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Discussions

Comparisons of stemflow yield and efficiency between two xerophytic shrubs: the effects of leaves and implications in drought tolerance

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Abstract.

Stemflow transports enriched precipitation to the rhizosphere and is highly important for the survival of xerophytic shrubs in water-stressed ecosystems. However, its ecological significance has generally been underestimated because it is relatively limited in amount, and the biotic mechanisms that affect it have not been thoroughly studied at the leaf scale. In this study, the branch stemflow volume (SF_b), the shrub stemflow equivalent water depth (SF_d), the stemflow percentage of incident precipitation (SF%), the stemflow productivity (SFP), the funnelling ratio (FR), the rainfall characteristics and the plant traits of branches and leaves of *C. korshinskii* and *S. psammophila* were measured during the 2014 and 2015 rainy seasons in the northern Loess Plateau of China. This study evaluated the stemflow production efficiency for the first time with the combined results of SFP and FR, and sought to determine the inter- and intra-specific differences in stemflow production and production efficiency, as well as the specific bio-/abiotic mechanisms that affected stemflow. The results indicated that precipitation amount was the most influential rainfall characteristic that affected stemflow in these two endemic shrub species and that stem biomass and leaf biomass were the most influential plant traits in *C. korshinskii* and *S. psammophila*, respectively. *C. korshinskii* had a greater stemflow production and production efficiency at all precipitation levels, and the largest inter-specific difference was generally in the 5–10-mm young shoots during the most frequent rainfall events of ≤2 mm. *C. korshinskii* had a lower precipitation threshold (0.9 mm vs. 2.1 mm for *S. psammophila*), which provided more available water from rainfall for stemflow. The leaves affected stemflow production, and the beneficial leaf traits contributed to the higher stemflow production of *C. korshinskii*. In summary, *C. korshinskii* might have greater drought tolerance and a competitive edge in a dryland ecosystem because of greater and more efficient stemflow production, a lower precipitation threshold and more advantageous leaf traits.

Keywords: Xerophytic shrub; Stemflow production; stemflow production efficiency; Threshold precipitation; Beneficial leaf traits.

1 Introduction

Stemflow channels divert precipitation pointedly into the root zone of a plant via preferential root paths, worm paths and soil macropores. The double-funnelling effects of stemflow and preferential flow create “hot spots” and “hot moments” by enhancing biogeochemical reactivity at the terrestrial-aquatic interface (McClain et al., 2003; Johnson and Lehmann, 2006), thus substantially contributing to the formation and maintenance of so-called “fertile islands” (Whitford et al., 1997), “resource islands” (Reynolds et al., 1999) or “hydrologic islands” (Rango et al., 2006). This effect is important for the normal function of rain-fed dryland ecosystems (Wang et al., 2011).

Shrubs are a representative plant functional type (PFT) in dryland ecosystems and have developed effective physiological drought tolerance by reducing water loss, e.g., through adjusting their photosynthetic and transpiration rate by regulating stomatal conductance and abscisic acid (ABA), titling their osmotic equilibrium by regulating the concentration of soluble sugars and inorganic ions, and removing free radicals (Ma et al., 2004, 2008). The efficient production of stemflow is a vital eco-hydrological flux involved in soil water replenishment (Pressland 1973) as well as an effective strategy to acquire water (Murakami, 2009) and withstand drought (Martinez-Meza and Whitford, 1996). However, because stemflow occurs in small amounts, previous studies have usually ignored stemflow (Llorens and Domingo, 2007) and have underestimated its disproportionately high influence on the survival and competitiveness of xerophytic shrub species. Therefore, the quantification of inter- and intra-specific stemflow production is important to assess the stemflow production efficiency and to elucidate the underlying bio-/abiotic mechanisms.

Stemflow production includes the stemflow volume and depth, and it describes the total flux channelled down to the base of a branch or a trunk, but stemflow data are unavailable for comparison of inter-specific differences caused by variations in the branch architecture, the

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canopy structure, the shrub species and the eco-zone. Herwitz (1986) introduced the funnelling ratio (FR), which is expressed as the quotient of the volume of stemflow produced and the product of the base area and the precipitation amount. It indicates the efficiency with which individual branches or shrubs capture raindrops and deliver the water to the root zone (Siegert and Levia, 2014). The FR allows a comparison of the inter- and intra-specific stemflow production under different precipitation conditions. However, the FR does not provide a connection between hydrological processes (e.g., rainfall redistribution) and the plant growth processes (e.g., biomass accumulation and allocation). Recently, Yuan et al. (2016) have introduced the parameter stemflow productivity (SFP), expressed as the volume of stemflow production per unit of branch biomass. The SFP describes the efficiency in an energy-conservation manner by comparing the stemflow volume of a unit biomass increment of different-sized branches.

The precipitation amount is an abiotic mechanism that has been recognized as the single most influential rainfall characteristic (Clements 1972; André et al., 2008; Van Stan et al., 2014). However, in terms of biotic mechanisms, although the canopy structure (Mauchamp and Janeau, 1993; Crockford and Richardson, 2000; Pypker et al., 2011) and branch architecture (Herwitz, 1987; Murakami 2009; (Herwitz, 1987;Murakami, 2009; Carlyle-Moses and Schooling, 2015) have been studied for years, the most important plant traits that vary with location and shrub species have not yet been determined. The effects of the leaves have been studied more recently at a smaller scale, e.g., leaf orientation (Crockford and Richardson, 2000), shape (Xu et al., 2005), arrangement pattern (Owens et al., 2006), pubescence (Garcia-Estringana et al., 2010), area (Sellin et al., 2012), epidermis microrelief (Roth-Nebelsick et al., 2012), amount (Li and Xiao, 2016), biomass (Yuan et al., 2016; Li et al., 2016), etc. Although comparisons of stemflow production during the foliated and dormant seasons usually indicate negative effects of leaves because the more stemflow occurred at the leafless period (Dolman, 1987; Neal et al., 1993; Murzyło et al., 2012), both negligible and positive effects have also been confirmed by Martinez-Meza and Whitford (1996) and Liang et al. (2009), respectively. Nevertheless, the validity of these findings has been called into question as a result of the seasonal variation of meteorological conditions and plant traits, e.g., wind speed (André et al., 2008), rainfall intensity (Dunkerley et al., 2014 a, b), air temperature and consequent precipitation type (snow-to-rain vs. snow) (Levia, 2004). Therefore, a controlled experiment with foliated and manually defoliated plants under the same stand conditions is needed to resolve these uncertainties.

In this study, the branch stemflow volume (SF_b), the shrub stemflow depth (SF_d), the stemflow percentage of the incident precipitation amount (SF%), the SFP and the FR were measured in two shrub species (*C. korshinskii* and *S. psammophila*) endemic to a semiarid area of northern China during the 2014 and 2015 rainy seasons. The objectives of this study were to (1) quantify the inter- and intra-specific stemflow production (SF_b, SF_d and SF%) and the production efficiency (SFP and FR); (2) investigate the effects of the rainfall characteristics and plant traits on the stemflow in these two shrub species; and (3) specifically identify leaf characteristics that affect the stemflow with respect to morphology, structural characteristics and the biomass partitioning pattern. The achievement of these research objectives would provide a novel characterization of plant drought tolerance and species competitiveness in terms of stemflow and further the understanding of the effects of leaves on the survival and growth of plants from an eco-hydrological perspective.

