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ORIGINAL ARTICLE

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Stemflow in two xerophytic shrubs and its significance to soil water and nutrient enrichment

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Abstract Shrub canopies are expected to funnel substantial amounts of intercepted rainwater with enriched nutrients as stemflow to shrub base in the desert ecosystems characterized by limited water and nutrients. However, lacking are quantitative studies on the water and nutrient enrichment of stemflow at the shrub basal area. In this study, stemflow were quantified for two xerophytic shrubs (*Caragana korshinskii* and *Artemisia ordosica*) in a revegetated desert ecosystem of Shapotou area in northwestern China. We also measured the ion concentrations of total nitrogen (TN), total phosphors (TP), NH_4^+–N, NO_3^-–N, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} and the pH and electric conductivity (EC) in stemflow, throughfall and bulk precipitation. Results indicated that stemflow accounted for 8.8 and 2.8 % of the gross rainfall for *C. korshinskii* and *A. ordosica*, respectively. Individual stemflow linearly increased with increasing rainfall depth. Stemflow increased with rainfall intensity when rainfall intensity was less than 2 mm h^{-1} but showed decreased tendency thereafter. An antecedent precipitation of 1.3 and 1.6 mm was necessary for stemflow initiation for *C. korshinskii* and *A. ordosica*, respectively. The mean (confidence intervals, $\alpha = 0.05$) funneling ratio was 82 (17) for *C. korshinskii* and 26 (7) for *A. ordosica*. Ion concentrations in stemflow were higher than in throughfall, and the concentration of most of the ions measured were significantly higher ($p < 0.05$) in stemflow than in bulk precipitation, with a nutrient enrichment ratio ranged 122.8–1677.0 for *C. korshinskii* and 12.6–1306.0 for *A. ordosica* among measured ions, respectively. Overall, the larger funneling ratios and enrichment ratios for the two shrubs suggest that stemflow plays a significant positive role in soil water replenishment and nutrient enrichment at deeper soil profile of root zone in the revegetated ecosystems under arid desert conditions.

Keywords Stemflow · Funneling ratio · Enrichment ratio · *C. korshinskii* · *A. ordosica*

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Introduction

Arid and semi-arid ecosystems are often characterized by vegetation patchiness, and the vegetation growth and ecosystem processes are typically limited by water and nutrient availability (Noy-Meir 1973; Kéfi et al. 2007). Revegetation experiments have been established for more than 50 years at Shapotou area in the southeastern fringe of the Tengger Desert, northwestern China, using mainly xerophytic shrubs such as *Caragana korshinskii*, *Hedysarum scoparium*, and *Artemisia ordosica*, which are considered as a successful model for desertification control and ecological restoration. The former sand dune landscape has been greatly transformed into a landscape characterized by a mosaic of the sparse shrubs and herbs and the bare interspaces covered by biological soil crusts (Li et al. 2006). Since rainfall is often the sole source of water replenishment in arid desert area, the availability of water and nutrients for vegetation growth and survival is critical to the development of this rain-fed revegetated desert ecosystem (Wang et al. 2005; Li et al. 2007) and merits great attention in the research of ecological restoration.

Vegetation canopy, by redistributing incident precipitation, affects the hydrological and biogeochemical fluxes between vegetation and soil (Dunkerley 2000; Levia and Frost 2003; Johnson and Lehmann 2006; Navar et al. 2009; Navar 2011). A part of the incident precipitation is intercepted by the canopy and evaporates directly back into the atmosphere (interception loss), and the remaining reaches the ground either as throughfall or stemflow. Throughfall is the part of precipitation that reaches the soil beneath canopy directly through canopy gaps (free throughfall) and via dripping of leaves, branches, and stems (released throughfall). Stemflow refers to the part of precipitation that is intercepted by leaves, twigs, and branches and eventually channeled into soil through trunk or stem. Stemflow accounts for approximately 5 to >10 % of incident gross precipitation, nevertheless its small fraction, it is a spatially localized point input of precipitation and solutes at the trunk that can easily be available for plant roots (Navar and Bryan 1990; MartinezMeza and Whitford 1996; Whitford et al. 1997; Crockford and Richardson 2000; Levia and Frost 2003; Li et al. 2008, 2009; Navar 2011; Wang et al. 2011). In addition, stemflow influences other ecological and hydrological processes such as surface runoff, soil erosion, groundwater recharge, spatial distribution pattern of soil moisture, chemistry of soil solution, the distribution of understory vegetation and epiphytes (Levia and Frost 2003), and a potential streamflow generation process (Herwitz 1986). Levia and Frost (2003) provided a thorough review of the quantitative and qualitative importance of stemflow in forested and agricultural ecosystems, and pointed out that in spite of the importance of stemflow as an input point of soil water and nutrient, stemflow is under-represented in the literature. This is particularly the case for that of shrubs and bushes in arid and semi-arid areas (Dunkerley 2000; Llorens and Domingo 2007).

Although stemflow is volumetrically insignificant when compared to throughfall at the stand scale, it can be significant in soil water replenishment along roots due to the funneling effects of vegetation canopy that collects the rainwater from a large area of canopy but delivers it to the soil in a much smaller trunk or stem basal area (Davie 2002; Levia and Frost 2003; Johnson and Lehmann 2006). Infiltration of stemflow alongside stems into deep soil profiles, creating islands of soil moisture, can be an important potential source of soil moisture allowing shrubs to remain physiologically active during drought spells (Navar and Bryan 1990; Navar 2011). For instance, Nulsen et al. (1986) observed that stemflow of a mallee can be delivered to soil along roots at a depth of 28 m and the stored water was used during the dry summer months. Meanwhile, stemflow often has higher nutrient concentrations than throughfall and bulk precipitation (Crockford et al. 1996; Whitford et al. 1997; Germer et al. 2012), and the nutrients input to the soil through stemflow are immediately available for plant uptake (Eaton et al. 1973). Stemflow was thus considered as an important biological transfer mechanism in soil nutrients and water enrichment in the arid and semi-arid environments with lacking water and nutrients, contributing to the development of "fertile islands" under shrub canopies (Garner and Steinberger 1989; Whitford et al. 1997; Li et al. 2011). One known study by Whitford et al. (1997) reported that the concentrations of total nitrogen (TN), total phosphors (TP), NH_4^+–N, NO_3^-–N, K^+, Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} were significantly higher in stemflow of *Larrea tridentate* than in the bulk precipitation in the northern Chihuahuan Desert. Overall, the present knowledge on stemflow enrichment is very weak, which is particularly the case in that of shrubs of arid and semi-arid areas (Llorens and Domingo 2007), and the published results are less comparable due to the lack in use of quantitative tools (Levia and Frost 2003; Llorens and Domingo 2007). As for quantitative tools, funneling ratio, proposed by Herwit (1986), allowing a quantification of the water enrichment of stemflow at the stem basal area, is a good parameter and gains increasing attention in stemflow studies (Llorens and Domingo 2007; Germer et al. 2010). Likewise, enrichment ratio, as having been used by, e.g., Levia and Herwitz (2000), Levia et al. (2011) in stemflow studies in forests, is considered as a meaningful quantitative tool for evaluating nutrient enrichment of the stemflow that were delivered to plant basal area.

