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Variations of Nutrients in Gross Rainfall, Stemflow, and Throughfall Within Revegetated Desert Ecosystems

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Abstract Revegetation in arid desert ecosystems is emerging as a practical strategy to cease sand dune encroachment and combat desertification worldwide. The revegetation is expected to affect the spatial distribution of rainfall to the ground within vegetation communities. However, the impact of revegetation on the temporal distribution of dry and/or wet dust fall trapped by shrub canopies via stemflow and throughfall remains a topic of concern for shrub "fertile islands." This study investigated whether xerophytic shrub community acts as a sink of various cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}), inorganic anions (Cl^- and SO_4^{2-}), total nitrogen, and total phosphorus to the revegetated desert ecosystems. Gross rainfall, the stemflow, and throughfall of two codominated xerophytic shrubs (*Caragana korshinskii* and *Artemisia ordosica*) were volumetrically measured after natural rainfall events, and their samples were chemically analyzed in the laboratory. Results showed that ions had higher concentrations in stemflow than in throughfall, followed by gross rainfall. Ion concentrations in stemflow and throughfall strongly depends on the first flush effect, rainfall depth, and the antecedent dry period before a rainfall event occurring. Concentrations of most of the ions in stemflow and throughfall collected after the first rainfall event of a year were obviously higher than other rainfall events for both shrub species, suggesting a first flush effect. Ion concentrations generally decreased with the increasing depth of gross rainfall, stemflow, and throughfall, while increased with prolonged antecedent dry period. Based on nutrient input by stemflow and throughfall at the community scale, we conclude that chemical enrichment of stemflow and throughfall plays an important role in forming the shrub fertile islands and contributes significantly to a sustainable succession of the revegetated desert ecosystems.

Keywords Gross rainfall · Stemflow · Throughfall · Ions concentrations · First flush · Revegetated desert ecosystems

1 Introduction

Water and nutrient availability are the most limiting factors for the vegetation growth and ecosystem functioning in dry lands (Gebauer and Ehleringer 2000; McClain et al. 2003). Incident gross rainfall is partitioned into interception loss, stemflow, and throughfall when passing through vegetation canopies, altering the hydrological and biogeochemical fluxes between vegetation and soil (Llorens and Domingo 2007). Interception loss is the part of the intercepted incident precipitation by canopy which evaporates directly back into the atmosphere during and after rainfall. Stemflow refers to the portion of gross rainfall that is intercepted by leaves, twigs, and branches and eventually delivers to the ground

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via trunks or stems, which can be further preferentially transported into soil-root system through roots (e.g., Johnson and Lehmann 2006). Throughfall is the rainfall portion that reaches the ground by passing directly through or dripping from vegetation canopies (Navar 2011). Meanwhile, stemflow and throughfall are chemically changed (solutes are normally enriched) to a great extent after they passed through vegetation canopies (Levia and Frost 2003). As such, stemflow and throughfall could be important sources of soil moisture and nutrients to the trunk/stem basal and under canopy area, and it helps to maintain soil water balance and nutrient budget of the plant in the root zone (Johnson and Lehmann 2006; Martinez-Meza and Whitford 1996; Tromble 1988; Wang et al. 2011; Wang et al. 2013; Whitford et al. 1997; Zhang et al. 2013).

Revegetation through planting xerophytic shrubs is one of the most successful measures to stabilize desert sand dunes and to protect the Baotou-Lanzhou railway against encroaching sand dunes at the southeast edge of the Tengger Desert, northwestern China (e.g., Li et al. 2006). Revegetation has several positive effects in arid desert areas with the most important ones being its ability to increase ground surface roughness, organic matter content, and soil water-holding capacity (Li 2012; Li et al. 2002; Wang et al. 2005) and improve soil texture and structure (Wang et al. 2005). Recent studies revealed feedback of the revegetated desert shrubs on the partitioning of incident precipitation into interception loss, throughfall and stemflow (e.g., Zhang et al. 2015), and its variations related to shrub traits, rainfall characteristics, and meteorological variables (Wang et al. 2012; Wang et al. 2013; Zhang et al. 2015). Hydrologically, stemflow, though relatively a small portion of gross rainfall, represents a significant component of water replenishment to the soil-root system favoring the growth and survival of shrubs; chemically, nutrients are normally found to be enriched in stemflow and throughfall (Navar et al. 2009; Zhang et al. 2013). Moreover, shrubs may accumulate mineral nutrients and water under the canopies, leading to a local increase in fertility and thereby forming the so-called fertile islands (Pugnaire et al. 1996), which are very common in arid and semiarid ecosystems worldwide (e.g., Schlesinger et al. 1996; Stock et al. 1999). While hydrologically and chemically enriched stemflow and throughfall (in particular the former) are considered as biological transport mechanisms that contribute to the formation and evolution of shrub "fertile islands" (e.g., Garner and Steinberger 1989; Whitford et al. 1997; Zhang et al. 2013). From the desert ecosystem management perspective, stemflow and throughfall may play an important role in the succession of water- and nutrient-limited revegetated ecosystem because of their ability to concentrate rainwater and enhance fertility around root zone.

The chemical composition of stemflow and throughfall is the result of the chemical interactions among meteorological factors, dry deposition, sticky exudations, and canopy leaching (André et al. 2008; Navar et al. 2009). Therein, meteorological factors are notably the length of the dry period preceding a rain event and the rainfall depth (e.g., Lovett and Lindberg 1984; Tobon et al. 2004; André et al. 2008). Although the general nutrient enrichment in stemflow and througfall relative to rainfall has been observed in desert ecosystems by several investigators (Whitford et al. 1997; Li et al. 2011; Zhang et al. 2013), the chemical variations in stemflow and throughfall remains largely unexplored. Specifically, very few studies have examined the temporal variations of nutrients and the rate of nutrient transfer by stemflow and throughfall of shrubs. To enhance our knowledge-base on this topic, the present study was initiated with the following objectives: (1) examine the effect of the first rainfall event of a year on the chemical enrichment in stemflow and throughfall (the first flush effect) of xerophytic shrubs; (2) investigate the seasonal variation of ion concentrations in stemflow and throughfall; (3) compare ion concentrations in gross rainfall, throughfall, and stemflow and their relations to the antecedent dry period and the rainfall depth; and (4) scale-up the nutrient fluxes from individual shrubs to community stand in terms of the coverage. To achieve these tasks, event-based gross rainfall, the stemflow and throughfall induced by *Caragana korshinskii* and *Artemisia ordosica* were volumetrically measured in the field and chemically analyzed in the laboratory. The current study is also expected to be of importance for a better understanding of the chemical role of stemflow and throughfall in forming the shrub fertile islands and in the sustainable succession of the revegetated desert ecosystems.

2 Materials and Methods

2.1 Site Information

The study was conducted 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.), located at the southeastern fringe of the Tengger Desert in northwestern China. Mean annual precipitation is 191 mm (1955–2005, SDRES) with 80 % of rain occurring between July and September with a coefficient of variation of 45.7 %. All plants rely on precipitation for their growth since the groundwater (50–80 m) is unavailable for roots. Dew formation and water adsorption on soil surface are assumed to be a minor water source of soil (Pan et al. 2010). Mean maximum air temperature is 24.7 °C in July, and the mean minimum is 6.1 °C in January. Annual mean potential evaporation is approximately 2800 mm (Li et al. 2007), resulting in a large annual moisture deficit. Annual mean wind velocity is approximately 2.8 m s^{-1}. The dune sand mainly consists of fine *Typic Psammaquents* sand (0.05–0.25 mm) with a clay content of 0.2 % (Berndtsson et al. 1996).