2 Materials and Methods

2.1 Study area

This study was conducted at the Liudaogou catchment (110°21′-110°23′E, 38°46′-38°51′N) in Shenmu County in the Shaanxi Province of China. It is 6.89 km^2 and

1094-1273 m above sea level (a.s.l.). This area has a semiarid continental climate with well-defined rainy and dry seasons. The mean annual precipitation (MAP) between 1971 and 2013 was 414 mm, with approximately 77% of the annual precipitation amount occurring during the rainy season (Jia et al., 2013), which lasts from July to September. The mean annual temperature and potential evaporation are 9.0 ℃ and 1337 mm·year^{-1} (Zhao and Shao, 2009), respectively. The coldest and warmest months are January and July, with an average monthly temperature of 9.7 ℃ and 23.7 ℃, respectively. Two soil types of Aeolian sandy soil and Ust-Sandiic Entisol dominate this catchment (Jia et al., 2011). Soil particles consist of 11.2%-14.3% clay, 30.1%-44.5% silt and 45.4%-50.9% sand in terms of the soil classification system of United States Department of Agriculture (Zhu and Shao, 2008). The original plants are scarcely present, except for very few surviving shrub species, e.g., *Ulmus macrocarpa*, *Xanthoceras sorbifolia*, *Rosa xanthina*, *Spiraea salicifolia*, etc. The currently predominant shrub species were planted decades ago, e.g., *S. psammophila*, *C. Korshinskii*, *Amorpha fruticosa*, etc., and the predominant grass species include *Medicago sativa*, *Stipa bungeana*, *Artemisia capillaris*, *Artemisia sacrorum*, etc. (Ai et al., 2015).

C. Korshinskii and *S. psammophila* are endemic shrub species in arid and semiarid northern China and were planted for wind-proofing and dune-stabilizing because of their great drought tolerance. Two representative experimental stands were established in the southwest of the Liudaogou catchment (Fig. 1). Both *C. korshinskii* and *S. psammophila* were planted approximately twenty years ago, and the two stands share a similar slope of 13-18°, a size of 3294-4056 m^2, and an elevation of 1179-1207 m a.s.l. However, the *C. korshinskii* experimental stand had a 224° aspect with a loess ground surface, whereas the *S. psammophila* experimental stand had a 113° aspect with a sand ground surface.

Fig. 1. Location of the experimental stands and facilities for stemflow measurements of *C. korshinskii* and *S. psammophila* at the Liudaogou catchment in the Loess Plateau of China.

2.2 Field experiments

Field experiments were conducted during the rainy seasons of 2014 (July 1 to October 3) and 2015 (June 1 to September 30) to measure the rainfall characteristics, plant traits and stemflow. To avoid the effects of gully micro-geomorphology on recording the rainfall characteristics, we installed an Onset® (Onset Computer Corp., Bourne, MA, USA) RG3-M tipping bucket rain gauge (0.2 mm per tip) at each experimental stand. Three 20-cm-diameter rain gauges were placed around to adjust the inherent underestimating of automatic precipitation recording (Groisman and Legates, 1994). Then, rainfall duration (RD, h), rainfall interval (RI, h), the average rainfall intensity (I, mm h^{-1}), the maximum rainfall intensity in 5 min (I_5, mm h^{-1}), 10 min (I_{10}, mm h^{-1}) and 30 min (I_{30}, mm h^{-1}) could be calculated accordingly. In this study, the individual rainfall events were greater than 0.2 mm and separated by a period of at least four hours without rain (Giacomin and Trucchi, 1992).

C. korshinskii and *S. psammophila*, as modular organisms and multi-stemmed shrub species, have branches of that exist as independent individuals. Therefore, we focused on the inter- and intra-specific branch stemflow by experimenting on sample shrubs that had a similar canopy structure. Four mature shrubs were selected for *C. korshinskii* (designated as C1, C2, C3 and C4) and *S. psammophila* (designated as S1, S2, S3 and S4) for the stemflow measurements. They had isolated canopies, similar intra-specific heights and canopy areas, e.g., 2.1 ± 0.2 m and 5.14 ± 0.26 m^2 for C1-C4, and 3.5 ± 0.2 m and 21.35 ± 5.21 m^2 for S1-S4. We measured the morphological characteristics of all the 180 branches of C1-C4 and all the 261 branches of S1-S4, including the branch basal diameter (BD, mm), branch length (BL, cm) and branch inclination angle (BA, °). The leaf area index (LAI) and the foliage orientation (MTA, the mean tilt angle of leaves) were measured using LiCor® (LiCor Biosciences Inc., Lincoln, NE, USA) 2200C plant canopy analyser approximately twice a month.

A total of 53 branches of *C. korshinskii* and 98 branches of *S. psammophila* were selected for stemflow measurements following the criteria: 1) no intercrossing stems; 2) no turning point in height from branch tip to the base; 3) representativeness in amount and branch size. Stemflow was collected using aluminum foil collars, which was fitted around the entire branch circumference and sealed by neutral silicone caulking (Fig. 1). A 0.5-cm-diameter PVC hose led the stemflow to lidded containers. The stemflow volume was measured within two hours after the rainfall ended during the daytime; if the rainfall ended at night, we took the measurement early the next morning.

Another three shrubs of each species were destructively measured for biomass and leaf traits. They had similar canopy heights and areas as those of the shrubs for which the stemflow was measured and were designated as C5-C7 (2.0-2.1 m and 5.84-6.77 m^2) and S5-S7 (3.0-3.4 m and 15.43-19.20 m^2), thus allowing the development of allometric models for the estimation of the corresponding biomass and leaf traits of C1-C4 and S1-S4 (Levia and Herwitz, 2005; Siles et al., 2010a, 2010b; Stephenson et al., 2014). A total of 66 branches for C5-C7 and 61 branches for S5-S7 were measured when the shrubs showed maximum vegetative growth during mid-August for the biomass of leaves and stems (BML and BMS, g), the leaf area of the branches (LAB, cm^2), and the leaf numbers of the branches (LNB). The BML and BMS were weighted after oven-drying of 48 hours. The detailed measurements have been reported in Yuan et al., (2016). The validity of the allometric models was verified by measuring another 13 branches of C5-C7 and 14 branches of S5-S7.

2.3 Calculations

Biomass and leaf traits were estimated by allometric models as an exponential function of BD (Siles et al., 2010a, b; Jonard et al., 2006):

$$PT_e = a * BD^b \quad (1)$$

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where *a* and *b* are constants, and PT_e refers to the estimated plant traits BML, BMS, LAB and LNB. The other plant traits could be calculated accordingly, including individual leaf area of branch (ILAB = 100*LAB/LNB, mm^2), the percentage of stem biomass to that of branch (PBMS = BMS/(BML+BMS)*100%, %), specific leaf weight (SLW = BML/LAB, g cm^{-2}), Huber value (HV = BBA/LAB = $3.14*BD^2/(400*LAB)$, unitless, where BBA is the branch basal area (cm^2)).

In this study, stemflow production was defined as the branch volume production (hereafter "stemflow production", SF_b, mL), the equivalent water depth on the basis of shrub canopy area (hereafter "stemflow depth", SF_d, mm), and the stemflow percentage of the incident precipitation amount (hereafter "stemflow percentage", SF%, %):

$$SF_d = 10 * \sum_{i=1}^{n} SF_{b_i} / CA \quad (2)$$

$$SF\% = (SF_d / P)*100\% \quad (3)$$

where SF_{bi} is the volume of stemflow production of branch *i* (mL), CA is the canopy area (cm^2), n is the number of branches, and P is the incident precipitation amount (mm).