Stemflow amounts are highly variable between plant species due to their morphological differences (Levia and Frost 2003; Navar 2011). MartinezMeza and Whitford (1996) reported a stemflow percentage of incident rainfall of 5.4, 10, and 10.5 % for shrub species *Prosopis glandulosa*, *Larrea tridentata*, and *Flourensia cernua*, respectively. Serrato and Diaz (1998) observed that for *Juniperus oxycedrus*, *Rosmarinus officinalis*, and *Thymus vulgaris*, the stemflow percentages were 18.6, 43.3, and 29.8 %, respectively. Llorens and Domingo (2007) reviewed that in the European Mediterranean area, stemflow percentage averaged 3 % with a variation coefficient of 111 % ranging from about 1 % for *Picea abies*, *Pinus sylvestris*, and *Quercus pyrenaica* and 12 % for *Pinus nigra*. Li et al. (2009) reported a stemflow percentage of 3.4 and 6.3 % for shrubs *H. scoparium* and *S. psammophila*, respectively. More recently, Garcia-Estringana et al. (2010) found the average stemflow percentage was 16 % for nine Mediterranean shrubs with a range of 3.8–26.4 % and Navar (2011) reported a 2.5 % for Tamaulipan thornscrub in northeastern Mexico. It is also worth noting that very few studies have investigated stemflow from individuals to stand scales (Levia and Frost 2003; Navar 2011), and of which Navar (2011) found that stemflow tripled when it was extrapolated from individual shrubs to stand scales. A better understanding of the characteristics of stemflow and its variation for shrub community is critically important in water balance of arid and semi-arid regions (Llorens and Domingo 2007; Li et al. 2008). Therefore, more studies in stemflow characteristics for various shrub species are called for to obtain an accurate representation of parameters in hydrological model (Llorens and Domingo 2007).

Stemflow may be an important localized source of soil water and nutrients available for vegetation growth and survival in a rain-fed revegetated desert ecosystem. However, little qualitative and quantitative work has been done on the stemflow of xerophytic shrubs and its effects on soil water and nutrient enrichment in this ecosystem. In the present study, we aimed to (1) quantify the stemflow of two xerophytic shrubs (*C. korshinskii* and *A. ordosica*) and determine its relationship to rainfall characteristics (depth and intensity); (2) by using funneling ratio and enrichment ratio, quantify the effects of stemflow of the two shrubs on soil water and nutrient enrichment.

Materials and methods

Site information

The study was conducted between June and November of 2011 at the Shapotou Desert Research and Experiment Station (SDRES) of Chinese Academy of Sciences (37°32′N, 105°02′E, an elevation of 1,300 m a.s.l.), located at the southeastern fringe of the Tengger Desert in northwestern China. Mean annual precipitation is only 191 mm (1955–2005, SDRES) with 80 % of rain occurring between July and September with a coefficient of variation as high as 45.7 %. Most storms are of small size with low intensity and around 70 % of the rainfall intensities are less than 5 mm h^{-1} (Wang et al. 2005). The precipitation is the only source of soil water replenishment because the groundwater is as deep as 50–80 m and it is unavailable for plant roots. Mean maximum air temperature is 24.7 °C in July and the mean minimum is −6.1 °C in January. The potential evapotranspiration is approximately 2,500 mm during the growing season, resulting in a large annual moisture deficit. 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 sand (0.05–0.25 mm), and the clay content is about 0.2 %. The sand can thus be classified as *Typic Psammaquents* (Berndtsson et al. 1996).

To protect the Baotou-Lanzhou railway against encroaching sand dunes in the Shapotou area, a 16,000-m-long (500-m widths to the north and 200 m to the south) artificially revegetated protection system was established along the Baotou-Lanzhou railway after the revegetation efforts in the 1950s–1980s, mainly by setting up of straw checkerboards in the moving sand soil and planting xerophytic shrubs (mainly *C. korshinskii*, *H. scoparium* and *A. ordosica*) within them. Li et al. (2006) had a detailed description about the revegetation procedure of study area.

The Water Balance Experimental Field (WBEF), 1 ha, is one of the revegetated enclosures here, established in 1989, by planting *C. korshinskii*, and *A. ordosica*. *C. korshinskii* is a multi-stemmed deciduous perennial shrub and looks like an inverted cone. The average height is 145 cm and the average canopy diameter is 130 cm. Leaves are pinnately compound and opposite or subopposite in arrangement and 6–10 cm long. Each pinna has 5–8 pairs of leaflets, which are ovate in shape with 7–8 mm in length and 2–5 mm in width. *A. ordosica* is a highly branched dwarf-shrub without obvious main stem and with plumose, full split needled leaves (length, 10–30 mm, width, 0.3–l mm). The average height is 64 cm and the average canopy diameter is 96 cm. Figure 1 displays the general view the two shrub species and their leaf characteristics.

Experiment design and field measurements

Stemflow was measured from 17 robust and healthy shrubs (ten for *C. korshinskii* and seven for *A. ordosica*) representing the two xerophytic shrub species in WBEF. Stemflow volume was measured by a graduated cylinder for each individual stem (*A. ordosica* has only one stem) after each rainfall event and summarized for a single shrub. Canopy area 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). Each stem basal diameter was measured with a Vernier caliper at the stem base. The total stem basal area for each individual shrub is the sum of the basal area of all its stems. Stemflow depth was calculated as

$$D_{SF} = \frac{V_{SF}}{CA} \tag{1}$$

where D_{SF} is the stemflow depth (mm), V_{SF} is the stemflow volume (L), CA is the canopy area (m^2).

The stemflow collection system can be seen in Fig. 1. It is done according to the following procedures: (1) using fine sandpapers to gently burnish the stem surface at about 10 cm above ground; (2) owing to the adhesiveness and plasticity of aluminum foil plates, a strip of aluminum foil plates (6 cm in width and 0.08 mm in thickness) are convolved tightly around the burnished stem surface in one and a half circles; (3) cut off another strip of aluminum foil plates, gently fold the strip along the length into halves, and fit the lower half part of strip tightly around the entire circumference of the stem, while keeping the higher half part of the strip 1 cm off the stem periphery. Through this, a collar, 3 cm in height with the bottom tightly sticking to the stem surface, constructed from flexible aluminum foil plates, is fitted around the entire circumference of stem; (4) use a 15-cm-long aperture plastic hose (1.5 cm in diameter) to connect the collar to a polyethylene bottle. Finally, a stemflow diversion system resembling a tobacco pipe is formed. Stemflow could be intercepted by the collar and then drained into the bottle through a hose. This stemflow collection system was found to be very effective in the stemflow collection of xerophytic shrubs during the field observations.

