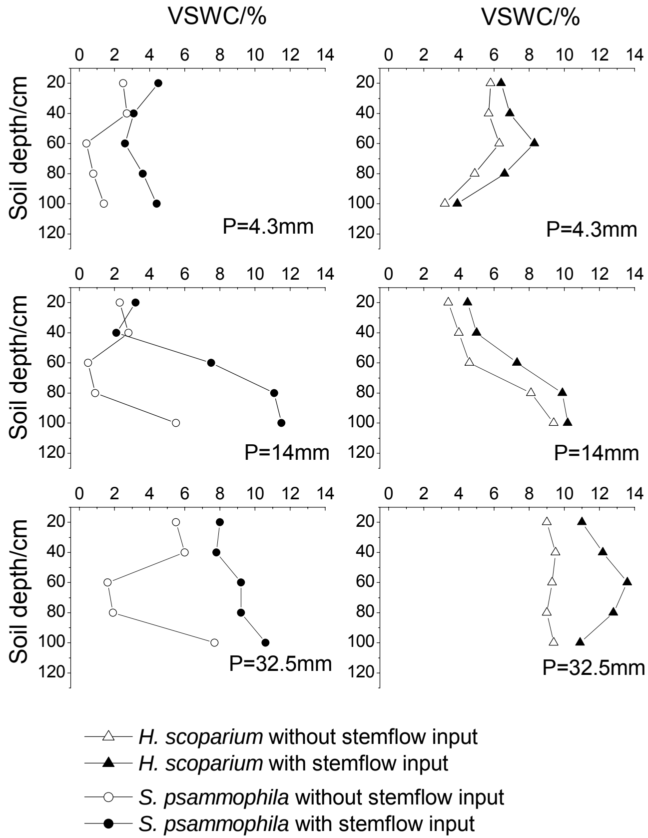

Fig. 11. Distribution of volumetric soil water contents (VSWC) for *H. scoparium* and *S. psammophila* with and without stemflow under three rainfall events characterized by high, medium and low amount.

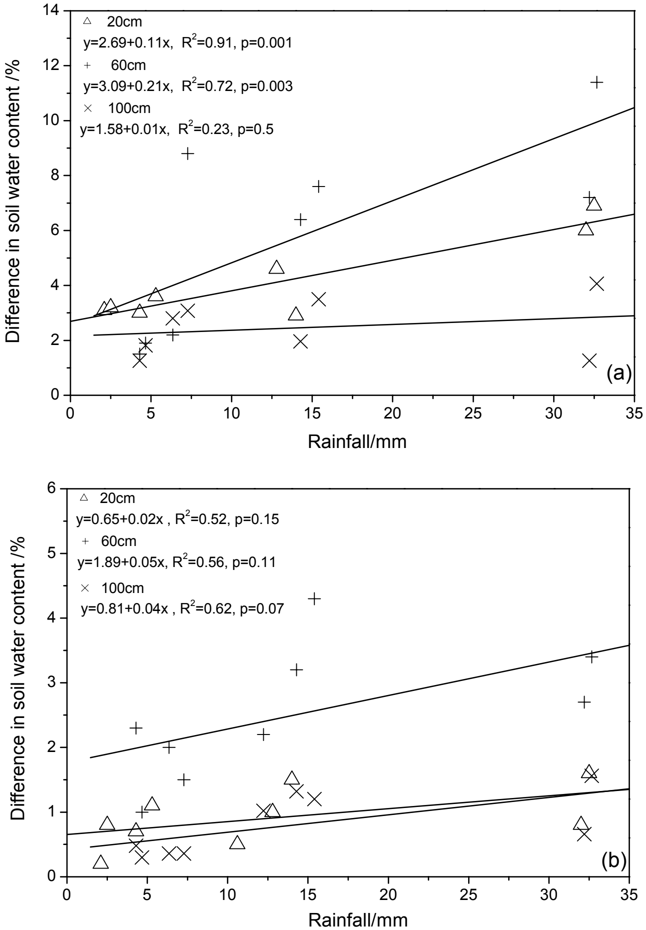

Fig. 12. Difference in soil water contents at various depths for *S. psammophila* **(a)** and *H. scoparium* **(b)** between the treatments with and without stemflow under different rainfall conditions.