This area experienced extensive revegetation efforts in the 1950–1980s, aiming to protect the Baotou-Lanzhou railway against encroaching sand dunes. A 16,000-m-long artificially revegetated protection system was established along the railway, with 500 m widths to the north and 200 m to the south. Initially, a sand barrier was set up with woven willow branches or bamboos to slow down wind erosion. Behind the barrier, 1 × 1 m wheat straw checkerboards were established with 15–20 cm straw inserted into the sand and 10–20 cm exposed above the surface. Xerophytic shrubs were then planted within the straw checkerboards. These steps allow a slow establishment of the xerophytic shrubs, and gradually the shifting sand dunes along the railway were stabilized. A more detailed description of the revegetation procedure can be found in Li et al. (2004, 2006).

The Water Balance Experimental Field (WBEF), 1 ha, was revegetated in 1989 by planting *C. korshinskii* and *A. ordosica*. *C. korshinskii* is a multi-stemmed deciduous perennial shrub species. Leaves are pinnately compound and opposite or subopposite in arrangement and 6 to 10 cm long. Each pinna has five to eight pairs of leaflets in ovate shape with 7–8 mm in length and 2–5 mm in width. *A. ordosica* is a highly branched dwarf-shrub species with plumose, full split needled leaves (length 10–30 mm, width 0.3–l mm). In WBEF, 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. The coverage is 41 and 47 % for *C. korshinskii* and *A. ordosica*, respectively.

2.2 Shrubs Selection and Measurements

Seventeen robust and healthy shrubs (ten for *C. korshinskii* and seven for *A. ordosica*) representing the two xerophytic shrub species in WBEF were selected for field observation. Canopy area was calculated by taking the east-west and north-south diameters through the center of the fullest part of the canopy (Martinez-Meza 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.

2.3 Field Measurements and Sampling

Measurements and sampling for this study occurred during two growing seasons (April to October) of 2012 and 2013. A total of 17 rainfall events were measured and sampled. Individual events were separated by at least 4 h without rainfall. Here, we define the first rainfall event of a year as first flush event (FF) and other rainfall events of the same year as non-first flush events (NFF). Therefore, 2 rainfall events (4.4 mm in April 11, 2012, and 8.4 mm in May 15, 2013) are considered as FF and the other 15 events as NFF.

Stemflow was collected using collars constructed from aluminum foil plates that were fitted around the entire circumference of the shrub stem (Zhang et al. 2015). The volume of stemflow was measured by a graduated cylinder for each individual stems (*A. ordosica* has only one stem) after each rainfall event and summarized for a single shrub.

Stemflow depth was calculated as

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

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

Throughfall collectors were installed at three directions (0°, 120°, and 240°) beneath the shrub canopy (Zhang et al. 2013). 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. All collectors were rinsed in distilled, deionized water before being used for sample collection. For individual shrub in each rainfall event, the throughfall depth was calculated as

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

where D_{TF} is the throughfall depth (mm), V_{TF} is the throughfall volume (L) for each collector, N is the number of throughfall collectors under each shrub canopy, and FA is the opening area (m^2) of a funnel used in the experiments.

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.

2.4 Chemical Analysis

Samples of gross rainfall, stemflow, and throughfall for chemical analysis were collected immediately at the end of each rainfall event, filtered through a 0.45-μm nylon membrane filter and then stored at 4 °C in a refrigerator. 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 determined using inductively coupled plasma (ICP) optical emission spectrometry (iCAP 6300; Thermo Fisher Scientific, Waltham, MA, USA). The Cl^- and SO_4^{2-} concentrations were determined using Dionex Ion Chromatography equipped with AS40 automated sampler. Total nitrogen (TN) and total phosphorus (TP) concentrations were determined using a TU-1800SPC ultravioletvisible spectrophotometer (Beijing Purkinje General Instrument Co., China).

2.5 Enrichment Ratio

To quantify the chemical enrichment of stemflow, the following equation proposed by Levia and Herwitz (2000) is used:

$$E = \frac{C_{SF} \times V_{SF}}{C_G \times B_A \times P_G} \tag{3}$$

where E is the enrichment ratio of stemflow, C_{SF} is the solute concentration in stemflow (mg L^{-1}), V_{SF} is stemflow volume (L), C_G is solute concentration in gross rainfall (mg L^{-1}), B_A is the stem basal area (m^2) of stemflow generating shrub, and P_G is depth equivalent of the incident gross rainfall (mm).

In Eq. (3), $\frac{V_{SF}}{B_A \times P_G}$ is also known as funnelling ratio (F), as proposed by Herwitz (1986). Since basal area is the true area over which stemflow is delivered to the soil, F represents the ratio of the amount of rainfall delivered to the shrub base to the rainfall that would have reached the ground in the absence of the shrub. F exceeding 1 indicates that canopy component other than the stems are contributing to the stemflow water input (Herwitz 1986). Thus, E couples both the water and solute inputs and allows the comparison of solute inputs between stemflow and precipitation per unit stem basal area. Expression of stemflow inputs using the enrichment ratio is considered as a meaningful and intuitive method (Levia et al. 2011), and has received great attention in recent stemflow studies (Levia and Germer 2015).

2.6 Scaling Up of Nutrient Fluxes

The annual nutrient fluxes (F_N, kg hm^{-2} a^{-1}) to the ground surface at the stand scale can be transferred from individual shrub in terms of the variables, including the community coverage (C, %), annual gross rainfall (P_G, mm), the percentage of effective rainfall (P_E, %) to generate stemflow, ratios of stemflow (R_S, %) and throughfall to gross rainfall (R_T, %), and the ion concentration in stemflow (I_{CS}, mg L^{-1}) and in throughfall (I_{CT}, mg L^{-1}),

$$\text{Annual nutrient fluxes by stemflow}: \ F_{NS} = P_G \times P_E \times R_S \times C \times I_{CS} \tag{4}$$

Annual nutrient fluxes by throughfall : F_{NT}

$$= P_G \times R_T \times C \times I_{CT} \quad (5)$$

Therein, P_G is 191 mm according to the long-term meteorological monitoring at Shapotou Desert Research and Experiment Station; P_E is 89 % according to previous study at the same place by Zhang et al. (2015); R_S is 9 and 3 % for *C. korshinskii* and *A. ordosica*, respectively (Zhang et al. 2015); C is 41 and 47 % for *C. korshinskii* and *A. ordosica*, respectively (Wang et al. 2013; Zhang et al. 2013); R_T is 74 and 75 % for *C. korshinskii* and *A. ordosica*, respectively (Zhang et al. 2015); I_{CS} and I_{CT} are derived from the current study.

2.7 Statistical Analyses

Descriptive statistics were compiled for enrichment ratios, the ratio of the solute concentration in stemflow and throughfall to that in gross rainfall, respectively. Since data of ion concentrations were not normally distributed, we tested the differences in ion concentrations between the GR, C-SF, C-TF, A-SF, and A-TF that are derived from NFF ($n = 15$), using one-way ANOVA with Tukey HSD post hoc, after logarithmetic transformation of the data. Linear fitting between ion concentrations and rainfall depth, stemflow depth, and throughfall depth were done in the semi-logarithmic coordinates. All the descriptive statistics, linear fitting, and ANOVA analyses were performed using the SPSS 16.0 statistical software (SPSS Inc., Chicago, USA).