Samples of incident gross rainfall and throughfall were collected to serve as the controls for evaluating the extent of chemical enrichment in the stemflow drainage. For throughfall collection, throughfall collectors were installed at three directions (0°, 120°, and 240°) beneath

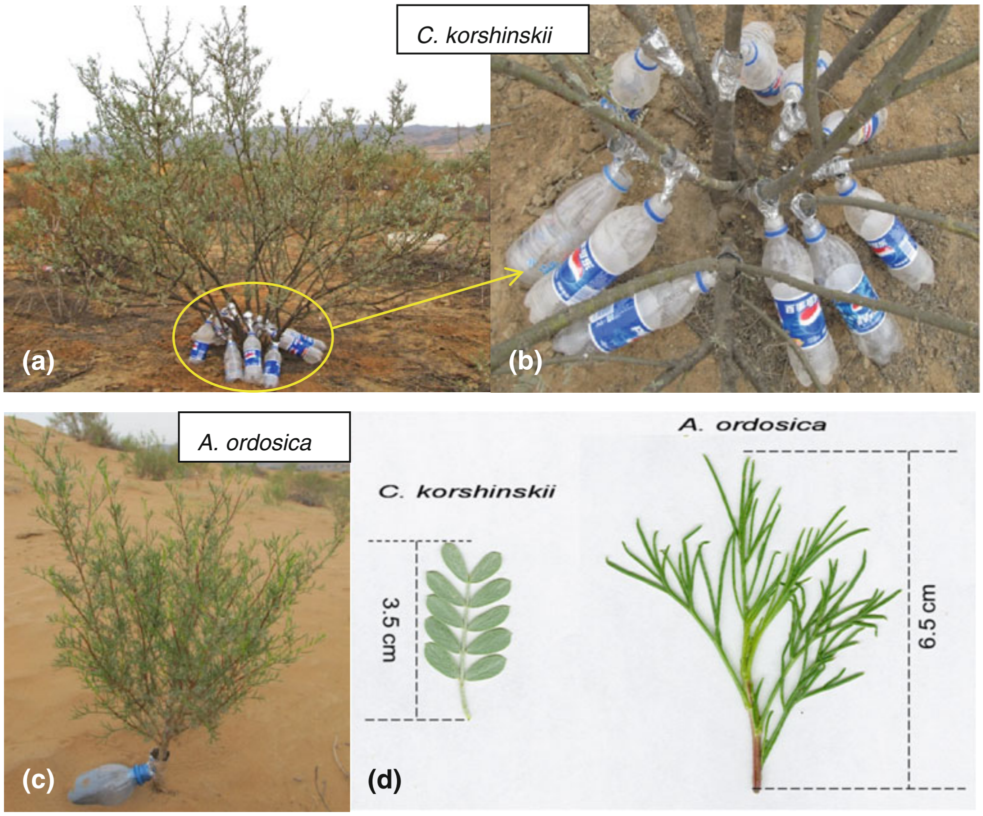

Fig. 1 Photographs showing the stemflow collection systems for *C. korshinskii* and *A. ordosica* and their leaf characteristics

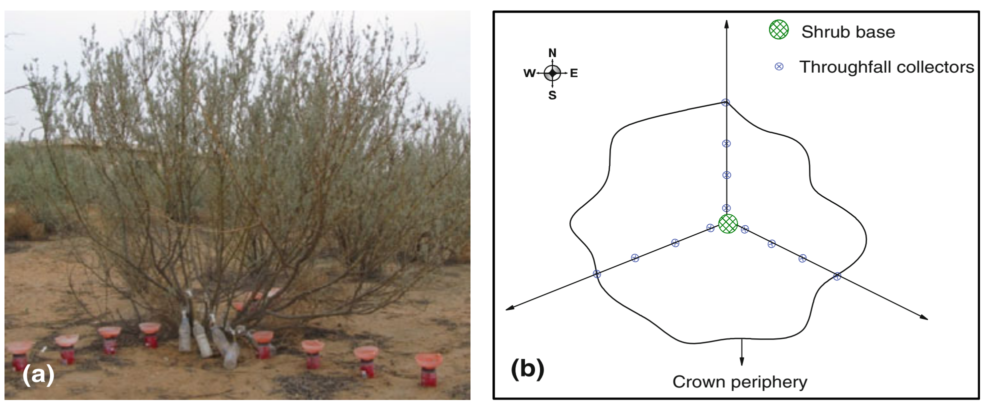

Fig. 2 Photograph (**a**) and schematic layout (**b**) showing throughfall collection for *C. korshinskii*

the shrub canopy, as shown in Fig. 2. A throughfall collector consists of a polyethylene funnel (11 cm in diameter) and a container under the funnel. In each direction, throughfall collectors (four for *C. korshinskii* and three for *A. ordosica*) were set up equidistantly from near the shrub base to crown periphery. As such, there were 12 and nine throughfall collectors for the throughfall collection of each shrub of *C. korshinskii* and *A. ordosica*, respectively. All collectors were rinsed three times in distilled, deionized water before being used for sample collection. Gross rainfall samples were collected by setting up two open-top glass containers (30 cm in inner diameter and 30 cm in height) in the open area.

For individual shrub in each rainfall event, the throughfall depth was calculated as

$$D_{\mathrm{TF}} = \frac{\sum_{i=1}^{N} (V_{\mathrm{TF}})_i}{N \times \mathrm{FA}} \tag{2}$$

where D_{TF} is throughfall depth (mm), V_{TF} is throughfall volume (L) for each collector, N is the number of throughfall collectors under each shrub canopy, FA is the opening area (m^2) of a funnel used in the experiments. For each rainfall event, canopy interception loss was calculated as the difference between the gross rainfall in the open area and the measured stemflow plus throughfall.

Wetting front depths within soil were observed by digging a soil profile from the shrub base to inter-shrub spaces after two rainfall events (a rainfall of 13.9 mm on July 28 and a 21.3 mm on August 15). The *C. korshinskii* for observing wetting front depth has a height of 220 cm and a crown diameter of 300 cm and the *A. ordosica* has a height of 85 cm and a crown diameter of 120 cm. The wetting front depth was measured using a ruler with a resolution of 1 mm in the soil profile every 20 cm starting from the shrub base.

A standard tipping bucket rain gauge (Adolf Thies GMVH & Co. KG, Germany) with a resolution of 0.1 mm and a mini logger recording 10-min rainfall intensity values was installed at an open area approximately 50 m from the study plot.

Chemical analyses

Samples of gross rainfall, stemflow, and throughfall for chemical analysis were collected immediately after the cessation of rainfall, filtered through a 0.45-μm nylon membrane filter and then stored at 4 °C in a refrigerator. Samples collected after five rainfall events were used for chemical analysis. The pH and electric conductivity (EC) were analyzed using a handled YSI 556 Multiparameter Water Quality Meter (resolution, 0.01; accuracy, ±0.2) within 2 h after sampling. Other laboratory chemical analyses were performed at Supervision and Testing Center of Mineral Resources, Lanzhou, Ministry of Land and Resources, China. Concentrations of cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were analyzed using inductively coupled plasma (ICP) spectrometry (iCAP 6300; Thermo Fisher Scientific, Waltham, MA, USA). The Cl^- and SO_4^{2-} concentrations were determined using ion chromatography. Total nitrogen (TN), total phosphorus (TP), NH_4^+–N, and NO_3^-–N concentration were measured using a TU-1800SPC ultraviolet-visible spectrophotometer (Beijing Purkinje General Instrument Co., China).

Funneling ratio and enrichment ratio

To assess the water enrichment effect of stemflow at shrub basal area, we use the funneling ratio (F) proposed by Herwitz (1986) for quantification and it was calculated as

$$F = \frac{V_{SF}}{B \times P_G} \tag{3}$$

where F is funneling ratio, V_{SF} is stemflow volume (L), B is the stem basal area (m^2) of stemflow generating shrub, and P_G is depth equivalent of the incident gross precipitation (mm). The product $B \times P_G$ is the volume of stemflow expected in a rain gauge occupying the same area as the stem basal area. F represents the ratio of the amount of precipitation delivered to the shrub base to the rainfall that would have reached the ground in the absence of the shrub. F exceeding one indicates that canopy component other than the stems are contributing to the stemflow input (Herwitz 1986).