Stemflow productivity (SFP, mL g^{-1}) was expressed as the SF_b (mL) of unit branch biomass (g) and represented the stemflow production efficiency of different-sized branches in terms of energy-conservation:

$$SFP = SF_b / (BML + BMS) \quad (4)$$

The funnelling ratio (FR) was computed as the quotient of SF_b and the product of P and BBA (Herwitz, 1986). A FR with a value greater than 1 indicated a positive effect of the canopy on the stemflow production (Carlyle-Moses and Price, 2006). The value of (P * BBA) equals to the precipitation amount that would have been caught by the rain gauge occupying the same basal area at the clearing:

$$FR = 10*SF_b / (P*BBA) \quad (5)$$

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2.4 Data analysis

A Pearson correlation analysis was performed to test the relationship between SF_b and each of the rainfall characteristics and plant traits. Significantly correlated variables were further tested with a partial correlation analysis for their separate effects on SF_b. Then, the qualified variables were fed into a stepwise regression with forward selection to identify the most influential bio-/abiotic factors (Carlyle-Moses and Schooling, 2015; Yuan et al., 2016). Similarly to a principal component analysis and ridge regression, stepwise regression has commonly been used because it gets a limited effect of multicollinearity (Návar and Bryan, 1990; Honda et al., 2015; Carlyle-Moses and Schooling, 2015). Moreover, we excluded variables that had a variance inflation factor (VIF) greater than 10 to minimize the effects of multicollinearity (O'Brien, 2007). The same analysis method was also applied to identify the most influential bio-/abiotic factors affecting SFP and FR. The level of significance was set at 95% confidence interval (p = 0.05). The SPSS 20.0 (IBM Corporation, Armonk, NY, USA), Origin 8.5 (OriginLab Corporation, Northampton, MA, USA), and Excel 2013 (Microsoft Corporation, Redmond, WA, USA) were used for data analysis.

3 Results

3.1 Species-specific variation of plant traits

According to the *Flora of China* and the field observation, both *C. korshinskii* and *S. psammophila* had an inverted-cone canopy and no trunk, with the branches running obliquely from the base. *S. psammophila* usually grew to 3-4 m and had an odd number of strip-shaped leaves of 24-mm in width and 4080-mm in length. The young leaves were pubescent and gradually became subglabrous (Chao and Gong, 1999) (Fig. 2). In comparison, *C. korshinskii* usually grew to 2 m and had pinnate compound leaves with 12-16 foliates in an opposite or sub-opposite arrangement (Wang et al., 2013). The leaf was concave and lanceolate-shaped,

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with an acute leaf apex and an obtuse base. Both sides of the leaves were densely sericeous with appressed hairs (Liu et al., 2010) (Fig. 2).

Fig. 2. Comparison of leaf morphologies of *C. korshinskii* and *S. psammophila*.

Allometric models were developed to estimate the biomass and leaf traits of the branches of *C. korshinskii* and *S. psammophila* measured for stemflow. The quality of the estimates was verified by linear regression. As shown in Fig. 3, the regression of LAB, LNB, BML and BMS of *C. korshinskii* had an approximately 1:1 slope (0.99 for the biomass indicators and 1.04 for the leaf traits) and an R^2 value of 0.93-0.95. According to Yuan et al., (2016), the regression of *S. psammophila* had a slope of 1.13 and an R^2 of 0.92. Therefore, those allometric models were appropriate.

Fig. 3. Verification of the allometric models for estimating the biomass and leaf traits of *C. korshinskii*. BML and BMS refer to the biomass of the leaves and stems, respectively, and LAB and LNB refer to the leaf area and the number of branches, respectively.

C. korshinskii had a similar average branch size and angle, but a shorter branch length than did *S. psammophila*, e.g., 12.48 ± 4.16 mm vs. 13.73 ± 4.36 mm, 60 ± 18 ° vs. 60 ± 20 °, and 161 ± 35 cm vs. 267.3 ± 49.7 cm, respectively. Regarding branch biomass accumulation, *C. korshinskii* had a smaller BML (an average of 19.93 ± 10.81 g) and a larger BMS (an average 141.07 ± 110.78 g) than did *S. psammophila* (an average of 27.85 ± 20.71 g and 130.65 ± 101.35 g, respectively). Both the BML and BMS increased with increasing branch size for these two shrub species. When expressed as a proportion, *C. korshinskii* had a larger PBMS than that of *S. psammophila* in all the BD categories. The PBMS-specific difference increased with an increasing branch size, ranging from 1.24% for the 5–10-mm branches to 7.22% for the >18-mm branches.

Although an increase in LAB and LNB and a decrease in ILAB were observed for both

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shrub species with an increase in branch size, *C. korshinskii* had a larger LAB (an average of 2509.05 ± 1355.30 cm^2) and LNB (an average of 12479 ± 8409), but a smaller ILAB (an average of 21.94 ± 2.99 mm^2) than did *S. psammophila* for each BD level (Table 1). The inter-specific differences in the leaf traits decreased with increasing branch size. The largest difference occurred for the 5–10-mm branches, e.g., LNB and LAB were 12.21-fold and 2.41-fold larger for *C. korshinskii*, and ILAB was 5.32-fold larger for *S. psammophila*. *C. korshinskii* had a larger SLW (an average of 126.04 ± 0.29 g cm^{-2}) and HV (0.0507 ± 0.0064) than did *S. psammophila* (73.87 ± 14.52 g cm^{-2} and 0.0009 ± 0.0001, respectively). As the branch size increased, the SLW of *S. psammophila* decreased from 95.62 g cm^{-2} for the 5–10-mm branches to 58.07 g cm^{-2} for the >18-mm branches, but the HV of *C. korshinskii* increased from 0.0438 to 0.0615.

Table 1. Comparison of branch morphology, biomass and leaf traits of *C. korshinskii* and *S. psammophila*.

3.2 Stemflow production of *C. korshinskii* and *S. psammophila*

In this study, stemflow production was expressed as SF_b on the branch scale and SF_d and SF% on the shrub scale. The SF_b was an average of 290.6 mL and 150.3 mL for individual branches of *C. korshinskii* and *S. psammophila*, respectively. The SF_b was positively correlated with the branch size and precipitation of these two shrub species. As the branch size increased, SF_b increased from 119.0 mL for the 5–10-mm branches to 679.9 mL for the >20-mm branches for *C. korshinskii* and from 43.0 mL to 281.8 mL for the corresponding BD categories of *S. psammophila*. However, with increasing precipitation, a larger intra-specific difference in SF_b was observed, which increased from 28.4 mL during rains ≤2 mm to 771.4 mL during rains >20 mm for *C. korshinskii* and from 9.0 mL to 444.3 mL for the corresponding precipitation categories of *S. psammophila*. The intra-specific differences in SF_b were significantly affected by the rainfall characteristics and the plant traits. Up to

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2375.9 mL of stemflow was measured for the >18-mm branches of *C. korshinskii* during rains >20 mm, but only 6.8 mL of stemflow occurred for the 5–10-mm branches during rains ≤2 mm. For comparison, a maximum SF_b of 2097.6 mL and a minimum of 1.8 mL were measured for *S. psammophila*.

C. korshinskii produced a larger SF_b than did *S. psammophila* for all BD and precipitation categories, and the inter-specific differences in SF_b also varied substantially with the rainfall characteristics and the plant traits. A maximum difference of 4.3-fold larger for the SF_b of *C. korshinskii* was observed for the >18-mm branches during rains ≤2 mm. As the precipitation increased, the SF_b-specific difference decreased from 3.2-fold larger for *C. korshinskii* during rains ≤2 mm to 1.7-fold larger during rains >20 mm. The largest SF_b-specific difference occurred for the 5–10-mm branches for almost all precipitation categories, but no clear trend of change was observed with increasing branch size (Table 2).