3 Results

3.1 Chemical Enrichment of Stemflow and Throughfall

The total stemflow volume collected in the ten shrubs of *C. korshinskii* amounted to 394.8 L (252.6 mm in terms of canopy area) during 17 rainfall events, with a mean of 2.32 L (1.49 mm) and a coefficient of variation (CV) of 82 % for each shrub per rainfall event; it amounted to 25.1 L (40.1 mm in terms of canopy area) for seven shrubs of *A. ordosica* with a mean of 0.51 L (0.34 mm) and a CV of 55 % for each shrub per rainfall event.

Ion concentrations in samples of stemflow, throughfall, and gross rainwater collected from FF (April 11, 2012, and May 15, 2013) were obviously higher than from NFF (Fig. 1), suggesting a first flush effect. The ion enrichment ratios of stemflow, the ratio of the solute concentration in stemflow, and throughfall to that in gross rainfall (C_{SF}/C_G and C_{TF}/C_G) in FF were also evidently higher than in NFF (Table 1), which corroborated the pronounced first flush effect.

Irrespective of first flush, the ion enrichment ratio of stemflow for *C. korshinskii* ranged 286–1173 among ions, with an average of 665 and a coefficient of variation of 41 %; it ranged 97–1331 for *A. ordosica*, with an average of 412 and a CV of 112 % (Table 1). Additionally, ion concentrations of stemflow for *C. korshinskii* and *A. ordosica* were exclusively higher than that of gross rainfall ($C_{SF}/C_G > 1$); this is also the case between throughfall and gross rainfall ($C_{TF}/C_G > 1$).

Ion concentrations in stemflow were generally higher than in throughfall for *C. korshinskii* and *A. ordosica*, followed by gross rainfall (Fig. 2). Whereas the concentrations of TN, Mg^{2+} and SO_4^{2-} differed significantly ($P < 0.05$) between stemflow and throughfall for *C. korshinskii* (Fig. 2a, d, h); they were TN, K^+, Mg^{2+}, and Cl^- for *A. ordosica* (Fig. 2a, c, d, g). Meanwhile, concentrations of all ions were significantly ($P < 0.05$) enriched in stemflow than in gross rainfall; ion concentrations measured in throughfall were all significantly higher ($P < 0.05$) than in gross rainfall, with the exceptions of TN and TP for *C. korshinskii* (Fig. 2a, b).

3.2 Seasonal Variation of Ion Concentrations

For both of *C. korshinskii* and *A. ordosica*, seasonal variation of ion concentrations in stemflow, throughfall, and gross rainfall showed an inverse parabolic trend during growing season: generally, it was the highest in April, then it began to decrease in May, reaching a relatively lower and stable level in June–September, and increased in October again (Fig. 3a–h); this tendency was inverse to the seasonal variations of rainfall depth (Fig. 3i).

Moreover, ion concentrations in gross rainfall, stemflow, and throughfall exclusively showed an increased tendency with prolonged effective antecedent dry period before a rainfall event occurring, which can well be fitted by a power function ($y = ax^b$) (Fig. 4). It should be noted that here, we define the effective antecedent dry period as the time period between two rainfall events that can generate stemflow.

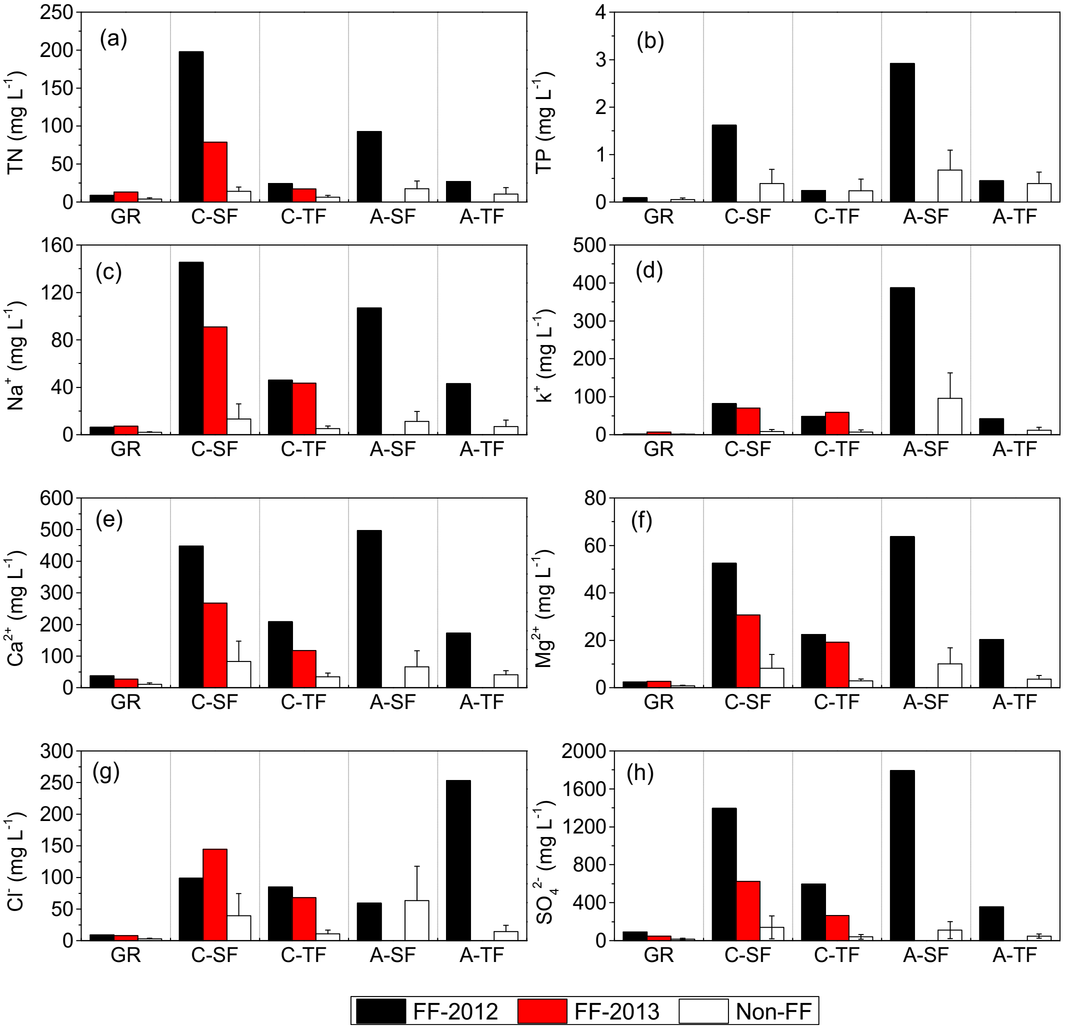


Fig. 1 Comparison of ion concentrations in stemflow, throughfall, and gross rainfall between the first rainfall events (FF, April 11, 2012, and May 15, 2013) and other rainfall events (NFF) in years 2012 and 2013. The ion concentrations data of stemflow and throughfall from *A. ordosica* on May 15, 2013, are not available. GR, C-SF, C-TF, A-SF, and A-TF represent gross rainfall, stemflow of *C. korshinskii*, throughfall of *C. korshinskii*, stemflow of *A. ordosica*, and throughfall of *A. ordosica*, respectively. *Error bars* represent confidence intervals ($\alpha = 0.05$). Data for ion concentrations of stemflow and throughfall for *A. ordosic*a in FF in 2013 are not available in the figure due to unexpected samples missing

3.3 Ion Concentrations in Relation to the Depth of Gross Rainfall, Stemflow, and Throughfall

Figure 5 shows the relationships of ion concentrations in gross rainfall, stemflow, and throughfall with the rainfall depth. For both of *C. korshinskii* and *A. ordosica*, measured ion concentrations generally decreased with increasing rainfall depth. A power relationship ($y = ax^b$) was found between the logarithmic values of ion concentrations and rainfall depth. Ion concentrations in stemflow of *C. korshinskii* (Fig. 6) and *A. ordosica* (Fig. 7) showed decreasing tendency with increasing stemflow depth, respectively. Likewise, ion concentrations in throughfall of *C. korshinskii* (Fig. 8) and *A. ordosica* (Fig. 9) showed decreasing tendency with increasing throughfall depth, with an exception for TP concentration of *C. korshinskii* (Fig. 8b).