The extent of chemical enrichment of stemflow was quantified by using the following equation developed by Levia and Herwitz (2000).

$$E = \frac{C_{SF} \times V_{SF}}{C_P \times B \times P_G} \tag{4}$$

where E is enrichment ratio of stemflow, C_{SF} is solute concentration in stemflow (mg l^{-1}) and C_P is solute concentration in bulk precipitation (mg l^{-1}). Substituting Eq. (3) into Eq. (4), we can get the following simplified equation:

$$E = F\frac{C_{SF}}{C_P} \tag{5}$$

Equation (5) combines E with F and allows the comparison of solute inputs between stemflow and precipitation per unit trunk basal area. Expression of stemflow inputs using the enrichment ratio, by coupling both the water and solute inputs, is a meaningful and intuitive method because basal area is the true area over which stemflow is delivered to the soil (Levia et al. 2011).

Statistical analyses

Descriptive statistics were compiled for rainfall characteristics (depth and intensity), stemflow amounts, funneling ratios, ion concentrations, and enrichment ratios. We used a t test to determine the differences in the percentage of stemflow, throughfall, and interception loss between *C. korshinskii* and *A. ordosica*, respectively. We used one-way ANOVA to test the differences in TN, TP, NH_4^+–N, NO_3^-–N, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, pH and EC between stemflow, throughfall and bulk precipitation, respectively. All the descriptive statistics and ANOVA analyses were performed using the SPSS 16.0 statistical software (SPSS Inc., Chicago, USA).

Results

Rainfall and stemflow

A total of 29 rainfall events during the study period were recorded with a total of 161.1 mm of rainfall. Stemflow was measurable for 17 rainfall events with a total of 154.7 mm, accounting for 96 % of the total rainfall amount and 59 % of the event number. The 17 rainfall events ranged from 1.9 to 20.2 mm with a mean of

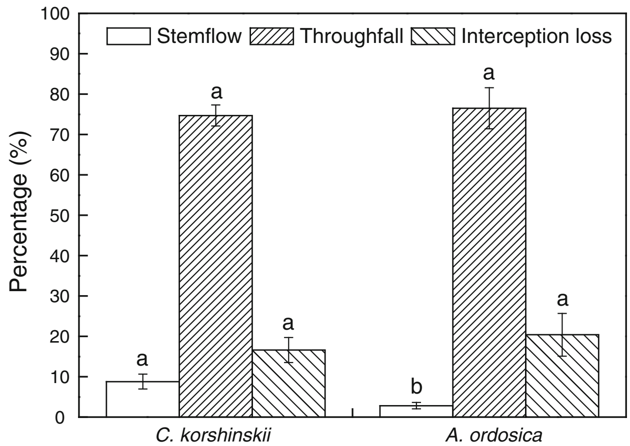

Fig. 3 Average percentage and confidence intervals ($\alpha = 0.05$) of stemflow, throughfall, and interception loss for *C. korshinskii* and *A. ordosica*, respectively. Values with *different letters* in the percentage of stemflow, throughfall and interception loss between *C. korshinskii* and *A. ordosica* are significant at $p < 0.05$

9.1 mm. The rainfall intensity ranged from 0.81 to 21.2 mm h^{-1} with a mean of 3.1 mm h^{-1}. Sixteen out of the 17 rainfall events had rainfall intensities less than 6 mm h^{-1}. Thus, the individual rainfall with intensity of 21.2 mm h^{-1} can be regarded as an extreme rainfall event.

Stemflow in *C. korshinskii* averaged (confidence intervals, $\alpha = 0.05$, similarly hereinafter) 8.8 % (1.9) of total incident rainfall in the range of 1.4–11.7 %, and it averaged 2.8 % (0.8) in the range of 0.7–5.2 % in *A. ordosica* (Fig. 3). Mean stemflow depth was 0.88 (0.33) mm in the range of 0.06–2.25 mm for *C. korshinskii*, and it was 0.29 (0.12) mm in the range of 0.03–0.68 mm for *A. ordosica*. Throughfall for *C. korshinskii* averaged 74.7 % (2.6) of total incident rainfall in the range of 66.1–84.5 % and it was 76.5 % (5.1) in the range of 48.8–88.2 % for *A. ordosica*. Interception loss for *C. korshinskii* averaged 16.6 % (3.1) of total incident rainfall in the range of 4.4–25.3 % and it was 20.4 % (5.3) in the range of 8.0–46.7 % for *A. ordosica*.

A significant positive linear relationship was found between individual rainfall and individual stemflow (Fig. 4a). According to the linear regression equations in Fig. 4a, the rainfall threshold value for stemflow generation was 1.3 and 1.6 mm for *C. korshinskii* and *A. ordosica*, respectively. However, stemflow percentage increased with rainfall and began to slightly decrease after a threshold value of 12 mm (Fig. 4b).

Figure 5 illustrates the relationship between rainfall intensity and stemflow and stemflow percentage. There was a weaker correlation between stemflow and rainfall intensity with a coefficient of determination of 0.35 for both *C. korshinskii* and *A. ordosica* (Fig. 5a). Generally, stemflow and stemflow percentage showed a pronounced increase tendency with increasing rainfall intensity when rainfall intensity was less than 2 mm h^{-1} and then ten-

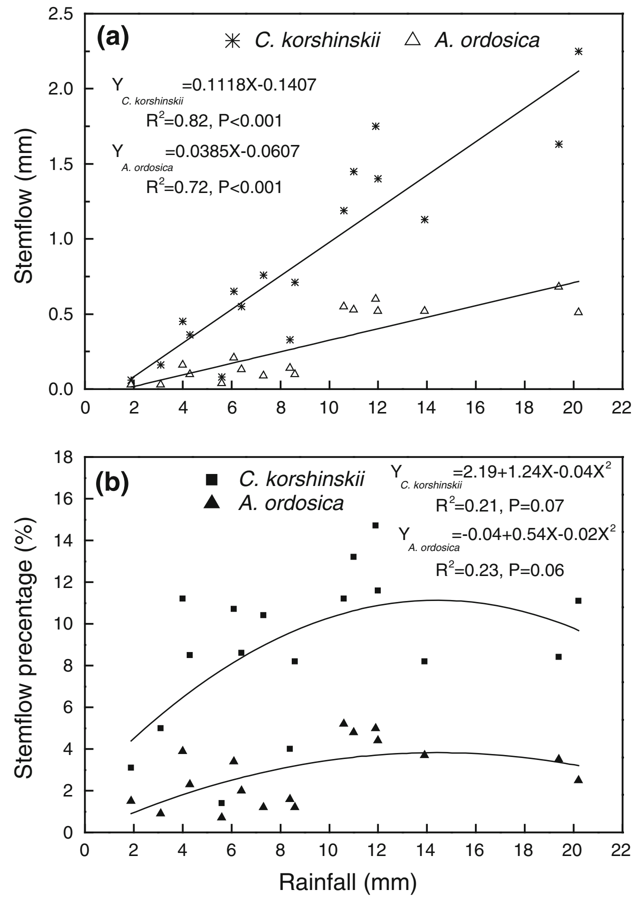

Fig. 4 Relationship between rainfall and stemflow (**a**) and stemflow percentage (**b**) for *C. korshinskii* and *A. ordosica*

ded to decrease. When rainfall intensity was less than 2 mm h^{-1}, a large variability was found in stemflow depth with a coefficient of variation (CV) of 97 % for *C. korshinskii* and 104 % for *A. ordosica*, and in stemflow percentage with a CV of 52 % for *C. korshinskii* and 65 % for *A. ordosica*.