SF_d and SF% averaged 1.00 mm and 8.0%, respectively, for individual *C. korshinskii* shrubs and 0.8 mm and 5.5%, respectively, for individual *S. psammophila* shrubs. These parameters increased with increasing precipitation, ranging from 0.09 mm and 5.8% during rains ≤2 mm to 2.64 mm and 8.9% during rains >20 mm for *C. korshinskii* and from 0.01 mm and 0.7% to 2.23 mm and 7.9% for the corresponding precipitation categories of *S. psammophila*, respectively. Additionally, the individual *C. korshinskii* shrubs had a larger stemflow than did *S. psammophila* for all precipitation categories. The maximum differences in SF_d and SF% were 8.5- and 8.3-fold larger for *C. korshinskii* during rains ≤2 mm and decreased with increasing precipitation to 1.2- and 1.1-fold larger during rains >20 mm.

Table 2. Comparison of stemflow production (SF_b, SF_d and SF%) between *C. korshinskii* and *S. psammophila*.

3.3 Stemflow production efficiency of *C. korshinskii* and *S. psammophila*

Combined results for SFP and FR, the stemflow production efficiency were assessed for

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C. korshinskii and *S. psammophila*. SFP averaged 1.95 mL g^{-1} and 1.19 mL g^{-1} for individual *C. korshinskii* and *S. psammophila* branches, respectively (Table 3). As precipitation increased, SFP increased from 0.19 mL g^{-1} during rains ≤2 mm to 5.08 mL g^{-1} during rains >20 mm for *C. korshinskii* and from 0.07 mL g^{-1} to 3.43 mL g^{-1} for the corresponding precipitation categories for *S. psammophila*. With an increase in branch size, SFP decreased from 2.19 mL g^{-1} for the 5–10-mm branches to 1.62 mL g^{-1} for the >18-mm branches of *C. korshinskii* and from 1.64 mL g^{-1} to 0.80 mL g^{-1} for the corresponding BD categories of *S. psammophila*. Maximum SFP values of 5.60 mL g^{-1} and 4.59 mL g^{-1} were recorded for *C. korshinskii* and *S. psammophila*, respectively. Additionally, *C. korshinskii* had a larger SFP than that of *S. psammophila* for all precipitation and BD categories. This inter-specific difference in SFP decreased with increasing precipitation from 2.5-fold larger for *C. korshinskii* during rains ≤2 mm to 1.5-fold larger during rains >20 mm, and it increased with increasing branch size: from 1.3-fold larger for *C. korshinskii* for the 5–10-mm branches to 2.0-fold larger for the >18-mm branches.

Table 3. Comparison of stemflow productivity (SFP) between *C. korshinskii* and *S. psammophila*.

FR averaged 172.3 and 69.3 for the individual branches of *C. korshinskii* and *S. psammophila*, respectively (Table 4). As the precipitation increased, an increasing trend was observed, ranging from 129.2 during rains ≤2 mm to 190.3 during rains >20 mm for *C. korshinskii* and from 36.7 to 96.1 during the corresponding precipitation categories for *S. psammophila*. FR increased with increasing BA from 149.9 for the ≤30º-branches to 198.2 for the >80 ºbranches of *C. korshinskii* and from 55.0 to 85.6 for the corresponding BA categories of *S. psammophila*. Maximum FR values of 276.0 and 115.7 were recorded for *C. korshinskii* and *S. psammophila*, respectively. Additionally, *C. korshinskii* had a larger FR than *S. psammophila* for all precipitation and BA categories. The inter-specific difference in

FR decreased with increasing precipitation from the 3.5-fold larger for *C. korshinskii* during rains ≤2 mm to 2.0-fold larger during rains >20 mm, and it decreased with an increase in the branch inclination angle: from 2.7-fold larger for *C. korshinskii* for the ≤30º-branches to 2.3-fold larger for the >80 º-branches.

Table 4. Comparison of the funnelling ratio (FR) for *C. korshinskii* and *S. psammophila*.

3.4 Bio/abiotic influential factors of stemflow production and production efficiency

For both *C. korshinskii* and *S. psammophila*, BA was the only plant trait that had no significant correlation with SF_b ($r < 0.13$, $p > 0.05$) as indicated by Pearson correlation analysis. The separate effects of the remaining plant traits were verified by using a partial correlation analysis, but BL, ILAB and PBMS failed this test. The remaining plant traits, including BD, LAB, LNB, BML and BMS, were regressed with SF_b by using the forward selection method. Biomass was finally identified as the most important biotic indicator that affected stemflow, which behaved differently in *C. korshinskii* for BMS and in *S. psammophila* for BML. The same analysis methods indicated that the precipitation amount was the most important rainfall characteristic that affected stemflow in these two shrub species.

SF_b and SF_d had a good linear relationship with the precipitation amount ($R^2 \geq 0.93$) for both shrub species (Fig. 4). The >0.9-mm and >2.1-mm rains were required to start SF_b for *C. korshinskii* and *S. psammophila*, respectively, results consistent with the 0.8-mm and 2.0-mm precipitation threshold calculated with SF_d. Moreover, the precipitation threshold increased with increasing branch size. The precipitation threshold values were 0.69 mm, 0.72 mm, 1.35 mm and 0.81 mm for the 5–10-mm, 10–15-mm, 15–18-mm and >18-mm branches of *C. korshinskii*, respectively, and 1.1 mm, 1.6 mm, 2.0 mm and 2.4 mm for the branches of *S. psammophila*, respectively.

The SF% of the two shrub species also increased with precipitation, but was inversely proportional and gradually approached asymptotic values of 9.1% and 7.7% for *C. korshinskii* and *S. psammophila*, respectively. As shown in Fig. 4, fast growth was evident during rains ≤10 mm, but SF% slightly increased afterwards for both shrub species.

Fig. 4. Relationships of branch stemflow production (SF_b), shrub stemflow depth (SF_d) and stemflow percentage (SF%) with precipitation amount (P) for *C. korshinskii* and *S. psammophila*.

Precipitation amount was the most important factor affecting SFP and FR for *C. korshinskii* and *S. psammophila*, but the most important biotic factor was different. BA was the most influential plant trait that affected FR, and ILAB was the most important plant trait affecting SFP during rains ≤10 mm. However, during heavy rain, BD and PBMS were the most significant biotic factors for *C. korshinskii* and *S. psammophila*, respectively.

4 Discussion

4.1 Effective utilization of precipitation via stemflow production

Stemflow in *C. korshinskii* and *S. psammophila* increased with increasing precipitation and branch size at both the branch (SF_b) and shrub scales (SF_d and SF%). However, *C. korshinskii* had larger SF_b, SF_d and SF% values than did *S. psammophila* for all precipitation categories. Although the greatest stemflow production was observed during rains >20 mm for the two shrub species, the inter-specific differences of SF_b, SF_d and SF% were highest at 3.2-, 8.5- and 8.3-fold larger for *C. korshinskii* during rains ≤2 mm, which indicated that *C. korshinskii* utilized precipitation far more effectively during rains ≤2 mm at the branch and shrub scale. These data indicate that stemflow was highly important for the survival of the xerophytic shrubs in extreme drought. Additionally, *C. korshinskii* had a 2.8-fold larger SF_b than that of *S. psammophila* for the 5–10-mm branches. Therefore, compared with *S.*

psammophila, more effectively might *C. korshinskii* utilize precipitation via greater stemflow production, particularly the 5–10-mm young shoots during rains ≤2 mm.