3.4 Fluxes of Chemical Solutes

Scaling up of nutrient input flux from individual shrubs to community can be seen in Table 2. Nutrient input by stemflow accounted for a considerable portion, and that by throughfall for all ions exceeded gross rainfall. The

Table 1 Enrichment ratio (*E*), C_{SF}/C_G (ratio of the solute concentration in stemflow to that in gross rainfall) and C_{TF}/C_G (ratio of the solute concentration in throughfall to that in gross rainfall) in the first flush rainfall events (FF) and non-first flush rainfall events (NFF) for *C. korshinskii* and *A. ordosica*, respectively

Ions	*C. korshinskii*									*A. ordosica*								
	E			C_{SF}/C_G			C_{TF}/C_G			E			C_{SF}/C_G			C_{TF}/C_G		
	FF		NFF	FF		NFF	FF		NFF	FF		NFF	FF		NFF	FF		NFF
	2012	2013		2012	2013		2012	2013		2012	2013		2012	2013		2012	2013	
TN	1865	500	286	22.8	6.1	3.5	2.8	1.3	1.6	233	NA	97	10.7	NA	4.4	3.1	NA	2.7
TP	1473	NA	644	18.0	NA	7.9	2.7	NA	4.9	707	NA	299	32.4	NA	13.7	5.0	NA	7.9
K^+	3276	803	428	40.0	9.8	5.2	23.6	8.2	4.5	4120	NA	1331	189.0	NA	61.0	20.4	NA	7.6
Na^+	1886	1038	565	23.0	12.7	6.9	7.3	6.1	2.6	369	NA	129	16.9	NA	5.9	6.8	NA	3.6
Ca^{2+}	969	801	646	11.8	9.8	7.9	5.5	4.3	3.3	286	NA	137	13.1	NA	6.3	4.6	NA	3.9
Mg^{2+}	1701	924	894	20.8	11.3	10.9	8.9	7.0	3.9	550	NA	294	25.3	NA	13.5	8.0	NA	4.7
Cl^-	879	1447	1173	10.7	17.7	14.3	9.2	8.3	3.9	140	NA	503	6.4	NA	23.1	27.5	NA	5.2
SO_4^{2-}	1250	1048	685	15.3	12.8	8.4	6.5	5.5	2.5	428	NA	145	19.6	NA	6.6	3.9	NA	2.9
Mean	1662	937	665	20.3	11.5	8.1	8.3	5.8	3.4	854	NA	367	39.2	NA	16.8	9.9	NA	4.8
SD	756	291	273	9.2	3.6	3.3	6.6	2.5	1.1	1332	NA	412	61.1	NA	18.9	9.0	NA	2.0
CV	45 %	31 %	41 %	45 %	31 %	41 %	80 %	42 %	33 %	156 %	NA	112 %	156 %	NA	112 %	91 %	NA	41 %

Values are means under NFF columns and $n = 15$ for each ion

TN total nitrogen, *TP* total phosphors, *NA* not available due to unexpected samples missing

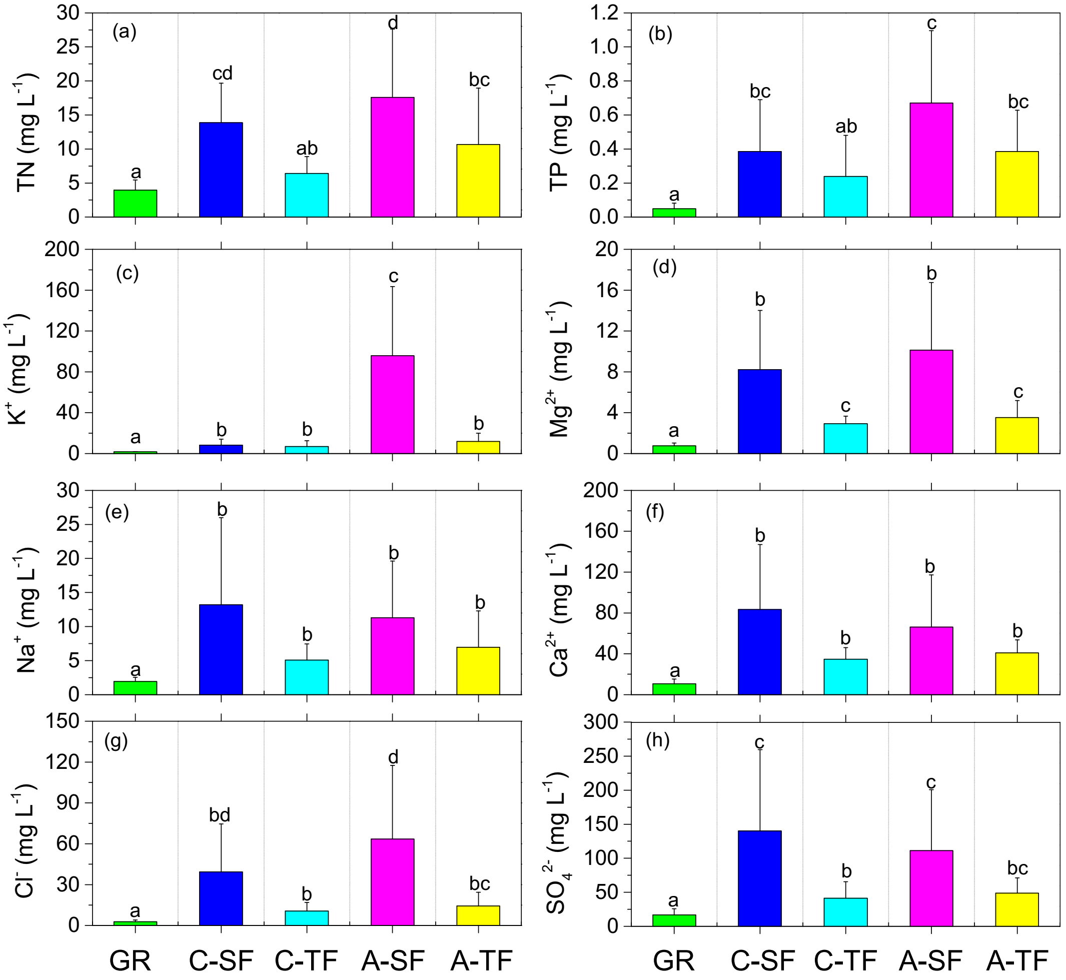


Fig. 2 Comparison of ion concentrations in the stemflow, throughfall, and gross rainfall that are derived from NFF. GR, C-SF, C-TF, A-SF, and A-TF represent gross rainfall, stemflow of *C. korshinskii*, throughfall of *C. korshinskii*, stemflow of *A. ordosica*, and throughfall of *A. ordosica*, respectively. *Error bars* represent confidence intervals ($\alpha = 0.05$). *Means with different letters* are significant at $P < 0.05$

chemical fluxes in gross rainfall showed the following trend: $SO_4^{2-} > Ca^{2+} > TN > Cl^- > Na^+ > K^+ > Mg^{2+} > TP$; the trend was $SO_4^{2-} > Ca^{2+} > Cl^- > K^+ > TN > Na^+ > Mg^{2+} > TP$ in stemflow and $Ca^{2+} > SO_4^{2-} > Cl^- > K^+ > TN > Na^+ > Mg^{2+} > TP$ in throughfall.