Funneling ratio and wetting front depth

The mean funneling ratio (*F*) was 82 (17) ranging from 13 to 133 for *C. korshinskii* and 26 (7) ranging from six to 42 for *A. ordosica* (Fig. 6). The *F* value increased with increasing stemflow and then tended to be stable when stemflow depth exceeded a threshold value (1.2 mm for *C. korshinskii* and 0.5 mm for *A. ordosica*), and a significant exponential relationship was found between *F* value and stemflow (Fig. 7).

Figure 8 shows the wetting front depths within soil from shrub base to inter-shrub spaces for *C. korshinskii* and *A. ordosica* after two rainfall events (13.9 mm in July 28 and 21.3 mm in August 15). The wetting front depths were much deeper at the shrub base than other

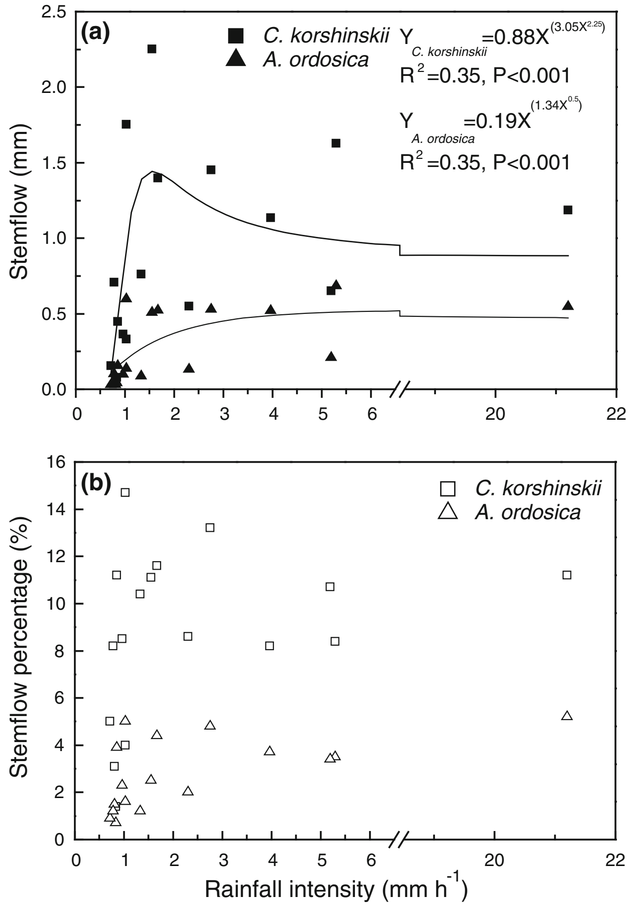

Fig. 5 Relationship between rainfall intensity and stemflow (**a**) and stemflow percentage (**b**) for *C. korshinskii* and *A. ordosica*

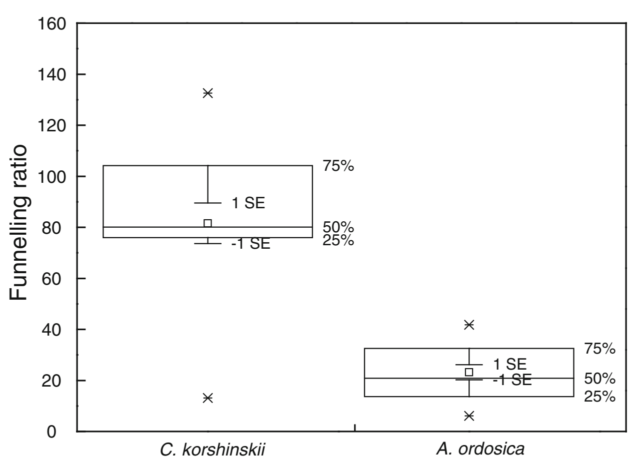

Fig. 6 Box-and-whisker diagrams showing the median, 25th, 50th, 75th percentiles and standard error for individual funneling ratio for *C. korshinskii* and *A. ordosica*. *Open square* represents mean value, – maximum and minimum value and × are 1st and 99th percentiles

sites. For example, the wetting front depth was 65 cm at the shrub base of *C. korshinskii* and 44 cm in the inter-shrub spaces (a distance of 180 cm to shrub base) after a rainfall of 21.3 mm.

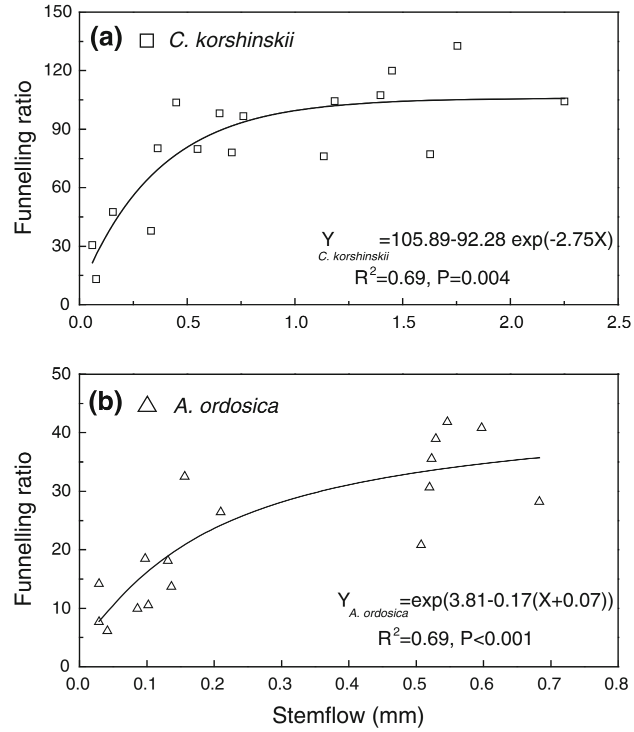

Fig. 7 Relationship between funneling ratio and stemflow for *C. korshinskii* (**a**) and *A. ordosica* (**b**)

Chemical enrichment in stemflow

Figure 9 shows that ion concentrations (TN, TP, NH_4^+–N, NO_3^-–N, K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}) in stemflow were higher than in throughfall and bulk precipitation, with an exception that NH_4^+–N concentration in throughfall was higher than in stemflow collected from *A. ordosica*. Meanwhile, the concentrations of all ions were more enriched in throughfall than in bulk precipitation. Significant differences ($p < 0.05$) were found in the concentrations of TN, NO_3^-–N, Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} between the stemflow of *C. korshinskii* and bulk precipitation. In contrast, significant differences ($p < 0.05$) in the concentrations of TN, TP, NH_4^+–N, NO_3^-–N, Na^+, K^+, Mg^{2+}, and Cl^- were found between the stemflow of *A. ordosica* and bulk precipitation. In addition, there were considerable variations in the concentration among ions in stemflow, throughfall and bulk precipitation, respectively. The pH was more acidic for stemflow than throughfall and bulk precipitation, suggesting an acidification effect of stemflow. Significant difference ($p < 0.05$) in EC was also found between stemflow and bulk precipitation.