The FR values indicated the efficiency with which individual branches could intercept and channel raindrops (Siegert and Levia, 2014), thus leading to greater stemflow production. The average FR of *S. psammophila* was 69.3, which agreed well with the 69.4 of *S. psammophila* in the Mu Us sandland in China (Yang et al., 2008). The average FR for *C. korshinskii* was 173.3, in contrast to the values of 156.1 (Jian et al., 2014) and 153.5 (Li et al., 2008) for *C. korshinskii* in the western Loess Plateau of China. Furthermore, these two shrub species had a larger FR than those of many other endemic xerophytic shrubs from water-stressed ecosystems, e.g., *Tamarix ramosissima* (24.8) (Li et al., 2008), *Artemisia sphaerocephala* (41.5) (Yang et al., 2008), *Reaumuria soongorica* (53.2) (Li et al., 2008), *Hippophae rhamnoides* (62.2) (Jian et al., 2014). Therefore, both *C. korshinskii* and *S. psammophila* utilized precipitation in a relatively efficient manner by producing stemflow, and *C. korshinskii* produced stemflow more efficiently. The FR-specific difference achieved a maximum of 3.5-fold larger for *C. korshinskii* during rains ≤2 mm and decreased with increasing precipitation to 2.0-fold larger during rains >20 mm.

SFP characterized stemflow production in terms of energy-conservation. *C. korshinskii* had a larger SFP than *S. psammophila* for all the precipitation and BD categories, and during rains ≤2 mm, the SFP-specific difference was maximized to 2.5-fold larger for *C. korshinskii*. Additionally, the 5–10-mm branches had the largest average SFP of 2.2 mL g^{-1} and 1.6 mL g^{-1} in return, which, during rains >20 mm, was maximized to 5.6 mL g^{-1} and 4.6 mL g^{-1} for *C. korshinskii* and *S. psammophila*, respectively (Table 3). Investing biomass into young shoots provides considerable water benefits for xerophytic shrubs. Therefore, compared with *S. psammophila*, more efficiently might *C. korshinskii* utilize precipitation by producing greater stemflow, particularly for 5–10-mm young shoots during rains ≤2 mm.

Stemflow may preferentially incorporate precipitation into the rhizosphere, retaining it as relatively stable soil moisture (Martinez-Meza and Whitford, 1996) and increasing drought tolerance, particularly during long periods without rain. It was particularly significant that young shoots were favoured in the presence of a greater water supply. Greater stemflow production provided *C. korshinskii* with greater drought tolerance and a competitive edge in water-stressed ecosystems.

4.2 Utilization of more rains via a low precipitation threshold to start stemflow

Precipitation below the threshold wet the canopy and then evaporated, so it did not generate stemflow. The ≤2.5-mm rains were entirely intercepted and evaporated to the atmosphere for the xerophytic Ashe juniper communities at the central Texas of USA (Owens et al., 2006), as well as most of the ≤5-mm rains, particularly at the beginning raining stage for xerophytic shrubs (*S. psammophila*, *Hedysarum scoparium*, *A. sphaerocephala* and *Artemisia ordosica*) at the Mu Us sandland of China (Yang, 2010). The precipitation threshold varied with factors such as the eco-zone, the PFT, the canopy structure, and the branch architecture. A greater precipitation threshold partly explained why the SF% of trees was smaller than that of shrubs (Llorens and Domingo, 2007). Particularly, the precipitation threshold of xerophytic shrub species was as small as 0.3 mm for *T. vulgaris* at the northern Lomo Herrero of Spain (Belmonte and Romero, 1998), but up to 2.7 mm for *A. farnesiana* at Linares of Mexico (Návar and Bryan, 1990). In this study, at least a 0.9-mm rainfall was necessary to initiate stemflow in *C. korshinskii*, which was in the range of 0.4-1.4 mm at the precipitation threshold for *C. korshinskii* (Li et al., 2009; Wang et al., 2014). This result was consistent with the 0.8 mm for *R. offcinalis* at the northern Lomo Herrero of Spain (Belmont and Romero, 1998) and 0.6 mm for *M. squamosa* at Qinghai-Tibet plateau of China (Zhang et al., 2015). Comparatively, *S. psammophila* needed a 2.1-mm precipitation threshold to initiate stemflow, which was consistent with the 2.2 mm threshold of *S. psammophila* in the Mu Us desert (Li et al., 2009) and the 1.9 mm threshold for *R. soongorica* at the west of Loess Plateau (Li et al., 2008) and the 1.8 mm threshold for *A. ordosica* at the Tengger desert of China (Wang et al., 2014). Generally, for many xerophytic shrub species, the precipitation threshold usually ranges between 0.4-2.2 mm, which is in accordance with the findings for stemflow production (SF_b, SF_d and SF%) and the production efficiency (SFP and FR), thus indicating that rains ≤2 mm were particularly significant for the endemic plants in water-stressed ecosystems.

Scant rainfall was the most prevalent type in arid and semiarid regions. Rains ≤5 mm accounted for 74.8% of the annual rainfall events and 27.7% of the annual precipitation amount at the Anjiapo catchment in the western Loess Plateau of China (with a MAP of 420 mm) (Jian et al., 2014). While at Haizetan in the south of Mu Us sandland of China (with a MAP of 394.7 mm), rains ≤5 mm accounted for 49.0% of all the rainfall events and 13.8% of the total precipitation amount of rainy season (lasting from May to September) (Yang 2010). Additionally, rains ≤2.54 mm accounted for 60% of the total rainfall events and 5.4% of the total precipitation amount at the eastern Edwards Plateau, the central Texas of USA (with a MAP of 600-900 mm) (Owens et al., 2006). In this study, rains ≤2 mm accounted for 45.7% of all the rainfall events and 7.2% of the precipitation amount during the 2014 and 2015 rainy seasons. In general, *C. korshinskii* and *S. psammophila* produced stemflow during 71 (75.5% of the total rainfall events) and 51 rainfall events (54.3% of the total rainfall events), respectively. Because the precipitation threshold for *S. psammophila* was 2.1 mm, 20 rainfall events of 12-mm, which encompassed 21.3% of all rainfall events, did not produce stemflow, but stemflow production under these water stress conditions was an extra benefit for *C. korshinskii*. Although the total amount was limited, it was of significant importance for the survival of the xerophytic shrubs, particularly during long intervals with no rainfall.

In addition to the meteorological characteristics, the canopy structure and branch architecture partly explained the inter-specific differences in the precipitation threshold (Crockford and Richardson, 2000; Levia and Frost, 2003). A large, tall canopy created a large rainfall interception area, also known as "canopy exposure" (Iida et al. 2011), particularly during windy conditions (Van Stan et al, 2011). However, this advantage in stemflow production might be offset by more consumption for wetting canopy and evaporation before stemflow is generated in arid and semiarid regions, in which considerable evapotranspiration potentially occurs. This phenomenon might be responsible for the smaller precipitation threshold for stemflow production in *C. korshinskii*, which had a canopy height of 2.1 $\pm$ 0.2 m and a canopy area of 5.14 $\pm$ 0.26 m^2, than *S. psammophila*, which had a canopy height of 3.5 $\pm$ 0.2 m and a canopy area of 21.35 $\pm$ 5.21 m^2. Additionally, the canopy structure and branch architecture also affected the water holding capacity (Herwitz, 1985), the interception loss (Dunkerley, 2000), and consequently the precipitation threshold for stemflow generation (Staelens et al., 2008). Nevertheless, the most influential plant traits had not determined yet, and further stemflow studies was required at the finer leaf scale and temporal scale in the future (Levia and Germer, 2015).