4 Discussion

4.1 First Flush Effect and the Effect of Antecedent Dry Period on Ion Concentrations

The shrub species from our revegetated desert ecosystem plays an important role in chemically enriching stemflow and throughfall, as having been found in other ecosystems (André et al. 2008; Germer et al. 2012; Levia et al. 2011; Macinnis-Ng et al. 2012; Shen et al. 2013). This enrichment can be mainly contributable to the chemical interactions among rainfall, dry deposition, sticky exudations, and canopy leaching (Navar et al. 2009).

In the present study, we found that ion concentrations were distinctly higher in the stemflow and throughfall samples collected after the first rainfall event of a year than in the samples taken after other rainfall events (Fig. 1). This is interpreted as an occurrence of a first flush effect, and to authors' knowledge, this is the first time the first flush effect was examined for shrubs of desert ecosystems. It is understandable that the initial stemflow and

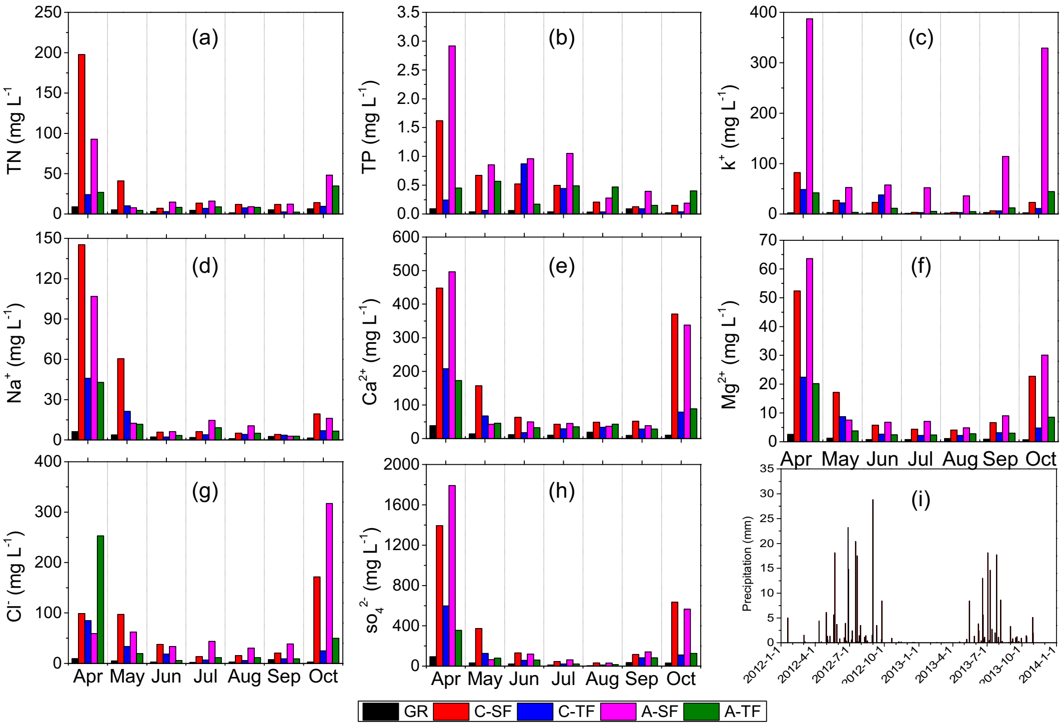


Fig. 3 Seasonal variation of ion concentrations (**a**–**h**) in stemflow, throughfall, and bulk precipitation during April to October of 2012 and 2013 and rainfall distribution in 2012 and 2013. GR, C-SF, C-TF, A-SF, and A-TF represent gross rainfall, stemflow of *C. korshinskii*, throughfall of *C. korshinskii*, stemflow of *A. ordosica*, and throughfall of *A. ordosica*, respectively

throughfall from shrub canopies after a dry period is more concentrated than subsequent stemflow and throughfall. During drought periods, shrub canopies are adhered by atmospheric particles (dust fall), which are washed out with the first rainfall events. In our study area, deposition is the main type of aeolian activity, and the dust fall concentrated during March to May (Zhang et al. 2014). In addition, little precipitation normally occurs during winter-spring season. This allows substantial amounts of atmospheric depositions being captured by shrub canopies during the windy drought season of late winter and early spring. The first flush rainfall events thus may act as an effective trigger by washing out of abundant nutrients within shrub canopies by way of stemflow and throughfall, which may be an important temporal and spatial redistribution source of soil nutrients available for vegetation growth and survival in the rain-fed revegetated desert ecosystems. Likewise, an increase in the ion concentrations of stemflow and throughfall of the first rainfall event implies that dust fall of the windy drought season and combined canopy entrapment can be considerably increased.

Ion concentrations in gross rainfall, stemflow, and throughfall exclusively showed an increased tendency with prolonged effective antecedent dry period before a rainfall event occurring (Fig. 4). For stemflow and throughfall, this is probably attributable to an increase in the air dust fall (e.g., dry deposition) captured by shrub canopy and the increased shrub exudation as dry periods increase. The substances trapped on the surface of leaves and branches were washed off by rainwater passing through the canopies in the subsequent forms of stemflow and throughfall. Tobon et al. (2004) concluded that the length of the antecedent dry period was the dominant factor affecting the temporal variability in throughfall and stemflow chemistry in Amazon forests. For gross rainfall, prolonged dry period normally corresponds to accumulated particles in the atmosphere which can be washed off as rain falls, implies the potential interferences of rainwater with air dust fall. Nativ and Mazor (1987) also observed higher concentrations of ions in rain following long breaks between consecutive rainfall events in the Negev Desert. Interestingly, Kidron and Starinsky (2012) reported higher