Table 1 shows the enrichment ratios (E), the ratios of ion concentrations in stemflow to bulk precipitation (C_{SF}/C_P) and the ratios of ion concentrations in throughfall to bulk precipitation (C_{TF}/C_P). There were considerable variations in E values among ions with a range of 122.8–1677.0 for *C. korshinskii* and 12.6–1306.0 for *A. ordosica*. Meanwhile, there were also considerable

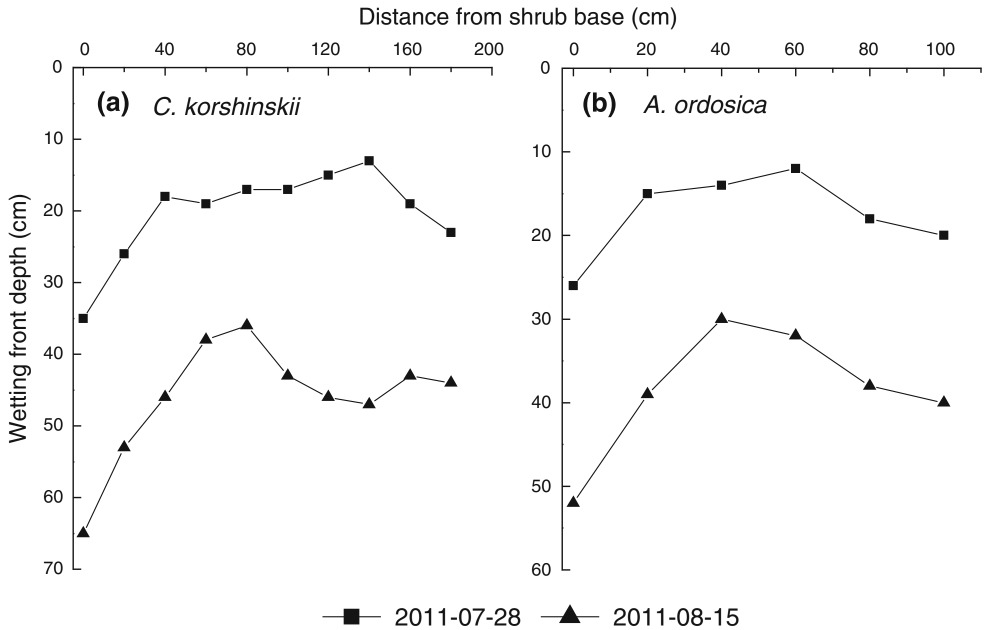

Fig. 8 Wetting front depths within soil from shrub base (0 cm) to the inter-shrub spaces (greater than a distance of 150 cm for *C. korshinskii* and 60 cm for *A. ordosica*) after two rainfall events occurring

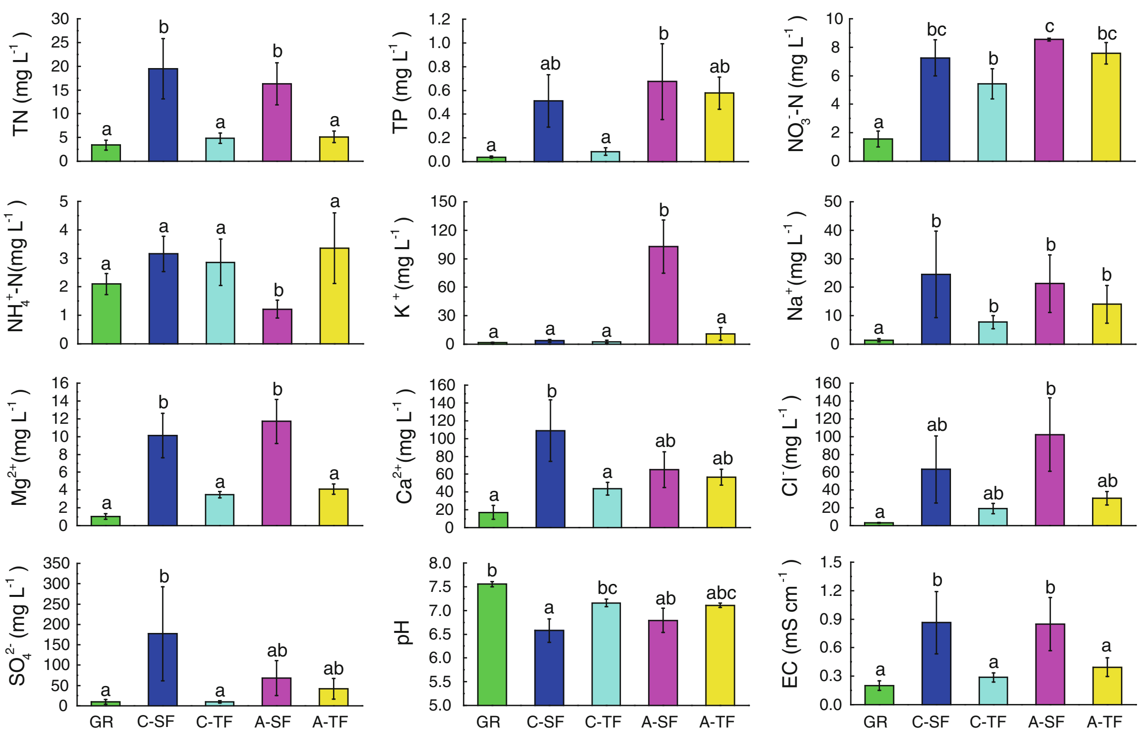

Fig. 9 Comparison of ion concentrations (TN, TP, NH_4^+–N, NO_3^-–N, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-}), pH and EC in stemflow, throughfall and bulk precipitation. *BP*, *C-SF*, *C-TF*, *A-SF*, and *A-TF* represent bulk precipitation, stemflow of *C. korshinskii*, throughfall of *C. korshinskii*, stemflow of *A. ordosica* and throughfall of *A. ordosica*, respectively. *Error bars* represent standard error ($n = 5$). Values with *different letters* (*a*–*c*) are significant at $p < 0.05$

variations in C_{SF}/C_P and C_{TF}/C_P values among ions. Averagely, ion concentrations in stemflow of *C. korshinskii* and *A. ordosica* were 10.1 and 15.9 times higher than in bulk precipitation, respectively, and 2.9 and 6.1 times higher in their throughfall than in bulk precipitation, respectively.