4.3 Secure stemflow production advantage via beneficial leaf traits

Further studies at the leaf scale indicated that leaf traits had a significant influence on stemflow (Návar and Bryan, 1990; Carlyle-Mose, 2004; Garcia-Estringana et al., 2010). At the individual shrub scale, the canopy gap, as represented by the LAI and the leaf mass, provided direct access for raindrops to the branch surface (Crockford and Richardson, 2000). The positive effects of LAI (Liang et al., 2009) and leaf biomass (Yuan et al., 2016) have already been confirmed for *Stewartia monadelpha* and *S. psammophila*, respectively. In a study of European beech saplings, Levia et al. (2015) assumed that a threshold number of

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leaves might exist for stemflow production. The positive effects could become negative if too many leaves enclose the branches, which would benefit throughfall instead. In general, factors such as a relatively large number of leaves (Li and Xiao, 2016), a large leaf area (Li et al., 2015), a scale-like leaf arrangement (Owens et al., 2006), a small individual leaf area (Sellin et al., 2012) , a concave leaf shape (Xu et al., 2005), a densely veined leaf structure, an upward leaf orientation (Crockford and Richardson, 2000), leaf pubescence (Garcia-Estringana et al., 2010), and the leaf epidermis microrelief (e.g., the non-hydrophobic leaf surface and the grooves within it) (Roth-Nebelsick et al., 2012) together result in the retention of a large amount of precipitation in the canopy, supplying water for stemflow production, and providing a beneficial morphology that enables the leaves to function as a highly efficient natural water collecting and channelling system.

According to the field observations in this study, *C. korshinskii* had better leaf morphology for stemflow production than did *S. psammophila*, owing to a lanceolate and concaved leaf shape, a pinnate compound leaf arrangement and a densely sericeous pressed pubescence (Fig. 2). Additionally, experimental measurements indicated that *C. korshinskii* had a larger MTA, LAB, LNB and SLW (an average of 54.4°, 2509.05 cm^2, 12479 and 126.04 g cm^{-2}, respectively) and a smaller ILAB (an average of 21.94 mm^2) than did *S. psammophila* (an average of 48.5°, 1797.93 cm^2, 2404, 73.87 g cm^{-2} and 87.52 mm^2, respectively). The larger SLW indicated that more biomass was deposited per unit leaf area. The concave leaf shape, upward leaf orientation (MTA) and densely veined leaf structure (ILAB) (Xu et al., 2005) provided stronger leaf structural support in *C. korshinskii* for the interception and transportation of precipitation, particularly during highly intense rains. Therefore, in addition to the leaf morphology, *C. korshinskii* was also equipped with more beneficial leaf structural characteristics for stemflow production.

However, given that BML had strong effects on stemflow in *S. psammophila* (Yuan et al., 2016), why were stem traits identified as the single most influential traits for stemflow production in *C. korshinskii*, as indicated by the BMS in this study? The answer may partly lie in the values of HV and PBMS. HV was computed as the cross-sectional area of the xylem divided by the total leaf area supported by the stems (Sellin et al., 2012). A higher HV indicates a potentially better water supply to leaves in terms of hydraulic conductance. However, it could also be interpreted as indicating that more stem tissues are required to support the unit leaf area for the normal function of the individual branch. The average HV of *C. korshinskii* was 0.0507 and increased from 0.0438 for the 5–10-mm branches to 0.0615 for the >18-mm branches and was an order of magnitude higher than in *S. psammophila*, which averaged 0.0009 and remained nearly the same for different BD categories. The optimal partitioning theory indicates that plants preferentially allocate biomass into the organs that harvest the most limiting resource (Thornley, 1972; Bloom et al., 1985) and finally reach the "functional equilibrium" of biomass allocation (Brouwer, 1963; Iwasa and Roughgarden, 1984). Therefore, a greater stem biomass might be required by *C. korshinskii* to support leaf development than in *S. psammophila*, thus allowing more carbohydrate produced and raindrops intercepted at the canopy. This possibility is consistent with the biomass allocation patterns and leaf areas of the shrub species in this study. *C. korshinskii* allocated more biomass into the stems with an average of PBMS of 85.6% and had a larger leaf area with an average of LAB of 2509.1 cm^2 than *S. psammophila*, which had an average PBMS and LAB of 81.9% and 1797.9 cm^2, respectively. The larger values of PBMS and LAB in *C. korshinskii* were observed for all BD categories (Table 1). Additionally, the larger PBMS helped to prevent the intercepted rain drops from falling off under windy conditions, which also benefited stemflow production in *C. korshinskii*.

5 Conclusions

Compared with *S. psammophila*, *C. korshinskii* produced a larger amount of stemflow more efficiently; an average 1.9, 1.3, 1.4, 1.6 and 2.5-fold increase in *C. korshinskii* was observed for the branch stemflow production (SF_b), the shrub stemflow depth (SF_d), the shrub stemflow percentage (SF%), the stemflow productivity (SFP) and the stemflow funnelling ratio (FR), respectively. The largest specific difference in stemflow production (SF_b, SF_d and SF%) and the production efficiency (SFP and FR) was during rains ≤2 mm, which were the most frequent rainfall events. Although the total amount of rainfall was limited, it was of great importance for *C. korshinskii* to survive and thrive, particularly during the extreme drought period. Additionally, the inter-specific differences in SF_b, SF_d, SF% and SFP were maximized for the 5–10-mm branches; this result was particularly significant because it encouraged young shoots by supplying more water.

Beneficial leaf traits, including a lanceolate and concaved leaf shape, a pinnate compound leaf arrangement, a densely sericeous pressed pubescence, an upward leaf orientation (MTA), a large leaf area (LAB), a relatively large number of leaves (LNB), a large leaf area index (LAI), a small individual leaf area (ILAB), and a large specific leaf weight (SLW), might be responsible for the superior stemflow production in *C. korshinskii*. Along with the canopy structure, these leaf traits may account for the lower precipitation threshold to initiate stemflow in *C. korshinskii* (0.9 mm) than in *S. psammophila* (2.1 mm). A lower precipitation threshold enabled *C. korshinskii* to harvest more water from rainfall via stemflow.

In conclusion, a higher and more efficient stemflow, a lower precipitation threshold and beneficial leaf traits provided *C. korshinskii* with greater drought tolerance and a competitive edge in a water-stressed ecosystem.

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Table captions

Table 1. Comparison of leaf traits, branch morphology and biomass indicators of *C. korshinskii* and *S. psammophila*.

Table 2. Comparison of stemflow production (SF_b, SF_d and $SF\%$) between *C. korshinskii* and *S. psammophila*.

Table 3. Comparison of stemflow productivity (SFP) between *C. korshinskii* and *S. psammophila*.

Table 4. Comparison of the funneling ratio (FR) for *C. korshinskii* and *S. psammophila*.

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Table 1. Comparison of leaf traits, branch morphology and biomass indicators of *C. korshinskii* and *S. psammophila*.