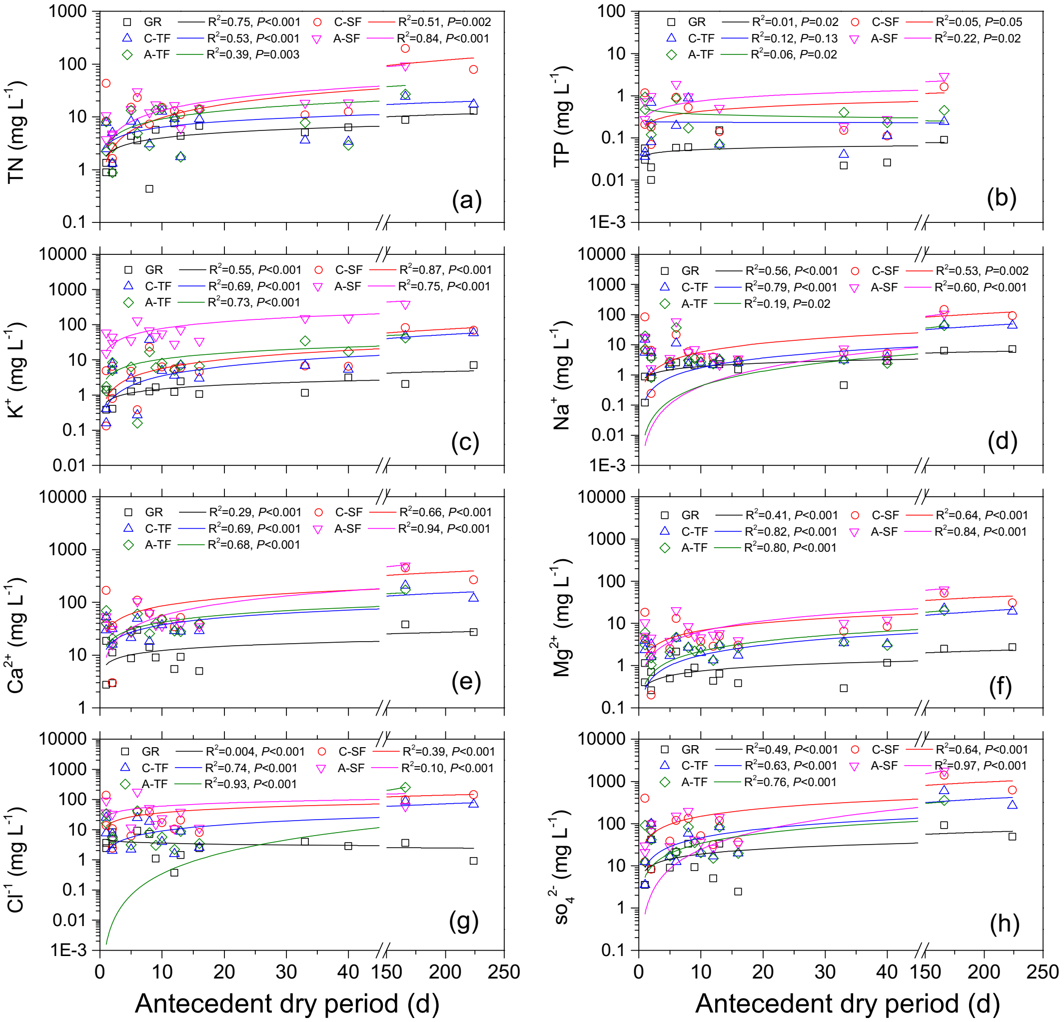


Fig. 4 Relationships between ion concentrations (gross rainfall and the stemflow and throughfall for *C. korshinskii* and *A. ordosica*, respectively) and the effective length of antecedent dry period. GR, C-SF, C-TF, A-SF, and A-TF represent gross rainfall, stemflow of *C. korshinskii*, throughfall of *C. korshinskii*, stemflow of *A. ordosica*, and throughfall of *A. ordosica*, respectively. Data are fitted by a power function ($y = ax^b$)

concentrations of ions in dew following a long break between consecutive dew events. Additionally, relatively higher ions enrichment of stemflow and throughfall could be found in our study in comparison to that of dew in Kidron and Starinsky (2012). Since the high concentrations in the stemflow and throughfall originate from atmospheric deposition and plant exudates (rather than only of atmospheric deposition in dew), it is expected that the differences in the chemical enrichment between the stemflow and throughfall and the dew can be partly explained by the plant exudates rather than by only the chemical composition of the atmospheric deposition.

4.2 Seasonal Variation of Nutrients and the Dilution Effect

There is a seasonal effect on the concentration of ions, generally, being higher in April and October than in other months during growing seasons (April to October). We also found that seasonal variation of ion concentrations in stemflow, throughfall, and gross rainfall seems inversely related to the seasonal variation of rainfall depth (Fig. 3). It should be noted that detailed rainfall characteristics of the two study years can be found in Zhang et al. (2015). Moreover, unsurprisingly, there is generally a decreasing trend of ion

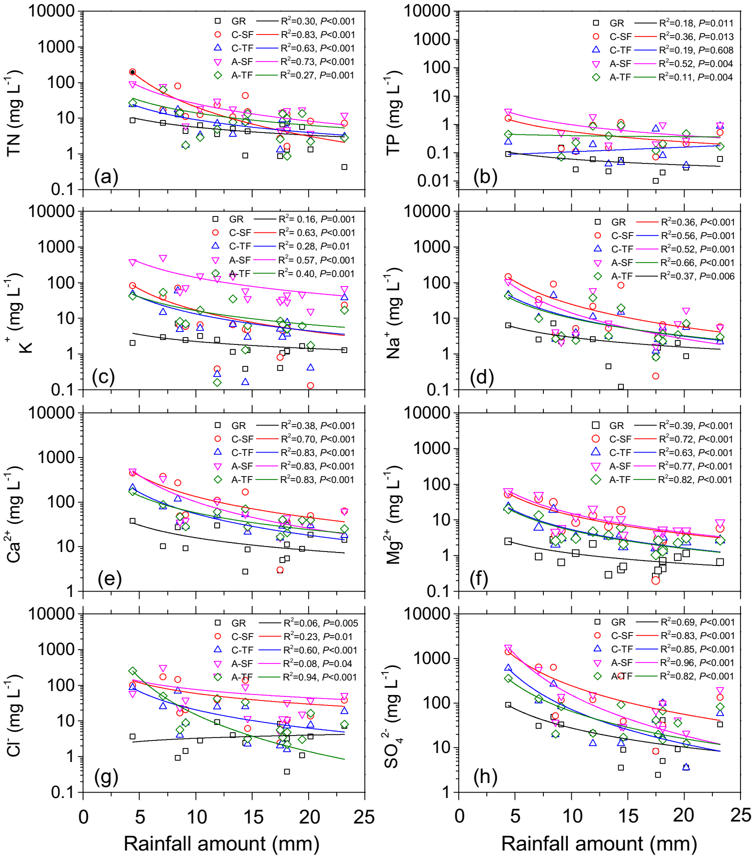


Fig. 5 Relationships between ion concentrations and individual rainfall depth. GR, C-SF, C-TF, A-SF, and A-TF represent gross rainfall, stemflow of *C. korshinskii*, throughfall of *C. korshinskii*, stemflow of *A. ordosica*, and throughfall of *A. ordosica*, respectively. Data are fitted by a power function ($y = ax^b$).

concentrations with increasing gross rainfall, stemflow, and throughfall (Figs. 5, 6, 7, 8, and 9). This indicates a dilution effect of ion concentrations due to increased rainfall depth. Dry deposition accumulated in the canopy during dry spells is normally washed quite effectively at the beginning of the rainfall episodes and is quickly exhausted, so that higher rainfall depths do not imply higher enrichments (Rodrigo et al. 2003). Results from lab rainfall simulation for potato leaves (Perez-Rodriguez et al. 2013) and vine leaves (Perez-Rodriguez et al. 2015) also suggests that the accumulated deposition of particles that are loosely attached to the leaves can easily be detached with a small rainfall episode. Similar dilution effect has been observed by several investigators during single rainfall events (Hansen et al. 1994; Leonardi and Flückiger 1987; Tobon et al. 2004).