Discussion

Relation between stemflow and rainfall

The cumulative stemflow depth was 14.9 and 4.9 mm during the study period for *C. korshinskii* and *A. ordosica*, respectively. The stemflow percentage was 8.8 and 2.8 % for *C. korshinskii* and *A. ordosica*, respectively. The interception loss was 16.6 and 20.4 % for *C. korshinskii* and *A. ordosica*, respectively. These findings indicated that *C. korshinskii* has a higher efficiency of stemflow production and lower interception loss than *A. ordosica*. The stemflow generation threshold value of rainfall was 1.3 and 1.6 mm for *C. korshinskii* and *A. ordosica*, respectively. These threshold values are comparable to that reported in other arid areas such as a threshold value of 2 mm reported by Navar (1993) for the *Acacia farnesiana–Prosopis laevigata* in northeastern Mexico, 1.3 mm for *Larrea tridentata* and *Flourensia cernua*, and 1.8 mm for *Prosopis glandulosa* in New Mexico reported by MartinezMeza and Whitford (1996), and 1.1 mm for *Salix psammophila* and 1.2 mm for *Hedysarum scoparium* reported by Li et al. (2009) in Mu Us land in northern China. A review by Llorens and Domingo (2007) summarized that the threshold value is 1–3 mm in the literature for different Mediterranean shrub species and the aerial structure may be a very important factor resulting in highly variable stemflow among species. *C. korshinskii* has several smooth stems and ovate small leaves and there are wax layers on the twigs, stems, and leaves, while *A. ordosica* has only one rough stem but numerous slender branches and small plumose, full split needled leaves (Fig. 1). In addition, the needle-leaved *A. ordosica* had a higher canopy water storage capacity than the ovate-leaved shrub *C. korshinskii* at the same magnitude of rainfall intensity (Wang et al. 2012). These canopy architecture differences between the two species probably produce a lower rainfall threshold value and higher stemflow production but lower interception loss for *C. korshinskii*.

Individual stemflow depth linearly increased with individual rainfall, which agrees well with, e.g., Li et al. (2008) and Wang et al. (2011), but deviates from measurements conducted on northeastern Mexican semi-arid shrubs since Navar (2011) found non-linear power equations with exponents larger than 1.0 fitted better this relationship. The stemflow percentage to rainfall first increased and then slightly decreased after a threshold value of 12 mm, which is slightly different from MartinezMeza and Whitford (1996) that stemflow first increased and then keep stable after a threshold value of rainfall of about 5 mm for *Larrea tridentate*, *Flourensia cernua* and *Prosopis glandulosa*. Stemflow, generally, increased until a rainfall intensity threshold value of 2 mm h^{-1} reached and then began to decline. Lower intensity rainfall is less effective at saturating canopy than higher intensity rainfall, while higher intensity rainfall may produce branchflow that exceeds the capacity of those branches and gives rise to increased water dripping (Herwitz 1987). Therefore, a threshold value of rainfall intensity may exist to form the largest temporal stemflow amount. The relationship between stemflow and rainfall intensity in the literature is quite controversial. Our result supports the findings by Carlyle-Moses and Price (2006) and Li et al. (2008), and disagrees with Mauchamp and Janeau (1993) and Crockford and Richardson (2000) that stemflow production decreased with rainfall intensity.

Funneling ratio and wetting front depths

Shrubs can funnel substantial amounts of rainwater as stemflow to shrub base than other sites. Our results showed that there was an average funneling ratio of 82 for *C. korshinskii* and 26 for *A. ordosica*, suggesting that the shrub basal area of *C. korshinskii* and *A. ordosica* can receive 82 and 26 times amount of rainwater by stemflow as compared to an open area, respectively. This was supported by our observations to wetting front depths with much deeper of that at the shrub base than other sites (Fig. 8), since stemflow water in desert shrubs is funneled preferentially along shrub roots within the soil matrix (e.g., MartinezMeza and Whitford 1996). Fewer other researchers have reported F values for shrubs under arid and semi-arid environments. Li et al. (2009) reported an average funneling ratio of 77.8 and 48.7 for shrubs *H. scoparium* and *S. psammophila*, respectively. Garcia-Estringana et al. (2010) observed that the average funneling ratio for nine Mediterranean shrubs was 104 with a range of 30–250. Stemflow of shrubs are thus considered to be an essential property available for growth and survival of shrubs, which may further contribute to the stability of shrub communities in harsh environments.

Relatively larger values of funneling ratios for *C. korshinskii* than *A. ordosica* also imply that *C. korshinskii* is more effective in stemflow production and more rainwater can thus be channeled into deeper soil layers. This was also supported by our observations that the wetting front depths at the shrub base of *C. korshinskii* were deeper than that of *A. ordosica* (Fig. 8). The difference in wetting front depths between *C. korshinskii* and *A. ordosica* could be explained by root distribution difference between the two shrubs. Shrub root distribution in the soil profile plays an important role in the development, depth, and magnitude of the wetting fronts, with deeper roots favoring deeper wetting front depths. An adult shrub of *C. korshinskii* generally has deeper roots than an adult sub-shrub of *A. ordosica*. In the study area, the coarse roots were concentrated in the upper 40 cm of the soil profile for *C. korshinskii* (Zhang et al. 2009) and 20 cm for *A. ordosica* (Zhang et al. 2008). Moreover, the funneling ratio, although, is important to try to understand wetting front depths in unmeasured wetting fronts, it is hard to be used to precisely estimate wetting front depths (Li et al. 2009), and difficulties would exist in the comparison between the estimated of wetting front depth by funneling ratios and the measured in the field due to complex roots structure and distribution and the great difference between stemflow infiltration processes and vertical rainfall infiltration processes (Liang et al. 2009). Long-term monitoring of the soil water content variations, in particular after rainfall, under shrubs in the soil profile through techniques such as widely used Time Domain Reflectometry probes, is a better way to determine the variations of wetting front depths, as reported by Wang et al. (2011).

Chemical enrichment of stemflow

Stemflow is a highly localized aqueous point input with elevated nutrient concentrations at the basal area of shrubs. In this study, ion concentrations (TN, TP, NH_4^+–N, NO_3^-–N, Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, and SO_4^{2-}) in stemflow were much higher than in throughfall and the concentration of most of the ions measured in stemflow were significantly higher ($p < 0.05$) than in the bulk precipitation (Fig. 9). Ion concentrations in stemflow of *C. korshinskii* and *A. ordosica* were 10.1 and 15.9 times higher than in bulk precipitation, respectively. However, due to shrubs' funneling effect and the nutrient enrichment in stemflow, the nutrients entering into the soil at shrub basal area could be quite substantial comparing with that in bulk precipitation falling at the open areas, with nutrient enrichment ratios (*E* values in Table 1) ranged 122.8–1,677.0 for *C. korshinskii* and 12.6–1,306.0 for *A. ordosica* among measured ions, respectively. Meanwhile, ion concentrations in throughfall of *C. korshinskii* and *A. ordosica* were averagely 2.9 and 6.1 times higher than in bulk precipitation, respectively. Nutrient enrichment in the stemflow and throughfall compared to bulk precipitation was mainly induced by the washing-off effect of rainfall within vegetation canopy: some of the chemical substances (atmospheric deposition and vegetation exudation) were washed off by rainwater passing through canopies and then channeled into soil via stemflow and throughfall (Levia and Frost 2003). Larger ion concentrations in stemflow than in throughfall were probably attributable to the longer residence time of stemflow in the vegetation canopy than throughfall, as indicated by Levia and Herwitz (2000). Nutrient enrichment in stemflow may contribute to the nutrient requirements of the shrubs. Throughfall, nevertheless its enriched nutrients, may be less significant compared to stemflow in the development of ''fertile island'' under the shrubs because rainwater in the form of throughfall is not a highly localized point input as stemflow and could not be directly channeled into the shrub basal area.