Plant traits		*C. korshinskii* (categorized by BD, mm)					*S. psammophila* (categorized by BD, mm)				
		5-10	10-15	15-18	>18	Avg. (BD)	5-10	10-15	15-18	>18	Avg. (BD)
Leaf traits	LAB (cm^2)	1202.7	2394.5	3791.2	5195.2	2509.1 ±1355.3	499.2	1317.7	2515.2	3533.6	1797.9 ±1118.0
	LNB	4787	11326	20071	29802	12479 ±8409	392	1456	3478	5551	2404 ±1922
	ILAB (mm^2)	25.4	21.3	18.9	17.5	21.9 ±3.0	135.1	93.1	72.6	64.3	93.1 ±27.8
	SLW (g cm^2)	126.4	126.0	125.7	125.6	126.0 ±0.3	95.6	74.5	63.0	58.1	73.9 ±14.5
	HV	0.0438	0.0513	0.0572	0.0615	0.0507 ±0.0064	0.0010	0.0009	0.0009	0.0009	0.0009 ±0.0001
Branch morphology	BD (mm)	8.17	12.49	16.61	20.16	12.48 ±4.16	7.91	12.48	16.92	19.76	13.73 ±4.36
	BL (cm)	137.9	160.3	195.9	200.7	161.5 ±35.0	212.5	260.2	290.4	320.1	267.3 ±49.7
	BA (°)	63	56	63	64	60 ±18	64	63	51	60	60 ±20
Biomass indicators	BML (g)	13.9	19.0	30.2	41.4	19.9 ±10.8	5.4	18.0	40.0	61.3	27.9 ±20.7
	BMS (g)	62.9	121.4	236.4	375.8	141.1 ±110.8	23.0	81.4	188.5	295.5	130.7 ±101.4
	PBMS (%)	82.0	86.3	88.7	90.0	85.6 ±3.1	80.8	81.8	82.5	82.8	81.9 ±0.8

Note: LAB and LNB are leaf area and number of branch, respectively. ILAB is individual leaf area of branch. SLW is the specific leaf weight, and HV was the Huber value. BD, BL and BA are average branch basal diameter, length and angle, respectively. BML and BMS are biomass of leaves and stems, respectively. PBMS is the percentage of leaf biomass to that of branch. The average values mentioned above are expressed as the means ± SE.

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Table 2. Comparison of stemflow production (SF_b, SF_d and $SF\%$) between *C. korshinskii* and *S. psammophila*.

Intra- and inter-specific differences	Stemflow indicators	BD categories (mm)	Precipitation categories (mm)						Avg.(P)
			≤2	2-5	5-10	10-15	15-20	>20	
Intra-specific differences in *C. korshinskii* (*CK*)	SF_b (mL)	5-10	10.7	29.8	73.5	109.9	227.6	306.1	119.0
		10-15	26.0	64.0	166.1	236.0	478.6	689.7	262.4
		15-18	44.3	103.3	279.9	416.6	826.0	1272.3	464.5
		>18	69.5	145.4	424.4	631.4	1226.9	1811.7	679.9
		Avg.(BD)	28.4	67.3	180.6	264.6	529.2	771.4	290.6
	SF_d (mm)	N/A	0.09	0.24	0.63	0.91	1.85	2.64	1.00
	$SF\%$ (%)	N/A	5.8	6.6	8.8	7.5	10.1	8.9	8.0
Intra-specific differences in *S. psammophila* (*SP*)	SF_b (mL)	5-10	2.8	8.9	28.8	47.2	66.5	120.0	43.0
		10-15	7.6	23.2	76.6	134.6	188.3	353.5	121.8
		15-18	12.0	35.9	121.6	223.4	319.4	592.6	201.5
		>18	16.2	52.3	165.5	289.2	439.6	860.4	281.8
		Avg.(BD)	9.0	28.0	91.6	162.2	234.8	444.3	150.3
	SF_d (mm)	N/A	0.01	0.11	0.48	0.89	1.27	2.23	0.78
	$SF\%$ (%)	N/A	0.7	3.0	6.1	6.8	7.2	7.9	5.5
Inter-specific differences (the ratio of the stemflow production of *CK* to that of *SP*)	SF_b	5-10	3.8	3.3	2.6	2.3	3.4	2.6	2.8
		10-15	3.4	2.8	2.2	1.8	2.5	2.0	2.2
		15-18	3.7	2.9	2.3	1.9	2.6	2.2	2.3
		>18	4.3	2.8	2.6	2.2	2.8	2.1	2.4
		Avg.(BD)	3.2	2.4	2.0	1.6	2.3	1.7	1.9
	SF_d	N/A	8.5	2.2	1.3	1.0	1.5	1.2	1.3
	$SF\%$	N/A	8.3	2.2	1.4	1.1	1.4	1.1	1.4

Note: BD is the branch basal diameter; P is the precipitation amount; *CK* and *SP* are the abbreviations of *C. korshinskii* and *S. psammophila*, respectively.

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Table 3. Comparison of stemflow productivity (SFP) between *C. korshinskii* and *S. psammophila*.

Intra- and inter-specific differences	BD categories (mm)	Precipitation categories (mm)						Avg.(P)
		≤2	2-5	5-10	10-15	15-20	>20	
Intra-specific differences in *C. korshinskii* (*CK*) (mL g^{-1})	5-10	0.20	0.56	1.37	2.04	4.18	5.60	2.19
	10-15	0.19	0.47	1.20	1.72	3.47	4.96	1.90
	15-18	0.17	0.38	1.05	1.55	3.08	4.74	1.73
	>18	0.15	0.35	1.00	1.46	2.95	4.35	1.62
	Avg.(BD)	0.19	0.47	1.21	1.78	3.60	5.08	1.95
Intra-specific differences in *S. psammophila* (*SP*) (mL g^{-1})	5-10	0.11	0.34	1.10	1.83	2.51	4.59	1.64
	10-15	0.08	0.25	0.82	1.43	1.98	3.72	1.29
	15-18	0.05	0.16	0.53	0.97	1.40	2.61	0.88
	>18	0.05	0.15	0.47	0.82	1.25	2.44	0.80
	Avg.(BD)	0.07	0.23	0.76	1.31	1.84	3.43	1.19
Inter-specific differences (the ratio of the SFP values of *CK* to that of *SP*)	5-10	1.8	1.7	1.3	1.1	1.7	1.2	1.3
	10-15	2.4	1.9	1.5	1.2	1.8	1.3	1.5
	15-18	2.8	2.4	2.0	1.6	2.2	1.8	2.0
	>18	3.0	2.3	2.1	1.8	2.4	1.8	2.0
	Avg.(BD)	2.7	2.0	1.6	1.4	2.0	1.5	1.6

Note: BD is the branch basal diameter; P is the precipitation amount; *CK* and *SP* are the abbreviations of *C. korshinskii* and *S. psammophila*, respectively.

Table 4. Comparison of the funneling ratio (FR) for *C. korshinskii* and *S. psammophila*.

Intra- and inter-specific differences	BA categories (°)	Precipitation categories (mm)						Avg.(P)
		≤2	2-5	5-10	10-15	15-20	>20	
Intra-specific differences in *C. korshinskii* (*CK*)	≤30	100.18	127.68	168.14	125.30	193.06	170.31	149.90
	30-60	125.89	133.77	178.5	157.84	205.19	182.07	164.65
	60-80	135.51	148.94	192.45	165.83	217.03	188.64	176.06
	>80	133.17	167.44	205.53	182.61	276.02	226.08	198.16
	Avg.(BA)	129.17	144.84	187.74	162.34	219.61	190.34	173.34
Intra-specific differences in *S. psammophila* (*SP*)	≤30	32.60	37.33	52.02	59.00	65.75	85.19	54.97
	30-60	34.50	43.44	65.67	70.63	77.74	92.28	64.78
	60-80	37.83	47.92	77.99	78.41	82.31	97.72	72.39
	>80	44.88	54.99	93.45	94.74	94.09	115.72	85.57
	Avg.(BA)	36.65	46.01	72.57	75.34	80.45	96.09	69.25
Inter-specific differences (the ratio of the FR values of *CK* to that of *SP*)	≤30	3.1	3.4	3.2	2.1	2.9	2.0	2.7
	30-60	3.7	3.1	2.7	2.2	2.6	2.0	2.5
	60-80	3.6	3.1	2.5	2.1	2.6	1.9	2.4
	>80	3.0	3.0	2.2	1.9	2.9	2.0	2.3
	Avg.(BA)	3.5	3.2	2.6	2.2	2.7	2.0	2.5

Note: BA is the branch inclined angle; P is the precipitation amount; *CK* and *SP* are the abbreviations of *C. korshinskii* and *S. psammophila*, respectively.