4.3 Stemflow and Its Chemical Importance

Most of the measured ions had significantly higher concentrations ($P < 0.05$) in stemflow than in throughfall for the two studied shrubs, and no significant differences in ions in stemflow and throughfall were found between two shrub species (Fig. 2). Differences between the chemistry of stemflow and throughfall solutions would result in spatial heterogeneity of the chemical composition of soil solution (Laclau et al. 2003). Higher 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). In fact, throughfall can thus be regarded as diluted stemflow, diluted by limited contact time with the canopy and by rainfall which did not contact the canopy (Crockford et al. 1996). Nevertheless, higher ion concentration in throughfall than in stemflow may still happen due to complex interactions between rainfall and vegetation canopy (Fig. 1g).

Studies that estimate nutrient fluxes in forests do not routinely consider stemflow because it is volumetrically minor in comparison with throughfall (Germer et al. 2012; Levia and Frost 2003). In our study, although stemflow only accounted for 9 and 3 % of incident gross

Fig. 6 Relationships between ion concentrations and stemflow depth of *C. korshinskii*

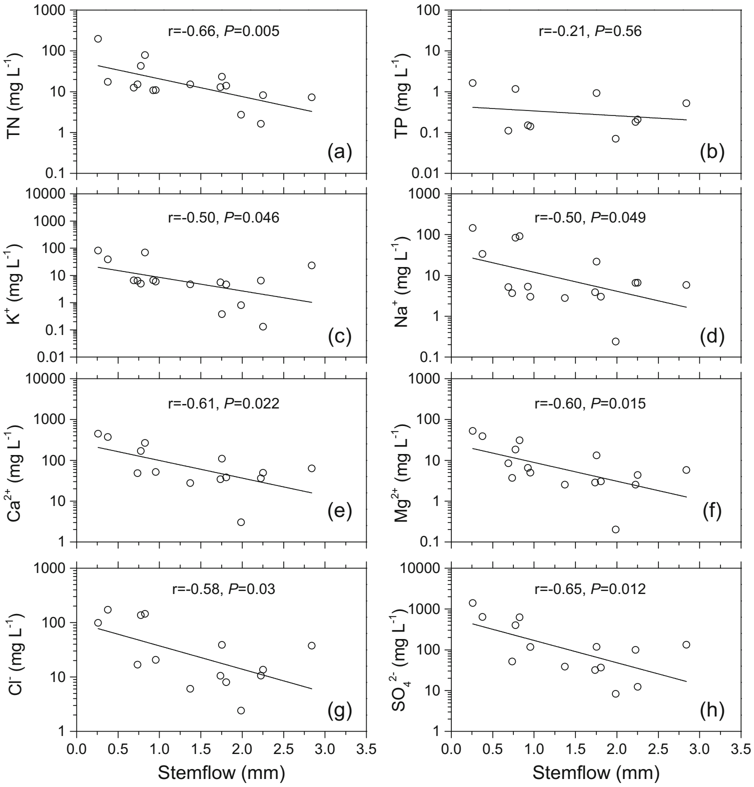


Fig. 7 Relationships between ion concentrations and stemflow depth of *A. ordosica*

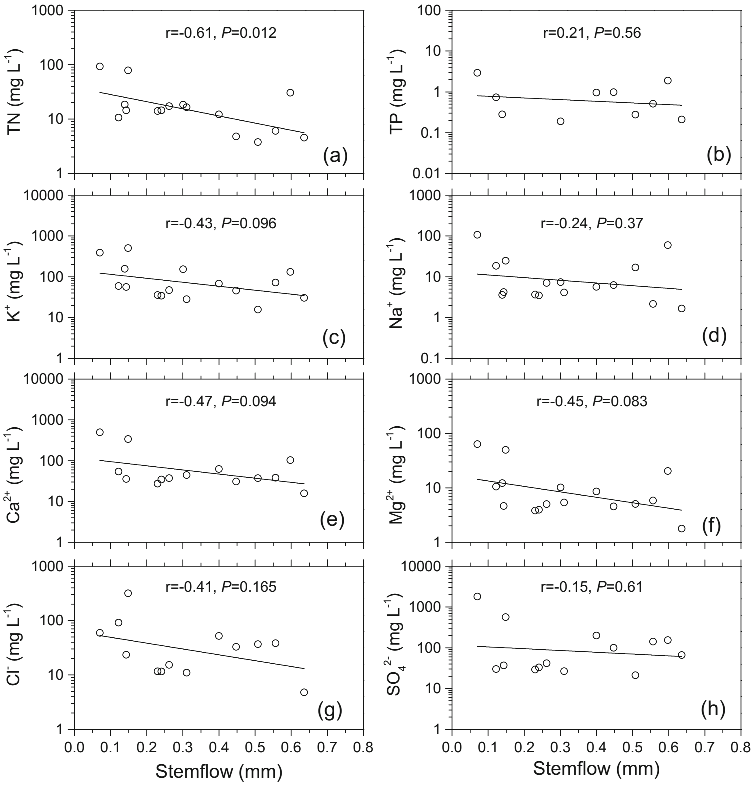
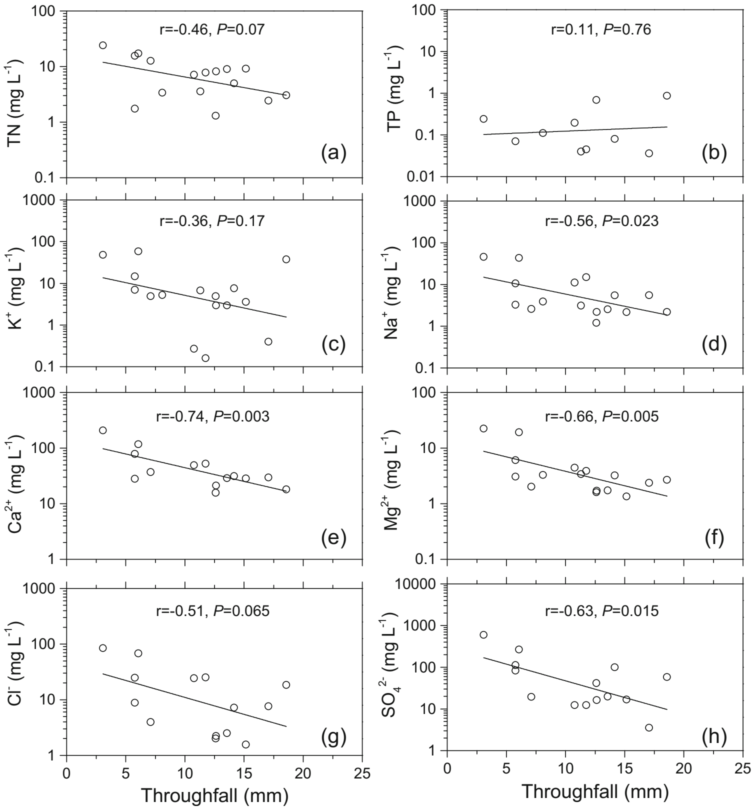


Fig. 8 Relationships between ion concentrations and throughfall depth of *C. korshinskii*