Our data (Fig. 9) in ion concentrations are comparable to the Whitford et al. (1997) and Li et al. (2011). Thereinto, Whitford et al. (1997) made a comparison in the concentrations of TN, TP, NH_4^+–N, NO_3^-–N, K^+, Na^+, Ca^{2+}, Mg^{2+}, and SO_4^{2-} between bulk precipitation, throughfall, and stemflow in shrub creosotebush, *Larrea tridentata*, in the northern Chihuahuan Desert, and proposed that stemflow is an important contributor to the development of ''fertile island''. Li et al. (2011) compared the ion concentration of NH_4^+–N, NO_3^-–N, K^+, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, PO_4^{3-}, CO_3^{2-}, and HCO_3^- between bulk precipitation and stemflow in shrub *Haloxylon ammodendron* at the southern periphery of Gurbantunggut Desert in central Asia and concluded the same conclusion as Whitford et al. (1997). In Table 2, we listed the data of ion concentrations from Whitford et al. (1997) and Li et al. (2011), and unfortunately, the term enrichment ratio was not introduced in their studies. We could easily find quite large differences in ion concentrations between Whitford et al. (1997) and Li et al. (2011) and ours, and we assume the differences may be related to shrub species, stemflow amount, rainfall characteristics, and other climatic conditions of different areas, etc. To the authors' knowledge, there are, however, no other published data in the literature available to

Table 1 Enrichment ratio (*E*), C_{SF}/C_P (ratio of the solute concentration in stemflow to that in bulk precipitation) and C_{TF}/C_P (ratio of the solute concentration in throughfall to that in bulk precipitation) for *C. korshinskii* and *A. ordosica*, respectively

Chemical parameter	*C. korshinskii*			*A. ordosica*		
	E	C_{SF}/C_P	C_{TF}/C_P	*E*	C_{SF}/C_P	C_{TF}/C_P
TN	464.0	5.7	1.4	103.9	4.8	1.5
TP	1,083.1	13.3	2.2	382.9	17.6	15.0
NO_3^-–N	379.0	4.6	3.5	119.4	5.5	4.9
NH_4^+–N	122.8	1.5	1.4	12.6	0.6	1.6
K^+	176.3	2.2	1.5	1,306.0	59.9	6.4
Na^+	1,442.6	17.7	5.6	334.8	15.4	10.1
Ca^{2+}	521.2	6.4	2.6	83.2	3.8	3.3
Mg^{2+}	804.7	9.9	3.4	248.6	11.4	4.0
Cl^-	1,677.0	20.6	6.2	726.0	33.3	10.0
SO_4^{2-}	1,534.1	18.8	1.0	158.0	7.2	4.4
Mean		10.1	2.9		15.9	6.1
SD		7.1	1.8		18.1	4.3
CV (%)		70	62		110	70

SD standard deviation, *CV* coefficient of variation

Table 2 Concentrations of ions (mg l^{-1}) in bulk precipitation, throughfall, and stemflow in creosotebush, *Larrea tridentata*, in the northern Chihuahuan Desert derived from Whitford et al. (1997) and the ion concentrations in bulk precipitation and stemflow in *Haloxylon ammodendron* at the southern periphery of Gurbantunggut Desert in Central Asia derived from Li et al. (2011)

Chemical parameter	Whitford et al. (1997)			Li et al. (2011)	
	Bulk precipitation	Stemflow	Throughfall	Bulk precipitation	Stemflow
TN	0.23	3.77	0.78	NA	NA
TP	0.03	0.27	0.07	NA	NA
NO_3^-–N	0.80	9.42	1.12	4.84 ± 1.16	168 ± 60.48
NH_4^+–N	0.08	0.25	0.09	26.2 ± 12.0	459.8 ± 103.7
K^+	0.02	0.95	0.12	15.5 ± 5.2	67.2 ± 12.6
Na^+	0.37	3.60	0.74	7.1 ± 2.0	30.4 ± 10.9
Mg^{2+}	0.10	0.87	0.16	7.8 ± 0.94	190.5 ± 73.4
Ca^{2+}	0.12	0.31	0.13	0.8 ± 0.66	10.4 ± 3.25
SO_4^{2-}	0.80	10.47	1.86	109 ± 189.6	704.5 ± 189.6
Cl^-	NA	NA	NA	26.6 ± 16.3	177.0 ± 70.8
PO_4^{3-}	NA	NA	NA	0 ± 0	33.6 ± 6.5
CO_3^{2-}	NA	NA	NA	0 ± 0	0 ± 0
HCO_3^-	NA	NA	NA	112.8 ± 11.6	371.8 ± 47.6

Data in Li et al. (2011) are mean ± standard error ($n = 5$)
NA means the data are not available

date in the stemflow chemistry of shrubs from arid and semi-arid areas, though relative sufficient studies relating stemflow chemistry had been conducted in forest ecosystems of different regions (e.g., Bellot and Escarre 1991; Crockford et al. 1996; Nakanishi et al. 2001; Tobon et al. 2004; Andre et al. 2008; Hofhansl et al. 2012). It seems that more quantifying studies urgently need to be done relating to the chemical enrichment of stemflow of shrubs concerning its widely acknowledged importance but currently very deficient studies.

Moreover, the pH was more acidic for stemflow than bulk precipitation, suggesting an acidification effect of stemflow, which is consistent with previous studies that are mostly reported in forest ecosystems that are subjected to long-term acid precipitation (e.g., Fan et al. 1999; Kaneko and Kofuji 2000; Matschonat and Falkengren-Grerup 2000). Studies from forest ecosystems show that acidification effect of stemflow affects the micro-environments and the species composition and density of soil microflora and fauna around tree trunk (Scheu and Poser 1996; Mitchell et al. 2005), which might further affect other soil processes such as decomposition and predation. Our research, however, is done in desert ecosystems with little or no acid rain. The acidification effects of stemflow to desert soil ecosystem is still little known. To assess this ecological phenomenon and its implications in the development of this revegetated ecosystem, it is necessary to conduct more detailed studies on soil microflora and soil fauna in the soils under shrub canopies.

Conclusions

Rainfall (depth and intensity) had a close relationship with stemflow of shrubs. Stemflow linearly increased with increasing rainfall depth, and it, generally, increased with rainfall intensity when rainfall intensity was less than 2 mm h^{-1} but decreased thereafter.

Ion concentrations in shrub stemflow were higher than in throughfall, and the concentration of most of the ions measured were significantly higher ($p < 0.05$) in stemflow than in bulk precipitation. Xerophytic shrubs have larger values of funneling ratios (82 ± 17 for *C. korshinskii* and 26 ± 7 for *A. ordosica*) and enrichment ratios (Table 1), suggesting that shrubs can funnel substantial amounts of intercepted rainwater as stemflow with highly enriched nutrients to shrub basal area. Through quantitative analysis, this report concludes that stemflow can be an important localized source of soil water and nutrients that can be channeled into the deeper soil profile of the root zone to favor the growth and survival of shrubs and we assume that there may exist a synergistic effect of rainwater accumulation and nutrient enrichment in the stemflow-influenced areas, which is beneficial for the adaptability and stability of shrub communities and plays a significant positive role in the development of this rain-fed revegetated desert ecosystem of study area, and thus it is also of great hydro-ecological importance in arid and semi-arid regions for the better vegetative restoration. A long-term monitoring of the amount of water and nutrients in stemflow and its transportation and redistribution in underground parts of shrubs are expected to provide a better evaluation of the stemflow's role in contributing to the stability of shrub communities and development of ecosystem in harsh environments.

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