Figure captions

Fig. 1. Location of the experimental stands and facilities for stemflow measurements of *C. korshinskii* and *S. psammophila* at the Liudaogou catchment in the Loess Plateau of China.

Fig. 2. Comparison of leaf morphologies of *C. korshinskii* and *S. psammophila*.

Fig. 3. Verification of the allometric models for estimating the biomass and leaf traits of *C. korshinskii*. BML and BMS refer to the biomass of the leaves and stems, respectively, and LAB and LNB refer to the leaf area and the number of branches, respectively.

Fig. 4. Relationships of branch stemflow production (SF_b), shrub stemflow depth (SF_d) and stemflow percentage ($SF\%$) with precipitation amount (P) for *C. korshinskii* and *S. psammophila*.

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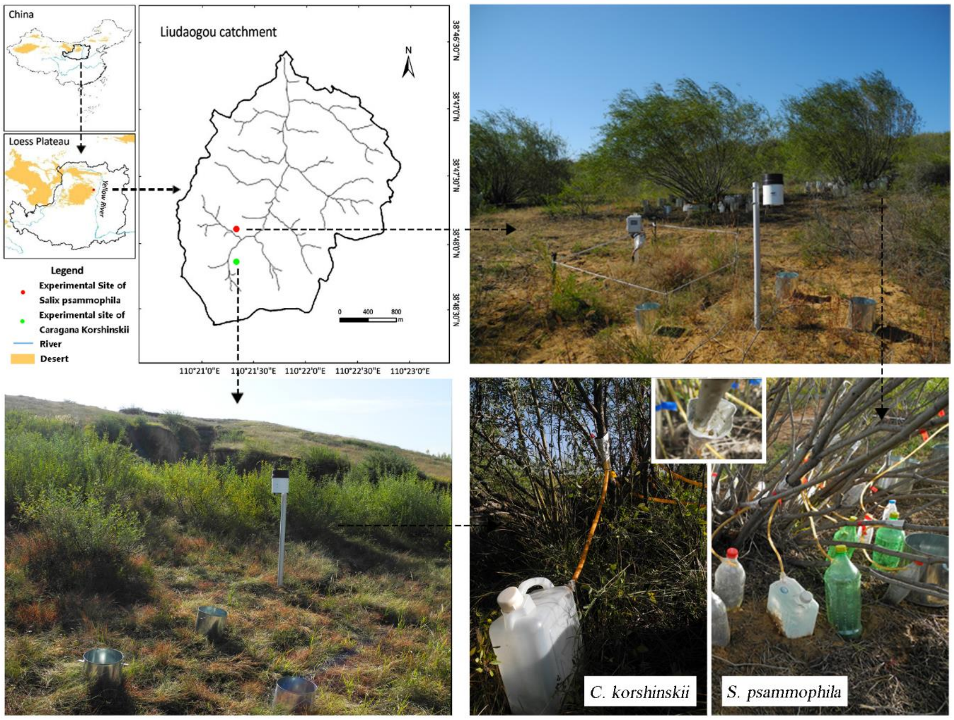

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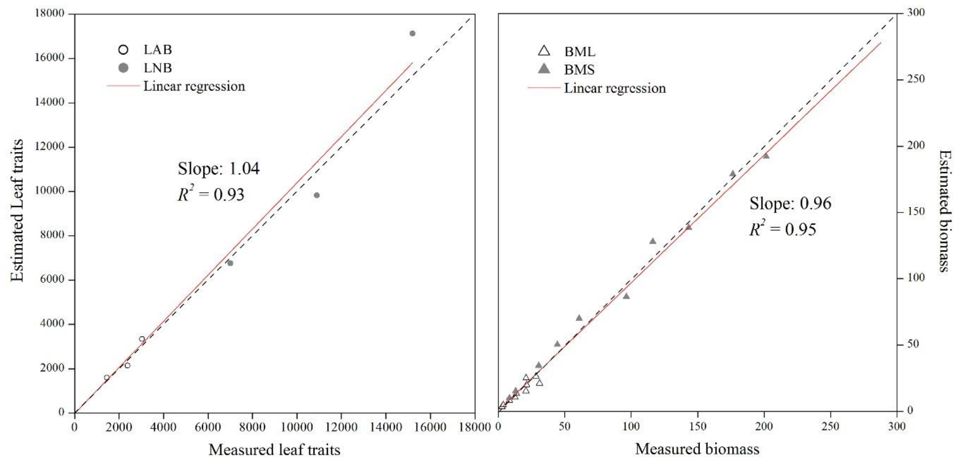

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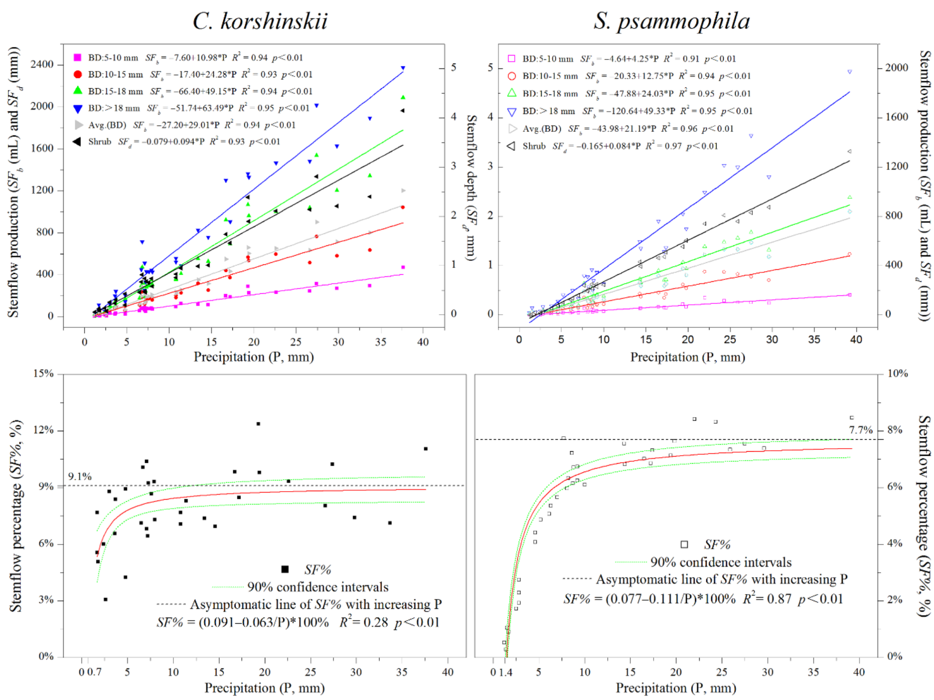

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