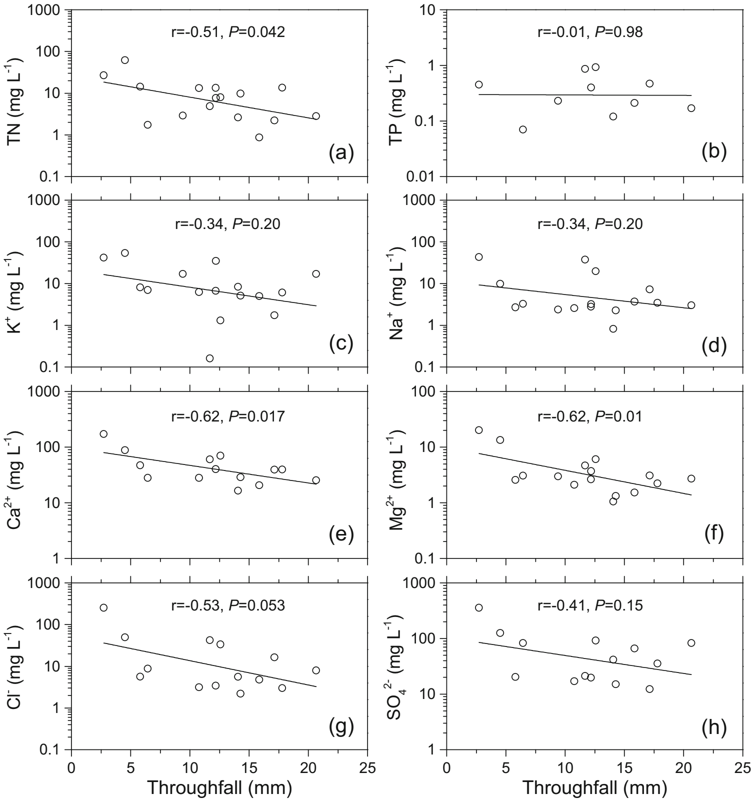


rainfall for *C. korshinskii* and *A. ordosica*, respectively (Zhang et al. 2015), the annual input of nutrients from stemflow of shrubs could be quite substantial due to high ion concentrations (Fig. 2, Tables 1 and 2). Neglecting stemflow solute fluxes would considerably underestimate total fluxes to the ground of this revegetated desert ecosystem, as having been found in some forested ecosystems (e.g., Crockford et al. 1996; Germer et al. 2012; Neary and Gizyn 1994; Staelens et al. 2007). Stemflow is known as a highly localized point input of rainfall and solutes at the tree trunk or shrub stem (Levia and Frost 2003). Therefore, we have to take into consideration that stemflow input is very local, i.e., around stem bases where fine roots are concentrated (e.g., Martinez-Meza and Whitford 1996; Johnson and Lehmann 2006; Schwärzel et al. 2012), which is well demonstrated by high stemflow enrichment ratio of measured ions (Table 2). Comparatively, nutrients from gross rainfall are distributed in the whole ecosystem, and nutrients from throughfall were mainly distributed in soils under projected canopy area. The persistently high stemflow solute fluxes may be particularly important for ecosystems with low nutrient availability. As such, we consider stemflow as an indispensable hydrological factor in estimating nutrient fluxes of the nutrient-limited arid desert ecosystems, which positively contributes to these ecosystems, strongly affects the distribution pattern of water and nutrient unevenly distributed in patches, subsequently, maximizes the productivity in these systems (Noy-Meir 1973).

4.4 Implications to Shrub Fertile Islands in Revegetated Desert Ecosystems

The long term revegetation efforts by planting xerophytic shrubs in our study area had turned the former landscape with bare and homogeneous moving sand dunes into a landscape characterized by a mosaic of the sparse shrubs and herbs and the inter-shrub spaces (Li et al. 2004, 2006). Shrub fertile islands has been a pronounced phenomenon in this revegetated ecosystems during the succession (e.g., Duan et al. 2004; Li et al. 2004). Generally, shrub fertile islands is the result of a range of interacting physical and biotic concentrating mechanism (Stock et al. 1999), while hydrologically

Fig. 9 Relationships between ion concentrations and throughfall depth of *A. ordosica*



and chemically enriched stemflow and throughfall (in particular the former) are considered as biological transport mechanisms that contribute to the formation and evolution of fertile islands (e.g., Garner and Steinberger 1989; Whitford et al. 1997; Zhang et al. 2013). We thereby assume that the nutrient-enriched stemflow and throughfall plays an important role in the formation as well as evolution of the shrub fertile islands in our revegetated desert ecosystems, and our results supported this point. Taking nitrogen as an example, which is the most limiting element for plant growth in soils of our study area (Su et al. 2013; Hu et al. 2015), our results showed that TN (though not necessarily fully available for plants or organisms) enrichment ratio was 286 and 97 for *C. korshinskii* and *A. ordosica*, respectively (Table 1), indicating that *C. korshinskii* and

Table 2 Yearly nutrient input (kg hm^{-2} a^{-1}) by gross rainfall (GR), throughfall (TF), and stemflow (SF) in the study site (Water Balance Experimental Field) at Shapotou Desert Research and Experiment Station, China

Nutrient	GR	*C. korshinskii*			*A. ordosica*			Total (*C. korshinskii* + *A. ordosica*)	
		SF	TF	SF+TF	SF	TF	SF+TF	SF	TF
TN	7.77	1.37	3.81	5.18	0.42	5.81	6.23	1.79	9.62
TP	0.09	0.03	0.17	0.20	0.02	0.25	0.27	0.05	0.42
K^+	3.16	0.84	6.54	7.38	2.10	7.35	9.45	2.95	13.89
Na^+	4.17	1.32	4.27	5.59	0.32	4.87	5.19	1.64	9.14
Ca^{2+}	22.73	6.23	23.55	29.78	1.65	27.46	29.11	7.88	51.01
Mg^{2+}	1.62	0.63	2.26	2.89	0.24	2.32	2.56	0.87	4.58
Cl^-	5.86	2.88	8.76	11.64	1.30	12.04	13.34	4.18	20.80
SO_4^{2-}	36.99	12.16	37.28	49.44	3.40	36.35	40.75	15.56	39.75

A. ordosica funneled 286 and 97 times amount of nutrients in stemflow to the stem basal area comparing with that in gross rainfall falling at the open areas. At the community scale, stemflow and throughfall together accounted for about 80 % of incident gross rainfall above shrub canopies (Zhang et al. 2015), while total TN input flux from under-canopy rainfall (stemflow plus throughfall) of *C. korshinskii* and *A. ordosica* was 1.5 times higher than that of gross rainfall (Table 2); importantly, nutrient input from stemflow and throughfall are confined to soils beneath shrub canopies.

5 Conclusions

This is the first time the first flush effect was examined for shrubs of desert ecosystems, being characterized by obviously higher ion concentrations in samples of stemflow, throughfall, and gross rainwater collected from first rainfall event than from other rainfall events. We also found that solutes had significant higher concentrations in stemflow than in throughfall, followed by gross rainfall, implying the chemical enrichment of stemflow and throughfall. Transfer of nutrients by way of stemflow and throughfall is both substantial in desert shrub ecosystem by scaling up nutrient input from invidual shrubs scale to community scale. Neglecting stemflow solute fluxes, as previous studies routinely did, would considerably underestimate total nutrient fluxes to the ground. Through quantitative analysis (e.g., enrichment ratio), we thus conclude that stemflow and throughfall are the important sources of nutrient input to revegetated desert ecosystems, plays an important role in forming the shrub fertile islands, and contributes significantly to a sustainable succession of the revegetated desert ecosystems.

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